The Genesis of Atlantic Lows Experiment: The Planetary-Boundary-Layer Subprogram of GALE[1]

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Abstract

The Genesis of Atlantic Lows Experiment (GALE), focused an intensive data-gathering effort along the mid-Atlantic coast of the United States from 15 January through 15 March 1986. Here, the general objectives and experimental layout are described with special emphasis on the planetary-boundary-layer (PBL) component of GALE.

Instrumentation is described for buoys, ships, research aircraft, and towers. The networks of the cross-chain long range aid to navigation (LORAN) atmospheric sounding system (CLASS) and the portable automated mesonet (PAM II) are described and their impact on the operation of GALE is outlined. Special use of dual-Doppler radar to obtain detailed wind measurements in the PBL is discussed.

Preliminary analyses for a selected observational period are given. Detailed observations of the offshore coastal front reveal direct mesoscale circulations imbedded in the frontal zone. Later in the period, during an intense cold-air outbreak, sensible-heat and latent-heat fluxes over the coastal ocean each attain values of about 500 W $\cdot$ m^{-2}. Coordinated aircraft operations are outlined for this case and a few early findings are given.

1. Introduction

Each winter, coastal storms blast sections of the East Coast of the United States with strong winds, rain, sleet and snow, flood low-lying areas, erode beaches, disrupt commerce, damage property, and injure many persons. The genesis of these storms, often initially as weak waves developing along a shallow coastal front just offshore of the mid-Atlantic coast is not well forecast. Their subsequent tracks and intensities are not particularly well-depicted by present operational-forecast models.

To better understand the development of winter storms the Genesis of Atlantic Lows Experiment (GALE), equipped with an ambitious array of surface and airborne sensors was conducted from 15 January through 15 March 1986. The objectives of GALE were to describe in detail the airflow, and mass and moisture fields in developing storms, to explore the links between mesoscale systems (such as rainbands, coastal fronts, and dry "tongues," for example) and the development of the larger-scale systems in which they are imbedded, and to improve numerical models to better predict these storms.

To meet these objectives, existing operational measurement networks were supplemented with specialized observing systems concentrated along the mid-Atlantic coast. During the field phase, National Weather Service (NWS) and other routine measurements were supplemented through: 1) additional radiosondes at 39 existing NWS sites; 2) Air Force dropwindsondes deployed over offshore waters of the Atlantic and the Gulf of Mexico; 3) digitized recording of NWS radar data from Athens, Georgia to Volens, Virginia; and 4) an augmented research and operational satellite program.

The NWS radiosonde network included essentially all routinely operational sites in the United States east of the Rocky Mountains and was supplemented by eleven sites in eastern Canada that were coordinated through the Canadian Atlantic Storms Project (CASP), a research effort concurrent with GALE that has been described by Stewart et al. (1987). During intensive observing periods (IOPs) of GALE, all or selected parts of the NWS network and relevant CASP sites launched sondes as frequently as every three hours to provide information over a larger outer area.

A variety of meteorological satellites provided data support for GALE. This support was particularly valuable since much of the area of interest was over the data-sparse ocean. Standard products from polar orbiters *NOAA-9, NOAA-6, DMSP F-7, NIMBUS-7,* and standard and specialized products from *NOAA-9, NIMBUS-7,* and the geostationary *GOES-6* platform were archived for the experiment.

Infrared imagery from *NOAA-9* is being processed by GALE investigators to produce detailed atmospheric-corrected sea-surface–temperature analyses. Ozone mapping from *NIMBUS-7* has been produced for GALE by Larko et al. (1986). Finally, up to five sounding sets daily "plus" wind fields derived from "cloud-drift" vectors and "water-vapor–drift" vectors up to three times daily have been produced from *GOES-6* data (Velden, 1987).

During the experiment, a McIDAS work station was located at Raleigh, North Carolina, for continuous monitoring of GOES-derived products. Ready access to satellite data proved invaluable in monitoring the progress of weather-system development, and updating aircraft missions, particularly those directed over oceanic areas.

Special new GALE systems added much detail to mesoscale observations along the piedmont, coastal plain, and near-shore waters of North and South Carolina. The locations of these systems are illustrated in Fig. 1. The systems included: 1) sixteen additional sounding sites, including eight Cross-chain–LORAN Atmospheric Sounding Systems (CLASS) recently developed by the National Center for Atmospheric Research (NCAR); 2) eight instrumented meteorological buoys, including six from North Carolina State University (NCSU) and two from the National Oceanic and Atmospheric Administration (NOAA); 3) a network of 50 portable automated mesonet (PAM II) surface stations; 4) eight research aircraft including NCAR's Lockheed Electra, Beechcraft Super King Air, and

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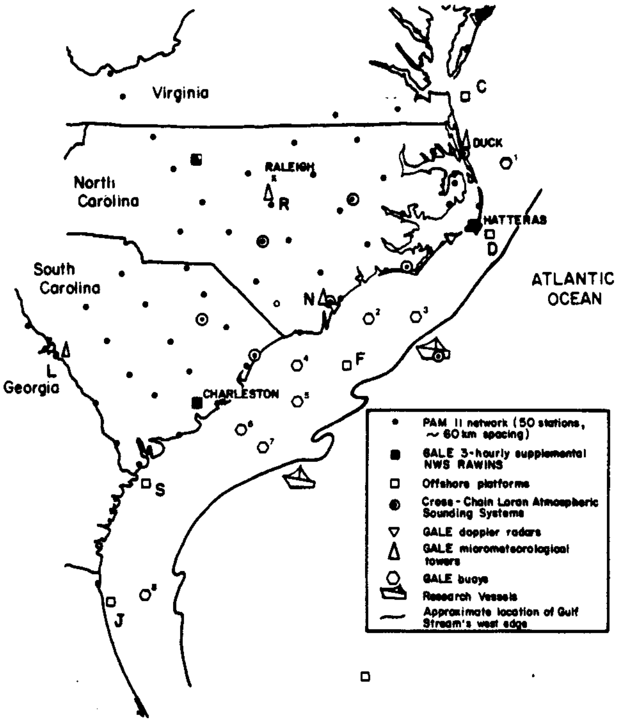


FIG. 1. GALE observational networks in the inner (intensive) GALE region. Included are all sites except pre-existing "routine" surface stations and research aircraft. The solid line offshore illustrates a typical location of the western edge of the Gulf Stream.

North American Sabreliner; NOAA's Lockheed P-3 and Cessna Citation-II; NASA's Lockheed Electra and ER-2; and the University of Washington's (UW) Convair C131A; 5) four scanning Doppler radars including NASA's SPANDAR at Wallops Island, Virginia; the Massachusetts Institute of Technology's Doppler unit at Wilmington, North Carolina; two NCAR units (CP-3 and CP-4) in dual-Doppler array and the University of Washington's vertically-directed unit near Cape Hatteras, North Carolina.

