CONVECTION AND PRECIPITATION/ ELECTRIFICATION EXPERIMENT

(CaPE)

Scientific Overview
and
Preliminary Experimental Design

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1. INTRODUCTION

This document describes the motivation, scientific objectives, and preliminary experimental design of a field project called the Convection and Precipitation/Electrification (CaPE) experiment planned to take place in central Florida during the summer of 1991. The CaPE experiment is designed to focus on four objectives that have been the basis of extensive research activity in recent years. They can be broadly defined as follows:

Theme 1.	Identification of the relationships among the co-evolving wind, water, and electric fields within convective clouds.
Theme 2.	Development of mesoscale numerical forecasts (2–12 hr) of wind, clouds, and thunderstorms, employing data assimilation.
Theme 3.	Improving techniques for performing short-period forecasts (nowcasts, < 2 hr) of convection initiation, downbursts, and tornadoes.
Theme 4.	The characterization of precipitation particles and remote estimation of rainfall.

The first theme has the goal of understanding the aspects of precipitation growth and charge transfer leading to cloud electrification and lightning production. The topic is of great practical as well as scientific interest. Lightning, for example, is the number one hazard to space launches, and stringent launch criteria are currently employed by NASA to minimize electrical hazard. The proposed research would represent one of the first attempts to combine multi-Doppler wind fields, microphysical retrievals using a multiparameter radar, and detailed microphysical and electrical measurements to study lightning phenomena.

The second theme involves the use of a mesoscale model to develop the capability of 2–12 hr forecasts over central Florida. This requires refinements and testing of model physics (e.g., precipitation parameterizations, surface energy budget model, cumulus parameterization schemes) and development and testing of algorithms for assimilating multiple data sources such as satellite and radars as well as rawinsonde and surface mesonet data.

The third theme is composed of two parts:

a) Predicting where and when convection will develop and subsequently decay;

b) Once convection begins, whether it has the potential to produce damaging winds, lightning, and heavy rainfall.

With regard to part (a), it is interesting that although meteorologists are capable of producing good forecasts for the 12–48 hr period of the potential of convection over large areas (e.g., forecasts issued by the National Severe Storms Forecast Center in Kansas City), the desired ability to make accurate mesoscale and site-specific forecasts over correspondingly shorter lead times has not been achieved.

Part (b) of this objective is related to the research of Theme 1 and involves gaining a better understanding of convective storm processes.

The fourth theme is one of great practical importance, that of determining quantitative precipitation totals. Current multiparameter radar techniques have shown promise in revealing microphysical characteristics within clouds that previously could only be determined by aircraft penetrations, and that need to be known to reduce the uncertainty in rainfall estimation using radar reflectivity factor alone.

Given these objectives, an important question arises: Why have the experiment in central Florida? Central Florida is an ideal location for the CaPE experiment for several reasons:

- The central Florida area has the highest annual number of days with thunderstorms in the United States (Court and Griffiths, 1986) almost assuring a large number of case studies.
- The regularity of the boundary layer forcing by sea breeze fronts leading to convection and considerable electrical activity makes it difficult to identify a better geographic area to address themes 1, 2, and 3.
- As discussed later in Section 3, other field programs will be operating in central Florida. One of the programs will be at Orlando in support of the FAA mission to warn major airports of weather events which will affect aircraft operations. Another is an ongoing effort by NASA to provide improved meteorological support for space vehicle launches at the Kennedy Space Center (KSC). The proposed CaPE network will significantly enhance existing mesonets associated with these programs, thus benefiting all participants.
- The Melbourne, Florida office of the National Weather Service will receive one of the first NEXRAD radars, and is enthusiastic about working with the scientific community on nowcasting problems as part of the NWS modernization effort.

The success of the CaPE experiment depends on multi-agency interest and support. Complementary programs by the FAA, NWS and KSC have already been mentioned. Another important research effort by NASA is the Tropical Rainfall Measuring Mission

(TRMM) (Simpson et al., 1988). This proposed satellite program will require testing of rain retrieval algorithms. The deployment of the CP-2 multiparameter radar during the CaPE experiment will play a major role in establishing validation measurements.

In order to improve short-term forecasts in support of spacecraft operations, NASA has implemented a fairly extensive mesonetwork surrounding the KSC (both conventional measurements and electric field measurements). The augmented surface network and state-of-the-art radars proposed for the CaPE experiment will provide a unique opportunity for both KSC personnel and the NWS Melbourne meteorologists to participate in nowcasting experiments, and for other project scientists to understand better the operational forecast problems. This arrangement should partially satisfy some of the recommendations made by the National Research Council (NRC, 1988) in regards to meteorological support for Space Shuttle operations.

The FAA has an interest in the nowcasting of thunderstorms and windshifts as it impacts terminal and en route operations. The CaPE experiment will aid this effort by testing nowcasting techniques previously developed for other locations (Dodge et al., 1986; Wilson et al., 1988).

The Air Force plans to operate a three-dimensional interferometric lightning imaging system being developed in France by the Office National d'Etudes et de Recherches Aerospatiales (ONERA) over the Cape Canaveral area. In addition, the Air Force Office of Scientific Research has approved a research initiative in atmospheric electricity beginning in fiscal 1991, with the primary objective of understanding the process of charge generation in clouds.

The National Science Foundation has an interest in the basic research objectives summarized above and expanded upon in the following section. With the combined support of the NSF, Air Force, FAA, NASA, and NWS, the CaPE experiment can be accomplished at a reasonable expenditure level for each agency.

2. RESEARCH OBJECTIVES

2.1 Electrification

Evidence from both laboratory and field studies strongly suggests that the non-inductive ice-ice collision process may be the primary mechanism of cloud electrification. Laboratory studies (e.g., Jayaratne et al., 1983) show that charges up to 100 femto-Coulombs can be transferred when an ice crystal collides with a simulated graupel that is undergoing riming when supercooled liquid water is present. When supercooled water is not present, the charge transfer per ice-ice collision is more than two orders of magnitude less. In the cold-base clouds of New Mexico and the high plains, Dye et al. (1985) and Dye et al. (1989) found that precipitation development preceded electrification by tens of minutes, and that ice particle concentrations of 10 to 100 per liter, millimetric graupel, and supercooled water coexisted at mid-levels in the cloud at the onset of electrical intensification. In these geographical regions, precipitation formation is dominated by the ice process. In Florida and in other parts of the southeastern U.S. where cloud bases are much warmer, precipitation can form via coalescence before the freezing level is reached. Goodman et al. (1989) used multiparameter radar to investigate warm-base clouds in Alabama, and found that lightning first occurred only after ice (probably graupel) was detected. There was no evidence of lightning until ice appeared, even though reflectivities in excess of 60 dBZ existed from large water drops. Although the association between the appearance of ice and the onset of electrification was strong, there were no in-situ measurements that could have established more definitively the microphysical characteristics of the clouds, nor were there coordinated measurements of electric field to determine the relationship between the region containing ice and regions of charge within the cloud.

In Florida, which has the highest annual lightning flash rate in the U.S., previous programs have investigated separately (e.g., FACE and TRIP) either the microphysical or electrical properties of clouds, but coordinated microphysical, electrical, and air-motion measurements have not been made. The laboratory and field measurements suggest that if the non-inductive process is correct, the most important regions for microphysical charge separation are those in which graupel, many ice particles, and supercooled water coexist. Updrafts are also necessary to provide a continuing supply of liquid water and to provide the time and framework necessary for graupel growth and macroscale gravitational charge separation. Current technology planned for CaPE provides the following capabilities: (1) multiparameter and Doppler radars to infer large-scale microphysical characteristics and three-dimensional air motions; (2) airborne in-situ measurements to identify the detailed microphysical and electrical structure in the limited volume sampled by the aircraft, and to substantiate microphysical conditions inferred from the radar measurements; (3) surface, balloon, and rocket measurements of electric field to determine the structure and evolution of the electric field; and (4) interferometer and electric field change networks to determine the occurrence and characteristics of the electrical discharges. While these components individually could contribute to our understanding of electrification in the Florida area, if we are to determine the locations within a cloud that has become electrified and the microphysical and dynamic conditions in that region, it is essential to tie the electrical measurements to the microphysical (both airborne and radar) measurements and air-motion measurements. The CaPE program, in conjunction with the ongoing electrical measurements at KSC, will bring together a more complete complement of measurements than has previously been assembled and should provide substantial new insight into the mechanisms of cloud electrification.

In addition to the surface network of electrical field mills at Kennedy Space Center, there are two ongoing studies underway that will be very beneficial to the CaPE effort; the Rocket Triggered Lightning Program (RTLP) and the Airborne Field Mill Project (ABFM). The main objective of the RTLP is to determine the meteorological conditions necessary and/or sufficient to initiate and propagate a triggered lightning discharge. The CaPE program should be immensely helpful in this effort. The French interferometer is part of the RTLP and the identification of lightning sources and channels will be very helpful to the electrification studies of CaPE. Likewise the interaction with the ABFM program (that has as its main objective, obtaining in-situ electric field measurements in a variety of cloud types to determine a climatology of clouds in which marginal electrification might be sufficient to trigger lightning artificially) and the CaPE electrical effort will be mutually beneficial and important. CaPE can provide microphysical measurements that are lacking in the ABFM, and the ABFM with the NASA/Langley Lear jet will help identify the electrical structure in the upper parts of clouds. Other efforts that will be important for the electrical studies are the lightning location networks and the surface electric field network. Other efforts that may be funded by the Air Force initiative include a new technique for determining lightning channels and structure from field changes, VHF information by the University of Florida, and balloon-borne electric field measurements by the University of Mississippi and NSSL.

