

# OBSERVATIONS OF A MESOSCALE CIRCULATION OVER THE GULF STREAM REGION

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Marine boundary layer structure and the existence of a shallow mesoscale circulation are documented for an east coast pre-storm period. These observations were made during the Genesis of Atlantic Lows Experiment (GALE) conducted during the winter of 1986 and consisted of data obtained by National Center for Atmospheric Research (NCAR) Electra and King Air aircraft, a research ship, buoys and a polar orbiting satellite.

Sea surface temperature (SST) data indicated strong horizontal gradients off the United States east coast, with a SST of 25C over the Gulf Stream. Cross sections flown by the NCAR King Air aircraft across one such Gulf Stream filament revealed the existence of a mesoscale circulation and low level convergence near the edges of the filament up to a height of at least 300 m. Observations from the NCAR Electra aircraft further south indicated two convergence zones, one near the western edge of the Gulf Stream and the other near the east coast with a divergence zone in between.

KEY WORDS: Mesoscale, boundary layer, cyclogenesis

## 1. INTRODUCTION

The amount of heat and moisture supplied to the atmosphere from the sea surface is very large in regions off the east coasts of the United States and China during winter (Bunker and Worthington, 1976) due to the presence of major boundary currents, the Gulf Stream and the Kuroshio, respectively. The temperatures within the Gulf Stream are often 10C or more warmer than the coastal ocean to the west, but are typically only a few degrees warmer than those to the east. During winter, the cold continent is bounded by the relatively warmer shelf/slope water, which is again bounded by the consistently warmer Gulf Stream waters. A slightly cooler Sargasso Sea region borders the Gulf Stream to the east. These horizontal gradients in the sea surface temperatures produce gradients in the surface turbulent heat fluxes causing the boundary layer to become baroclinic (Wayland and Raman, 1989).

The western edge of the Gulf Stream is often referred to as the Gulf Stream front. High resolution satellite observations of the sea surface temperatures (SST) suggest that, south of 32° N, the Gulf Stream front follows the 100 m isobath with onshore-offshore displacements of the Gulf Stream front seldom exceeding 25 km (Pietrafesa 1983, 1989). Although this front could also be defined with reference to a change in the surface currents, it essentially implies a sharp change in surface temperatures in this paper. A topographic feature on the upper slope of the ocean bottom located near 32° N, 79° W known as the "Charleston bump" causes an eastward deflection of the Gulf Stream resulting in a quasi-permanent excursion of the Gulf Stream front downstream. Frequently observed features of the Gulf Stream in this region are the

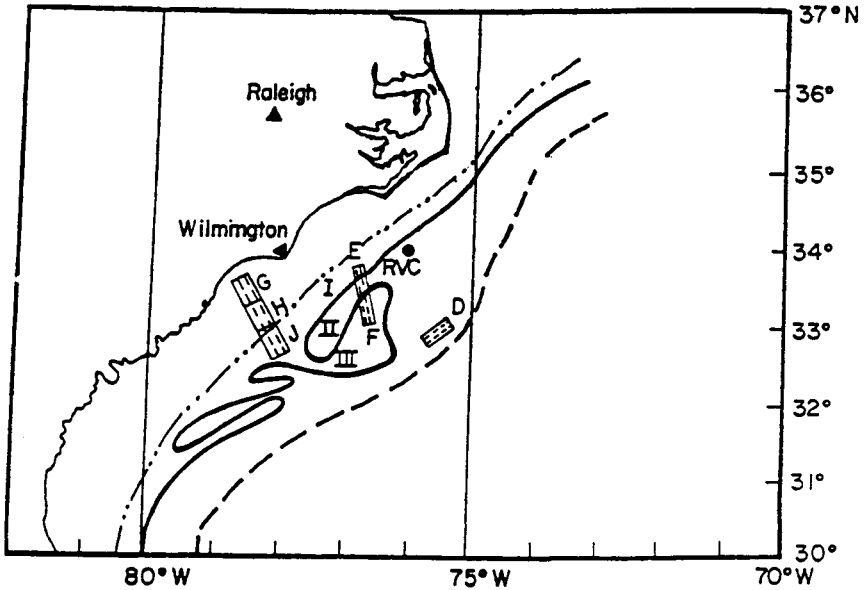


FIGURE 1 The position of the Western Edge of the Gulf Stream (Solid line) along with the King Air and Electra flight tracks across the Gulf Stream Filament are indicated. Dashed line indicates the eastern edge of the Gulf Stream, dashed dotted line indicates the mid shelf waters respectively. RVC indicates the location of the ship Research Vessel/Cape Hatteras. Regions I, II and III indicate upwind, over and downwind of the filament respectively.

