DUAL DOPPLER RADAR ANALYSIS OF THE MARINE MIXED LAYER DURING A COLD AIR OUTBREAK OVER A STRONG SEA SURFACE TEMPERATURE GRADIENT

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ABSTRACT

An investigation of the structure of the marine boundary layer using metallic half wavelength chaff and dual Doppler radars is described. The measurements were made in cold air flow over a warm and complex sea surface temperature structure. Radar derived mixed layer height contours, vertical wind contours, divergence fields and eddy wind fields are displayed.

1. INTRODUCTION

The use of half wavelength metallic chaff as a radio frequency energy scatterer was an early facet of electronic counter measures. The relationship between the chaff density and radar cross section is given by Schlesinger (1961). Chaff is typically 25-micron diameter aluminum coated mylar thread cut to near one half the wavelength of the observing radar. The terminal velocity of chaff at centimeter radar wavelengths is 20 to 30 cm/sec. Coherent radar measurements of radial velocity in chaff are not contaminated by the relatively large terminal velocities associated with hydrometeor targets. Recently there has been a resurgence in the use of chaff by radar meteorologists studying the planetary boundary layer (PBL) in clear air. A thorough review of atmospheric boundary layer radar experiments is given by Kropfli (1983). This paper describes single and multiple Doppler radar PBL experiments which employed intrinsic clear air scatterers (turbulent or inhomogeneous media) as well as half wavelength chaff. Dual doppler radar analysis calculates the three-dimensional cartesian wind field from simultaneous measurements of radial velocity in the same boundary layer volume by two coherent radars. Theses calculations are closed by a vertical integration of the mass continuity equation. To date there have been two dual Doppler radar chaff experiments which observed the three-dimensional mesoscale velocity structure of the marine atmospheric boundary layer (MABL). The results of a dual Doppler radar chaff experiment over the Santa Barbara Channel in California are given by Kropfli and Wilczak (1986). This paper describes the mesoscale horizontal velocity field in a stable MABL as measured by two 3-cm wavelength coherent radars on a 42-km baseline.

A mesoscale MABL experiment was conducted off the Outer Banks of North Carolina on March 2, 1986, during the Genesis of Atlantic Lows Experiment (GALE). The field phase of GALE was from 15 January to 15 March 1986. The experimental area stretched from the Gulf Stream across coastal Georgia, South Carolina, North Carolina, and Virginia to the Appalachians. The objectives of GALE were to study the mesoscale and air-sea interaction processes in East Coast winter storms. Improved temporal and spatial measurements were made throughout the GALE measurement area with numerous soundings, surface measurements, ships, aircraft, radars, and satellite imagery. Details of GALE are given by Dirks et. al. (1988). One of the specific tasks of GALE was to study the three-dimensional mesoscale structure of the atmospheric

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boundary layer and the associated energy and momentum fluxes over an area ranging from the Gulf Stream to the Appalachian Mountains approximately 500 kilometers from the coast. The planetary boundary layer subprogram of GALE employed specialized offshore observing platforms, research ships, research aircraft, Doppler radars, meteorological towers, mobile surface observations teams, soundings, and portable automated surface measurement networks. Raman and Riordan (1988) describe the boundary layer sub program of GALE.

In order to study the mesoscale structure of the MABL around the meteorologically active Cape Hatteras area, a dual Doppler radar experiment was designed. Half-wavelength chaff was dispersed in the clear MABL between 1320 and 1600 GMT on March 2, 1986. A schematic representation of the radar locations and dual Doppler coverage areas are shown in Fig. 1. The chaff was released along the line indicated by Fig. 1 over the Pamlico Sound. The chaff advected in northwest flow from the Pamlico Sound, over the barrier islands of Ocracoke and Hatteras, to the Atlantic shelf water and on to the warmer sea surface temperatures (SST) of the Gulf Stream.