2.2 4-D Data Assimilation and Mesoscale Forecasting

One of the major problems in mesoscale forecasting is that of obtaining sufficient input data on the mesoscale to produce realistic initial conditions for the forecast model. This is particularly true of a tropical or semi-tropical region such as central Florida where deep cumulus convection is the predominant weather type. On undisturbed days the sea breeze circulation is the main factor in generating deep convection. Under such conditions the experience is that mesoscale prediction of sea-breeze generated convection is reasonably straightforward as long as the model has sufficient resolution and can simulate the complex surface energy budget of swamp and land regions over the peninsula.

The problem is that with the limited number of standard NWS soundings over the Florida peninsula, weak oceanic synoptic and mesoscale disturbances can move into the region without being detected in the initial data input into the model. Therefore, a reliable, general purpose mesoscale model must have the capability of ingesting mesoscale data from a variety of sources such as satellite, Doppler radar, wind profilers, and conventional data.

The proposed experiment is an excellent opportunity to gain experience in assimilating multiple data sources in the Regional Atmospheric Modeling System (RAMS) developed at Colorado State University (Tripoli and Cotton, 1989) in an environment dominated by convective weather systems. The radar network will provide an excellent opportunity for determining storm winds and precipitation structure. The wind data can be directly inserted into the model, while the precipitation data can be used to infer latent heating rates which can then be ingested in the model. The previous CSU experience of assimilating wind-only data has demonstrated that it is necessary to infer somehow the thermal field along with the wind field; otherwise the assimilated winds are readily rejected by the model. Thus, the possible inference of cloud heating rates from a multiparameter radar along with other thermodynamic data from satellite and soundings is essential to the improvement of mesoscale forecasting.

The RAMS model will be configured to provide an optimum representation of the central Florida region. This will include multiple-nested fine-scale grids with detailed parameterizations of surface characteristics. The model will be used to simulate the observed convergence patterns and subsequent boundary layer deformations leading to the initiation of deep convection. In so doing, and as a second objective, the capabilities of the model as a practical regional operational forecasting system in the 2–12 hr time frame will be assessed (and, if necessary, possible further requirements will be considered). The latter objective is a continuation of the operational experiments performed at the KSC during 1987 (Lyons et al., 1987).

The region of the Kennedy Space Center is an ideal test site as the terrain is rather simple and for the most part the weather is relatively simple as well (i.e., synoptic-scale baroclinic disturbance are relatively infrequent). As mentioned previously the major difficulty is that weather disturbance over the ocean are poorly resolved. The focus of the proposed research is to minimize this problem. The testable hypothesis is that initializing a mesoscale model with data from platforms such as Doppler radars, a polarimetric radar, and wind profilers, will make cumulus convection predictable. This hypothesis can be examined by running the CSU RAMS in near real time and comparing the results with the data collected on actual convective events.

2.3 Short-Term Forecasts

2.3.1 Convection initiation

Exciting advances have occurred in the last few years regarding the ability to make time and space specific:

1) 2–12 hr sea breeze thunderstorm initiation forecasts (Lyons et al., 1987);

2) 0–2 hr forecasts of convective storm initiation (Wilson and Schreiber, 1986);

3) 0–60 minute forecasts of lightning and wind shifts (Watson et al., 1987).

The advances represented in the work of Wilson and Schreiber can be attributed in large measure to the ability of sensitive Doppler radar to monitor convergence lines in the optically clear boundary layer. The great majority of work of this type has taken place in the High Plains of eastern Colorado and has resulted in the operational testing of nowcasting activities (including microburst and tornado prediction) for the aviation system at Denver's Stapleton Airport and the general public. Forecasters from NCAR, NOAA/PROFS and the Denver NWS have participated in these experiments. Fig. 1 shows the results of probability forecasts for >30 dBZ storms occurring within a 10 km radius circle centered on Stapleton Airport. The results are from a nowcasting experiment conducted by NCAR during the summer of 1988 (Mueller and Wilson, 1989). These forecasts include the processes of storm advection and initiation, and outperform those based on either extrapolation or persistence.

There is a strong scientific and operational forecasting desire to test this technology in other climatic areas. Satellite (Purdom, 1982), mesonet (Watson et al., 1987) and modeling (Pielke, 1974) studies indicate that convective storms in Florida are initiated by sea-breeze fronts and gust fronts. The use of Doppler radar to monitor these convergence lines should improve the nowcasting of thunderstorms and tornadoes as demonstrated in Colorado. Investigation of the evolving boundary layer structure and its influence on the development of convective storms was one of the goals of the Convection Initiation and Downburst Experiment (CINDE) conducted near Denver, Colorado in 1987 (Wilson et al., 1988). It is proposed now that the CINDE work be extended to the humid, near-tropical environment of central Florida. The underlying hypothesis is that, under weak synoptic forcing, boundary-layer convergence zones and their interaction with horizontal convective rolls determine when and where convection will initiate. In particular, even though the atmosphere may be convectively unstable, storms will not form in the absence of these boundaries. Testing this hypothesis will require (1) sensitive Doppler radars that can detect clear-air motions, (2) thermodynamic soundings from fixed and mobile platforms, and (3) aircraft measurements in the boundary layer. Listed below are specific proposed studies:

a. Investigate the origin of boundary layer convergence lines that lead to the development of thunderstorms. These lines include river and sea breeze fronts, thunderstorm outflows, horizontal convective rolls, synoptic fronts, gravity waves, topography and vegetation-generated thermodynamic contrasts.

b. Investigate the horizontal and vertical structure of the convergence lines and the effect of this structure on storm development. In particular, details of the airflow in the vicinity of the convergence lines, the thermal contrast across the convergence lines, and the depth of the convergence zone in relation to storm

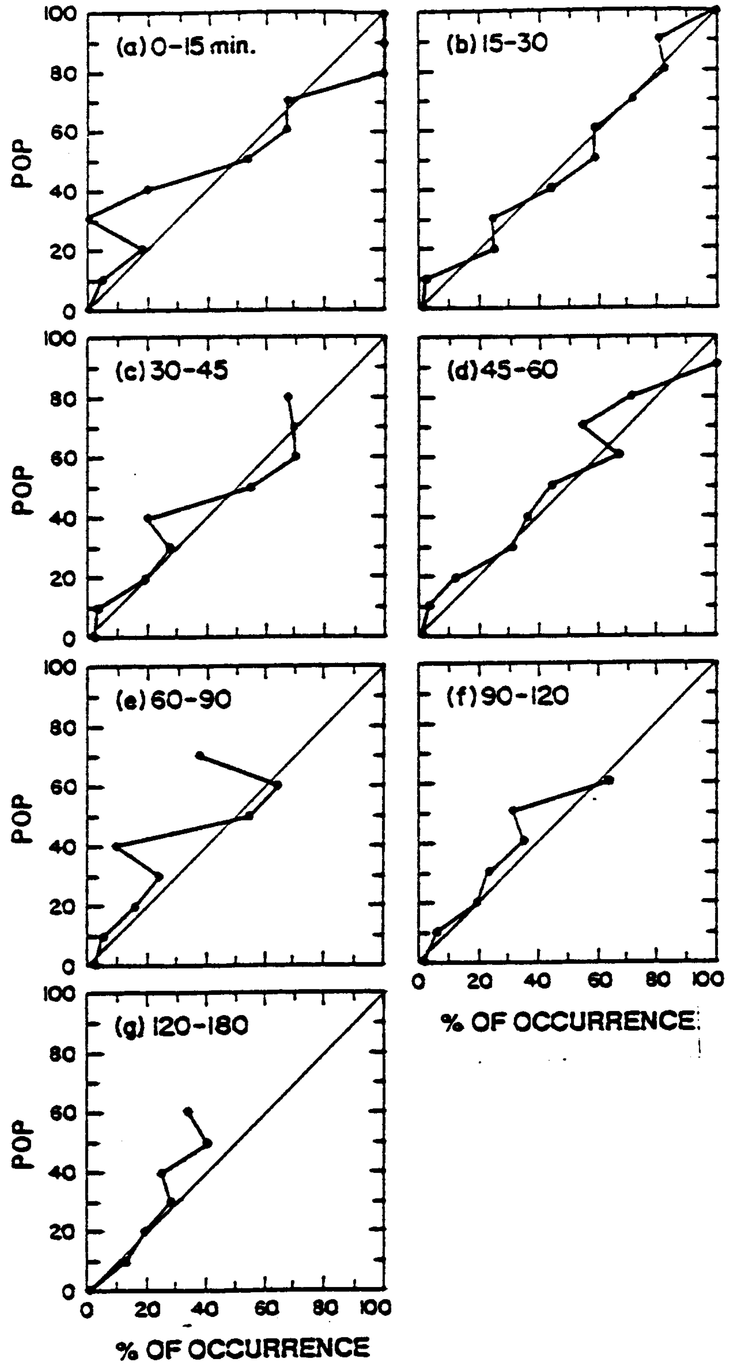


Fig. 1 Results of probability of precipitation (POP) forecasts versus percent of observed precipitation for each of seven forecast intervals (time period indicated in upper left corner). The forecast area was for a 10 km radius circle and precipitation was defined as the presence of a radar precipitation echo > 30 dBZ at 1 km height (from Mueller and Wilson, 1989).

development will be studied. It is desired to test the hypothesis of Rotunno et al. (1988) that the ambient low-level vertical wind shear is an important factor in determining if new convection will be initiated along a convergence line. Based on experience in CINDE, two King Air aircraft will be necessary to determine the structure of the convergence lines with sufficient space and time resolution.

c. Investigate the role of horizontal convective rolls, interacting convergence lines and the interaction of both horizontal rolls and convergence lines on precise location and initiation of storms.

d. Study the factors controlling storm evolution and investigate means to predict intensity changes. Previous work has concentrated primarily on forecasting storm initiation and it is apparent that considerable improvement in forecasting storm evolution, including dissipation, is required.

e. Conduct a joint experiment with NCAR, NASA/AF and NWS on short period (0–1 hr) forecasting of thunderstorm occurrence. This experiment would be conducted at the KSC forecast office.