The interaction of the atmosphere with the ocean in the nearshore waters of the Carolinas is thought to be of crucial importance in storm and frontal formation. This interaction may be of particular importance where continental air masses first encounter the very warm Gulf Stream waters, particularly where this warm current closely approaches the mainland. Somewhat analogous oceanic processes such as the dynamics of Gulf Stream instability and the genesis of the oceanic mid-shelf front are thought to be shaped by atmospheric events. Consequently, in conjunction with the larger-scale atmospheric component of GALE; a coordinated physical-oceanography program was conducted to better understand air-sea-interaction processes. Included were measurements of currents, salinity, and temperatures using moored and shipboard systems, and Aircraft Airborn Expendable Bathy Thermographs (AXBTs). Fifty hours of planetary-boundary-layer (PBL) time on the NOAA P-3 were also a component of the physical-oceanography program.

With such a widely spread array of measurement platforms, GALE was the largest field project ever attempted in the eastern United States. Strategies used to support the scientific objectives were manifold, but generally emphasized investigation of mesoscale processes and mesoscale phenomena including, for example: tropospheric-stratospheric–exchange processes and the behavior of upper-tropospheric jet cores; cloud microphysics and the structure of rainbands, including the role of gravity waves in rainband organization; precipitation processes near developing fronts and cyclones; cold-air damming and coastal front development; detailed frontal structure and cyclone evolution, especially during early genesis stages; modification of the marine PBL during frontogenesis and cyclogenesis; the enhancement of mesoscale systems by the Gulf Stream.

An important component of GALE implicit in its scientific objectives was the investigation of exchange processes among various circulation scales, as, for example, the links between the microscale air-sea interaction, the mesoscale structure of the planetary boundary layer (PBL), the transport of latent heat and sensible heat through the PBL into the storm, the interactions between cloud dynamics, rainband organization, and cyclogenesis.

2. Overall field summary

Thirteen IOPs spanned almost 800 h, or about half the total field season. Table 1 lists the dates and times of these data-gathering periods as they are defined and described in the GALE Field Program Summary (Mercer and Kreizberg, 1986).

In all, there were three cases of cyclones, which deepened at a rate of at least 1 mb per hour sustained over a 24-h period, and that originated in or near the inner GALE region. In addition during the IOPs, four-more cyclones met this deepening criterion (1 mb per hour in the northwest Atlantic over 24 hours) adjacent to the GALE region. There were six cases of "explosive" development (10-mb deepening in six h or less). The first half of the field season was the most active in that most of the strongest cyclones occurred before mid February.

In all, 3 580 soundings, including over 300 dropwindsondes, were made; with roughly half of the soundings within the inner region. Aircraft flew over 900 hours in support of GALE IOPs (Kreizberg, 1987).

a. The second intensive observing period

The second IOP was the longest during the program (over 5 days) and included a variety of key events ranging from cold-air damming and coastal frontogenesis, to three cases of cyclogenesis and a spectacular cold-air outbreak. Many investigators are using segments of this IOP's measurements in their first detailed analysis of the field data. (Early analysis samples for the period are described for the PBL subprogram later in this article.)

The second IOP began at 1200 UTC on 23 January, some six hours prior to a case of coastal frontogenesis and ended with a spectacular cold-air outbreak on 28 January. There are three cyclones that formed in the GALE area during this IOP. One was a small storm that formed and moved north along the coastal front after the front had propagated inland on the twenty-fifth of January.

After the reinforced coastal front moved offshore in the lee of the small storm, a second, much larger but "less-concentrated" cyclone formed on the front early on the 27th. The initial cyclone center not resolvable in operational data, appeared as a series of short frontal waves; a growing low-pressure

TABLE 1. GALE intensive observing periods.

Intensive Observing Period	Date and Time (UTC)	Major Events
1	1/18 00 - 1/20 21	Upper-level cyclogenesis, coastal wave
2	1/23 12 - 1/29 04	Rapid, large near-shore and cold-air cyclogeneses, cold-air outbreak
3	2/2 18 - 2/4 23	Offshore cyclogenesis
4	2/6 07 - 2/8 00	Convective activity and quasi-stationary front
5	2/9 00 - 2/13 23	Far-offshore cyclogenesis, cold-air cyclogenesis, cold-air outbreak
6	2/14 00 - 2/15 17	Offshore cyclogenesis
7	2/21 12 - 2/22 06	Surface wave passage and offshore cyclogenesis
8	2/22 17 - 2/24 01	Weak coastal cyclogenesis and strong convection over Gulf Stream
9	2/24 18 - 2/26 19	Strong offshore cyclogenesis
10	2/27 00 - 2/28 12	Alberta clipper and nearshore cyclogenesis
11	2/28 21 - 3/2 21	Moderate far-offshore cyclogenesis
12	3/6 17 - 3/9 21	Anticyclogenesis
13	3/11 17 - 3/15 00	Coastal front and onshore cyclogenesis

system eventually formed off the New Jersey coast by 1200 UTC on 27 January. The storm typically produced snow depths of 15 cm to 20 cm over the region northwest of the GALE intensive area; maximum depths were of the order of 30 cm.

On the 27th, a third cyclone formed in the cold air south of Cape Hatteras, intensified rapidly, and moved northward producing 5 cm to 8 cm of largely unforecast snow from North Carolina to New York. On the 28th, the secondary surge of cold air behind this cyclone produced temperatures as low as −27°C at 850-mb level. The R/V *Endeavor* 100-km southeast of Charleston, South Carolina, at 0000 UTC on the 28th in 20 to 25 $m \cdot s^{-1}$ winds and nearly zero visibility in "sea smoke," reported an air temperature of −2°C at ten meters with sea temperatures of 20°C.

An overall view of the GALE data collected during the most-active phase of the second IOP is illustrated in Fig. 2, taken from Mercer and Kreitzberg (1986). Routine data are not included as, for example, normal 12 UTC and 00 UTC soundings. It can be seen that on 26 January soundings at three-hour intervals were available for nearly all sites in the eastern United States and that for much of the day 90-min soundings from the inner network of CLASS sites were available. On the 27th the inner network was shut down at 0600 UTC as the western part of the outer national network was gradually deactivated. Six research aircraft flew a combined total of about 80 h in two days on missions to explore the marine boundary layer, the tropopause-fold region, frontal rainbands, and cyclonic and frontal structures. The Air Weather Service conducted extensive dropwindsonde flights throughout much of the two-day period. Finally, as shown in Fig. 2, special GALE radars and digitized NWS radars virtually operated continuously through the 26th. The two research ships were on station taking hourly surface observations and providing some sounding support. Not included in the illustration are PAM II and satellite coverage. The former operated continuously throughout the 60-day field season with "five-minute" data available from nearly all sites. Special satellite products for the IOP include 23 sets of VISSR [visible infrared spin scan radiometer] atmospheric sounder of (VAS) soundings, 23 sets of cloud-derived wind fields or water-vapor–derived wind fields, 12 sets of *NOAA*-9 soundings, as well as "routine" high-resolution Geostationary Operational Environmental Satellite (GOES) and NOAA imagery.

3. Boundary-layer observing systems

Focus on one subcomponent of the. Since many of GALE's scientific objectives involved PBL processes, some specialized aspects of GALE's PBL component will be described in more detail here.

The boundary-layer observing systems were operated in coordination with other components of GALE in order to provide real-time information for operational decisions. A block diagram in Fig. 3 shows the general organizational structure of GALE operations in relation to the PBL subprogram.

a. Specialized offshore platforms

Six of the meteorological buoys (see Fig. 4) furnished by North Carolina State University (NCSU) and moored along the continental shelf were equipped with sensors manufactured by Aanderaa Instruments to measure and record wind speed and direction, air pressure, relative humidity, and air and sea temperature.