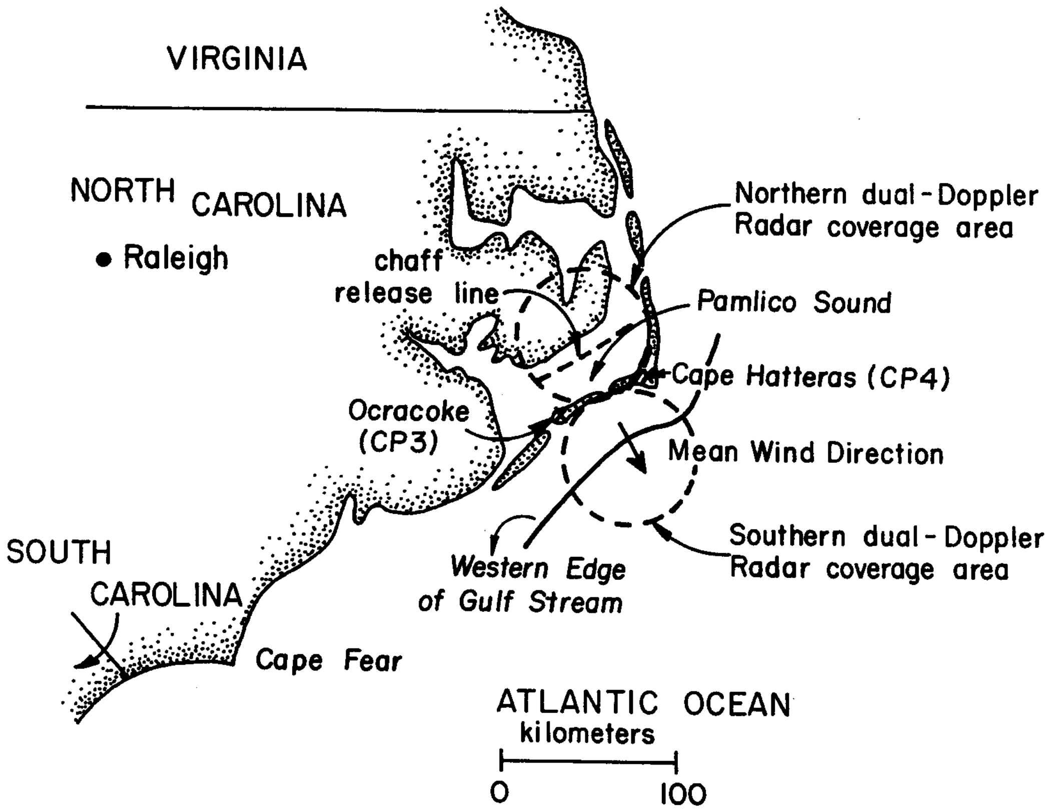

Figure 1. GALE dual Doppler research area. The chaff plane flew 500 m ASL. The mean wind direction is for the March 2, 1986, experiment described in this paper.

The National Center for Atmospheric Research (NCAR) coherent pulsed radar number 4 (CP4) was located on Hatteras Island (75.53 deg W, 35.23 deg N). Another Doppler radar, CP3, was located on Ocracoke Island (75.97 deg W, 35.10 deg N). Radial velocity and reflectivity were measured in the advecting chaff cloud by the two coordinated 5.5-cm wavelength radars. The performance characteristics of these two radars is given in the GALE Experiment Design Document (1985). The baseline separation between CP3 and CP4 was 42 km. The northern dual Doppler coverage area was used to make measurements over the Pamlico Sound. The southern dual Doppler coverage are was used to make measurements over the Atlantic shelf water and Gulf Stream. A limitation of the dual Doppler techniques is that the boundary layer volume immediately above the radar baseline is unanalyzable.

As Fig. 1 indicates, the two radars are in a region characterized by the marine boundary layer. The Outer Banks of North Carolina are narrow strips of land 0.5 to 3.0 km in width. These strips of mostly sand are disected by several inlets which have come and gone over the centuries with hurricanes and winter cyclones. Hatteras Inlet bisects the radar baseline. The Outer Banks separate the wide shallow waters of the Pamlico and Albemarle Sounds from the Atlantic shelf waters and Gulf Stream. (The 16th century navigator Giovanni da Verrazzano believed upon viewing the Outer Banks that they separated the Atlantic Ocean from the Pacific!) The schematic representation of the western edge of the Gulf Stream in Fig. 1 indicates a seasonal average of the 20 deg c sea surface temperature (SST). Detailed SST contours derived from NOAA-7 imagery for March 2, 1986, will be presented in a later section.

The chaff plane flew at 500 meters above sea level (ASL) along the line indicated in Fig. 1 as the chaff was exhausted from a 4-inch diameter tube. This chaff line mixed down to the surface and up to the top of the boundary layer in approximately 40 minutes. Radar observations were made in this chaff cloud as it advected in northwest flow. This paper describes the mesoscale structure of the MABL using radar measurements made in the chaff cloud when it was near the western edge of the Gulf Stream at 1456 GMT on March 2, 1986.

2. SURFACE OBSERVATIONS

The surface weather map at 1200 GMT for March 2, 1986, is shown in Fig. 2. The boundary layer experiment discussed in this paper represents the concluding measurements of GALE Intensive Observation Period number 11 (IOP #11). This IOP produced extensive measurements over the Atlantic off the coast of North Carolina during a case of moderate offshore cyclogenesis. The synoptic scale surface analysis in Fig. 2 indicates that the low pressure system located off the coast of North Carolina the previous day (1 March 1986) had moved to 40.5 deg N and 64.0 deg W. A quiescent surface trough was located parallel to the radar baseline. A high pressure system was analyzed west of Florida at 26.0 deg N and 87.0 deg W. Both radar sites and the chaff pilot reported clear skies. The temperature and dewpoint reported by the National Weather Service (NWS), Hatteras station, were 2 and -6 deg C respectively. The winds were 8m/sec from a northwesterly direction (330 deg).