The latter experiment would be patterned after similar nowcasting projects carried out in Denver for aviation weather (Mueller and Wilson, 1989). Operational forecasters from both the National Weather Service at Melbourne and Air Force forecasters from KSC would participate in the experiment along with NCAR research scientists. It is also planned to integrate NOAA personnel who have been developing operational lightning forecasts at KSC (Watson et al., 1987). The approach of mixing research and operational forecasters in the same experiment has previously proved very beneficial to both groups in experiments in Colorado; it is one of the important objectives of STORM-Central and the Center for Operational Meteorology, Education, and Training (COMET). With the planned deployment of the NEXRAD radar (Milner, 1986) in Melbourne, Florida by December 1990, an exciting opportunity for intercomparisons with the NCAR research radars is also possible. Critical in this study will be evaluation of the algorithms that are being implemented on the new operational radars and their ability to detect boundary layer convergence lines.

2.3.2 Downbursts

Knowledge about downburst/microburst phenomena associated with cold-based clouds where ice processes dominate was advanced considerably by the JAWS Project (McCarthy et al., 1982) and CINDE, particularly the low reflectivity or virga microburst (Wakimoto, 1985). However, the high reflectivity microburst more typical of humid regions requires additional research.

The MIST Project (Dodge et al., 1986) operated in the summer of 1986 in Alabama, and was an important step in improving our understanding of this type of microburst.

However, only one case was thoroughly documented (Wakimoto and Bringi, 1988). Analyses at two times for this case, the 20 July storm, are shown in Fig. 2. The study revealed several aspects of the forcing of the downdraft. Initially, the descent of the main precipitation core decelerated the strong updraft. This observation is consistent with the suggestion that the descending core signals the beginning stages of the downdraft (Roberts and Wilson, 1989). Once the precipitation core descended several kilometers and passed through cloud base into the dry adiabatic sub-cloud layer, negative vertical velocities developed. The precipitation core was no longer co-located with the developing downdraft owing to the increased role of evaporative cooling. This can be seen in Fig. 2, as the downdraft center is not co-located with the highest reflectivity below cloud base at 1325 CST.

The dynamic and microphysical factors that differentiate microburst from non-microburst producing storms are not known and require further study. From the analysis shown in Fig. 2, it might seem surprising that the majority of storms do not produce microbursts, since the visual evolution shown in Fig. 2 is common to many storms not producing strong wind shear events. Interestingly, Fujita (personal communication) has determined, based on a search of all anemometer data in Florida during the Thunderstorm project, that no microburst was recorded in the dense mesonet of that experiment.

In recent years, there have been several numerical modeling efforts that have hypothesized that the amount and, most importantly, the type of precipitation will determine the convective downdraft and outflow intensity, given the same environment (Srivastava, 1985, 1987; Knupp, 1989; Proctor, 1989). It is proposed to test that hypothesis with high resolution multi-Doppler analyses combined with multiparameter radar data and in-situ aircraft measurements. The high occurrence of thunderstorms over Florida should provide a reasonable number of case studies (see Sec. 4 for a short discussion of the storm climatology).

In addition, the details of the microphysical processes in microburst and non-microburst storms are still poorly understood. Using a 1–D model, Srivastava (1987) has shown the importance of the inclusion of melting in driving the low-level downdraft. However, equally important is the latent heat released by freezing, invigorating the updraft and hence, altering the storm structure and eventual precipitation core that forms. The CP–2 radar is expected to play a large role in studying this problem.

2.3.3 Tornadogenesis

Observational studies based predominantly in Oklahoma have led to an improved understanding of the rotating thunderstorm known as the supercell. These storms are associated with the most intense tornadoes. However, the recent work of Wakimoto and Wilson (1989) has led to a greater awareness of tornadoes not spawned by supercells. The

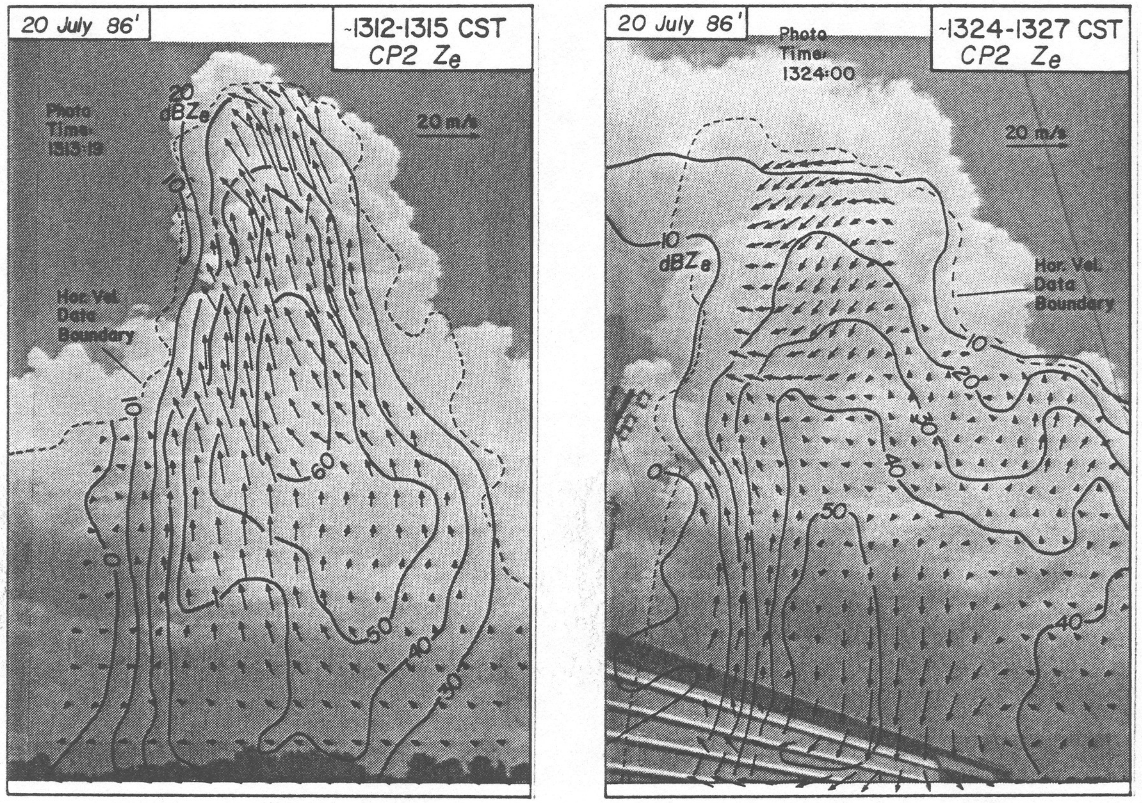


Fig. 2 Multi-Doppler analysis of the 20 July storm during the MIST Project. At ≈ 1313 CST, the main precipitation core has begun to descend as the updraft decelerates. The beginning stages of a strong microburst is evident at ≈ 1325 CST. Note the displacement between the downdraft center and the 50 dBZ contour.

schematic model of Wakimoto and Wilson is shown in Fig. 3. In the beginning stage, the horizontal shear across the convergence boundary has resulted in low-level shearing instabilities labeled A, B, and C. At the same time, cumulus clouds have formed over the boundary owing to the forced uplift. The clouds continue to develop as the small vortices propagate along the boundary in the middle stages. In the final stage, vortex C has co-located with the updraft of a towering cumulus and developed into a tornado under the influence of vortex stretching. Recently, Crook et al. (1989) have proposed that these small scale vortices may not be shear instabilities but develop as a result of the interaction of boundary layer horizontal convective rolls with the convergence boundary.

These non-supercell tornado studies were based entirely in Colorado and the application of the resulting concepts to other geographic areas needs to be determined. Interestingly, Fig. 4 shows that the frequency of tornadoes at Orlando exceeds that at Oklahoma City. It is hypothesized that these weaker tornadoes (and waterspouts) are not spawned from supercells, which are not common in the region, but rather form via the mechanism shown in Fig. 3. This hypothesis can be tested in an experiment in central Florida by collecting high resolution dual-Doppler data at low levels combined with the surface and upper-level thermodynamic data. In addition, the mechanism proposed by Crook et al. can be examined with the data listed above plus detailed aircraft mapping of the boundary layer. If the above hypotheses are correct then it will be of some interest to develop algorithms to identify these low-level vortices, and the early deployment of the NEXRAD radar at Melbourne, Florida (scheduled to be the second to come on line) will be of great value.

2.4 Microphysics of Warm-Based Storms and Rainfall Estimation

2.4.1 Large raindrops in first echoes

It has only been in the last few years that multiparameter radar techniques have been used to understand the microphysical evolution in warm-based convective clouds (e.g., Illingsworth, 1988; Wakimoto and Bringi, 1988) such as those that occur over central Florida. One important observation has been the unusually high values of differential reflectivity (Z_{DR}) that have been detected within storms in their early echoing stage (10–30 dBZ). The Z_{DR} technique, which is summarized in Fig. 5, sends pulses at two different polarizations (horizontal and vertical) to determine the shape and precipitation type within storms.