Wind instrumentation included a 3-cup anemometer housing a rotating magnet and reed-contact system. The sum of contacts over a selected interval provided a measurement of the average wind speed. Wind direction was measured by a vane and compass, which were sampled instantaneously at 30 minute intervals. Both the compass and vane were oil damped, and to reduce buoy rotation caused by waves and swell, the buoy was furnished with a fixed plywood airfoil.

A temperature-compensated silicon-resistor–type barometer measured pressure, and a hair hygrometer with a deflectable silicon beam measured relative humidity. Platinum-resistance thermometers were used to measure air temperature and sea temperature.

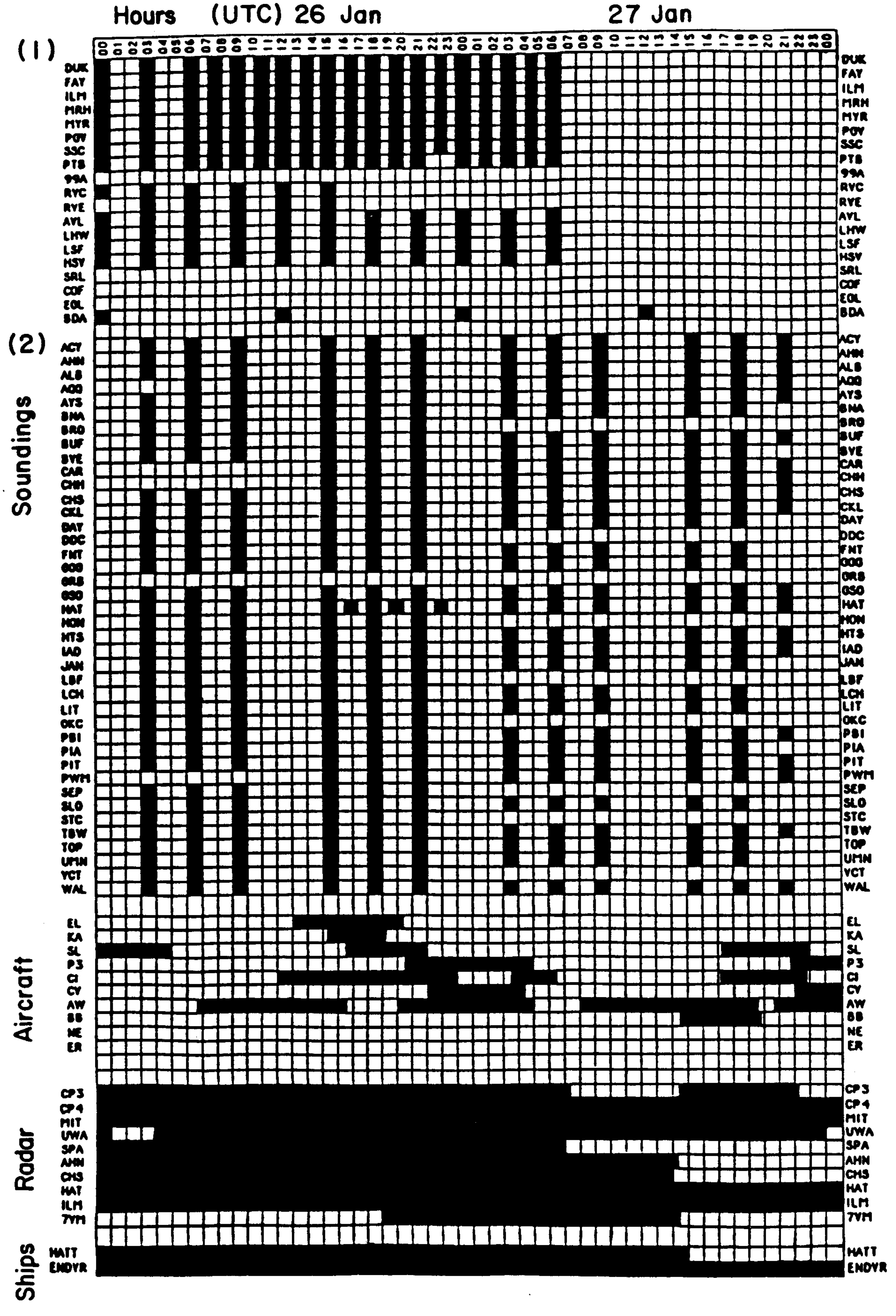
The instruments were mounted on a horizontal arm 3 m above the sea surface. The air-temperature sensor and humidity sensor were housed in passively ventilated radiation shields. The sea's temperature was measured at a depth of 2 m.

Readings from each instrument were sampled at 30-min intervals and were recorded on magnetic tape. Between IOPs, one of the research ships normally visited buoy sites to perform visual checks, instrument intercomparisons, and to replace recording tapes and batteries. For security, each buoy was equipped with a navigational light, radar reflector, and an Argos satellite beacon, which transmitted the buoy's location at regular intervals.

Table 2 gives the depth of the water where the buoys were

TABLE 2. Depth of buoy mooring.

Buoy #	1	2	4	5	6	8
Depth (m)	36	26	22	36	25	30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moored. These small depths made mooring somewhat difficult, since short mooring lines are not elastic enough to provide sufficient allowance for tides and swell while maintaining enough tension to avoid fouling. The mooring design to maintain line tension incorporated a deadweight anchor consisting of a 1 600-kg stack of railroad-car wheels and a counterweight of heavy chain (see Fig. 4). An acoustic release and a set of floats to aid in buoy retrieval was also incorporated into the design.

Prior to GALE, NOAA instrumented the offshore platforms in the "Coastal-Marine Aids to Navigation" (CMAN) network with temperature, wind direction and speed, and pressure sensors. The locations are depicted as open squares in Fig. 1 and include, from north to south: Chesapeake (C), Diamond Shoals (D), Frying Pan Shoals (F), Savannah (S), and St. Johns (J) Navigational Light Towers. Measurement heights varied from site to site, ranging from 14-m to 47-m above the sea surface.

Two NOAA research buoys were instrumented and deployed for GALE. These measured and transmitted observations of air and sea temperature, pressure and wind as a complement to the NCSU near-shore buoy network. The NOAA buoys and the Diamond Shoals Navigational Light relayed data via satellite at 30-min intervals, while the remaining platforms relayed data hourly.

b. Research ships

R/V *Cape Hatteras* and R/V *Endeavor* were the two research ships used for GALE. Wind speed, direction, air temperature, and relative humidity were measured at a height of about 16-m above the water level on the *Cape Hatteras* and 10-m above water level on the *Endeavor*. Air pressure on both ships was measured at a height of 3 m. Sea-surface temperature was measured with a thermistor at a depth of about 1-m below the surface.

Wind speed and direction were measured using a propellor-vane type of instrument and corrected for ship motion using information on ship heading, course, and "speed over ground." Care was taken to insure unobstructed flow for the instruments with proper orientation of the ship during observation periods, which typically varied from 15 min to 30 min. Air temperature was measured using a thermistor housed in an aspirator and protected from direct radiation. Mean relative humidity was measured using a capacitance-type humidity sensor protected with a cintered filter. Measurements of air temperature and relative humidity were closely monitored by comparison with readings from aspirated psychrometers.[3]

FIG. 2. (On facing page) Time chart of activity at selected sites for a two-day part of an Intensive Observing Period.

