Genesis of Atlantic Lows Experiment (GALE): An Overview

Abstract

The field phase of the Genesis of Atlantic Lows Experiment (GALE) was conducted from 15 January to 15 March 1986. The objectives of GALE were to study mesoscale and air-sea interaction processes in East Coast winter storms, with particular emphasis on their contributions to cyclogenesis. The project area, special observing systems, and field operations are described. There were thirteen special observing periods during the field phase including eight cases of cyclogenesis. Meteorological and oceanographic phenomena on which special observations were collected include: cyclogenesis, rainbands, cold fronts, coastal fronts, cold-air damming, jet streaks, tropopause folding, low-level jets, cold-air outbreaks, lightning, and marine boundary layer interactions with Gulf Stream and mid-shelf oceanic fronts. Preliminary research findings and operational implications are presented. GALE data documents are listed. The GALE data set is open to all interested scientists.

1. Introduction

Major winter storms, characterized by “crippling” ice, heavy snow, and gale-force winds, often batter the East Coast from the Carolinas northward. These storms cause unfortunate loss of life and annually cost an average of more than a billion dollars in property damage. Memorable examples include the President’s Day snowstorm of 18–19 February 1979, which deposited 60 cm of snow on the middle Atlantic States, the 6–7 April 1982 snowstorm and windstorm in which more than 50 people lost their lives, and the 11–12 February 1983 blizzard with record-breaking snowfalls and freezing rain that paralyzed the northeast and caused 70 deaths.

In particular, those cyclones that develop rapidly just off the Carolina coast and move northward along the coast are often the most poorly predicted by current numerical forecasting models. It is believed that this is at least partly due to an inadequate understanding of subsynoptic-scale and air-sea-interaction processes within these storms and to a lack of data on space and time scales commensurate with their development.

The past decade has seen some significant advances in our understanding of extratropical cyclones and their associated fronts, and in the development of numerical models capable of reproducing some observed synoptic and mesoscale features of these systems. There remain, however, many gaps in our knowledge. For example, little is known about the dynamical-coupling mechanisms between the jet stream and lower-level frontogenesis and cyclogenesis, the role of boundary-layer processes in frontogenesis and cyclogenesis, the contributions of air-sea interaction and Gulf Stream heating to storm energetics, the effects of cloud processes and precipitation processes on the dynamics and evolution of cyclones and fronts, the role of turbulent processes in the vertical transport of heat and momentum, the changes of potential vorticity and the dissipation of kinetic energy within cyclones, the nature of the interactions between mesoscale and microscale processes, and the role of gravity waves in organizing precipitation elements. It also is not known whether conceptual models of the organization and structures of mesoscale rainbands in mature cyclones that have been documented on the West Coast of the United States and in the United Kingdom apply to earlier stages of developing cyclones; the degree to which numerical models can reproduce mesoscale structures in cyclones also has received comparatively little attention.

In September 1979 the challenges and opportunities for extratropical-cyclone research were first crystallized in a workshop held in Seattle, Washington. A National Academy of Sciences committee and panel further recommended enhanced research efforts on extratropical cyclones, with particular emphasis on the analysis and interpretation of data from new field projects.

In September 1982 a group of university scientists (representing Drexel University, Massachusetts Institute of Technology, North Carolina State University, State University of New York, and University of Washington) informally met to consider field-study plans for East Coast storms and initiated the program that later would become known as the Genesis of Atlantic Lows Experiment (GALE).*

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3 The selection of the particular area and time period for the GALE field program was based on the results of climatological studies of winter cyclones and cyclogenesis. There is a distinct maximum in the frequency of winter cyclones on the East Coast along a “wide band” centered on Cape Hatteras (Colucci, 1976), with the maximum monthly frequency of cyclones occurring from January to March (Whittaker and Horn, 1981). (Many of the cyclones that develop south of Cape Hatteras, along the Carolina Coast, develop “explosively” and exhibit strong frontogenesis.) Kocin and Uccellini (1984) examined the characteristics of 18 storms that deposited major snow accumulations within the Washington–Boston corridor. The paths of surface low-pressure centers for nearly all of these storms passed through the coastal region of the Carolinas and many secondary lows were initiated there.

In view of these statistics, the GALE field project was scheduled for 15 January to 15 March 1986, centered on the coastal region of North Carolina and South Carolina. The conservative expectation was that during this period about five cases of cyclogenesis would be encountered. In addition, during the two-month period of the field project, detailed information on many other types of frontal systems and mesoscale weather features that affect the Carolina coast was expected.

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1 National Center for Atmospheric Research, Boulder, CO 80307 (The National Center for Atmospheric Research is sponsored by the National Science Foundation.). © 1988 American Meteorological Society
2. Scientific objectives

The prediction of severe East Coast winter-storm development is a very difficult forecast problem and a fundamental scientific one. A full understanding of the mechanisms involved in storm development could not begin to be achieved until a comprehensive mesoscale data set for several representative storms had been collected and used in conjunction with numerical mesoscale-model simulations for diagnostic analysis. A number of scientific ‘core’ objectives were defined for GALE to this end. To achieve these objectives, specific tasks had to be carried out. Finally, a comprehensive field program like GALE offers exceptional opportunities for special investigations that need a large data collection network. These investigations are referred to as supporting objectives.

a. Core objectives
The core objectives of GALE were

1) to describe the airflow, mass, and moisture fields in East Coast winter storms with special emphasis on mesoscale processes;
2) to understand the physical mechanisms controlling the formation and rapid development of East Coast storms;
3) to develop and test numerical models for the prediction of East Coast storms.

b. Specific tasks
The specific tasks that had to be carried out to fulfill the core objectives of GALE were the following:

1) To study the three-dimensional structure of the boundary layer and associated energy and momentum fluxes from the Gulf Stream to the Appalachian Mountains.
2) To study the mesoscale structure of fronts on the East Coast.
3) To study the role of orography with emphasis on cold-air ‘‘damming’’ near the Appalachian Mountain range.
4) To study the spatial and temporal changes in the structure of high-level and low-level jet streaks associated with East Coast cyclones.
5) To study the mesoscale organization of convective and stratiform precipitation systems on the East Coast.
6) To do numerical simulations of East Coast storms and the associated boundary-layer and precipitation systems for testing hypotheses concerning physical mechanisms, for providing data sets for diagnostic studies, and for evaluating parameterization methods.
7) To use GALE data for testing and refining operational objective analyses and operational prediction models.

c. Supporting objectives
The supporting objectives of GALE were to study the following:

1) Cloud and precipitation processes associated with East Coast cyclones, with emphasis on simultaneous radar and in situ measurements.
2) The role of gravity waves and other mechanisms in the organization of precipitation bands.
3) The evolution of stratospheric and tropospheric exchange processes in relation to rapid cyclogenesis.