These large Z_{DR} values in early echoes have been interpreted as regions of large (> 4 mm) raindrops at very low concentrations ($<1\ \mathrm{m}^{-3}$) (Caylor and Illingsworth, 1987). Combining multiparameter measurements with aircraft penetrations will not only confirm this observation but also determine the evolution of the raindrop size distribution in

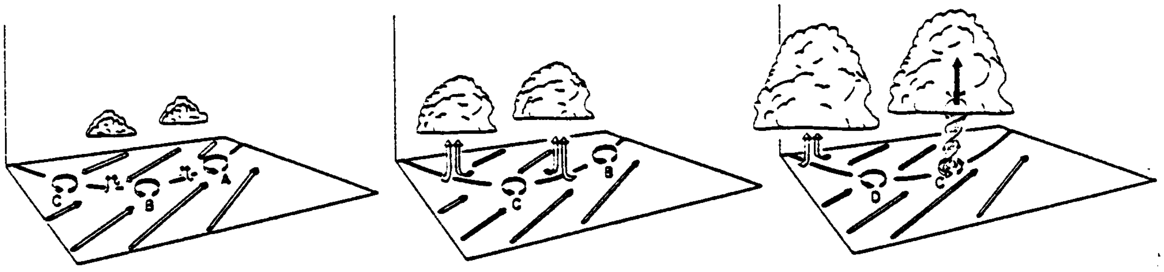


Fig. 3 A schematic model of the evolution of the non-supercell tornado. The black line represents the convergence boundary. A, B, and C denote the locations of the low-level shear vortices.

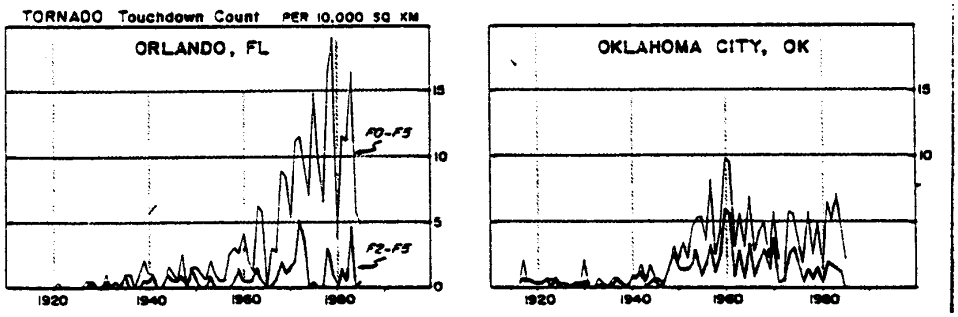


Fig. 4 Tornado touchdown count for Orlando, Florida and Oklahoma City, Oklahoma. The thin black line represents the total number of tornadoes (F0 - F5) and the thick black line represents the stronger ones (F2- F5). Based on calculations from Fujita.

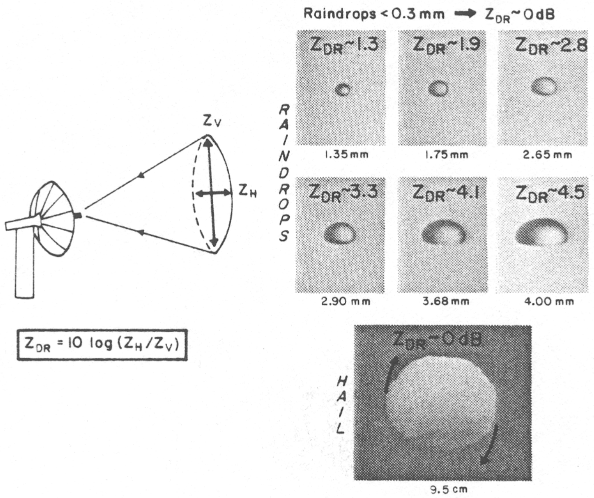


Fig. 5 Summary of typical Z_{DR} values for raindrops of various sizes and hail. These values are based on the median volume diameter. Measuring Z_{DR} is one capability of a multiparameter radar.

these warm-based clouds. Both observations are important for parameterizing microphysical data as input to mesoscale model simulations addressing quantitative precipitation forecasting.

The hypothesis is that first echoes with unusually large values of differential reflectivity consist of a very low concentration of large raindrops which form on ultra-giant nuclei present in low background concentrations. The first part of this hypothesis can be tested using CP–2 radar measurements and aircraft penetrations.

2.4.2 Remote detection of cloud glaciation

The onset of ice formation in clouds appears to be central to the process of thunderstorm charging, as previously discussed. The ice process also plays a pivotal role in determining the total precipitation production, the precipitation efficiency of storms, and the amount of condensate entering the anvil. In certain cases the latent heat of fusion can also alter important aspects of the storm's dynamics and life cycle. It is therefore of great interest to characterize the longevity and extent of supercooled raindrops aloft, and to examine more critically the details of the glaciation process. The hypothesis in CaPE is that the temporal evolution of vertical profiles of polarimetric radar variables such as differential reflectivity, linear depolarization ratio, X-band attenuation and differential propagation phase shift can be used to detect and quantify the onset of drop freezing, secondary ice crystal production and mixed-phase zones. The approach will be to combine wind fields with multiparameter radar data and aircraft data collected at different altitudes.

2.4.3 Multiparameter-radar measurement of rainfall

The estimation of area-wide rainfall from radar reflectivity measurements has received a great deal of attention (see, e.g., Battan, 1973). The addition of microwave polarization techniques in recent years has increased greatly the accuracy with which such measurements should be possible. Preliminary results suggest that for low rain rates, <20 mm hr^{-1}, a reflectivity-rainfall (Z–R) relation is optimum; for moderate rain rates (20–80 mm hr^{-1}) a Z–Z_{DR} method is optimum, while for rain rates in excess of 80 mm hr^{-1}, a technique called the differential propagation phase shift K_{DP} (Sachidananda and Zrnic, 1986) is optimum. In addition, Jameson (1983, 1989) suggests that rainfall rate can be estimated using dual-wavelength data; that is, using reflectivity at 10-cm wavelength combined with attenuation at 3 cm. Because a multiparameter radar has the advantage that all of the measurements are made over identical sampling volumes, valid internal comparisons can be made among the results from all the different techniques.

Recently, List et al. (1987) have argued that equilibrium drop size distributions should be observable in intense and persistent rain. Zawadzki and Antonio (1988) used a disdrometer to show that equilibrium distributions can be observed but that they need not be unique. Multiparameter radar observations can be used to remotely sense equilibrium distributions since these distributions have the same shape but are scaled by the rain water contents. Thus, for equilibrium distributions, differential reflectivity should be nearly constant while the X-band attenuation and differential propagation phase shift (K_{DP}) should be nearly proportional to the rain water content.

Recent advances in multiparameter radar techniques enable the determination of rain and ice contributions to the total reflectivity of mixed-phase regions (Golestani et al., 1989). Such regions of mixed-phase precipitation exist below the melting level but can also exist aloft due for example to wet growth of hail and the associated shedding of water drops, and during the glaciation-transition period.

In contrast to the suggested use of multiparameter data as input into numerical models, the goal of this objective is that of real-time quantitative precipitation measurement. As discussed in Sec. 2.4.4, it is anticipated that the TRMM complement of rain-measuring instruments will be flown on a NASA high altitude aircraft (ER–2) over the "ground-truth" network, and that coordinated measurements with the CP–2 radar would be extremely useful in evaluating the TRMM rain algorithms (Meneghini and Atlas, 1986). It is proposed that CP–2 data be coupled with vector microwave radiative transfer models for intercomparison with dual-polarized multi-frequency radiometers flown on the NASA high altitude aircraft. These studies will further enhance our understanding of the relationships between cloud radiative and microphysical-dynamical processes (Simpson et al., 1988). In addition, these rainfall estimates will be compared with predicted precipitation totals from the mesoscale numerical models. The key hypothesis is that a multiparameter radar will significantly improve the retrieval of rainfall rates.

2.4.4 Radiometer measurements from a high altitude aircraft

The CaPE experiment affords an opportunity to use the NASA ER–2 aircraft to meet an obvious requirement for additional high resolution microwave data sets over precipitating cloud systems. The goals are to understand the relations among black-body temperature (T_B), rain rate, and cloud structure, and to test multi-channel rain algorithms. There is a very strong need for data over oceanic, convective systems, such as occur to the east of KSC. Although some excellent data above cloud systems over land were obtained during COHMEX (e.g., Adler et al., 1990; Spencer et al., 1989), no oceanic data over deep convective systems were collected. This type of data is required because the oceanic systems can be quite different in terms of vertical velocity and microphysics. Both factors are critical to understanding the cloud/remote sensing relations and to conducting accurate retrievals of rainfall. There are also serious questions to answer concerning rain/no rain boundaries and the effect of cloud water on retrievals.

The scientific objectives can be summarized as:

1. Documentation of T_B, cloud structure and rain relations in convective systems over land and water with special emphasis on oceanic cloud systems;
2. Verification of cloud model calculations and their use in simulating aircraft and satellite observations (this is accomplished using the coupled cloud model/microwave radiative transfer model approach);
3. Verification of rain and rain structure algorithms. High resolution microwave data sets are important for testing algorithms without the non-linear spatial averaging effect of the satellite field-of-view;
4. Other objectives related to remote sensing of soil moisture and vegetation.