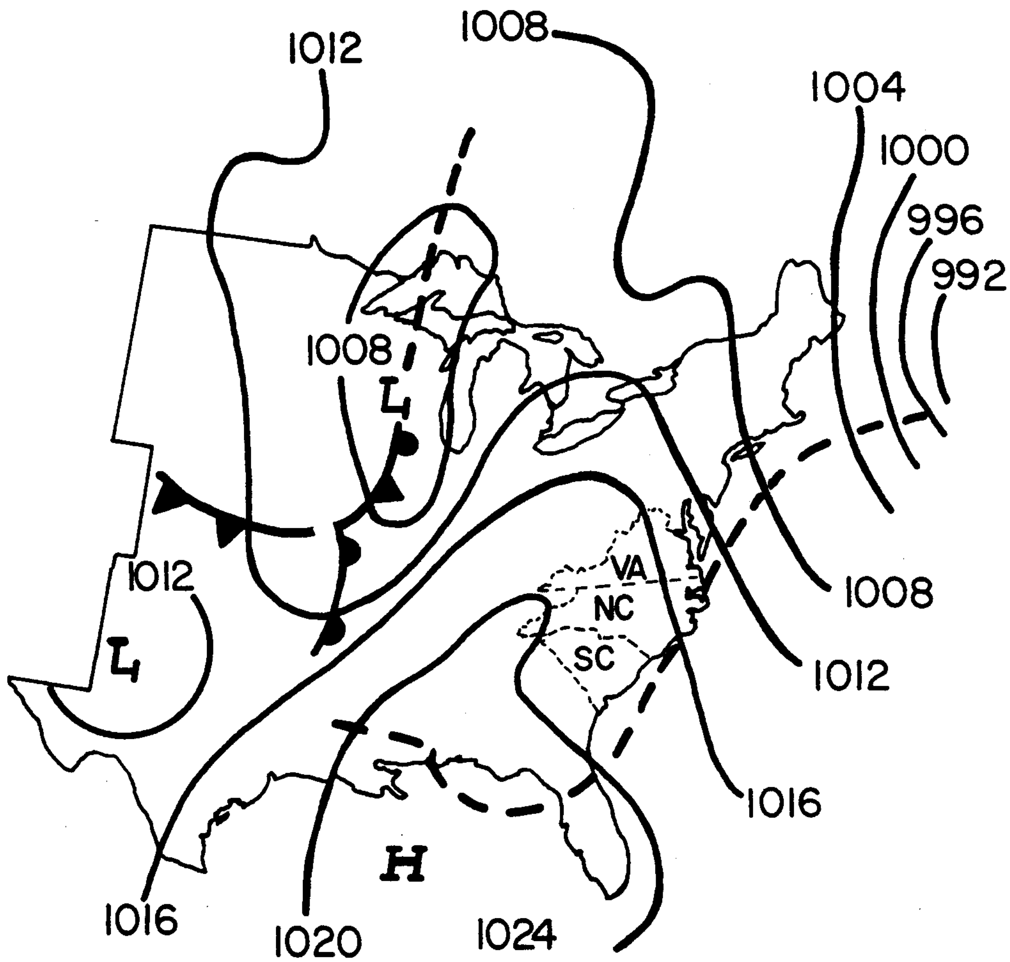

Figure 2. Synoptic weather pattern at 1200 GMT on March 2, 1986. The GALE dual Doppler research area is at the coast of North Carolina. The sky over the research area was clear during the dual Doppler experiment period. Pressure is in millibars.

Surface mesoscale observations for 1500 GMT were provided by the NCAR Portable Automated Mesoscale Network (PAM). The PAM Network is described by Dirks et al. (1988). The locations of the PAM stations near the radar measurement area are shown in Fig. 3. Temperature and dew point in degrees centigrade are indicated along with the wind vector at each PAM station. Notice the relatively strong winds near Cape Hatteras. This is due mainly to the long fetch over the smooth Pamlico Sound during this type of flow. In the last three years, Hatteras natives have named this area of the Pamlico Sound "Canadian Hole" because of the spring influx of wind-surfing Canadians and New Englanders. These data indicate that there was considerable moistening of the boundary layer as it advected across the Pamlico Sound with no noticeable change in the air temperature. Fig. 4 represents the 35 km gridded eddy wind field produced from the PAM data. This plot is generated by subtracting the 15-minute mean of all the PAM station winds from each PAM station wind vector. A northeast eddy wind component over the northeast end of the Pamlico Sound and a more northerly component over the southeast Pamlico Sound can be seen in Fig. 4. As will be shown later, this wind field caused the initial chaff lie to bend near the middle as it advected over Pamlico Sound. The maximum air to sea surface temperature difference over the Pamlico Sound was 5 deg C with the water warmer than the air.

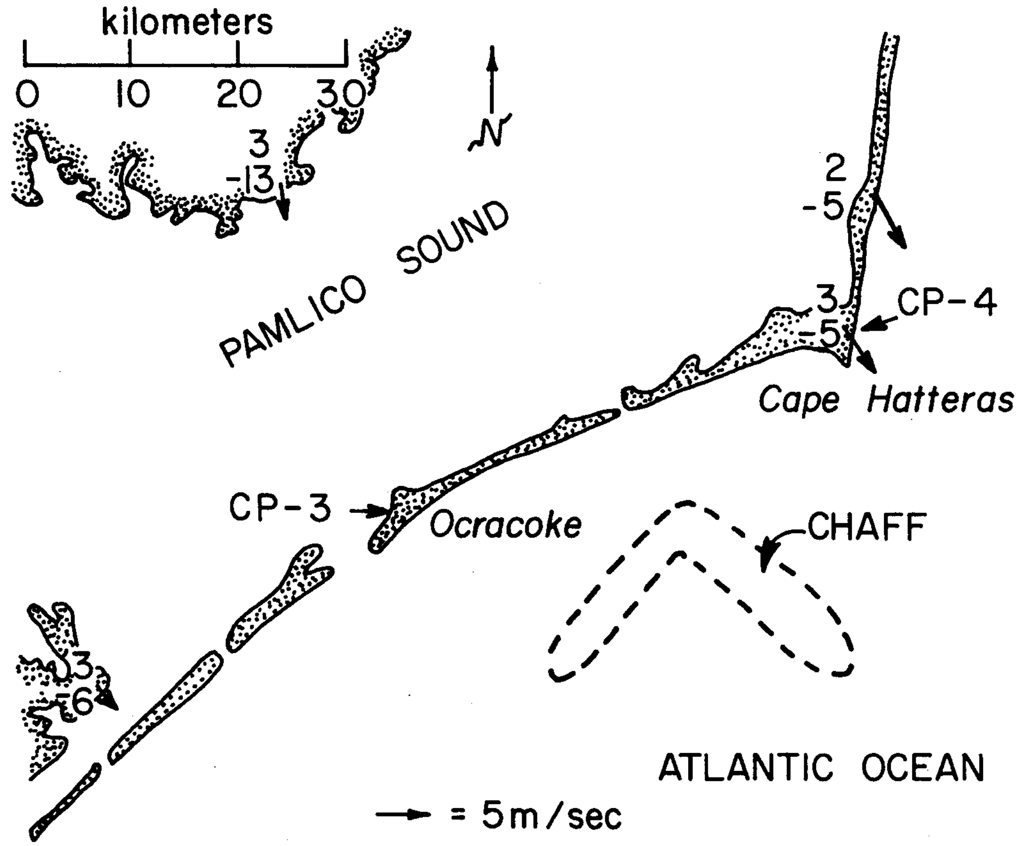

Figure 3. Surface mesoscale observations at 1500 GMT on March 2, 1986. Temperature and dew points are in degrees centigrade. The chaff cloud location at 1456 GMT is shown. Radar derived wind fields in this chaff cloud at 1456 GMT are described in this paper.