Sounding sites include, from top to bottom: 1) All inner network CLASS, supplementary sites, and ships, as well as routine NWS sites placed on intensive schedules. These include: in North Carolina, Duck (DUK), Fayetteville (FAY), Wilmington (ILM), Beaufort (MRH), and Greenville (PGV); in South Carolina, Myrtle Beach (MYR), and Sumter (SSC); and in Virginia, Petersburg (PTB). Ships include the R/V *Cape Hatteras* (RVC) and the R/V *Endeavor* (RVE). The remaining symbols are those routinely used by the National Weather Service, and 2) NWS sounding sites in the outer network.

Aircraft platforms include the NCAR Electra (EL), King Air (KA), and Sabraliner (SA), the NOAA P-3 (P3) and Citation (CI), the University of Washington C-131A (CV), the US Air Force dropsonde aircraft (AW), and the MIT Beach Barron (BB).

Radar sites include scanning Doppler radars from NCAR (CP3 and CP4) and MIT (MIT), the University of Washington's vertically-pointing Doppler radar (UWA), the NASA SPANDAR (SPA) located at Wallops Island, Virginia, and digitized NWS radars at Athens, Georgia (AHN), Hatteras and Wilmington, North Carolina (HAT and ILM), and Volens, Virginia (7VM).

Surface hourly observations from ships include the R/V *Cape Hatteras* (HATT) and the R/V *Endeavor* (ENDVR).

Not included here are routine 12-hour radiosonde launches from all NWS sites, and continuously scheduled PAM II, buoy, and routine surface observation sites.

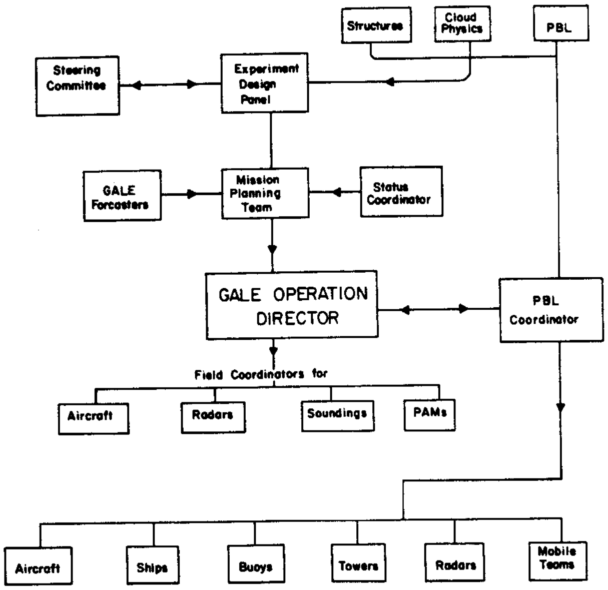

FIG. 3. Organizational structures for the operational field phase of GALE with emphasis on the Planetary Boundary-Layer (PBL) component.

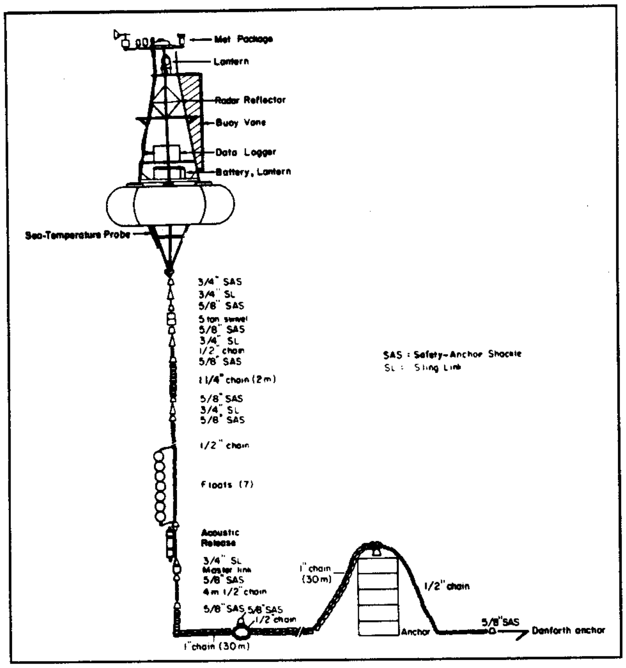

FIG. 4. Mooring design for the six North Carolina State University GALE buoys.

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[3] Hourly observations were processed by a Seadata ASCII Interface Loop (SAIL) system controlled by a Hewlett-Packard computer and recorded on diskettes. The SAIL system provided real-time data display. The data were also stored on a Campbell data logger.

TABLE 3. Instrumentation on the research aircraft, NCAR King Air.

Parameter	Sensor
Position	Inertial navigation system (INS)
Position	LORAN-C
Aircraft velocity	INS
Aircraft altitude	INS
True heading	INS
u, v, w, and turbulence	INS and gust probe
Pressure	Variable capacitance, fuselage
Pressure	Variable capacitance, wing
Airspeed	Variable capacitance, radome
Airspeed	Variable capacitance, wing
Airspeed	Variable, radome total p
Temperature	Platinum resistance
Temperature	Platinum resistance, de-iced
Temperature	Platinum resistance, rev. flow
Temperature	Platinum, fast response
Dew point	Cooled-mirror hygrometer (2)
Water-vapor density	Lyman-α sensor
Geometric altitude	Radar altimeter
Liquid water content	Hot wire (JW)
Liquid water content	Hot wire (King)
Supercooled water	Icing rate
Cloud droplets	FSSP
Hydrometeors	260X optical-array probe
Hydrometeors	1D 200Y optical-array probe
Hydrometeors	2DP optical-array probe
Visible radiation	Pyranometers (2, up and down)
Infrared radiation	Pyrgeometers (2, up and down)
Sea-surface temperature	Radiometric thermometer
Photography	Starboard, forward video

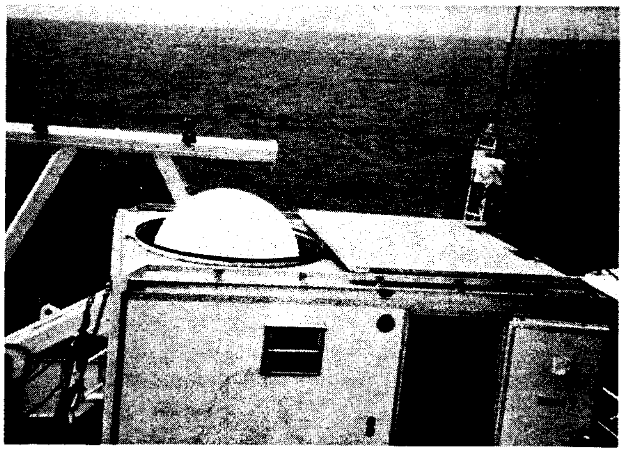

FIG. 5. A view of the CLASS van aboard the R/V Cape Hatteras during a balloon launch.

TABLE 4. Instrumentation on the research aircraft, NOAA P-3.