It is hypothesized that the vertical structure of oceanic deep convective systems (to four or five levels) can be retrieved using multi-frequency passive microwave data using techniques such as that developed by Kummerow et al. (1989). The CaPE data set will be crucial to test this idea, with the CP–2 radar being used to verify the results. The ER–2 9.6 GHz Doppler radar will also be useful in verifying the passive retrievals and to develop algorithms combining active and passive observations to retrieve rain amounts and rain structure. On occasion a King Air will provide additional radiative measurements below thunderstorm anvils and stratiform regions.

3. CaPE NETWORK DESIGN

In order to attain the objectives listed in Sec. 2, a preliminary network design has been assembled and is shown in Figs. 6 and 7. The following is a list of the CaPE equipment requirements:

- CP–2 (multiparameter), CP–3, and CP–4 Doppler radars.
- 60 PAM (Portable Automated Mesonet) stations.
- 6 CLASS (Cross-chain Loran Atmospheric Sounding System). Four will be at fixed sites and two will be mobile.
- 2 King Air aircraft, T–28, ER–2, "Explorer" sailplane.

There are several other instrumented aircraft being proposed, including high performance Lear jets used mainly for detailed electrical measurements, a second ER–2 involved with studies of stratosphere/troposphere exchange and the radiation budget of storm anvils, and a P–3 aircraft involved with TRMM-related studies. Their status should be known in the near future.

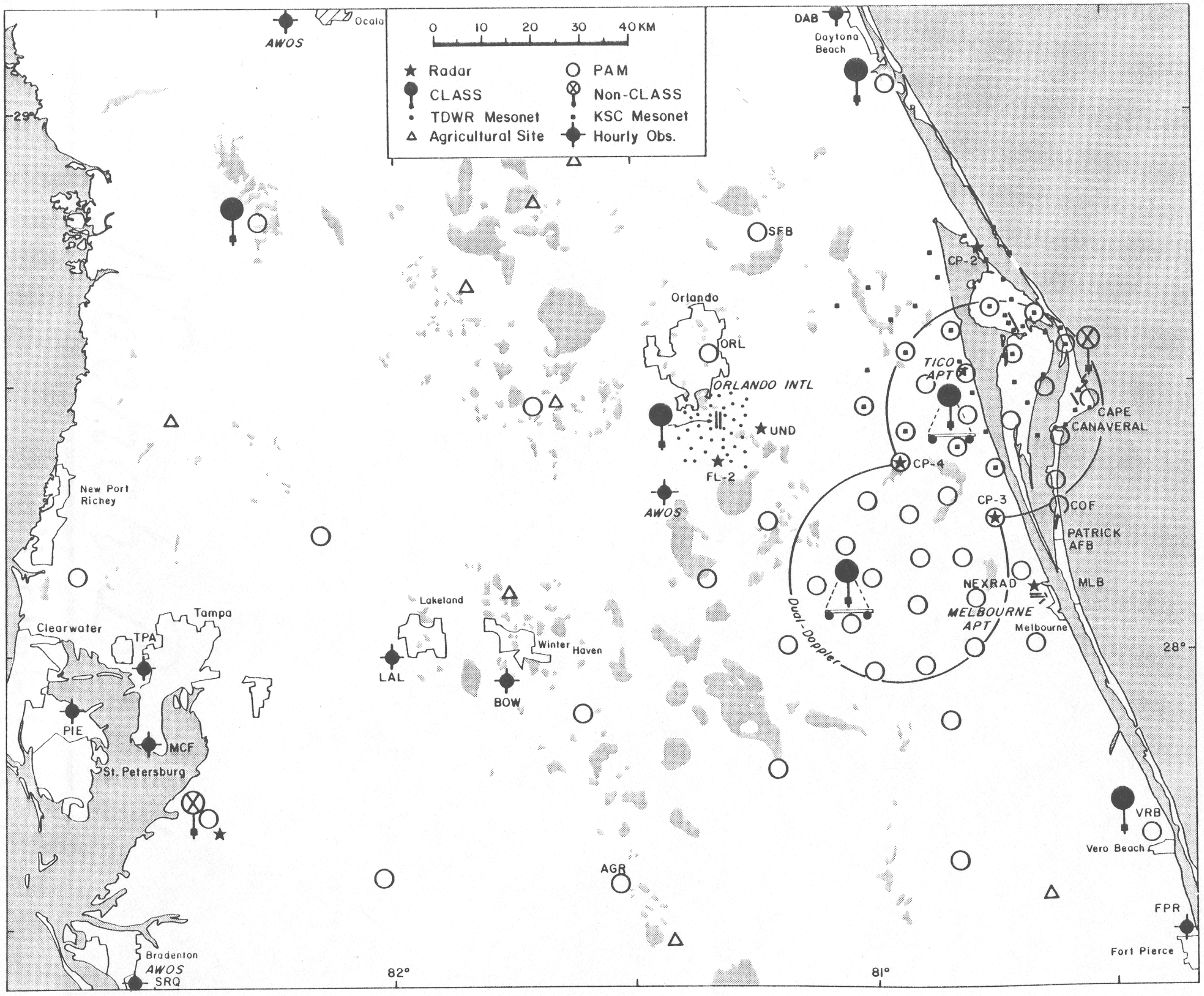
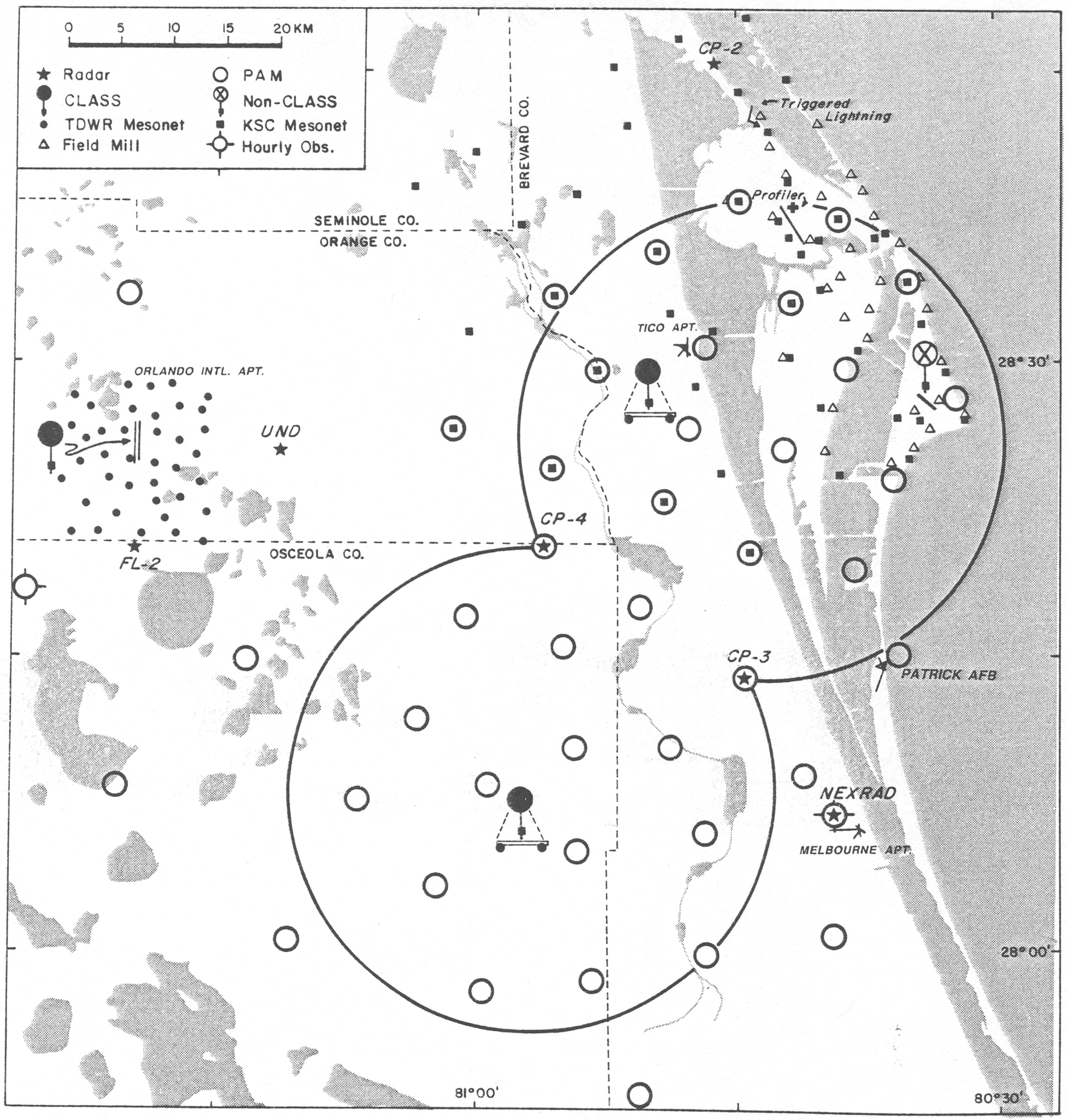


Fig. 6 Proposed CaPE observation network. Areas shaded in gray represent water. The interlocking circles represent the ≥ 30 degree dual-Doppler scanning region between CP-3 and CP-4. The legend indicates the various observing systems. The two CLASS sounders within the dual-Doppler lobes are mobile.



CAPE Network

Fig. 7 Enlarged version of Fig. 6 focusing on the primary experimental area.