A dual Doppler analysis of the chaff cloud over the Pamlico Sound indicated a highly turbulent and well mixed MABL up to 2.1 km. On the Atlantic Ocean side of the narrow Outer Banks, the shelf water surface temperatures drop to as low as 5 deg C. The air-sea temperature difference over the Atlantic shelf was reduced from 5 to 2 deg C. The resulting MABL was therefore more shallow with the mixed layer heights down to 800 meters. As the chaff cloud advected towards the Gulf Stream, the SST field became more complex with horizontal temperature gradients as high as 2 deg C per kilometer.

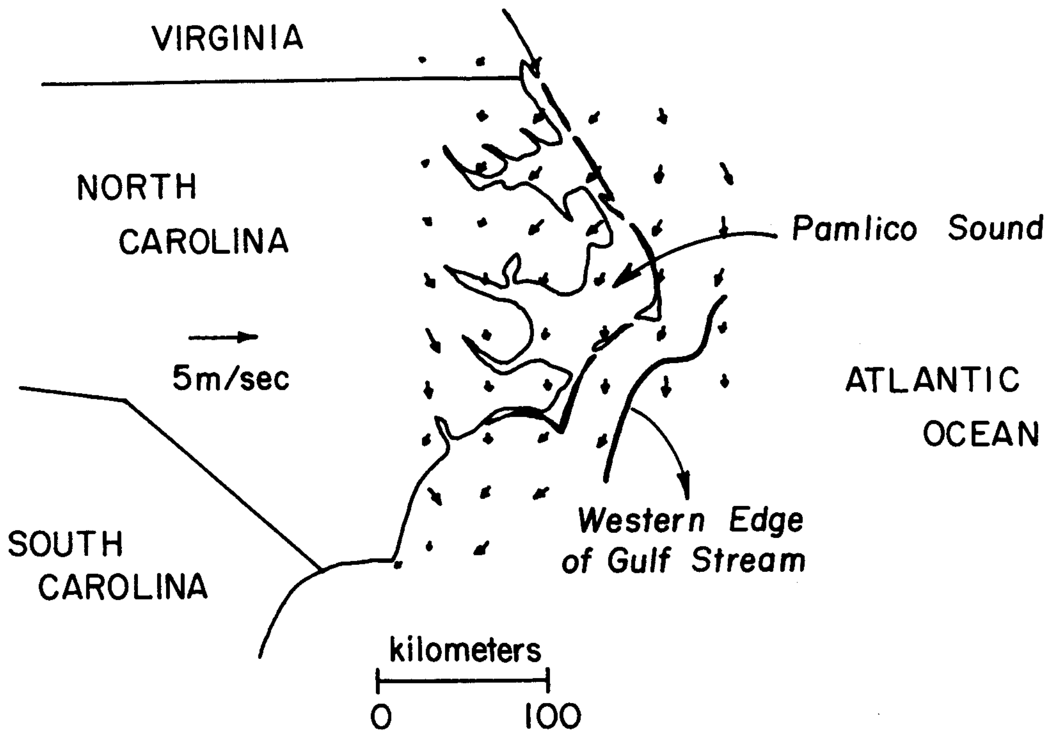

Figure 4. Eddy wind field at 1500 GMT on March 2, 1986. Grid points are 35 kilometers apart. Data were acquired from the NCAR PAM network.

3. MARINE BOUNDARY LAYER STRUCTURE OVER THE GULF STREAM

The MABL investigated during this experiment was expected to be influenced by baroclinic effects introduced by the large temperature gradients associated with the Gulf Stream. Arya and Wyngaard (1975) predict that the actual wind shear in the bulk of the mixed layer will be smaller than the magnitude of the imposed geostrophic wind shear. The magnitude of the geostrophic wind shear is approximately proportional to the horizontal temperature gradient. Calculating the geostrophic shear involves evaluating the thermal wind equations. Calculations of geostrophic shear over the Atlantic shelf to Gulf Stream mesoscale area using the surface SST data produce very large values of geostrophic shear up to 50 m/sec/km. These surface temperature gradients generally diminish rapidly with height in the well mixed MABL. Computations of the geostrophic shear using horizontal surface air temperature gradients would produce more reasonable values of baroclinicity.

The increasing thermal instability associated with cold air advecting over a positive SST gradient was expected to enhance the formation of the helical roll vortex. This well-known coherent boundary layer structure was reviewed by LeMone (1973). The neutral boundary layer model given by Brown (1970) indicates a stable to helical roll circulation transition for mean winds greater than 7 m/sec. Mean wind speeds in excess of 7 m/sec were estimated over the Pamlico Sound and Gulf Stream during post-frontal northwest flow.