Fig. 1. Broad topographical features of the Southeastern United States and coastal waters. (Approximate mean position of the western edge of the Gulf Stream is along the 50 m isobath.)

4) The influence of cold-air outbreaks over the relatively warm coastal ocean on frontogenesis and cyclogenesis.
5) The response of the coastal ocean waters to winter storms and cold-air outbreaks.
6) The application of conceptual models and enhanced mesoscale data to short-range forecasting of significant weather.
7) The subsequent evolution of major cyclones traveling northward from the GALE observational network.

3. Geographical, meteorological, and oceanographical setting

East Coast cyclogenesis is viewed as a “scale-interaction” problem in which both synoptic-scale processes and mesoscale processes play important roles. The synoptic-scale trough-ridge patterns provide the general dynamical environment in which cyclogenesis is initiated and maintained. However, a number of topographical features of the East Coast, along with the Gulf Stream, provide mesoscale forcing that modulates the growth of cyclones and helps focus cyclogenesis along the coast.

a. Geographic features
Broad topographical features of the central East Coast are shown in Figure 1. The Appalachian Mountains provide a northeast-southwest orographical barrier typically 1.0 km–1.5 km in height. The east-facing slopes of the Appalachians, the rolling Piedmont, and the flat coastal plain each form a zone roughly 100 km to 150 km wide, oriented northeast-southwest and aligned approximately parallel to the coast. The varying concave, convex shape of the coastline itself is a potential factor
Fig. 2. Example of Type B cyclogenesis (a) Original cyclone over South Central United States with cold-air damming along eastern sea-board. (b) Secondary cyclogenesis near Cape Hatteras 12 hours later. (From Miller, 1946.)

in cyclogenesis (Godev, 1971) and coastal-front formation (Bosart, 1975).

The southeastern United States continental shelf (South Atlantic Bight; Bumpas, 1973) extends about 100 km–150 km offshore. Seaward of the shelf “break” lies the “meandering” Gulf Stream, approximately 100 km in width, which is also aligned roughly parallel to the coast (Fig. 1).

b. Meteorological features
Austin (1941) and Miller (1946) categorized two types of cyclogenesis along the East Coast of the United States, Type-A and Type-B. Type-A cyclogenesis typically occurs over the ocean, and the cyclones subsequently move northeastward so that often only the western portion of the precipitation shield affects land. This type of cyclogenesis is generally similar to conventional polar-front cyclogenesis, although the Gulf Stream may play a role through diabatic heating and destabilization.

Type-B cyclogenesis occurs near the coastline and to the southeast of an older cyclone over the Midwest or Great Lakes (Fig. 2). Cyclogenesis is often preceded by a wedge of cold continental air and high-pressure on the east slopes of the Appalachians, extending southwestward from New England or eastern Canada. The presence of the cold-air dome east of the Appalachians retards the northward movement of the warm front there, while its northward progress is unimpeded over the ocean. A secondary cyclone sometimes forms on this “wave” on the warm front. Type-B cyclogenesis was the “classic case” of greatest interest in GALE.

Synoptic-scale fronts pass through the Carolina coastal region in association with the cyclonic systems and also in association with storm centers moving north of the region. Approximately 10 to 15 cold fronts occur in a typical two-month period in January–March (GALE, 1985). Warm-front passages are rare, reflecting the persistence of cold-air damming.

A number of mesoscale phenomena and mesoscale processes are associated with East Coast storms. These are discussed in detail in the GALE Experiment Design (GALE, 1985). Their individual roles in cyclogenesis need to be determined. For example, the study by Kocin and Uccellini (1984) showed that cold-air damming and coastal frontogenesis were associated with nearly all their storms. Table 1 summarizes the meteorological processes believed to be involved in the development of the East Coast storms.

c. Oceanographical features
The oceanic regime off the East Coast of the United States is complex, with highly variable coastline and continental-shelf geometries, spatially and temporally varying hydrographic frontal structures, and the presence of the warm and swiftly flowing Gulf Stream. The detailed nature of the oceanic response to wintertime atmospheric forcing is also complex.

The Gulf Stream flows generally northward and northeastward over the continental slope off the coast of the southeastern United States (Fig. 1). The surface of the stream averages about 100 km in width from the Florida Straits all the way to Cape Hatteras, and the main body of the stream is generally about 1,000-m deep. Surface temperatures in the swiftly flowing core of the stream usually exceed 22°C year round. In the GALE study area during winter, the Stream’s shoreward sea-surface-temperature front may possess gradients ranging upwards of 1°C • km⁻¹ over several kilometers. It is not uncommon to observe abrupt changes of 8°C to 10°C over less than 1 km (Bane et al., 1981). Gulf Stream meanders and their accompanying frontal eddies constitute the dominant form of oceanic mesoscale variability along the Gulf Stream front within the GALE area. Between Charleston and Cape Hatteras, the Gulf Stream meanders and frontal eddies have amplitudes approaching 50 km, and the position of the stream’s sea-surface-temperature front may vary by as much as 40 km from its mean (Bane and Brooks, 1979).

In the outer continental shelf low-frequency current variability (depths > 40 m) has been shown to be primarily produced by northward propagating Gulf Stream meanders and frontal eddies. These “events” travel to the north along the shelf break at speeds of 40 to 70 cm • sec and have periods of six to eight days. They appear to result from instabilities within the Gulf Stream that have no apparent relation to local wind forcing (Lee and Atkinson, 1983).
Table 1. Scales of motion and meteorological processes involved in the development of East Coast storms.