warm-core folded-back filaments or “shingles” (Von Arx, et al. 1955). The southward oriented shingles are long, tongue-like extrusions of the Gulf Stream surface waters onto the shelf (Figure 1). Pietrafesa (1983) showed that the frequency of these events is between 2–12 per month on the North Carolina shelf. Typical length and width of the Gulf Stream filaments are 100–300 km and 10–50 km respectively. Gulf Stream filaments occur more frequently during winter. East coast storms also develop or intensify in this region during winter.

The Genesis of Atlantic Lows Experiment (GALE) was conducted in the mid-Atlantic coastal region of the United States from 15 January to 15 March, 1986 (Dirks, et al. 1988). The main objective of the GALE study was to investigate the processes and the mechanisms involved in the development of east coast storms. The purpose of this paper is to present boundary layer observations of mesoscale circulations associated with the Gulf Stream and a Gulf Stream filament and to report the formation of a meso-low and its intensification into a mid-latitude cyclone.

## 2. OBSERVATIONS

Observations made during GALE have been discussed in detail by Mercer and Kreitzberg (1986), Dirks, et al. (1988) and Raman and Riordan (1988). A variety of National Weather Service and GALE surface and upper-air data are used in this study.

Observations made with the National Center for Atmospheric Research (NCAR) King Air and Electra research aircraft on 10 February 1986 will be examined to study the mesoscale circulation over the Gulf Stream and a Gulf Stream filament. Aircraft data will be the primary dataset, but supporting observations from special surface data, and vertical soundings using Cross Chain Loran Atmospheric Sounding Systems (CLASS), mini-radiosondes, special National Weather Service (NWS) rawinsondes and Omega dropsinsondes will also be used.

The special GALE surface data were obtained from 51 Portable Automated Mesonet (PAM) II sites, eight instrumented GALE research buoys, National Oceanic and Atmospheric Administration (NOAA) buoys and platforms and one research vessel, R/V Cape Hatteras (RVC in Figure 1). The SST field used in this study was derived from the NOAA-9 infrared imagery. This 1.1 km high resolution imagery helped in resolving the strong sea surface temperature gradients associated with the Gulf Stream and its filaments. Reports by observers onboard the King Air were useful in providing first hand observations not easily obtainable from synoptic weather maps, ship or dropwindsonde data. These observations mostly pertained to the type, height and structure of the clouds.

### 2.1 Flight Plan

Figure 1 shows the flight tracks of NCAR King Air and Electra aircraft on 10 February, 1986. Positions of the filaments and the western edge of the Gulf Stream on 10 February are also indicated. Several stacks were flown by both aircraft. A stack is a flight pattern involving multiple aircraft legs at different altitudes but at the same location to study the vertical structure of the boundary layer. Stacks (*G* to *J*) were flown by the Electra aircraft across a convergence zone over the Mid-Shelf waters (MS) and stacks *D* and *E-F* were flown by the King Air aircraft over the Gulf Stream and across the Gulf Stream filament respectively. Table 1 provides the information on variation of SST across the coastal waters obtained from Electra aircraft.

The initial flight goals of the King Air aircraft were to map the SST contours across the Gulf Stream and to obtain boundary layer data at different levels across a front-like feature believed to be a quiescent coastal front by the observers on board. The King Air aircraft departed from Raleigh-Durham airport (RDU) at 1200 UTC. A level wing descent from 1500 m was first flown at *D* (32.8N, 75.8W) over the Gulf Stream waters (SST = 24C) at 1300 UTC. A stack consisting of a series of 300–400 sec legs (23.1–30.8 km in length) at four altitudes (50 m, 80 m, 150 m and 290 m) were flown in the

TABLE 1  
Variation of SST across the coastal waters obtained from Electra.