Sea Surface Temperature contours as observed by the polar orbiter NOAA-7 are shown in Fig. 5. The horizontal resolution is 4 km. Notice the strong SST gradient southeast of the radar baseline. The 10 deg C and 20 deg C SST contours are located at strong SST gradients that loosely define the cross-current dimensions of the Gulf Stream. Preliminary data from airborne microwave radiometer measurements of SST's made along the mean wind direction indicate the 10-and 20-deg C contours are approximately 13 and 30 km offshore respectively. Small-scale eddies in the Gulf Stream between 13 and 30 km offshore are indicated by these preliminary airborne radiometer data as well as by in situ measurements made by the research vessel Cape Hatteras (Raman and Riordan, 1988). The general SST structure between the 10-deg C and 20-deg C SST contours along the mean wind direction is thus a step function with smaller scale, sometimes quasi-periodic, variations riding on the 17 km step function. The SST gradient at the 10 to 20 deg C step is as high as 10 deg C per kilometer in some locations. The advecting chaff cloud encountered a complex SST field which produced baroclinicity in the surface layer of the MABL. The Gulf Stream eddies introduce the possibility of the surface layer thermal wind equations switching polarity as the chaff cloud advected across the Gulf Stream.

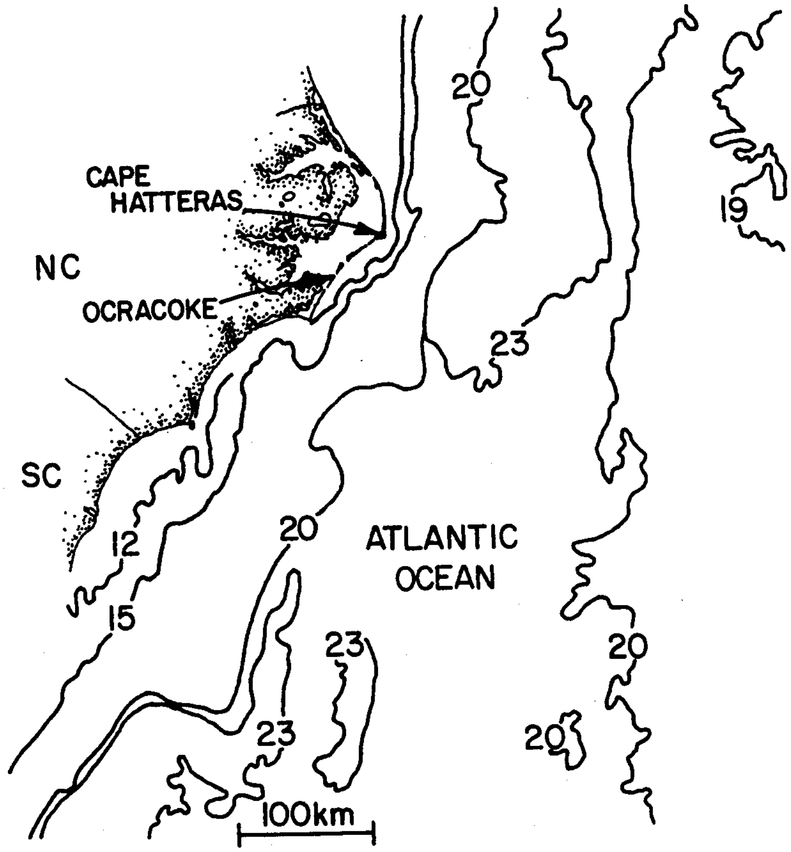

Figure 5. Sea surface temperature contours on March 2, 1986. Resolution of the NOAA-7 data is 4 km.

Topography of the height of the marine boundary layer as it appears over the northwest edge of the Gulf Stream is shown in Fig. 6. Most of the chaff cloud is between the 10-deg C and 20-deg C SST contours. The rounded apex of the chaff cloud was between 24 and 32 km east of Ocracoke. The leading edge of the chaff cloud is characterized by areas of steeper topography in the mesoscale mixed layer height field. Mesa-like structures in the mixed layer height field in Fig. 6 are noticeable along the leading edge. The mesa located between 18 and 22 km east of Ocracoke and between 30 and 32 km have a wavelength of 2 km and a peak to peak amplitude of 1 km. The radar derived convergence at 100 meters ASL associated with these mesa was 0.002/sec. This is the order of magnitude for convergence one would expect in strong convection. Typical values of wind field divergence are given in Huschke (1980). The lagging edge of the chaff cloud has a more sloping mixed layer height field. The along mean wind wavelength of the mixed layer height variations is on the order of 4 km. Observations of the boundary layer height profile were also made over the measurement area by the NASA Electra research aircraft. The downward-looking lidar data indicate the same 4 km along mean wind wavelength for the mixed-layer height field (Boers, 1987). Notice the 700 meter trough in the mixed-layer height field between 21 and 23 km east of Ocracoke as described in Fig. 6. The measured radar reflectivity is proportional to the concentration of chaff (chaff fibers/volume). The chaff concentration is generally highest along the horizontal axis of the chaff cloud. This gives the impression that the horizontal mixing occurs in both directions along the mean wind axis. This axial chaff concentration core is discontinuous across the 700 meter ASL trough. A 4 to 1 chaff concentration variation is observed throughout the chaff cloud axis vertical plane across this trough in the mixed-layer height field. This implies mixing isolation in the axial direction between the two parts of the chaff cloud. The northwest and southeast ends of this trough are associated with radar derived convergence at 100 m ASL of .002/sec. The radar-derived eddy flow field shown in Fig. 9 indicates strongest southeast inflow for the chaff cloud to be associated with this trough. Southeast eddy winds up to 8 m/sec are found at the southeast side of the trough from 100 to 400 m ASL.