<table>
<thead>
<tr>
<th>Scale</th>
<th>Meteorological Phenomena</th>
<th>Important Processes for the Development of East Coast Storms</th>
</tr>
</thead>
<tbody>
<tr>
<td>Synoptic scale;</td>
<td>Upper-level trough, embedded jet streaks and fronts</td>
<td>Provide source of vorticity and kinetic energy, upper-level divergence, and associated upward vertical motion.</td>
</tr>
<tr>
<td>24–48 h; ≥2000 km</td>
<td></td>
<td>Enhances upper-level baroclinicity, divergence, kinetic energy, and vorticity; reduce hydrodynamic stability; focus stratospheric-tropospheric exchange processes; provide a source of potential vorticity upstream of the developing cyclone.</td>
</tr>
<tr>
<td>Meso-α scale;</td>
<td>Amplifying upper-level troughs and associated jet streaks</td>
<td>Enhances moisture transport and provides lifting mechanism for developing precipitation systems, increases warm-air advection of low levels to aid in the development of a thermal ridge.</td>
</tr>
<tr>
<td>3–24 h; 200–2000 km;</td>
<td></td>
<td>Focus low-level baroclinic zone, upward vertical motion and temperature advection in narrow area along the coast; enhance precipitation rate.</td>
</tr>
<tr>
<td>Low-level jet</td>
<td></td>
<td>Accelerate low-level response to upper-level forcing (i.e., increase low-level winds, convergence, and warm-air advection), provide extra energy source for coastal frontogenesis, explosive cyclogenesis, and associated precipitation systems; reduce static stability of boundary-layer air mass, which will aid cyclogenesis; influence the spatial scale and growth rate of the entire storm system.</td>
</tr>
<tr>
<td>Coastal front, cold-air damming</td>
<td></td>
<td>Contributes to cold-air damming and to cyclogenetic instabilities.</td>
</tr>
<tr>
<td>Oceanic sensible and latent heat fluxes, latent heat release</td>
<td></td>
<td>Advepts cold Canadian air east of the Appalachians for damming process and over the western Atlantic (destabilization of maritime air mass).</td>
</tr>
<tr>
<td>Flow interaction with Appalachian Mountains</td>
<td></td>
<td>Weather Service stations (NWS) and military stations and special sites operated specifically for the GALE field program.</td>
</tr>
<tr>
<td>Strong anticyclone eastern Great Lakes or New England (north of incipient low)</td>
<td></td>
<td>Three areas of particular significance to GALE were defined for reference in a description of the experimental design (Fig. 3):</td>
</tr>
</tbody>
</table>

a. Inner GALE Area

Meso-β processes could be resolved and local meso-γ processes (including convective clouds, boundary-layer fluxes and microphysical processes) could be examined. The Inner GALE Area was approximately 500-km wide, centered on the coast, and extended 1000 km from Georgia to Virginia. Portable-automated-mesonet (PAM)II, Doppler radars, ships, buoys, and most aircraft flights and Cross-chain Loran Atmospheric Sounding System (CLASS) rawinsonde sites were in this area.

b. Regional GALE Area

Meso-α processes of frontogenesis and cyclogenesis could be examined. The Regional GALE Area was 1,000-km wide (from the ridge of the Appalachians to 500-km offshore), and 1,500-km long (from Florida to New Jersey). This included the area where cold-air damming and primary cyclogenesis occurred and is the framework within which processes in the Inner GALE Area occurred. Special observations in this area included intensive dropwindsondes, extra rawinsonde sites, airborne measurements, digitized NWS radar data, and increased observations from standard surface stations.

c. Outer GALE Area

The synoptic features in the cyclone and jet-stream circulations could be identified and observed with increased temporal resolution prior to their arrival and after they left the Regional

4. Experiment design

Because it is a scale-interaction problem, the meso-β–scale GALE observing region was nested in a meso-α–scale domain of sufficient size to incorporate continental and marine components. Data collection extended west of the Appalachians, in order to evaluate the effect of orography on modifying large-scale systems or establishing mesoscale systems, and near the shore and offshore where the cyclogenesis occurs. In addition, data had to be collected with temporal resolution adequate to study the mesoscale processes. The GALE data set combines standard observations with special observations at National

Adamec and Elsberry, 1985).

The following customary definitions of mesoscale are used: 1) Meso-α scale = 200 to 2,000 km; 2) Meso-β scale = 20 to 200 km; 3) Meso-γ scale = 2 to 20 km.
The Canadian Atlantic Storms Program (CASP) field phase coincided in time with GALE and had similar scientific objectives (Stewart et al., 1987). CASP studied winter storms along the east coast of Canada. Several, but not all, cases dealt with the same storms. Enhanced downstream observations extended into the Canadian Maritime Provinces when major cyclonic storms developed and moved into that area.

5. Intensive observing periods

Periods during which high-resolution observations were made were referred to as Intensive Observing Periods (IOPs). The existing operational system, combined with the special research observing systems, formed a composite observing system of great flexibility during IOPs. Routine observational systems, such as the existing NWS rawinsonde network could be called upon to increase their frequency of observations. "Fixed" special observing systems, such as the Doppler radars and satellites were operated in selected modes. Mobile observing systems, such as the aircraft and ships, could be deployed into areas of special interest.

Major IOPs required 24-h prediction in order to alert some components of the observing systems 12 h to 24 h in advance. Some components also required advance notice of the end of an IOP. Because some local weather events were difficult to predict, the operations plan permitted quick response of more limited observing systems to these events. These quick-response IOPs generally involved only the special mesoscale observing systems located within the Regional GALE Area.

The observing facilities are listed in Table 2 and the manner in which the systems were utilized during IOPs is described here.