Electra (Stack <i>G-J</i> ) Segment	SST (C)	Region	Location
<i>G</i>	10–13	i	Near shore waters
<i>H</i>	13–16	ii	Cold shelf waters
<i>H-J</i>	16–19	iii	Mid shelf waters
<i>J</i>	19–22	iv	Near Gulf Stream waters

subcloud layer. The aircraft then flew back to Wilmington for refueling. A vertical stack consisting of a series of level 300–720 sec legs (23.1–55.5 km in length) was flown at four altitudes in the subcloud layer at *E-F* (33N, 77W) after refueling at 1630 UTC. This stack was flown perpendicular to the Gulf Stream filament. The filament was oriented NE-SW approximately parallel to the Gulf Stream as shown in Figure 1. The SST varied from 18C near the midshelf front to 24C at the filament. The SST of the cold core waters between the filament and the western edge of the Gulf Stream was 19C.

The NCAR Electra aircraft departed from Raleigh at 1630 UTC and did vertical profiles along the M-surfaces over land. At about 1800 UTC, seven level flight legs were flown across this frontal feature at altitudes of 50 m, 90 m, 150 m, 200 m, 320 m, 630 m and 1200 m (SST = 9–23C and location = 33N, 78W) for 12 to 20 minutes (a distance of 100–140 km) southwest of the filament. The length of each leg flown by the Electra aircraft at different altitudes was divided into three to four segments (approximate duration of 4–5 min) based on the SST values. The first segment represents near shore waters (*G*) with SST between 10C and 13C, the second represents near shore shelf waters (*H*) with SST between 13C and 16C, the third represents mid-shelf waters (*H-J*) with SST between 16C and 19C and the fourth represents the Gulf Stream waters (*J*) with SST between 19C and 22C. These SST values are summarized in Table 1. Scientists onboard the Electra reported multiple cloud layers. Observations were taken over a period of about 6 hours (1200 UTC–1800 UTC). However, approximate stationary conditions were assumed during this period for both aircraft and other data (ship, buoy and PAMs).

## 2.2 Aircraft Data and Analysis

Instrumentation onboard the King Air is similar to that of the Electra. A description of the instrumentation onboard the Electra is discussed in detail by LeMone and Pennell (1990) and Lenschow and Spyers-Duran (1986). Only a brief discussion of the primary aircraft mean and turbulence data and analysis utilized in this study is included here. Both low rate (1 Hz) and high-rate (20 Hz) data were obtained from the aircraft instrumentation system.

The Aircraft Data System (ADS) is an onboard computer specifically designed for real-time data processing/display and archiving of all meteorological data collected during flight. The central element is the Litton LTN-51 inertial navigation system (INS), which outputs the aircraft latitude and longitude at 1-sec intervals.

Onboard the King Air and the Electra aircraft, ambient temperature was measured by a Rosemount temperature probe, dew point by an EG&G dewpoint hygrometer and pressure by a Rosemount pressure transducer. A radome gust probe with pressure ports on the nose of the King Air was used for sensing air motion, whereas for Electra aircraft, vane gust probe system was used (see LeMone and Pennell, 1980 for more details). Both the mean and the turbulent fluctuations of the three wind components were obtained from the radome after correcting for the aircraft motion measured by the inertial navigation system (INS). The SST was measured using downward-looking, narrow bandwidth narrow field of view (2°) Barnes Engineering Model PRT-5 precision radiation thermometer (Miller and Friesen, 1985).

The data were then pre-processed at NCAR and made available to the GALE Data Center for distribution. The data were separated into flight legs at near constant

heading and altitude to avoid any contamination due to aircraft turns, climbs or descents. The exceptions to this procedure involved the previously mentioned ramp soundings (vertical profiles) made by the Electra and King Air aircraft where descent/ascent was made along a constant heading, attempting to profile the boundary layer during this particular maneuver.

### 3. SYNOPTIC SETTING

GALE Intensive Observation Period (IOP) #5 was characterized by pre-storm conditions on 9 February and offshore development of a meso-low on 10 February, 1986 as shown in Figure 2. National Weather Service (NWS) analysis positioned a weak surface low over South Carolina with a trough axis extending southwest and a stationary front over the Florida panhandle on 9 February, 1200 UTC (Figure 2a). Twelve hours later (Figure 2b), low pressure over South Carolina filled and a high pressure system moved over the east coast of the United States causing northerly winds offshore of North Carolina. In the GALE region this eastward shift of the anticyclone was accompanied by the gradual veering of offshore winds from north-northeasterly to east-northeasterly. Over land, however, the wind direction remained northeasterly as a small-scale ridge of high pressure extended southwestward along the Piedmont east of the Appalachians (Figure 2b). The feature is generally associated with cold air damming along the east coast (Richwein 1980). In particular, such damming east of the northern Appalachians has been shown to be important in some subsequent coastal front formation offshore of the New England coast (Bosart et al., 1975). At 1200 UTC on 10 February, a trough extended southwest towards the South Carolina coast from a low pressure system located off North Carolina (Figure 2c). By 1500–2100 UTC (Figures 2d and 2e) on 10 February, there was a stationary front off the coast almost parallel to the Gulf Stream. This front had the characteristics of a coastal front with winds turning from northeasterly on the cold side to southwesterly on the other side of this front.