There are two other networks that will be deployed during the summer of 1991 that supplement the CaPE network. The Kennedy Space Center (KSC) is surrounded by a fairly dense network of wind anemometers as shown in Figs. 6 and 7. In association with the Terminal Doppler Weather Radar program (TDWR), two Doppler radars will be located near the Orlando International Airport. The locations of these (FL–2 and UND) are shown along with the area where approximately 40 mesonet stations will be densely distributed for microburst detection.

The primary dual-Doppler radars will be CP–3 and CP–4, while the CP–2 radar will be used to supplement the reconstruction of the kinematic wind fields, but more importantly, to obtain the best possible vertical resolution of the storm microphysical structure.

4. FIELD EXPERIMENT SCHEDULE

Neumann (1971) has shown that June, July, and August are the peak months for thunderstorms in Florida, with roughly 50% of the days at any one location reporting thunder. We have selected a seven week period (8 July–23 August) during this maximum for the field phase. For the months of July and August the weather stations at Kennedy Space Center, Orlando, and Melbourne report thunderstorms on the average on 47%, 56% and 60% of the days, respectively.

Based on data from a network of magnetic direction finders over central Florida, Holle et al. (1988) have examined the frequency of lightning flashes. Their data show that thunderstorms are most common from about 1200 to 2000 EST, with the peak between 1400 and 1700. Numerous observational and theoretical studies have shown that the interaction between the synoptic wind field and the sea-breeze circulation determines the timing and location of convective activity across the Florida peninsula. Watson et al. (1990) have shown that with on-shore flow along the east coast, the sea breeze convergence zone develops early, but the circulation is relatively weak. In this situation, the sea-breeze front moves a considerable distance inland. The convection tends to be relatively weak also, developing along the coast during the morning and inland during the afternoon.

In contrast, when there are off-shore low level winds, the convergence zone develops later, but the circulation is stronger. In this case the convergence line remains quasi-stationary near the coast line and the most active thunderstorms tend to be along this boundary. When the low-level synoptic winds are parallel to the coast line, the sea- breeze circulation and convection are similar to calm wind situations; sea-breezes form on both coasts and move inland and eventually collide. In this case the primary activity is first along the coasts then later in central Florida. Based on the above, the plan in CaPE is to conduct normal operations from 1000 to 1900 EST, with earlier start times likely under conditions of synoptic scale low-level easterly flow.

5. PRELIMINARY EXPERIMENTAL DESIGN

The following is the preliminary experimental design for the CaPE program, to be followed later this year by an operations plan that describes more complete and detailed data collection strategies for each experiment.

5.1 Radar Network

The CP–3 and CP–4 radars form a dual-Doppler network with a baseline of 23 km (Fig 7). An extensive search was made to find these sites, which allow for unobstructed views above 0.0 to 0.5° in essentially all directions. For the studies of convection and tornado initiation, winds with high resolution in time (2–3 min) and space (150–400 m) throughout the boundary layer are essential. These radar sites are nearly ideal for this purpose.

For the control of the overall experiment, and nowcasting in particular, it will be necessary to obtain 360° PPI scans about once every 6 min from CP–3. These scans would be used to monitor boundary layer convergence lines and storm growth at elevation angles of about 0.5, 2.0 and 5.0°. One minute would be required to complete the 3 scans. These scans would be transmitted via a T1 line to the CaPE Field Control Center (FCC) and to the AF/NWS/NCAR nowcasting experiment site at KSC.

Prior to deep convection a dual-Doppler sector containing convergence lines or horizontal convective rolls would be selected for scanning. Generally both CP–3 and CP–4 would perform coordinated dual-Doppler scans to a height of about 4 km with a planned volume scan period of 2.5 min. This would allow for a horizontal and vertical spacing of radar beams of less than 1°. The scan limits, scan speeds, and sampling rates would be determined at the FCC by a scan optimization program. Scan parameters would then be sent by the optimization program via phone line to each radar.

The synthesized horizontal and vertical winds will be used to quantify the evolving three-dimensional structure of the divergence profiles and vertical motion profiles associated with convergence lines and resulting cloud and storm growth. The wind fields will also be used to study the role of horizontal convective rolls which intersect the convergence lines in determining storm spacing and in generating misoscale vortices that may eventually become tornadoes.

Once storms develop in the dual-Doppler lobe, scanning would be altered to reach storm top so that winds could be obtained throughout the entire storm in accordance with the needs of those conducting lightning, downburst, tornado, storm evolution and multiparameter radar studies. For a 15-km high storm centered in the field mill network around Cape Canaveral it would be possible to obtain data at 1° intervals to storm top.

The primary function of CP–2 will be to collect multiparameter data for lightning, microphysical and rainfall measurement studies. CP–2 should have dual-wavelength (3 and 10 cm), linear depolarization ratio and Z_{DR} capabilities. As discussed earlier, these measurements have been shown to be highly successful in determining the bulk microphysical characteristics of precipitation. In particular, the mixed phase regions of water and ice are thought to be critical for charge transfer and separation in thunderstorms. The multiparameter data together with other electrical measurements planned will provide a unique data set.

The proposed location of CP–2 is north of the field mill network (Fig. 7), so that data can be collected over the field mills without scanning a large range in azimuth, and so that measurements can also be made of rainstorms over the ocean. CP–2 would scan in combined RHI and PPI modes. The scans would be coordinated with CP–3 and CP–4 so that the multiparameter measurements can be set within the framework of dual-Doppler wind fields during analysis. Over much of the field mill network the CP–2 Doppler data could be combined with the CP–3 and CP–4 data to obtain triple Doppler wind estimates to improve vertical velocity measurements in the upper levels of the storms. The three radars can then be used to measure the co-evolving wind and microphysical fields to test electrification theories.

Prior to storm development, CP–2 would be scanned primarily at low elevation angles to increase the coverage area of multiple-Doppler winds for the convection initiation studies.

5.2 PAM

A network of 55 PAM stations is planned and will be deployed on two scales. Approximately 40 of the stations will be concentrated in the dual-Doppler lobes with an average spacing of about 10 km. The stations in the northeast lobe overlap with the KSC anemometer network, thus providing a spacing in that region of about 5 km for wind observations. Since the KSC network measures primarily wind, the density of moisture and temperature measurements is not increased. PAM stations will be co-located with KSC stations at several sites to provide wind observations at both the 10 m (PAM) and 16 m (KSC) heights. The remaining 15 PAM stations will be deployed across the peninsula of central Florida in order to monitor the position of sea breeze fronts and outflow boundaries outside of the region covered by the radars. The real-time data are expected to be useful not only for the conduct of CaPE field operations, but also for the NWS Forecast Offices at Melbourne and Tampa, and for the NWS/AF/NCAR nowcasting experiment. Existing conventional weather stations, FAA AWOS stations and agriculture stations may supplement this statewide network but the data may not be available in a form to incorporate in the PAM display.

The PAM rainfall data will be used to supplement the existing operational rain gage networks and special rain gages for the TRMM program to assist in the studies of rainfall measurement by radar.

5.3 Sounding Network

A network of four stationary CLASS and two mobile CLASS is planned. Efforts are underway to supplement these with soundings from the NWS at Tampa and West Palm Beach, and from the Air Force at Cape Canaveral. Airsounde and acoustic sounders have also been requested from the Air Force. Soundings would be released at 3 hourly intervals at 11, 14, 17, 20 and 23 GMT. A primary use of these soundings would be to initialize mesoscale numerical models for forecasting convective storms over the region.

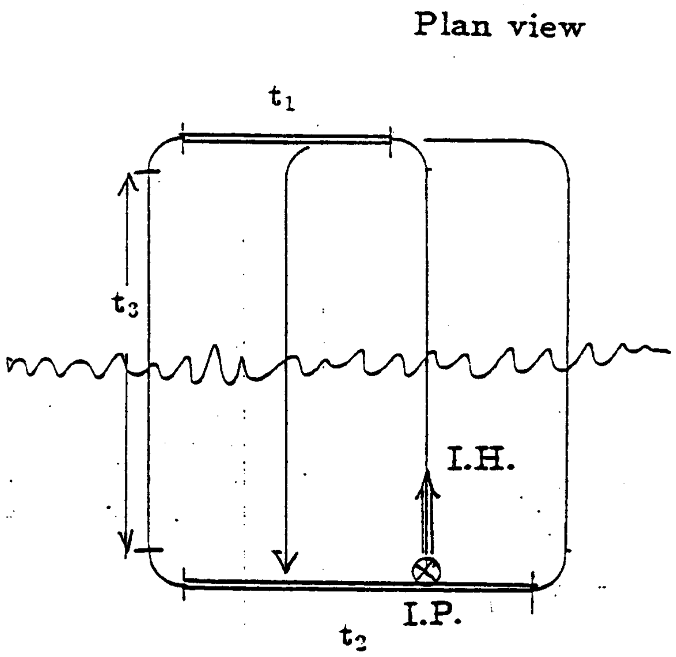
Two mobile CLASS stations would be operated within the dual-Doppler lobes. Their purpose would be to sample conditions on either sides of convergence lines and to monitor local stability changes generated by the convergence lines. The wind profiles would be used to assess the importance of vertical wind shear in the boundary layer on new storm development. Attempts would also be made to obtain soundings in the updrafts of newly developing storms to document the thermodynamics of air feeding the storm updrafts.

The mobile CLASS vehicles would be directed via radio from the operations center. It is proposed that the CLASS sounding data be transmitted back to the operations center via satellite for near real-time display and analysis, and to monitor data quality.