<table>
<thead>
<tr>
<th>System</th>
<th>System Type/Agency</th>
<th>Number Deployed</th>
<th>Measurements</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sounding</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NWS Network</td>
<td>ART type, NOAA</td>
<td>9 Regional Area</td>
<td>State*</td>
<td>3-hrly during IOPs only</td>
</tr>
<tr>
<td></td>
<td></td>
<td>30 Outer Area</td>
<td>State</td>
<td></td>
</tr>
<tr>
<td>CLASS System</td>
<td>Cross-Chain LORAN, NCAR</td>
<td>8 stations</td>
<td>LSU station was on ship</td>
<td></td>
</tr>
<tr>
<td>Standard Loran Units</td>
<td>Drexel (2) DOE (1) LSU (1)</td>
<td>4 stations</td>
<td>State</td>
<td>3-hrly, IOP only</td>
</tr>
<tr>
<td>GMD System</td>
<td>AWS (5) NASA (1)</td>
<td>4 stations</td>
<td>State</td>
<td></td>
</tr>
<tr>
<td>Mini-radiosondes</td>
<td>NCSU</td>
<td>2</td>
<td>State–no winds</td>
<td>Used shipboard or mobile on land</td>
</tr>
<tr>
<td>Omega Dropwindsonde</td>
<td>NOAA, AWS</td>
<td>Deployed by NOAA, USAF, NCAR aircraft</td>
<td>State*</td>
<td>USAF–Part of National Winter Storms program</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Surface</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PAM System</td>
<td>PAM II, NCAR</td>
<td>50</td>
<td>State, Rainfall</td>
<td>Inner area, 5 min.</td>
</tr>
<tr>
<td>NOAA Buoys, Platforms</td>
<td>NOAA-E, C-Man</td>
<td>2, 6</td>
<td>State, Sea State</td>
<td>Satellite transmission (hourly)</td>
</tr>
<tr>
<td>Research Buoys</td>
<td>NCSU</td>
<td>6</td>
<td>State, SST</td>
<td>Recorded only</td>
</tr>
<tr>
<td>Micro-met Towers</td>
<td>CPL (2) Savannah (1) CERC (1)</td>
<td>4 stations</td>
<td>State, Turbulence</td>
<td>Multiple level observations</td>
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<tr>
<td>NOAA, Military, FAA</td>
<td>Standard sensors,</td>
<td></td>
<td>State, Rainfall</td>
<td>Regional area, Hourly WX observations</td>
</tr>
<tr>
<td>Standard Stations</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lightning Detectors</td>
<td>SUNY Albany</td>
<td>6 Inner Area</td>
<td>Strikes, Sign of charge</td>
<td>Cloud-ground</td>
</tr>
<tr>
<td>Current Meters</td>
<td>U. of Miami, Skidaway</td>
<td>13 Regional Area</td>
<td>Current, temp., bottom pressure</td>
<td>Lines off Myrtle Beach and Charleston, SC</td>
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<tr>
<td>Tide Gauges</td>
<td>Army Corps Engineers</td>
<td>10</td>
<td>Sea-level height</td>
<td>North Carolina Coast</td>
</tr>
<tr>
<td>Ships</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>R/V Cape Hatteras</td>
<td>Duke University</td>
<td>1</td>
<td>State, SST, Turbulence, Atmos. Soundings, CTD</td>
<td>Full field project</td>
</tr>
<tr>
<td>R/V Endeavor</td>
<td>U. Rhode Island</td>
<td>1</td>
<td>State, Atmos. soundings, CTD</td>
<td>Jan. 8–Feb. 3</td>
</tr>
<tr>
<td>Ships of Opportunity</td>
<td>NAVY, USCG, Commercial</td>
<td></td>
<td>State</td>
<td>3–6 hrly, Regional Area</td>
</tr>
<tr>
<td>Aircraft**</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Electra L-188</td>
<td>NASA</td>
<td>1</td>
<td>Air motion, Air Chemistry, Thermodynamics, Radiometry</td>
<td>Boundary-layer Lidar studies</td>
</tr>
<tr>
<td>ER-2</td>
<td>NASA</td>
<td>1</td>
<td>Radiometry</td>
<td>Microwave Signature Studies</td>
</tr>
</tbody>
</table>

*State = pressure, temperature, relative humidity, windspeed, and direction.

**Table 2 is continued on the next page.
a. Sounding operations
The GALE sounding operations were designed to provide three-dimensional fields with time resolution adequate to resolve the structure and evolution of mesoscale weather systems in the GALE observational network. The following tasks were incorporated into the design of the GALE sounding operations:

1) Determine the structure and evolution of mesoscale features passing through the nested network.
2) Provide a nested observing network adequate to determine scale interactions from the synoptic scale down to the meso-γ scale.
3) Provide lateral boundary conditions for regional and mesoscale models.
4) Provide initialization and verification data for regional and mesoscale numerical models.
5) Provide information on orographic, coastal, and oceanic influences on coastal winter storms.

The rawinsonde network in the Outer GALE Area (Fig. 3) is composed of NWS sites which, though spaced on the synoptic scale, provided launches every three hours. This network provided the information necessary to describe the rapidly changing mesoscale structure of cyclones. In some cases the rawinsonde operations in the Outer Area were staggered, beginning earlier in the upstream (western) region and extending later in the downstream (northeast) region. Standard National Winter Storm Program dropwindsonde flights (Federal Coordinator for Meteorological Services and Supporting Research, 1985), when available, provided synoptic-scale data over the northern Gulf of Mexico and up to 1,000 km off the East Coast of the United States.

When rapidly changing mesoscale features were present in the Regional GALE Area the CLASS soundings were launched at 90 min intervals. GALE dropwindsonde flights off the Carolina coast sought to complement the dense land-based network. With optimum scheduling, one of the GALE aircraft would release Omega dropwindsondes (ODWs) during a portion of each 6-h period of the storm. The basic purpose of the

<table>
<thead>
<tr>
<th>System</th>
<th>System Type/Agency</th>
<th>Number Deployed</th>
<th>Measurements</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>King Air 200T</td>
<td>NCAR</td>
<td>1</td>
<td>Air motion, Thermodynamics, Microphysics</td>
<td>Air-sea interaction, Turbulence structure</td>
</tr>
<tr>
<td>Sabreliner NA 265-60</td>
<td>NCAR</td>
<td>1</td>
<td>Air motion, Air motion, Thermodynamics, Cloud physics</td>
<td>Jet-stream</td>
</tr>
<tr>
<td>Electra L-188L</td>
<td>NCAR</td>
<td>1</td>
<td>Boundary-layer, Air-sea interaction, Turbulence structure</td>
<td>Boundary-layer, Air-sea interaction, Turbulence structure</td>
</tr>
<tr>
<td>WP-3D (NOAA-42)</td>
<td>NOAA</td>
<td>1</td>
<td>Air motion, Thermodynamics, Cloud physics</td>
<td>Boundary-layer, Air-sea interaction, Mesoscale structure, Doppler radar ODW deployment</td>
</tr>
<tr>
<td>Citation CE-500</td>
<td>NOAA</td>
<td>1</td>
<td>Atmospheric soundings</td>
<td>Mesoscale structure, Air chemistry</td>
</tr>
<tr>
<td>Convair C-131A</td>
<td>U. of Washington</td>
<td>1</td>
<td>Cloud physics, Air chemistry, Thermodynamics</td>
<td>Cloud Electrification Studies</td>
</tr>
<tr>
<td>Beech Baron</td>
<td>ARA/MIT</td>
<td>1</td>
<td>State*, Electric field, SST</td>
<td></td>
</tr>
<tr>
<td>Radars</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C-band Doppler</td>
<td>NCAR (2), MIT (1)</td>
<td>3</td>
<td>Doppler velocity, Reflectivity, Spectrum Width</td>
<td>NCAR radars in Dual Doppler pair (45 km baseline) MIT at Ft. Fisher, NC</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Doppler velocity reflectivity, multi-parameter</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>capabilities</td>
<td></td>
</tr>
<tr>
<td>SPANDAR S-band</td>
<td>NASA</td>
<td>1</td>
<td>Doppler velocity spectrum</td>
<td>Vertically pointing only</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TPQ-11 K-band</td>
<td>U. of Washington</td>
<td>1</td>
<td>Doppler velocity spectrum</td>
<td>Tail radar (Doppler, X-band) rotates perpendicular to flight track. Lower-fuselage radar (C-band) rotates in azimuth. 8 radars digitally recorded</td>
</tr>
<tr>
<td>NOAA 42 Radars</td>
<td>NOAA</td>
<td>1</td>
<td>Doppler velocity reflectivity, reflectivity</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>1 non-Doppler</td>
<td></td>
<td></td>
</tr>
<tr>
<td>WSR 57/74 Non-Doppler</td>
<td>NOAA</td>
<td>5 Inner Area</td>
<td>Reflectivity, S-band/C-band</td>
<td></td>
</tr>
<tr>
<td>Satellite</td>
<td></td>
<td>10 Regional Area</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nimbus-7</td>
<td>NASA</td>
<td>1</td>
<td>TOMS, ERB, SST, THR</td>
<td>Polar orbit (twice daily)</td>
</tr>
<tr>
<td>GOES-6</td>
<td>NOAA</td>
<td>1</td>
<td>Visible, IR, Imagery, VAS</td>
<td>Geostationary 108°W</td>
</tr>
<tr>
<td>DMSP</td>
<td>DOD</td>
<td>2</td>
<td>Imagery, Profiling</td>
<td>Both polar orbit (twice daily)</td>
</tr>
<tr>
<td>NOAA-9</td>
<td>NOAA</td>
<td>1</td>
<td>Imagery, AVHRR, Profiling</td>
<td>Polar orbit (twice daily)</td>
</tr>
</tbody>
</table>