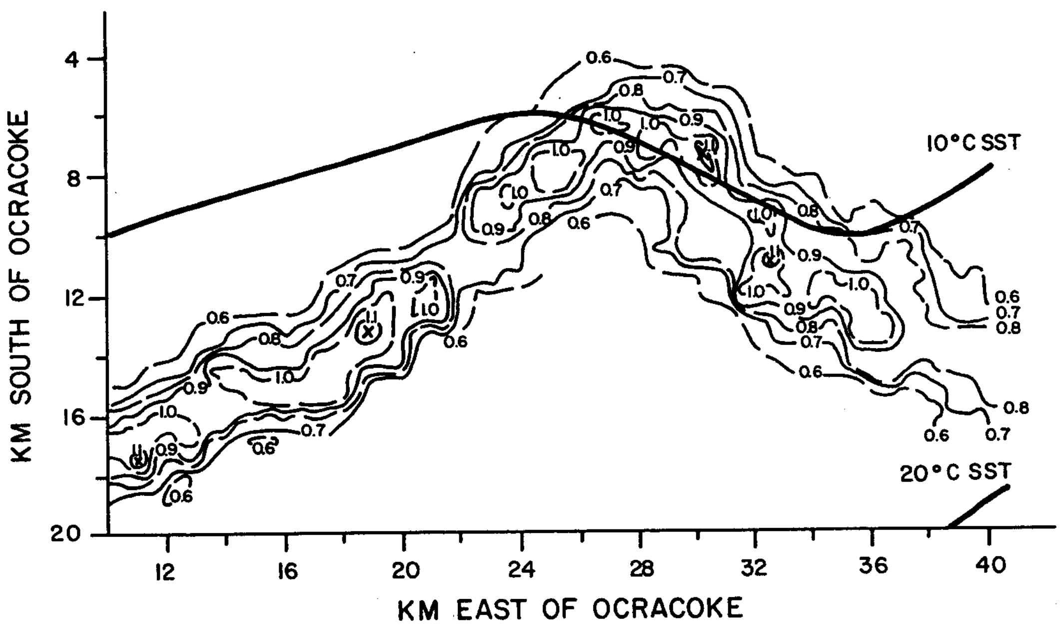

Figure 6. Mixed layer height contours at 1456 GMT on March 2, 1986. Recall the location of this chaff cloud at 1456 GMT in Figure 3. The axes of this figure are measured relative to CP3 located at Ocracoke. The 10 and 20 degree centigrade sea surface temperature contours are indicated. Height contours are in kilometers. For example, the mixed layer height 13 kilometers south of Ocracoke and 19 kilometers east of Ocracoke is 1.1 kilometers.

The approximately constant 600-meter height in the mixed-layer field along the lagging edge of the chaff cloud in Fig. 6 appears to have been produced by strong outflow from 22 km to 27 km east of Ocracoke. The horizontal eddy wind analysis to be discussed below shows strong outflow along this trailing edge up to 500 m ASL. Radar-derived vertical wind profiles indicate this area of the chaff cloud is dominated by downdrafts with core velocities up to 0.7 m/sec. These downdrafts are on the order of 2 km across in the horizontal dimension. The updraft associated with this trailing edge is only 1 km across and has vertical core velocities near 0.5 m/sec.

Fig. 7 is the radar-derived vertical wind contours in the horizontal plane at 300 m ASL for the 1456 GMT scan. At this height the large area of downdraft associated with the trailing edge is easily seen. The 0.2 m/sec updraft along this trailing edge probably causes a one kilometer peak in the mixed layer height field. The updraft areas along the leading edge from 18 to 22 km east of Ocracoke are associated with the leading edge mesa structures in the mixed-layer height field shown in Fig. 6. The 0.6 m/sec updraft centered 7.0 km south and 31.0 km east of Ocracoke contributes to the 1.1 km peak height in the mixed layer located at 7.5 km south of Ocracoke and 30.0 km east of Ocracoke. The downdraft immediately to the southeast results in an area of mixed-layer height variation which is less steep than that due to the adjacent updraft previously described. This mixed-layer height variation can be observed along the lagging edge of the mixed layer height field from 31 to 33 km east of Ocracoke in Fig. 6.

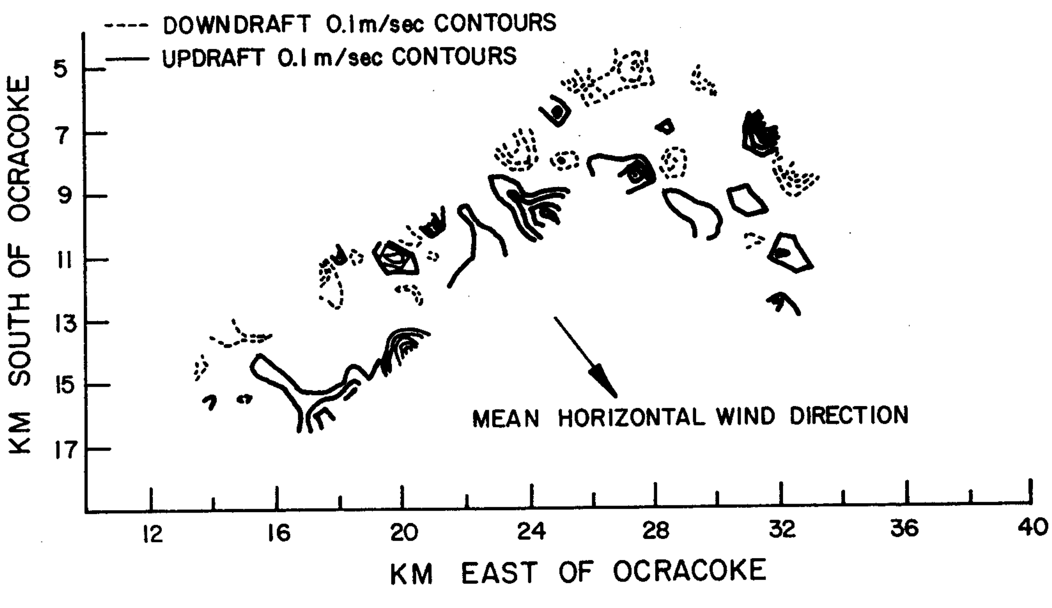

Figure 7. Radar derived vertical wind contours at 300 meters ASL at 1456 GMT on March 2, 1986. The dashed contours are 0.1 m/sec downdrafts. The solid contours are 0.1 m/sec updrafts. for example, the core updraft, velocity 20 kilometers east of Ocracoke and 11 kilometers south of Ocracoke is 0.3 m/sec.