Parameter	Sensor
Position	Inertial/Omega
u, v, w	Inertial/Omega
Heading	Inertial/Omega
Pitch	Inertial/Omega
Roll	Inertial/Omega
Ambient pressure	Transducer
Dynamic pressure	Transducer
True altitude	Radar Altimeter
Air temperature	Platinum resistance Radiometer
Dew point	Cooled Mirror
Surface temperature	Radiometer
Cloud liquid water	Hot Wire
Cloud particle images	Optical Spectrometer
Precip particle images	Optical Spectrometer
PPI reflectivity	C-band radar
PHI reflectivity	X-band radar
RHI Doppler	X-band radar
Photography	16-mm, color, time lapse
Turbulence	INS and gust probe

High-frequency (10 per second) velocity and temperature fluctuations were also measured at a height of 16 m on the *Hatteras* to compute spectra and estimate the energy-dissipation rate from the inertial subrange.[4]

At regular intervals during IOPs, the oceanic mixed layer was probed using a conductivity, temperature, and depth (CTD) system;[5] the system could not be operated during rough seas.

The CLASS facility was installed on the R/V *Cape Hatteras* to provide detailed atmospheric soundings over the data-sparse oceanic region of GALE. A typical launch is shown in Fig. 5. A second LORAN atmospheric sounding system was deployed aboard the R/V *Endeavor*.

c. *Research aircraft*

Three research aircraft equipped with gust probes were used for the GALE boundary-layer study. They were the NCAR King Air, the NCAR Electra and the NOAA P-3, all based at the Raleigh-Durham airport. The NCAR aircraft were equipped with high-resolution instruments for measuring turbulence parameters that were sampled at up to 20 times per second, and to obtain mean quantities slow-response sensors measured at one sample per second. Details of instrumentation on the NCAR King Air and the NOAA P-3 are given in Tables 3 and 4, respectively. Instrumentation on the NCAR Electra was essentially similar to that on the King Air.[6]

In addition to these research aircraft, the NASA Electra, equipped with a downward-looking lidar, was used to map the height of the PBL. This aircraft was based in Hampton, Virginia, and typically flew at about 3000 m in coordination with the other three aircraft. Some of its flights were also coordinated with Doppler-radar studies of a "chaff-filled" PBL.[7]

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[4] The spectra can be used to compute friction velocity and friction temperature, which in turn with appropriate stability corrections will "give" fluxes of momentum and sensible heat. Velocity fluctuations were measured using a hotwire anemometer and temperature fluctuations with a platinum-resistance thermometer. These observations were recorded directly on magnetic tape at 10 samples per second for later analysis.

[5] Data from the C&D system were recorded by the SAIL system and the profiles of temperature and salinity were displayed in real time.

[6] All the observations were recorded aboard the aircraft by the NCAR Aircraft Data System on nine-track digital tapes during flight. Real-time analysis of the vertical variation of wind, air temperature, and humidity were made to determine the height of the boundary layer and the mean wind direction; this helped in determining the flight altitudes as a function of boundary-layer height. Flight tracks were carefully chosen to account for sharp discontinuities in the sea-surface temperature in the vicinity of the Gulf Stream and the mid-shelf oceanic front where temperature changes of about 10°C were observed. In order to account for the drifts in the Lyman-α humidity sensors, during the post-flight analysis "on-board calibration" was made using the slow-response cooled-mirror hygrometer.

[7] The total number of aircraft hours utilized for boundary-layer studies during GALE was about 225 h with King Air flights totalling 104 h; NCAR Electra, 51 h; NOAA P-3, 50 h; and NASA Electra, 20 h.

TABLE 5. Number of aircraft hours per mission type.

Aircraft	Quiescent	Pre-storm	Coastal Front	Cold-Air Outbreak	Tower-Aircraft* Intercomparison
King Air	35.7	17.0	24.7	22.2	4.2
NCAR Electra	21.3	7.2	4.4	18.1	0
NASA Electra	0	0	0	20.5	0
NOAA-P3	0	0	0	50.0	0
TOTAL	57.0	24.2	29.1	110.8	4.2

* A tower-aircraft intercomparison flight using the NCAR King Air and a 20-m micrometeorological tower on a research pier at Duck, North Carolina, was carried out to compare mean and turbulence parameters. (Details of instrumentation on the 20-m tower are given in a later section.)

TABLE 6. Characteristics of the Doppler radars (CP-3 & CP-4).

Wavelength:	5.5 cm
Pulse length:	150 m
Range gates:	512 to 1024
Peak power:	400 kw
Beamwidth:	1.1 degrees
Pulse-repetition frequency:	625 to 1667 pulses/sec
Azimuth rotation:	0 to 25 deg/sec
Elevation rotation:	0 to 15 deg/sec

TABLE 7. GALE PBL Radar Experiments.

Date	Time (UTC)	Description
12 Feb 1986	1347–1715	Strong cold-air outbreak
23 Feb 1986	1800–2306	Weak cold-air outbreak with complex horizontal wind structure
02 Mar 1986	1313–1757	Weak cold-air outbreak 48 h after cold frontal passage
08 Mar 1986	1750–2200	Quiescent coastal front, cold-air damming south of the radar network
15 Mar 1986	2100–2320	Stable boundary layer

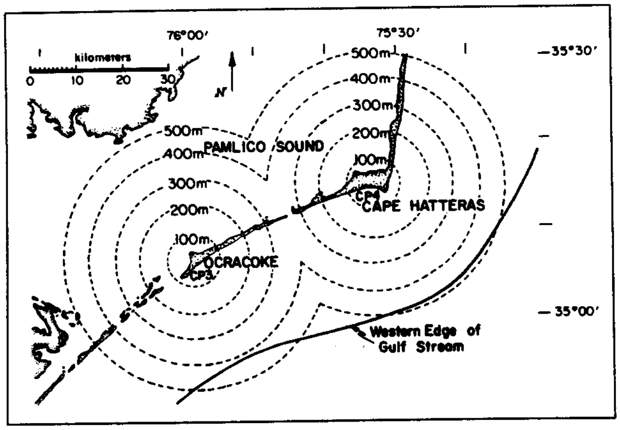

FIG. 6. Doppler-radar sites on the Outer Banks of North Carolina. Dashed circles indicate beamwidth dimensions at selected ranges. Dual-Doppler measurements are possible where the dashed circles overlap.

To accomplish GALE's objectives, the PBL's structure was investigated during 1) quiescent conditions, 2) pre-storm conditions, 3) coastal frontogenesis, and 4) cold-air outbreaks. The approximate number of aircraft flight hours devoted to each of these investigations is given in Table 5.

d. Doppler radars

Figure 6 shows the locations of the two NCAR Doppler radars. The contours of the beamwidth dimension as a function of range are indicated by the dashed circles. The CP-4, (5.5-cm) radar was located at Buxton, North Carolina, near Cape Hatteras (34.23°N, 75.53°W), while the CP-3 (5.5-cm) radar was located near Ocracoke, North Carolina (34.10°N, 75.97°W). The baseline separation between CP-3 and CP-4 was approximately 44 km. The principle characteristics of CP-3 and CP-4 are virtually identical and are listed in Table 6.