*State = pressure, temperature, relative humidity, windspeed, and direction.
ODW observations spaced at 150-km intervals within 500 km of the coast was to extend the meso-α land-network soundings over water.

b. Surface measurements

The surface measurements were designed to provide surface data fields of standard meteorological parameters within the Inner GALE Area with meso-β scale resolution and provide the surface observing complement to the tasks listed under the sounding operations. The spatial domain of the networks (Fig. 4) sought to contain meso-β scale phenomena associated with developing East Coast storms and permit their observation over periods of approximately 12 h. Standard measurements included air temperature, dew-point temperature, barometric pressure, wind speed, and wind direction. In addition, land-based stations measured precipitation, and sea-based stations measured sea temperature.

The fifty-station PAM-II network provided 5-min meteorological surface observations over the eastern half of North Carolina and South Carolina and southeastern Virginia. The northeast-southwest PAM-II network orientation “mirrored” the coastline and mountains, and recognized the tendency for meteorological-parameter gradients to align perpendicular to the coast. A line of four stations extended northwestward to support a sounding cross-section for cold-wedge studies. This cross-section also provided some continuity for surface observations of cold fronts and other systems crossing the mountains. Data from all PAM-II stations were transmitted via a GOES satellite link to base stations in Boulder, Colorado, the GALE Forecast and Operations Centers at Raleigh-Durham Airport (RDU), and to the secondary control center at Cape Hatteras.

The SUNY-Albany lightning-detection network provided for the detection of cloud-ground lightning over the entire Regional GALE Area over land and up to at least 300-km offshore. A new station was installed near Cape Hatteras to improve offshore coverage for GALE, providing a total of six stations in the Inner GALE Area (Fig. 4). Displays of lightning data were available in real time for operational and forecast use.

The four meteorological towers were located at three inland sites and one coastal site in the Inner GALE Area. The towers provided micrometeorological observations during selected periods of the observing program and routine mean data throughout the GALE period. Observations consisted of 15 min averages of wind speed components, air temperature, and humidity at two or more levels. Turbulent fluctuations of the three components of wind, temperature, and humidity at one level were measured at the Coastal Engineering Research Center (CERC) tower at Duck, North Carolina. CERC tower data are averaged hourly.

Deployment of the eight special GALE buoys, six North Carolina State University (NCSU) buoys and two NOAA-E buoys, supported studies of the development of the coastal front and augmented observations in the data-sparse oceanic region in the Inner GALE Area. Their placement was designed to maintain a regular spacing of roughly 60 km and extend surface measurements offshore at a comparable resolution to the PAM network in the region where coastal fronts were likely to occur.

Ten special tide gauges were also installed by the Army Corps of Engineers along the North Carolina coast (Fig. 5) to measure the effects of coastal storms on sea level.

c. Ships and moorings

Two oceanographic research vessels (R/V) participated in the GALE field program, the R/V Endeavor (U. Rhode Island) and the R/V Cape Hatteras (Duke/UNC Oceanographic Con-
sortium). The primary operating areas for the ships are shown in Fig. 5.

The R/E Endeavor conducted routine oceanographic transects perpendicular to the shore near Charleston or Myrtle Beach, South Carolina, in the neighborhood of linear arrays of surface and subsurface instrumental moorings that extended from near shore to the Gulf Stream. The eight moorings were instrumented to measure bottom pressure and ocean currents and ocean temperatures at several levels. The objective was to measure heat and mass fluxes to determine the response of the shelf water and Gulf Stream to atmospheric forcing during periods of cyclogenesis and subsequent cold-air outbreaks. During the IOPs the ship remained at the Gulf Stream end of the transect (Fig. 5) and collected hourly surface observations, atmospheric soundings and CTD (conductivity, temperature, depth) profiles.

The R/V Cape Hatteras operated routinely off Wilmington, North Carolina (Fig. 5) in support of marine boundary-layer studies. During IOPs the ship was situated at station A for hourly surface observations, atmospheric soundings and CTD profiles, between IOPs the ship collected biological oceanographic samples. Both ships also provided intercomparisons for the buoy network between IOPs.

d. Aircraft operations

Generic flight tracks for each of the research airplanes were developed for a variety of weather scenarios. These tracks and the deployment strategy for aircraft operations were designed to provide:

1) in situ measurements of mesoscale features and processes in cloud, and in precipitation regions and their environments.
2) in situ measurements of mesoscale features and processes in the planetary and marine boundary-layer, with special emphasis on turbulent processes.
3) in situ measurements in the upper troposphere to define the structure of the jet stream.
4) in situ measurements of flight-level data in the vicinity of mesoscale phenomena, especially frontal zones.
5) information about the horizontal and vertical air-motion field, especially in offshore regions, utilizing the Doppler radar aboard the NOAA WP-3.
6) a platform for Omega dropwindsonde deployment in offshore regions of the study area.
7) a platform for aircraft-expendable–bathythermograph (AXBT) deployment in offshore regions to determine the effects of atmospheric forcing on the ocean.

e. Radar operations

Operational strategies for the GALE radars were designed to:

1) Document the horizontal distribution of precipitation over the Regional GALE observational area (including part of the upstream and downstream areas), and to document the full three-dimensional distribution of precipitation over the Inner GALE observational area.
2) Provide information about horizontal and vertical air-motion fields in the Inner GALE Area (dual Doppler radars).
3) Provide space and time continuity of boundary-layer features and estimates of boundary-layer heights, winds, and mesoscale-turbulence properties (NCAR Doppler radars using special low-level scans).
4) Provide information about hydrometeor size and fall speed utilizing standard Doppler data and Doppler-velocity spectra, dual-polarization data, and vertically-pointing, dual-wavelength data.
5) Provide information for real-time operational decisions, both for the broad surveillance of precipitation and for rapidly updated information on the positions and speeds of precipitation features and wind-shift lines.