Radar-derived convergence contours in the horizontal plane at 100 m ASL are given in Fig. 8. Convergence as high as .003/sec was estimated along the leading edge of the chaff cloud. The mesa structures in the mixed-layer height field in Fig. 6 along the leading edge of the chaff cloud from 18 to 22 km and 30 to 33 km east of Ocracoke are coincident with the area of convergence in Fig. 8. The leading edge with a 0.002 m/sec convergence zone 22.5 km east of Ocracoke is associated with the 700 m ASL trough described by the mixed-layer height topography of Fig. 6.

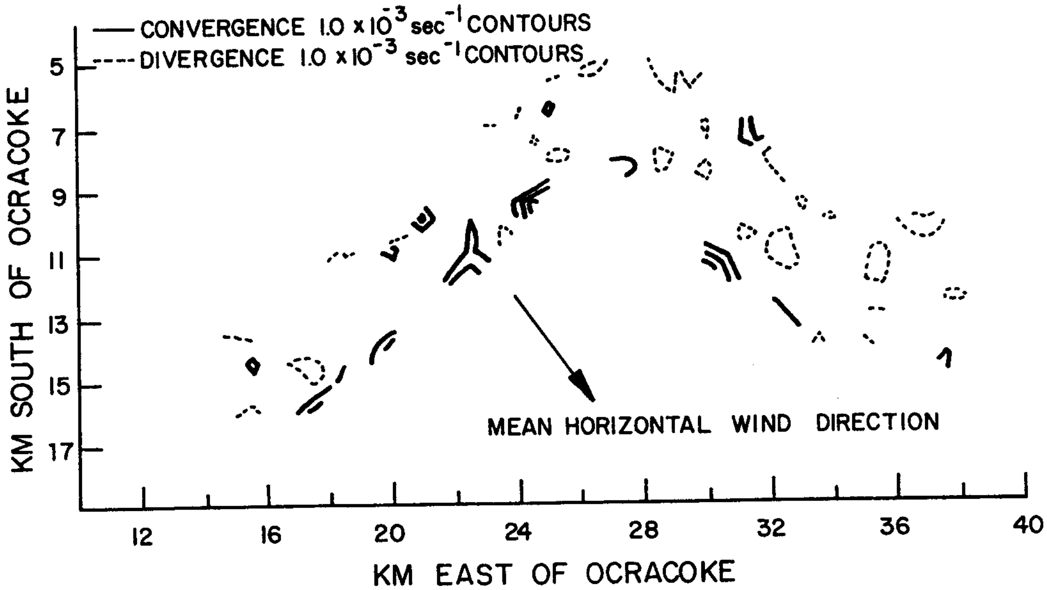

Figure 8. Radar derived divergence contours at 100 meters ASL at 1456 GMT on March 2, 1986. The dashed contours are 0.001 sec^{-1} divergence. The solid contours are 0.001 sec^{-1} convergence. For example, the core convergence 21 kilometers east of Ocracoke and 10 kilometers south of Ocracoke is 0.002 sec^{-1}.

The radar-derived eddy flow field of the 1456 GMT scan at 100 m ASL is shown in Fig. 9. The eddy field is calculated by subtracting the mean horizontal wind over the 0.5 km horizontal wind field grid at 100 m ASL from the wind vector at each grid point. The wide area of outflow associated with the lagging edge of the chaff cloud apex is striking. The areas of leading edge inflow are associated with the convergence zones shown in Fig. 8. The area of lagging edge outflow 37 km east of Ocracoke appears to have horizontally stretched the chaff cloud to the northeast. If the leading edge mixed-layer height field at 36 km east of Ocracoke in Fig. 6 is compared to the eddy field in Fig. 9, the two figures seem to indicate a mesa structure being formed in the mixed layer height field.