The range-gate dimension was chosen to be 150 m for the PBL experiments during GALE. The range at which the pulse volume is approximately equal in range and angular dimensions is 9 km.[8]

Chaff was dispersed by a twin-engine aircraft along a line perpendicular to the mean PBL wind at an altitude near the midpoint of the mixed layer. The chaff-dispersal line was located 40-min upwind from the radar network. The length of the line varied, but was always designed such that a linear advection of the line would produce echo targets for at least a 20-km radius around each radar.

Five chaff experiments were conducted during GALE (Marshall et al. 1986). Three of the experiments examined cold-air outbreaks following cold-front passages. Generally, the cold,

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[8] Scan parameters were chosen such that the standard deviation for the radial-velocity estimate with the antenna at 0.0 degrees elevation angle was less than or equal to 0.4 $m \cdot s^{-1}$. The pulse-repetition frequency for all scans was 1 666 pulses per second. The temporal scale chosen for possible observation of such boundary-layer phenomena as coastal fronts, boundary-layer rolls, and cold-air outbreaks was 60 min. A scan sequence was designed to take less than 30 min. Each scan sequence was comprised of a set of three scan types designed to supply appropriate data for three data-analysis techniques. A velocity-azimuth display scan began each sequence. These scans were designed to take advantage of the mean wind and turbulence analysis around 360 degrees of azimuth (Kropfli, 1984). The scan sequence then continued with high-speed sector scans to obtain data for the single Doppler dynamic constraint analysis techniques (Lilly and Moeng, 1984). The scan sequence concluded with CP-3 and CP-4 completing a dual Doppler observation.

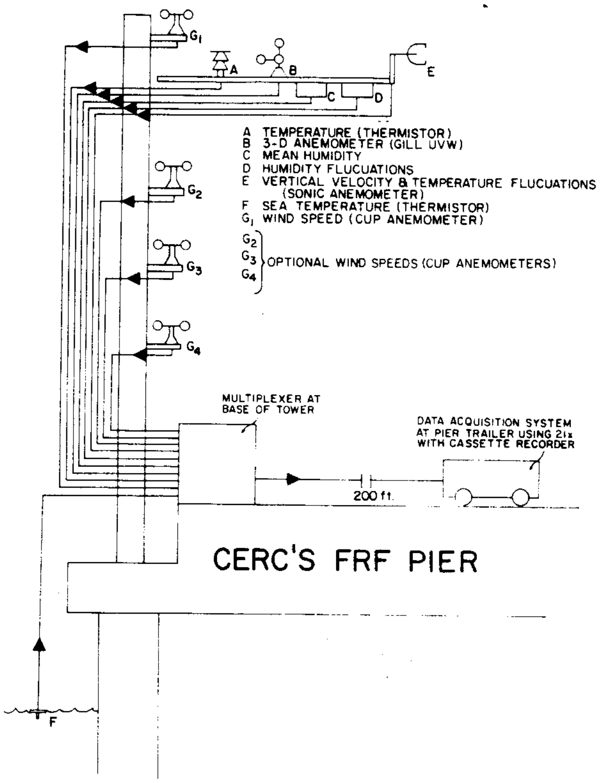

FIG. 7. Schematic illustration of micrometeorological instruments at the Coastal Engineering Research Center's (CERC's) Field Research Facility (FRF) at Duck, North Carolina. The facility extends seaward over 500 m from the beach, allowing over-water measurements from a stable platform.

dry northwesterly flow advected polar or arctic air across the coastal area of North Carolina, then offshore or over the Pamlico Sound, and the Gulf Stream. A fourth event was a quiescent coastal front with evidence of cold-air damming. The prevailing surface wind was out of the north. The fifth even was a stable PBL with surface winds out of the south. The events are summarized in Table 7 (see previous page).

e. Meteorological towers

A 20-m–high tower located on a research pier extending to about 560 m into the ocean near Duck, North Carolina, was used to make micrometeorological measurements. The purpose of these observations was to construct a time history of momentum, heat, and water-vapor fluxes for different IOPs during GALE using a stable platform.

Vertical velocity fluctuations were measured using both a one-dimensional sonic anemometer and a propellor-type anemometer. Horizontal velocity fluctuations were measured with the Gill UVW anemometer and a hot-wire anemometer. Because of the hostile environmental conditions to which the sensors are exposed in the marine surface layer, backup instruments were necessary for each parameter being measured. A line diagram showing the deployment of the instruments on the tower is shown in Fig. 7. Details of the instrumentation are given in Table 8. The data were collected using two modes on separate micro-processor–controlled Campbell data loggers. Mode one produced hourly means, standard deviations, and covariances, whereas mode two produced instantaneous, unprocessed data at a rate of 10 samples per second for later analysis of spectra and other statistical parameters.

Other measurements available for the GALE period include Carolina Power and Light Company towers near Raleigh (R) and one near the North Carolina coast (N), and the Savannah River Laboratory tower in South Carolina (L), all of which measured selected mean and "turbulence" variables at several heights.

f. Mobile teams

Two mobile teams with portable observing systems to measure air temperature and relative humidity and to launch mini-radiosondes were deployed during various IOPs to determine the location, movement, and characteristics of coastal fronts over land. Operating principally along eastern North Carolina highways, the teams were coordinated via the central GALE facility at Raleigh. Surface measurements and upper-air measurements were generally obtained on both sides of the surface wind-shift line. Detailed measurements of the thermodynamic structure of the boundary layer in and near the frontal zone were thus obtained.

g. CLASS and conventional soundings

A mesoscale array of seven CLASS sites, nested within an augmented network of conventional radiosondes, was deployed over the coastal plain of the Carolinas and an eighth site was "located" in the Gulf Stream on the R/V *Cape Hatteras*.[9] During IOPs launches from these locations were often scheduled every one and one-half to 3 h.

"Profiles" with a vertical resolution as great as 40 m provided a detailed description of the winds and thermodynamic structure from the surface to the stratosphere. The high resolution will be particularly useful in the boundary layer. A sample wind profile from the R/V *Cape Hatteras* is illustrated in Fig. 8 as the plot was generated onsite from flight data.[10]

h. The portable automated mesonet (PAM II)

A mesoscale network of 50 automatic surface stations was deployed in a "9 by 5" array aligned parallel to the coast from

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[9] The CLASS system consists of a Vaisala instrument package measuring temperature, humidity, and pressure and modified to receive LORAN signals and relay them to a ground station. The ground station, developed at NCAR, includes a launch and tracking facility with menu-driven software that organizes instrument calibration, optimum LORAN navigation, launch and tracking procedures, and data processing (Laursen et al. 1986).

The winds are computed via the ANI-7000 navigation system that simultaneously collects data from several LORAN chains rather than the usual single chain. The resulting redundancy allows computation of winds with expected errors of less than 0.5 $m \cdot s^{-1}$ for the GALE region (Passi and Morel, 1986). Thus, the system has a potential for accuracy that is greatly increased over conventional sounding systems and appears particularly well-suited for use in a mesoscale study.

[10] The CLASS system met its first large-scale test during the experiment and performed very well even in adverse weather. For example, on the R/V *Cape Hatteras* over 200 launches were made, often during winds of over 20 $m \cdot s^{-1}$. Only two launches were unsuccessful. These were due to the fouling of the sonde train by ship antennas during extreme conditions, with, in one case, winds gusting to over 35 $m \cdot s^{-1}$ in heavy rain, sea spray, and lightning.