The standard NWS radar network includes 10 radars that provided useful coverage in the vicinity of the Regional GALE Area. Dial-up capabilities of these radars were used for real-time operational decisions and short-term forecasting. Digital recording of the data at improved reflectivity resolution was performed at eight radars. These digital data were important for tracking precipitation systems and estimating precipitation intensity in the Regional GALE area.

Four ground-based scanning Doppler radars collected data along the Atlantic coast from Delaware to South Carolina (Fig. 6). The Doppler-radar network together with the NOAA WP-3D airborne Doppler radar were deployed to provide air-motion fields within a significant part of the Inner GALE Area. The TPQ-11 radar provided a continuous time series of radar reflectivities and of hydrometeor vertical velocities in cloud and precipitation overhead, which could be related to features observed in either of the dual-Doppler "regions" through time-to-space conversion.

The ground-based scanning Doppler radars were operated in various modes, depending on the scientific objective. Common to all operational modes were the interleaving of scans designed to study smaller and larger scales of organization, thereby enabling both scales to be observed essentially simultaneously. Specifically, scans of the full observable volume were performed by all the ground-based scanning Doppler radars once every 20 to 30 min.

f. Satellite systems

The meteorological satellites in operation during GALE were GOES-6, NOAA-9, NOAA-6, DMSP F-6, DMSP F-7, and NIMBUS-7. All provided standard data products except GOES-6, which was operated in the rapid interval scan operations (RI-SOP) mode when possible during certain IOP segments when VAS soundings were not required. Special derived products not available in real time were corrected sea-surface-temperature fields from NOAA-9, ozone mapping from NIMBUS-7, and wind vectors from GOES-6.

A McIDAS workstation at Raleigh provided nearly real-time monitoring of GOES-6 products for operational decisions and short-term forecasting. This facility was invaluable for planning and monitoring offshore operations.

6. Field operations

a. Organization

The GALE Operations Center was located at the Raleigh-Durham Airport (RDU). The organizational diagram for operations is shown in Fig. 7. Thanks to the generous support of several
local organizations, many operational functions made use of existing facilities.

The GALE Operations Forecast Center (OFC) was co-located with the Raleigh Weather Service Forecast Office (WSFO). WSFO forecasters routinely interacted with the project staff. The Operations Forecast Center (OFC) was the focal point for transmission of all routine and special meteorological data for both operational and archiving purposes. Special facilities included an AFOS terminal, McIDAS terminal, PE-3230 superminicomputer (displaying special-sounding data), PAM II field base station, DIFAX ground station, the University of Illinois and The Pennsylvania State University special-products terminal, NWS radar dial-up, and SUNY-Albany lightning-detection—network display. The OFC provided both long-range forecasts for scientific planning purposes and nowcasting for aircraft and ship operations. Special support for long-range forecasts was provided by the National Meteorological Center (NMC).

The GALE Operations Control Center (OCC), located in a temporary structure adjacent to the Raleigh WSFO, was the communications and control center for all field operations. To assist in the directing of aircraft and other operational decisions the operations director and his staff had access to real-time observational displays similar to those available in the OFC. FAA and military controllers were available in the OCC to coordinate and monitor GALE aircraft operations within the context of other air traffic. A particularly critical function was the coordinated use of restricted airspace during a large fraction of GALE flight operations. Second-level control functions for highly coordinated aircraft and Doppler-radar operations in the coastal region were carried out at the dual—Doppler-radar location at Cape Hatteras. This location also served as an emergency back-up control center.

The day-to-day selection of scientific missions was made by the Mission Planning Team (MPT). The MPT was responsible for the overall guidance of the field program and the fulfillment of the scientific objectives. All investigators involved in GALE and present in the field contributed to the direction of the overall field program. The operations staff was responsible for executing the decisions of the MPT. Part of the RDU National Guard Armory was used for mission-planning meetings, work space for scientists, and data-management functions.

The primary concern of the data-management team in the field was to ensure that all possible data were obtained and saved. These data included logs, notes, sketches, and preliminary analyses. The GALE Data Management Plan also placed great emphasis on providing partially verified preliminary data sets during and shortly after the field phase. Utilizing new NMC data products and an on-line GALE data-management computer system, near-real-time data monitoring and validation procedures were carried out in the field. These quality-control procedures provided a useful preliminary data set within a few months of the field program.

b. Operational summary
The field program was as an operational success and quality data sets were collected in support of all GALE objectives. The 13 IOPs extended over about 36 days of the 60-day period. Nine aircraft flew nearly 900 h, two research vessels participated on a total of 80 days, and about 4,000 special soundings were launched, including over 1,500 launches at 3-hourly in-
tervals from 39 NWS sites covering the eastern half of the United States. Approximately 500 soundings (rawinsondes and dropwindsondes) were made over the Atlantic coastal waters. In addition, nearly continuous data were collected at 4 coastal Doppler-radar sites, 50 PAM stations, 8 research buoys, and 4 micrometeorological towers.

There were no major system failures and no serious accidents during the experiment. Aircraft downtime for maintenance and repair was at or below normal for most aircraft. Airspace constraints were the most-serious limitation to the observing program. Most coastal and offshore flights were conducted in restricted military airspace that required 6-h prior clearance and were frequently in direct competition with military requests. Cooperation by the FAA and military schedulers and users was superb and crucial to the successful aircraft operations conducted in an area so heavily used by commercial, military, and research aircraft. Even so, some missions were compromised by the inability to place the research aircraft where and when required.

The greatest adverse impact was on the regional dropwindsonde program. The combined effects of restricted airspace and performance limitations of the deployment aircraft yielded a regional dropwindsonde program that was only about 50-per-cent effective. This was partially compensated by the excellent performance of the shipboard CLASS system and by the large number of dropwindsonde flights made in support of the National Winter Storm Program (19 missions).