Mesoscale surface analyses of the winds from the PAM network, ships and buoys from 1200–2100 UTC, 10 February in the region offshore of the Carolinas indicated (see Figure 7) that the flow along the coast was northeasterly from Cape Hatteras (35.3N, 75.5W) to Charleston, South Carolina (33N, 80W) with southwesterly flow offshore over the Gulf Stream. The results from the observational analyses presented in the following section will confirm the mesoscale circulation over a Gulf filament.

## 4. DISCUSSION OF RESULTS

### 4.1 *Sea Surface Temperature Distribution*

The Gulf Stream position was obtained from the report provided by the NOAA/AOML (Atlantic Oceanographical Meteorological Laboratory) at 1800 UTC on 10 February based on the Advanced Very High Resolution Radiometer (AVHRR) data and is shown in Figure 1. The solid line indicates the maximum sea surface temperature contour of 24C indicating the western edge of the Gulf Stream. The

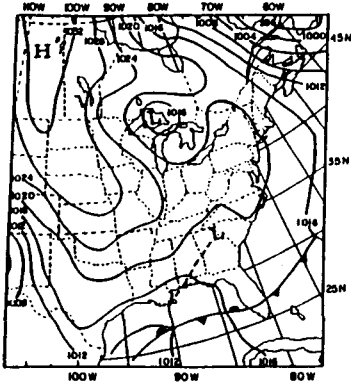
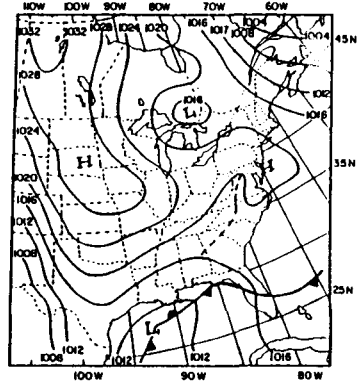
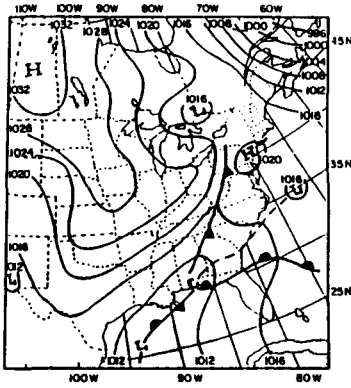
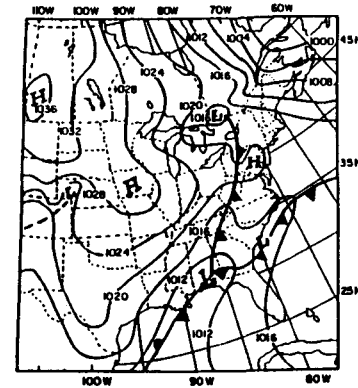
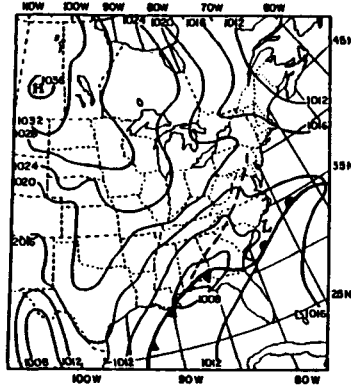
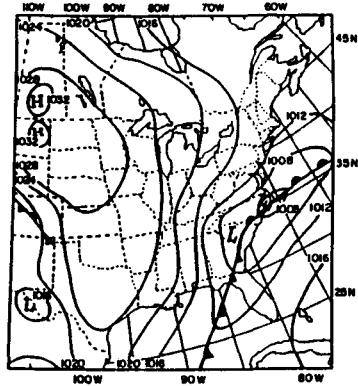
**(a)** 9 FEBRUARY 1986  
1200 UTC**(b)** 10 FEBRUARY 1986  
0000 UTC**(c)** 10 FEBRUARY 1986  
1200 UTC**(d)** 10 FEBRUARY 1986  
1800 UTC**(e)** 10 FEBRUARY 1986  
2100 UTC**(f)** 11 FEBRUARY 1986  
1200 UTC