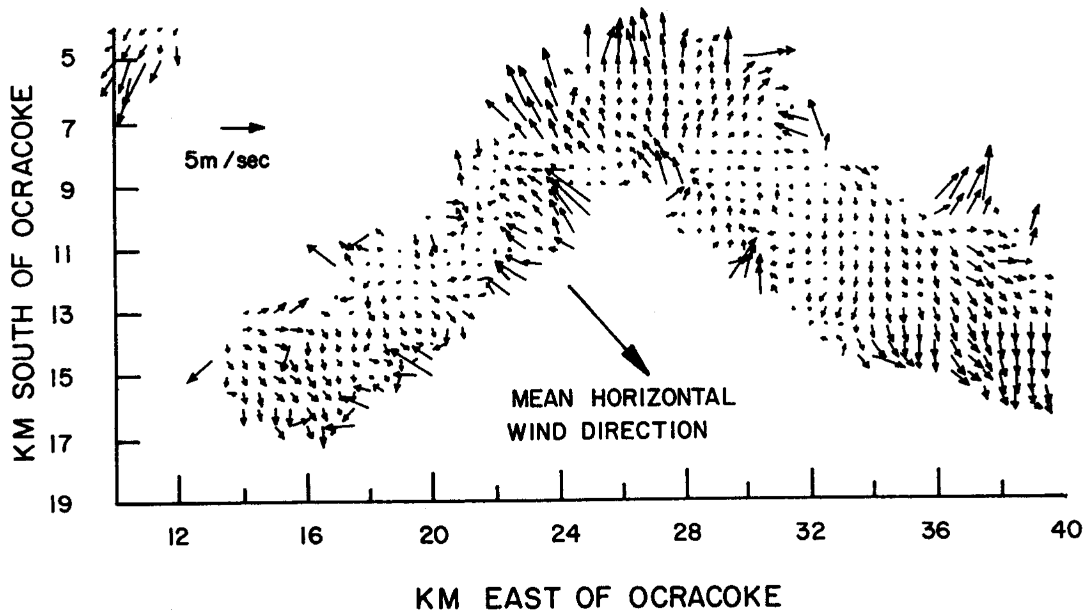

Figure 9. Radar derived eddy flow field at 100 meters ASL at 1456 GMT on March 2, 1986.

Fig. 10 is a plot of vertical wind contours in a vertical plane 6.0 km south of Ocracoke. The plane is in the west-east direction. The dashed lines are the downdrafts in 0.1 m/sec increments. The updrafts are represented by the narrow solid lines in 0.1 m/sec increments. The bold solid lines are the 0.0 m/sec contours. As the reader views Fig. 10 from left to right, a west to east plane through the three dimensional vertical wind field is observed. Fig. 10 describes the vertical wind structure along the lagging edge of the mixed layer height field as described 6 km south of Ocracoke in Fig. 6. Notice in Fig. 10 the three 1.5 km wide areas of downdraft separated by the two narrow weak updrafts. The downdraft core velocities are as high as 0.5 m/sec. The updraft velocities are at the most an order of magnitude below these downdraft magnitudes. The weak updraft region between 27.0 and 27.5 km east of Ocracoke is the north west edge of an updraft region supporting the ridge in the mixed layer height field between 7 and 8 km south of Ocracoke.

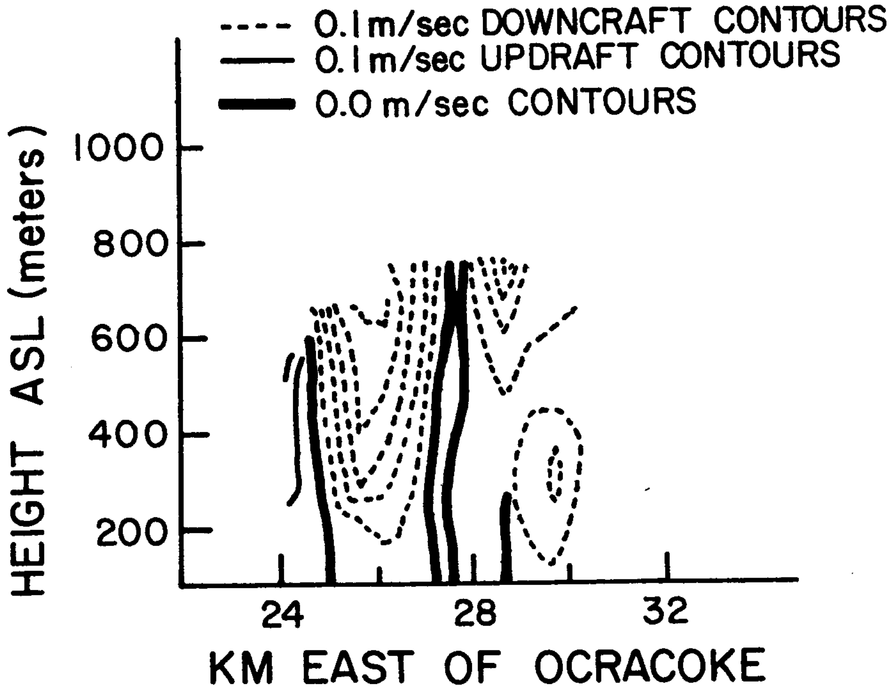

Figure 10. Radar derived vertical wind contours at at 1456 GMT on March 2, 1986. This is in the vertical plane 6 kilometers south of Ocracoke. The dashed lines are 0.1 m/sec downdraft contours. The bold solid lines are the 0.0 m/sec vertical wind contours. The thin solid lines are 0.1 m/sec updraft contours. For example, there is a 0.5 m/sec core downdraft at 600 meters ASL 26 kilometers east of Ocracoke.

4. CONCLUSIONS

The mesoscale structure of the marine boundary layer can be described in terms of three-dimensional velocity and spatial structure as measured by two radars observing the same chaff cloud.

The effect of convective mixing appeared to reduce baroclinic effects in the mixed layer. A vertical plot of the mean horizontal wind averaged over 0.5 km radar derived wind grid every 100 m ASL for the entire 1456 GMT chaff cloud indicates the layer to be well mixed. The windspeed averaged 6.0 m/sec (+/-0.1 m/sec) up to 900 m ASL. The wind direction averaged 292 deg (+/-1.0 deg) throughout this same layer. Well-organized roll vortices were not observed. In fact the mesoscale mixed layer height variations were in the mean wind direction. These variations in the height of the mixed layer would be found in the cross wind direction if the secondary roll vortice circulation had been present.

The spatial wavelengths of the entrainment layer processes appear to be smaller than the resolution of the three dimensional cartesian wind field derived from the dual radar data. These dimensions were 100 m in the vertical and 500 m in the horizontal. A shorter radar baseline would have improved the spatial resolution of the radar measurements in the entrainment layer. This experimental design trade off would also results in a dual doppler coverage area of smaller horizontal extent.

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