Aided by the GALE special observing network, operational forecasting of major IOP events proved to be very successful. Alerts, 24 h in advance of upstream rawinsonde operations, were predicted adequately. There were no significant false alarms and, at worst, the intensity of weather systems was misjudged. Prediction of mesoscale events within the GALE Regional Area proved more difficult. The greatest difficulty was with 6–12 h predictions of precipitation over the coastal and offshore regions of Doppler-radar coverage. In particular, pinpointing the time and location of rainbands forming in situ over the Gulf Stream proved to be most evasive. Identifying regions of incipient oceanic cyclogenesis 6–12 h in advance also proved difficult; most forecasts of these events tended to be too slow on development and on storm motion.

7. Meteorological summary

Field operations for GALE during 15 January to 15 March 1986 were broken down into 13 IOPs. There were five large-scale weather patterns predominant during this period (see Table 3). Within this period there were 8 cyclogenesis events in the Regional GALE Area. Although none of these produced a major winter storm along the northeastern United States coast, several snowfalls of 10 to 15 cm were reported and several cases were associated with poor operational forecasts. Five of the cyclogenesis events produced pressure falls exceeding 24 mb in 24 h, however, most occurred too far offshore to seriously affect coastal regions.

A breakdown of weather associated with each IOP is shown in Table 4. Precipitation was light for most systems passing over the land-based Regional GALE networks, with the total precipitation for this period considerably below normal throughout the southeastern United States. Overall, the number of significant weather events was higher than average, although most systems were weak and fast moving. Specific occurrences of cold-air damming and coastal fronts were fewer and less intense than normal.

The key features observed during the IOPs are summarized in Table 5. Some special comments on specific phenomena follow.

1) Cyclogenesis. Substantial data sets were collected for six of eight cyclogenesis events during GALE, three over land and three along the coast or offshore. At least two cases had quite complete large-scale coverage. IOP 1 included the development of a pronounced cut-off cyclone aloft without any appreciable surface cyclogenesis. IOP 2 included two major cyclogenesis events and will be a high priority study. IOP 6 and IOP 8 involved prediction errors for snowfall in the Washington–Baltimore area. IOP 10 covered a cyclogenesis event over the PAM network with subsequent “explosive” development offshore. Observations of an incipient oceanic cyclogenesis during IOP 11 implied a warm-core circulation. The data set includes both Type A and Type B cyclogenesis and contains a mixture of cases involving jet streaks, mid-tropospheric trough, low-level baroclinicity, and diabatic heating in varying proportions.

2) Rainbands and mesoscale precipitation. Aircraft in situ observations and airborne and surface Doppler-radar systems provided detailed measurements of at least eight cold fronts, five warm fronts, five rainbands associated with the Gulf Stream,

**Table 3.** Five large-scale weather patterns predominant during 15 January to 15 March 1986.

<table>
<thead>
<tr>
<th>Date</th>
<th>Weather pattern</th>
</tr>
</thead>
<tbody>
<tr>
<td>15–30 January</td>
<td>Zonal flow with large amplitude</td>
</tr>
<tr>
<td></td>
<td>disturbances</td>
</tr>
<tr>
<td>31 January–12 February</td>
<td>Split flow in central US; WSW</td>
</tr>
<tr>
<td></td>
<td>flow across Carolina with weak</td>
</tr>
<tr>
<td>13–27 February</td>
<td>Zonal flow with small disturbances</td>
</tr>
<tr>
<td>28 February–8 March</td>
<td>Major trough in Eastern US</td>
</tr>
<tr>
<td>9–15 March</td>
<td>WSW flow across Carolina with</td>
</tr>
<tr>
<td></td>
<td>unstable air</td>
</tr>
</tbody>
</table>
and three-other convective rainbands. These are well-suited for comparisons with observations of fronts and rainbands in other areas.

Digitized NWS radar data and special surface rainfall networks, such as PAM, provided measurements of mesoscale rainfall patterns. A semi-permanent band, associated with the Gulf Stream, was often observed (Hobbs, 1987). Unfortunately the lack of heavy precipitation events in the PAM/CLASS network will limit the opportunities to document the role of latent-heat release in East Coast cyclogenesis. Seven of the ten flights by the NASA ER-2 included mapping of the microwave signatures of precipitation systems in coordination with ground-based radars and some in situ aircraft observations. These should augment the coverage of offshore precipitation systems. Also, valuable airborne and surface data sets on precipitation and cloud chemistry were obtained.

3) Jet streaks and tropopause folding. The NCAR Sabreliner flew twelve jet-stream missions to observe mesoscale jetstream and tropopause-fold features in connection with surface cyclogenesis and frontal passage. Moderate-to-strong tropopause folds were found on nine of the missions. Two diagnostic tools were primarily responsible for the efficient location of the tropopause folds. First, quantitative interpretation of satellite water-vapor-band brightness temperature allowed a detailed view of the shape and evolving depth of the stratospheric penetration. Second, in-flight ozone and wind-shear measurements helped to locate the sharp boundaries of the tropopause fold and jet stream.

IOP 1 contains an excellent data set consisting of three-hourly rawinsondes, total ozone mapping spectrometer (TOMS), in situ aircraft measurements and VAS imagery. The data will be valuable for the study of tropopause folding upstream and prior to onshore cyclone development and the processes leading to stratospheric extrusions and jet-streak/trough amplifications. IOP 10 also included an excellent data set for studying jet-streak dynamics and associated tropopause folds upstream and over the GALE network.

4) Cold-air damming. Pronounced cold-air damming events occurred only during IOP 2 and IOP 13 since most of the high-pressure systems during GALE tracked southeastward rather than toward New England. During IOP 2 a shallow but long-lasting cold-air damming event occurred with low-level jets of opposing directions observed east and west of the Appalachians, near the top of the boundary layer.

5) Coastal front. Coastal frontogenesis events were much less common than expected during the two-month program. The best cases occurred with cold-air damming during IOP 2 and IOP 13. In both of these cases coastal frontogenesis offshore was followed by onshore movement into the PAM/CLASS network. During IOP 13 the coastal front moved west of RDU and appeared to be associated with subsequent convective development. Mobile meteorological teams were utilized to intercept coastal fronts over land during IOP 12 and IOP 13. In at least one case, the initial coastal front was observed to coincide with the shoreward boundary of the Gulf Stream.

6) Boundary-layer processes. A major element of the boundary-layer studies was the joint atmospheric boundary-layer and physical-oceanographic study of air-sea interaction processes over the continental shelf and Gulf Stream within the GALE Regional Area. In particular the rates at which latent heat and sensible heat were released from the ocean during strong, cold atmospheric forcing, and the effects those heat releases had on the ocean were studied. This study utilized the combined resources of three aircraft gust probe systems and aircraft deployed AXBTs (aircraft expendable baththermo-objects); two research vessels with shipboard meteorological instruments, atmospheric sounding systems, CTD (conductivity, temperature, depth) and XBT ocean profilers; eight special meteorological buoys on the continental shelf; and metallic chaff dispersed in the marine boundary layer for Doppler-radar tracking. Moderate to strong cold-air outbreaks occurred in association with IOPs 2, 4, and 5.