FIGURE 2 NMC surface pressure analysis for a 12 UTC on 9 Feb.; b 00 UTC on 10 Feb.; c 12 UTC on 10 Feb.; d 18 UTC on 10 Feb.; e 21 UTC on 10 Feb.; f 12 UTC on 11 February, 1986. Isobars are given every 4 mb.

oceanic mid shelf waters (MS) between the coast and western edge of the Gulf Stream near the shelf break is shown in Figure 1 as a dashed dotted line. It corresponds to a temperature contour of 17C and generally occurs during winter. The eastern edge of the Gulf Stream is indicated by the dashed line. The region of coastal shelf waters is between the coast and the mid shelf front. The SST data indicates that three filaments formed and moved north to a location off the Carolina capes on 10 February and persisted until 12 February. It is apparent that the filament *E-F* is the same one observed on February 10 by the aircraft radiometer as shown in Figure 3a.

#### 4.2 Mesoscale Convergence Over the Filament

Figures 3a and 3b show the spatial variation of the wind direction across the Gulf Stream filament at 50 m and 80 m altitudes respectively over regions I, II and III indicated in Figure 1. The plots in Figure 3 were obtained using 10 Hz averages of the high frequency data (20 Hz). Region I is upwind of the filament (near the MSF), region II over the filament and region III downwind of the filament over the cold core eddy between the filament and the Gulf Stream. Distances were obtained using the average ground speed of the aircraft and were consistent with the aircraft positions. The filament width was determined from the sharp changes in SST.

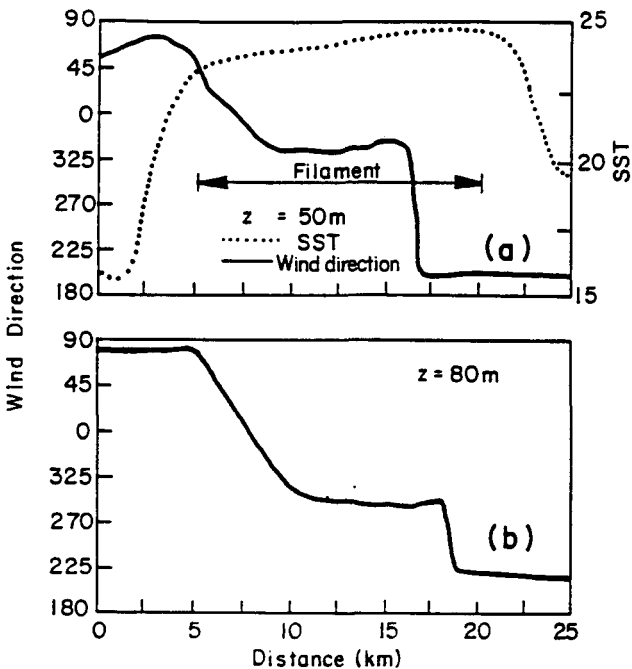


FIGURE 3 Spatial variation of wind direction at a 50 m and b 80 m altitudes. Data obtained from the King Air aircraft transect at stack *E-F* across the Gulf Stream Filament on 10 February. Data points are averaged for every 10 sec. Dotted line indicates the SST variation. Position of the filament corresponds to changes in SST.

Considerable variation in the wind direction occurred across the filament in response to sharp SST gradients (Figure 3a). The SST varied by about  $7^{\circ}\text{C}$  across the filament edges. In region I west of the filament (cooler water) the winds were northeasterly. However, the winds backed to northwesterly ( $300^{\circ}$ ) in region II over the filament. In region III, winds turned to southwesterly ( $200^{\circ}$ ). Similar behavior was also observed by the Electra aircraft over a region about 150 km southwest of the filament as will be discussed in the following section. Figure 3b shows the variation of wind direction across the Gulf Stream filament at an altitude of 80 m. The variation is similar to that observed at 50 m. A similar change in wind direction was also observed at the higher altitudes of 150 m and 290 m (not shown). However, variation in the wind direction across the filament decreased with increasing altitude due to the decreasing influence of the SST gradient at higher levels.