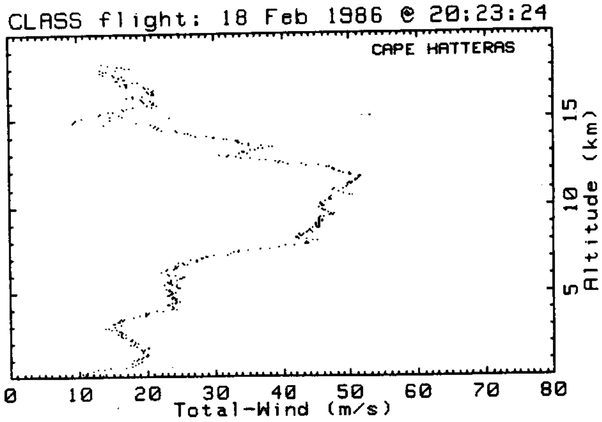

FIG. 8. A sample CLASS wind-speed profile as obtained in real time from the R/V *Cape Hatteras*.

TABLE 8. Instrumentation on the Micrometeorological Tower at Duck, North Carolina.

Parameter	Sensor
Wind speed	Propeller-vane type and cup anemometer
Wind direction	Propeller-vane type
Longitudinal and lateral velocity fluctuations	Propellers
Vertical velocity fluctuations	Propellers One-dimensional sonic anemometer
Air temperature	Thermistor
Temperature fluctuations	Thermocouple Platinum-resistance type
Sea temperature	Encapsulated thermistor
Mean humidity	Capacitance type
Humidity fluctuations	Lyman-α

southeast Virginia to the Georgia–South Carolina border plus an added single line of 5 stations transecting the Appalachians (Fig. 1). Each station measured dry-bulb temperature, and wet-bulb temperature, pressure, u and v wind components, and rainfall all reported at 5-minute intervals. Measurements were relayed via satellite to NCAR and to the operations center at Raleigh for immediate use in decision making. A complete description of the PAM II instrumentation is given by Brock et al. (1986).

Access to frequent plots of the PAM II data were extremely helpful during the experiment. Location and evolution of frontal zones, as well as smaller-scale sea-breeze confluence zones and convective outflow boundaries, for example, could be readily monitored. Mobile teams could be dispatched to areas of interest and plans could be continuously updated.

4. Preliminary examination of PBL data

Coordinated observations from various platforms were calibrated, edited, subjected to quality control at participating institutions, and archived at the GALE Data Center, Drexel University. Calibration and editing of the aircraft data were performed at the respective NCAR and NOAA facilities. Observations from the research vessels, the Duck tower, and buoys were processed at NCSU. The GALE Data Center "quality checked" all sounding data. Mini-radiosonde data were handled at NCSU and transferred to Drexel after subjecting the observations to quality-control procedures. Boundary-layer Doppler-radar data were analyzed by NCSU using NCAR facilities. Some preliminary analyses of selected cases during GALE are presented in this section.

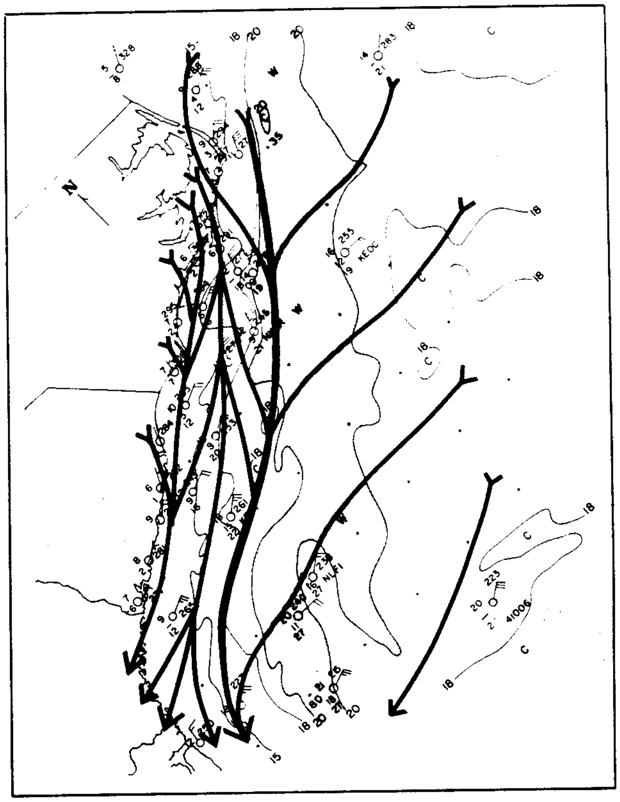

FIG. 9. Surface-streamline analysis for 0000 UTC on 25 January 1986. Plotted data include reports from coastal PAM stations, offshore light towers, buoys, research ships, and ships of opportunity. Cloud cover is not included. Thin lines illustrate clear-sky black-body temperatures (°C) as derived from *NOAA-9* imagery. The approximate location of the Gulf Stream is shaded.

a. Coastal-front formation

A preliminary analysis of surface-marine data including measurements from the wide variety of "routine" and special GALE platforms for the case of the developing coastal front on 0000 UTC 25 January is illustrated in Fig. 9.

In order to compare wind measurements taken at a variety of heights ranging from 3 m on buoys to over 40 m on some light towers, wind speeds have been adjusted to a reference height of 10 m for platforms of known height. This included all offshore sites except ships-of-opportunity. The method of adjustment, described by Riordan (1987) used the log-power law and assumed neutral stability and a drag coefficient that varied with wind speed.

A rough estimate of the sea-surface temperature field as derived from *NOAA-9* infrared imagery is also illustrated in Fig. 9. It should be noted that the illustrated ocean-temperature field is preliminary and has not been corrected for atmospheric effects and is thus likely to be cold-biased by several degrees Celsius, especially in warm areas. However, the locations of gradients should be well-represented.

The streamline analysis in Fig. 9 depicts a narrow zone of confluence aligned with the west edge of the Gulf Stream. This confluence lies within a zone of strong horizontal gradient in air temperature and marks the surface location of a developing coastal front. Previous work by Bosart (1973 and 1975) has documented similar fronts near the coast of New England and has shown them to be generally shallow, boundary-layer features, which are nevertheless important in precipitation and cyclogenetic processes. A brief study by Riordan et al. (1985) describes measurements near a coastal front off the North Carolina coast and showed many similar features.

Examination of available "ship" data and "buoy" data show no hint of frontal passage anywhere east of the front's position at 0000 UTC. This suggests that the frontogenesis begins near the western edge of the Gulf Stream.

East of the front, air of relatively uniformly higher temperatures is flowing generally westward. To the west, cooler air characterized by a strong horizontal temperature gradient is flowing southwestward parallel to the coastline. Large air-temperature–sea-temperature differences and rather-strong wind speeds shows that this cool continental air was being modified rapidly by the warmer sea surface. In fact, this airmass and flow regime had characterized the whole offshore region prior to 0000 UTC, before winds east of the Gulf Stream began to veer shoreward.