5.4 Aircraft

Two King Air aircraft, one operated by NCAR and the other by the University of Wyoming, will be essential to the convection initiation studies. Fig. 8 shows possible flight patterns for a quasi-stationary convergence line prior to storm development. The two aircraft would fly coordinated box patterns, labelled CI-1, across the convergence line. The legs perpendicular to the convergence line should be 20–30 km long while those legs parallel to the line should be about 15 km long, sufficient to cross at least three convective horizontal rolls. One aircraft would fly the box patterns at heights equivalent to the convergent and non-divergent regions of the boundary. The second aircraft would fly directly above, in the divergent region. The purpose here is to monitor with high spatial and temporal resolution the evolution of the kinematic and thermodynamic fields in the region of the convergence lines prior to and during storm growth.

Fig. 9 shows a generic flight plan for cases in which emphasis is to be placed on vertical structure, such as with a moving gust front or sea breeze. In this case the aircraft fly in a stacked mode making repeated passes across the front with altitude changes after each pass. An attempt will be made to sample Kelvin-Helmholtz waves that may be present



t_1	t_2
1 min	1′ 50″
1′ 15″	2′ 15″
1′ 20″	2′ 40″

$t_3 = (2\text{–}5 \text{ min})$

Fig. 8 Flight pattern CI-1, designed to map boundary-layer conditions across radar-detected clear-air boundaries (squiggly line). Flight track begins at an initial point (I.P.) with an initial heading (I.H.), both of which are determined in consultation with an Aircraft Coordinator in the Field Coordination Center (FCC). Flight legs oriented normal to the boundary may be 2 to 5 min in duration (12 to 30 km in length). Separation between cross-line legs is determined by flight time t_1 (see table at right), that also uniquely defines t_2 when standard-rate turns are incorporated.

Pattern CI-1 is designed to provide horizontal mapping both along and across convergence boundaries. When flown simultaneously by two or more aircraft in stacked, in-train formation, it provides vertical resolution as well. Vertical separation in such a mode could be as small at 500 ft. A simplified version of the CI-1 flight track would be to fly repeated box-shaped patterns without regard to the times, line-parallel legs.

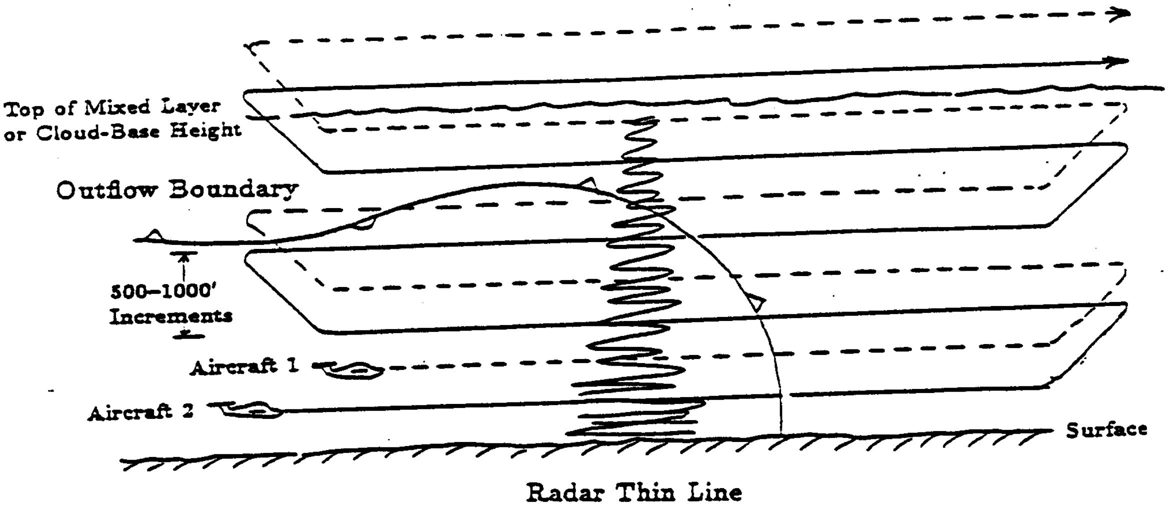


Fig. 9 Flight pattern CI-2. This is a generic pattern designed to measure the vertical structure of the boundary layer across clear-air convergence lines and/or outflow boundaries. Factors determining the spatial coverage and the flight time required to obtain a complete boundary-layer profile are: (1) the length of the horizontal legs, (2) the number of available aircraft, (3) the vertical spacing between them, and (4) the depth of the mixed layer.

Typical leg length will be 30 km and minimum vertical separation between aircraft flying a stacked in-train formation will be 500 ft. Climatology indicates that the boundary depth will vary from about 1 to 2 km.

along the top of the density current and examine what role they may play in the initiation of storms.

During the towering cumulus stage of storm development, the project aircraft will make repeated cloud penetrations at various levels, using a simple "figure 8" pattern, a "race-track" pattern, or the rosette pattern shown in Fig. 10a (the data there are from the 1987 CINDE experiment). Fig. 10b shows the vertical profile of a developing cloud. Initially, the two King Air aircraft would be present as a continuation of their convection initiation flight patterns. One King Air would remain at cloud base to monitor conditions there, while the second would start cloud penetrations at specified altitudes. As the cloud grows, other aircraft would be added to the stack as the situation warrants. The sailplane will be released from tow and enter the growing cloud through its side, while the T–28 and possibly a Lear jet would make repeated cloud penetrations. The T–28 would emphasize the mixed-phase region between 0 to –15°C, and the Lear would fly near the cloud top.

Electric field data from airborne field mills and the KSC field mill network will be used to determine when the King Air aircraft, which are susceptible to lightning damage, should be withdrawn from the cloud. The operations center, in conjunction with a designated lead airborne scientist, will coordinate which aircraft are involved in a particular study.

In well developed thunderstorms, the T–28 and Lear jet are the primary platforms for in-situ measurements, since the King Airs must stay clear of lightning. Fig. 11 shows three variations of proposed flight plans to monitor the electrical and microphysical development of mature storms. The ER–2 will attempt to overfly storms in the Doppler network, and in some cases one King Air will be directed to fly under the storm anvil, in coordination with the ER–2, and make measurements of the up and downwelling infrared radiative flux.

5.5 Photography

Photography is planned from five sites: CP–2, CP–3, and CP–4, and two other sites with good visibility along the coast, one near Cape Canaveral and the other near Cocoa Beach. Both 8 and 16-mm movie cameras and 35-mm slide cameras will be used. The purpose is to document cloud positions, growth rates, and sizes during their life cycle. This is particularly valuable for convection initiation studies prior to detection of clouds by radar.

5.6 Field Control Center

The experiment will be directed from the Field Control Center that will be located at either the Melbourne National Weather Service or TICO airport near Tittusville (pending final decision on where the aircraft will be hangared). It will be housed in the two MOCCA vans described by Wilson et al. (1988). Seven positions for coordinating operations will

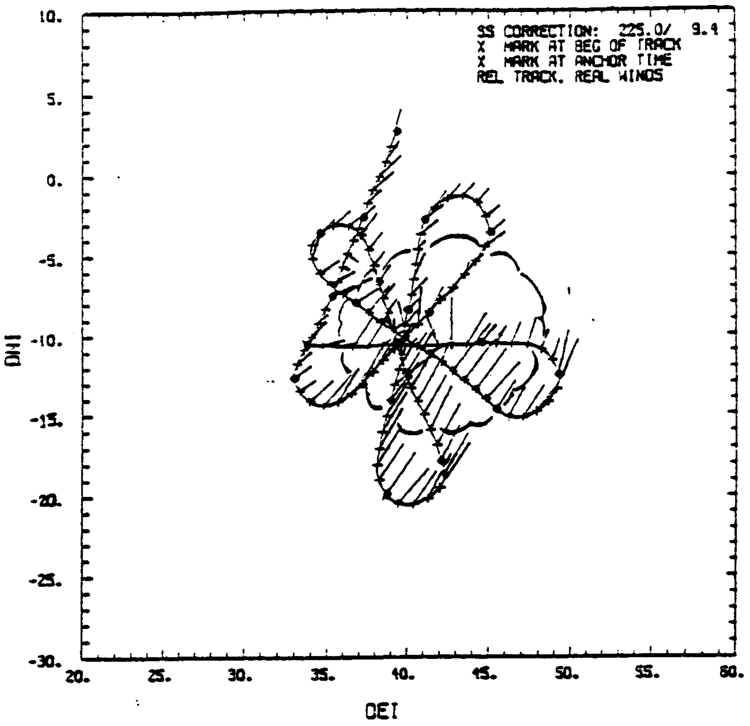


Fig. 10a Example of the horizontal flight pattern to be flown by both King Airs in studies of developing cumulus and cumulus congestus (cloud boundaries are sketched schematically). The example shown was flown while tracking a persistent cloud feature using on-board "pointer" software to direct the aircraft, as is proposed in the CaPE experiment. The basic "rosette" pattern results when the horizontal drift of the cloud system is subtracted from the aircraft ground speed in post-flight analysis.