Studies of the planetary boundary layer over land utilized the PAM/CLASS network and three existing micrometeorological towers in addition to the aircraft gust probe systems (one additional micrometeorological tower was located along the coast).

7) Continental shelf oceanography. The R/V Endeavor
2. Preliminary results\(^6\)

a. Preliminary scientific findings

Scientists in the field followed the observations on a daily basis in order to guide the research program. In doing so they developed a variety of impressions. Preliminary post-field-phase evaluation of “quick-look” data have refined these impressions. The following briefly describe some of the preliminary findings:

1) Rapid, intense coastal cyclogenesis is associated with fairly precise timing and positioning of several interrelated mesoscale phenomena such as offshore latent-heat release, the formation of coastal fronts, cold-air damming on the east slopes of the Appalachians and jet-stream position.

2) Limited measurements in an offshore “incipient” cyclone suggest a warm-core structure more typical of tropical cyclones than continental cyclones.

3) During several cyclogenesis events slantwise convection was found to occur, whereby direct aircraft measurements along so-called M surfaces showed that nearly neutral stability indeed existed along these surfaces.

4) Modifications of existing regional forecast models tested against GALE cases showed significant improvements in the capability to forecast East Coast cyclogenetic events, including redevelopments.

5) Some model studies indicate rapid surface cyclogenesis in areas of large surface fluxes offshore.

6) In addition to migrating rainbands, intense, well-organized rainbands occur frequently and are oriented along the Gulf Stream near Cape Hatteras. The energy released through these intense convective systems has the potential to be a major driving force in coastal cyclogenesis.

7) Quite-shallow (3 km tops) cumulus clouds over the ocean regularly produce high reflectivities (40-50 dBz) and lightning, a comparatively rare occurrence in West Coast storms.

8) In at least one case the coastal front originated over the oceanic Gulf Stream front, (i.e., the western boundary of the Gulf Stream core) in another case over the mid-shelf oceanic front. The westward movement of the coastal front and its landfall prior to cyclogenesis was observed and, in some cases, the formation of weak waves and vorticity centers along the coastal front were also observed.

9) Pronounced cold-air damming events, while occurring only twice, were associated with “bomb” category cyclogenesis.

10) Air-mass transformation in the marine boundary layer over the Gulf Stream during cold-air outbreaks occurs rapidly; cloud bases descend and cloud tops ascend. Over distances of 150 Km the mixed-layer height may rise 1500 m and the specific humidity may increase by 3 g/kg.

11) Large amounts of latent heat are extracted from the Gulf Stream through air-sea interaction during cold-air outbreaks. Temperature differences greater than 24°C were measured between the sea surface and cold air flowing over the Gulf Stream. Total heat fluxes during these events over the Gulf Stream core exceeded 1200 W m\(^{-2}\).

12) Changes in wind direction and/or speed frequently occurred in the marine boundary layer immediately over ocean temperature fronts, together with changes in the magnitudes of the turbulent fluxes of heat and moisture.

13) The Mid-shelf oceanic fronts were observed to form during cyclone passage and their formation was modelled numerically.

14) Investigations of tropopause folding in East Coast cyclogenesis indicated stratospheric air descending below the 500-mb level.

15) There are more winter thunderstorms over the ocean than previously thought, especially over the Gulf Stream core, with a sharp cut-off of lightning activity at its western edge. Lightning from clouds to the ocean surface in the Gulf Stream area often carries positive charge. Research flights found indications of negatively charged cloud tops, suggesting an inverted polarity.

\(^6\) Further details on the GALE Field Experiment and GALE data set are available in the following GALE publications: 1) GALE Experiment Design, October 1985; 2) GALE Operations Plan, January 1986; 3) GALE Field Program Summary, May 1986; 4) GALE Data Users Guide, March 1987. The first two are available from: GALE Project Office—NCAR, P.O. Box 3000, Boulder, CO 80307. The latter two are available from: GALE Data Center, Drexel University, Dept. of Physics and Atmospheric Science, Philadelphia, PA 19104.

Operating on the principle of full data sharing, GALE data are available to interested scientists upon request. Inquiries should be made to the GALE Data Center referencing the GALE Data User’s Guide.
b. Operational implications for future field programs

The experience of the GALE field program provided valuable operational insights for consideration in future mesoscale field programs. The following are major operational implications identified by the GALE operational and scientific staff.

1) Six to twelve hour predictions of the onset of precipitation over the coastal and offshore regions were difficult, even with the greatly enhanced real-time observing capabilities available to GALE. Effectively scheduling operational support for these events requires carefully planned standby procedures (e.g., aircraft and radar personnel).

2) Existing “ground” communications links with research aircraft were inadequate for effective ground-to-air coordination during mesoscale research operations. There is a critical need to acquire satellite-linked voice communications systems for these facilities. (To a lesser degree this is also a problem for communications with ships.) A two-way digital link would also be desirable to exchange basic weather data.

3) Effective deployment of dropwindsondes in heavy air-traffic areas can only be accomplished utilizing a “safe” sondes (i.e., one that can be dropped from standard flight levels without posing a hazard to other aircraft at lower levels). Such a sondes could also be deployed over land.

4) The coordination of research-aircraft operations for mesoscale studies can best be accomplished if FAA liaison personnel are assigned to the project operations center and they have the authority to provide separation between project aircraft operating within released airspace blocks.

5) The central control for facility operations in mesoscale field programs needs all available current observations for effective real-time decision making. This includes the transmission and display of data from research radars, including Doppler-wind fields (even low-resolution data would be very helpful). Real-time telemetry of buoy data is desirable. Ideally, one would like to overlay various displays of real-time data.

6) While careful, detailed pre-planning of aircraft flights leads to both safer and scientifically more-productive operations there needs to be flexibility in adjusting to specific weather conditions as they evolve. Changes are best conducted from a control center with real-time data display and good communications with the aircraft rather than improvised onboard the aircraft.

7) Weather forecasting and “nowcasting” functions need to be separated in mesoscale field programs. Safe aircraft operations and optimized operational decision making requires the dedicated support of nowcasting personnel.

8) Preliminary data analysis on-site during the field phase provides early error detection and feedback into the experiment itself. Many special data sources can be fed, nearly in real time, into a central-computer, undergo preliminary quality control, be merged with other data, and then used to produce special products for preliminary analyses shortly after an event.

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