A new finding is that smaller-scale confluence-difluence axes appear to align parallel to the coast in the region over the shelf waters west of the coastal front. Subsequent analyses (not shown) trace the evolution of a land-breeze circulation and an apparent "sea-breeze" cell to the east, and attest to the continuity of these parallel axes. Work is currently being done to trace the role of these axes on the evolution and behavior of the coastal front.

The feature, "briefly shown here," became a major feature of the second IOP. The northern half of the front propagated inland over North Carolina where the "first" cyclogenesis occurred.

b. *Variation of the surface fluxes of heat and momentum*

Surface turbulent fluxes[11] of momentum and sensible heat and latent heat estimated from the measurements at the Meteorological Buoy #2 (see Fig. 1 for location) are shown in Fig. 10.

Sensible-heat fluxes and latent-heat fluxes at Buoy #2 show a significant variation for different synoptic events during IOP 2. In general, the latent-heat flux is larger than the sensible-heat flux except during cold-air outbreaks when both fluxes are of the same order of magnitude. The 28 January cold-air outbreak was the strongest of its kind during GALE (Uccellini et al. 1987) with an air-sea–temperature difference of about 20°C and surface wind speeds in excess of 15 m · s^{-1}. This produced a total heat flux of about 1000 W · m^{-2}. Values of about 800 W · m^{-2} have been observed over the Gulf Stream even during moderate cold-air out breaks (SethuRaman et al. 1986). Surface-heat fluxes of this magnitude produced strong convective conditions and significant evaporation. This case produced a spectacular display of intense "steam devils" and very low (bases about 100 m) clouds. A photograph of this visible convection process over the Gulf Stream is shown in Fig. 11. This event along with other cold-air outbreaks is being studied with observations from all the platforms.

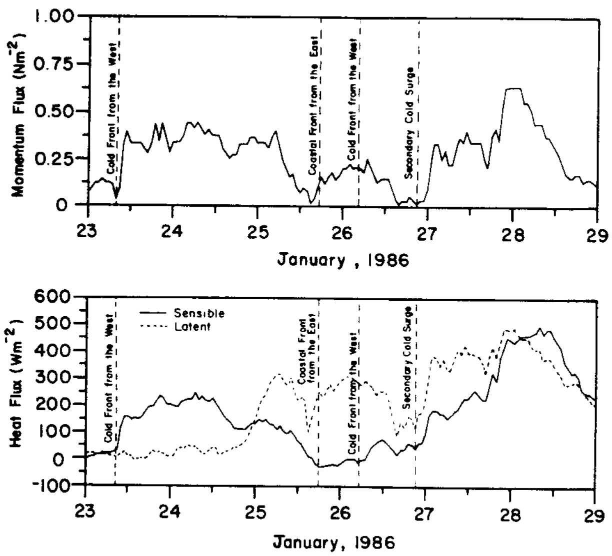

FIG. 10. Momentum flux, sensible-heat flux and latent-heat flux during the second IOP derived from measurements at Buoy 2 east of Duck, North Carolina (see Fig. 1). Times of major synoptic-scale events at Buoy 2 are also indicated.

FIG. 11. Photo taken from the NCAR King Air research aircraft on 28 January 1986 from a height of 60 m above the Gulf Stream east of Cape Hatteras, North Carolina.

c. *Structure of the marine boundary layer*

Coordinated flight tracks for the NCAR Electra and King Air and the sounding locations from the R/V *Cape Hatteras* are shown in Fig. 12. The NCAR Electra was flown at various

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[11] The fluxes were obtained using an iteration technique suggested by Liu et al. (1979). This procedure matches profiles in the atmospheric surface layer, where molecular constraints can be neglected, with the inner part of the surface layer close to the sea surface where the molecular effect is important. Matching is done using similarity-type profiles of wind, temperature, and specific humidity. An iteration technique is used to obtain convergent solutions for the flux parameters such as friction velocity, u*, and friction temperature, θ*. This method has the advantage over the bulk aerodynamic method in that it is not necessary to assume an exchange coefficient relationship to compute the fluxes, but there are uncertainties of this method during high wind conditions when viscous sublayer thickness becomes very small. Applicability of this method for high winds is being investigated with the data obtained during GALE.

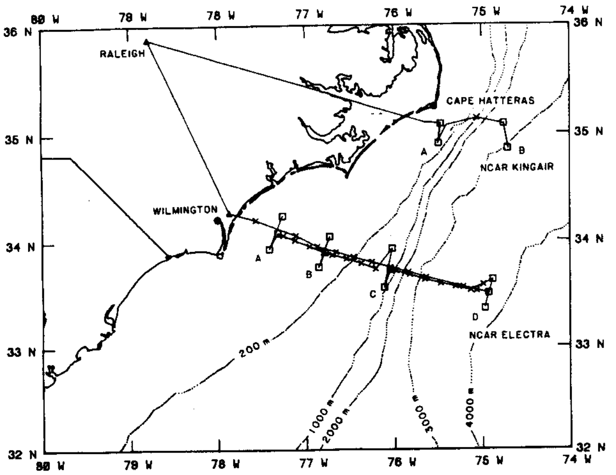

FIG. 12. Flight tracks for the NCAR King Air and Electra for 28 January 1986. Boxes indicate locations of vertical profiles measured by the aircraft as they changed altitude from 2440 m to 60 m. Cross-legs labeled A through D indicate locations of 5-level stacked transects during which turbulence measurements were obtained. Low-altitude transects are indicated by X's. Dotted lines indicate water depth in meters (W). Simultaneous surface observations and sounding were taken by the R/V *Cape Hatteras* directly below the Electra's flight track as the ship transited from near shore to near the transect labeled C.

altitudes ranging from 61 m to 2440 m above sea level to study the mean and turbulent structure of the intensive cold-air outbreak on 28 January. Preliminary results (Wayland and Sethu Raman, 1987) indicate a well-developed convective boundary layer with heights of about 1000 m over the Gulf Stream.

Another important aspect of the marine boundary-layer being investigated using the GALE data is the mesoscale variations of the Thermal Internal Boundary Layers (TIBL) that form at the sea-surface–temperature discontinuities (Jones and Sethu Raman, 1987). With strong horizontal temperature gradients between the shelf water (about 7°C), mid-shelf front zone (about 15°C) and Gulf Stream (about 25°C), air-mass modification (Stunder and Sethu Raman, 1985) will be important in the understanding of the effect of advection in the baroclinic processes.

5. Summary

A wide array of observing platforms was deployed for the two-month winter field program of GALE. Coordinated experiments using these observing systems and other tropospheric measurements were conducted to study the mesoscale processes responsible for East Coast cyclogenesis. Preliminary analyses indicate the existence of significant baroclinic structure in the boundary-layer produced by large sea-surface–temperature gradients induced by the presence of the Gulf Stream. Strong cold-air outbreaks occurred in January and February causing very-large surface heat fluxes. Analyses of the boundary-layer data are in progress at NCSU and elsewhere and it is believed that they will provide better understanding and parameterization of the boundary-layer physics in numerical weather-forecasting models.

This report has provided a general GALE overview and a snapshot of some early analyses currently being pursued. The analysis of PBL structures and processes clearly addresses only one aspect of the GALE objectives. Larger-scale structures and processes and scale interactions are being addressed by other investigators. Hopefully many new scientists will join in data analysis and modeling efforts that will become the vital second half of GALE.

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