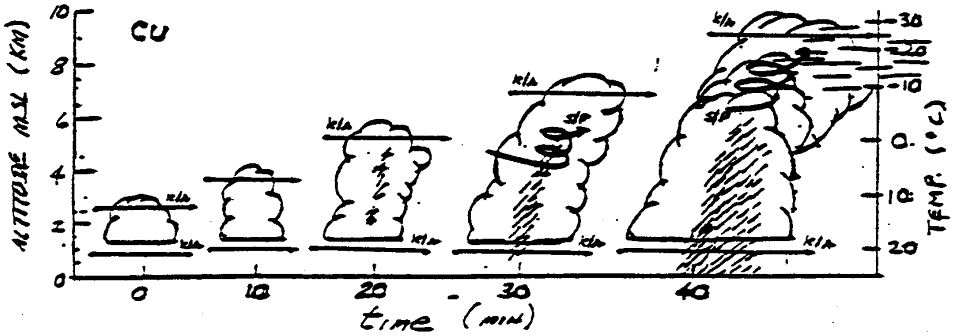


Fig. 10b An example of the basic profile for kinematic, microphysical and electrical studies of developing cumulus and cumulus congestus (CU patterns). Snapshots of cloud development are sketched at 10-min intervals and approximate height and temperature scales are given on the left and right, respectively. In the example shown, the King Airs fly the rosette pattern, illustrated in Fig. 10a, to monitor conditions at cloud base and cloud top, while the sailplane enters from the side to investigate microphysical and electrical development.

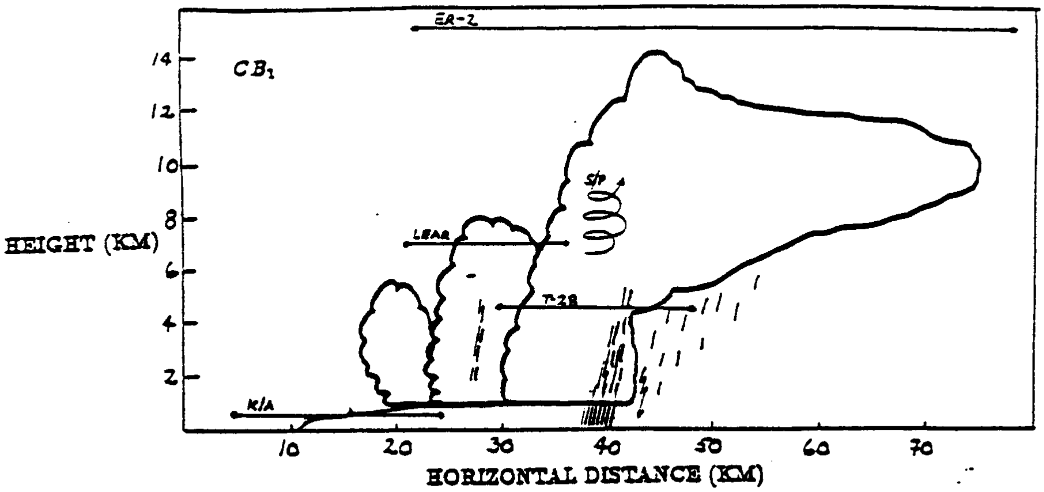


Fig. 11a. Pattern CB-1 with the King Airs flying across the outflow boundary away from potential lightning and heavy rain regions. Patterns would be similar to those designed for the CI studies. The ER-2 will always fly well above cloud top, but the sailplane (S/P), the Lear Jet, and the T-28 could be deployed at varying levels above cloud base near and within the storm.

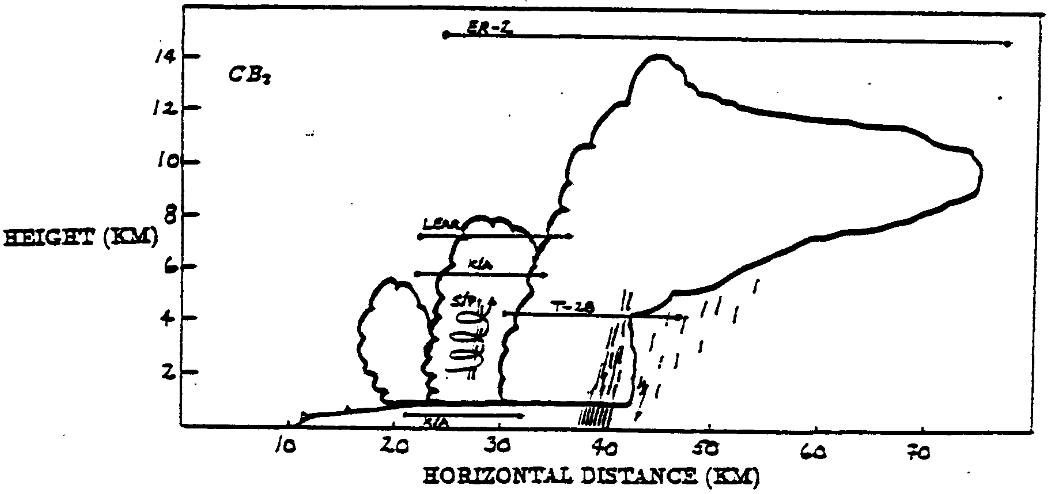


Fig. 11b. Pattern CB-2 with the King Airs flying either racetrack or rosette patterns in developing cumulus towers adjacent to a mature storm using patterns similar to those used in the CU experiments.

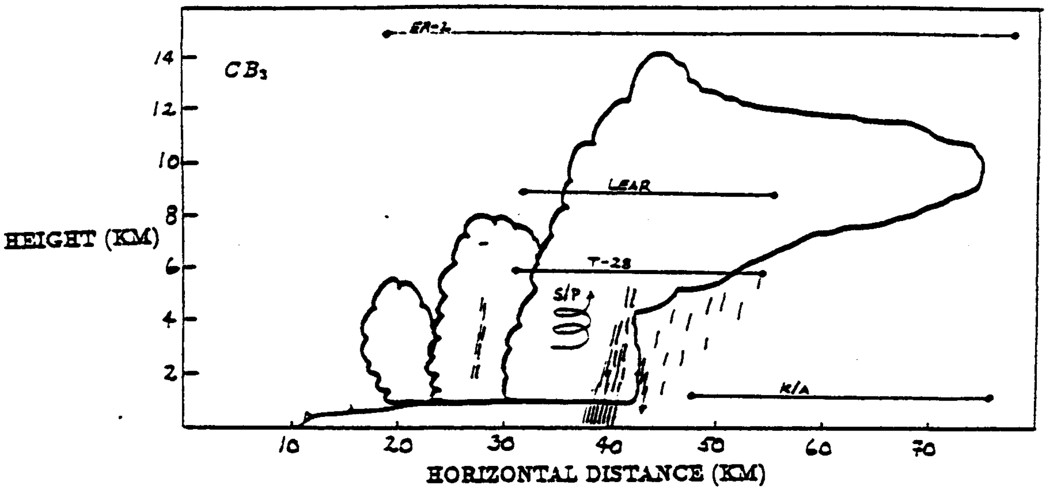


Fig. 11c. Pattern CB-3 in which the King Air(s) may fly at various levels under the anvil of a mature storm to obtain infrared measurements in support of the TRMM rainfall estimation studies.

be available within the FCC. They are (1) Operations Director who oversees and coordinates the overall field program, (2) project analyst/nowcaster who provides nowcasts and advice on experiments to be considered based on the developing weather, (3) radar coordinator/optimizer who executes the scan optimizer program and directs radar scanning, (4) sounding and photography coordinator, (5) two aircraft coordinators, and (6) a scientist monitoring the electrical activity of the network and coordinating that part of the program.

CaPE investigators are working with the NCAR Research Data Program and Research Applications Program to develop the necessary communication hardware and workstations to conduct these tasks. Both of these groups have developed workstations that provide many of the capabilities necessary to run the program effectively. In CaPE it will be essential to anticipate storm development in order to concentrate observing facilities on the proper locations. For this reason a nowcasting capability is required with access to a high resolution radar display with time lapse capabilities. Also necessary for this function is satellite imagery of clouds. The satellite data will be obtained from a McIdas-type workstation termed MIDS that will be provided by the Air Force. Also since it is necessary to direct sounding crews and aircraft to specific areas of interest, it is necessary to have an accurate and simple means for plotting their location and easily communicating with them. Control of radar scanning from the FCC is highly desirable to ensure accurate coordination.

6. DATA MANAGEMENT IN CaPE

Data collection, data archives, and data distribution are critical aspects of any research program, and CaPE is no exception. Problems in any of these areas will jeopardize the success of the program. In order to ensure the success, a number of data management activities must be carried out. These activities range from overall data management planning to field data management and archival and distribution of data collected during the program.

CaPE will be the first major field experiment to utilize some of the new observing capabilities envisioned for the national STORM program, most notably NEXRAD radar. The STORM Project Office can gain valuable experience with these data by participating in CaPE, and is developing plans to coordinate the data management activities.

A preliminary investigation indicates that plans for the disposition of data from many of the systems proposed for use in CaPE are well in hand. However, plans for others require considerably more development. The following table presents a summary of current plans for proposed systems, along with the organization responsible for archival and distribution of data. Potential problem areas and data sets without currently planned archival centers are noted with an asterisk.

Data Collection Systems and Cognizant Organizations.

	NETWORK	ORGANIZATION
SURFACE		
	PAM	NCAR/ATD
	FLOWS Mesonet	Lincoln Labs
	KSC Anemometers	Air Force
	Operational NWS (hourly)	*
	ASOS/AWOS	*
	Air Force	Air Force
SOUNDINGS		
	CLASS	NCAR/ATD
	Profiler	NASA/Marshal
	Operational NWS	*
	Air Force	Air Force
	Acoustic Sounders	Air Force
RADARS		
	CP-2, CP-3, CP-4	NCAR/ATD
	FL-2	Lincoln Labs
	UND	Univ. of North Dakota
	NEXRAD	STORM Project Office
	Lightning and Electrical Data	Air Force
AIRCRAFT		
	Aircraft data will be archived and distributed by each aircraft's parent organization.	
SATELLITE		NESDIS

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