Variations of east-west (u-component) and north-south (v-component) wind speeds across the filament at 50 m and 80 m altitudes are shown in Figure 4. The filament width obtained from the SST distribution is also indicated. Magnitude of the mean wind speed further upwind of the filament (about 15 km west) at a height of 50 m was  $4.8\text{ m s}^{-1}$ . The mean wind speed increased by about a factor of two to  $9\text{ m s}^{-1}$  within a distance of 15 km. This is believed to be due to the acceleration of the near surface

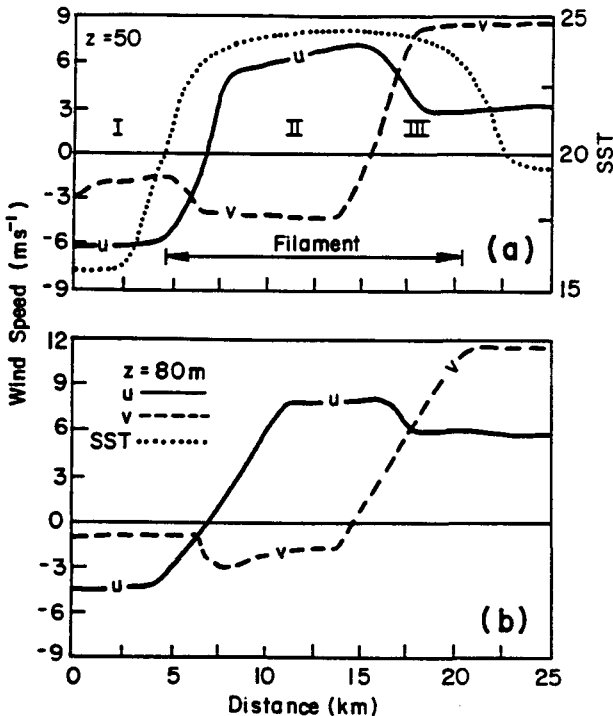


FIGURE 4 Spatial variation of east-west (u-component) and north-south (v-component) wind speeds at a 50 m and b 80 m altitudes. Data obtained from the King Air aircraft transect at stack E-F across the Gulf Stream Filament on 10 February. Data points are averaged for every 10 sec. Dotted line indicates the SST variation. Position of the filament corresponds to changes in SST.



winds over the Gulf Stream filament caused by a mesoscale local pressure gradient which induced low-level convergence. A low-level jet also formed over the filament as will be shown later. Mean wind speeds upwind and over the filament at 80 m altitude was  $4.5 \text{ m s}^{-1}$  and  $7.8 \text{ m s}^{-1}$  respectively (Figure 4b). The winds increased by a factor of 1.6 at this height as compared to 1.9 for  $z = 50 \text{ m}$ . At 150 m altitude, the wind speeds increased by a factor of only 1.5. Acceleration of the wind associated with the SST gradient thus decreased slowly with height.

The mean wind speed downwind of the filament over the cold core water at 50 m, 80 m and 150 m altitudes was  $9.5 \text{ m s}^{-1}$ ,  $10.5 \text{ m s}^{-1}$  and  $11.0 \text{ m s}^{-1}$  respectively. Acceleration of the wind over the cold core waters could be due to the influence of the low level convergence associated with the warm Gulf Stream adjacent to the cold core. Because of its larger size (approximately 100 km in width) and slightly higher temperatures than the filament, the speeds are higher. These local convergences are definitely three-dimensional, although the effects presented here are from a two-dimensional cross-section. Mesoscale analyses indicating these convergences are discussed in Section 4.3. This convergence and consequent acceleration of the wind near SST discontinuities was also observed by other investigators (Holt and Raman 1990 and Rogers 1989). Numerical modeling studies by Huang and Raman (1988, 1990, 1992) indicate this wind acceleration is due to a sea breeze type circulation superimposed on the mean flow. Although the changes in wind speed and direction across surface temperature discontinuities have been observed and modeled before, this is the first set of observations indicating mesoscale convergence over a Gulf Stream filament.

#### 4.3 Mesoscale Convergence Near The Gulf Stream

In this section the observations made by the Electra aircraft over the Atlantic ocean southwest of the filament will be presented and discussed in conjunction with the low level acceleration of the winds recorded by the King Air over the filament. Location of the flight track was shown in Figure 1.

Figure 5 shows the spatial variation of SST, wind direction and wind speed from G to J at heights of 50 m, 90 m and 150 m altitudes. Four separate regions (i, ii, iii and iv) are indicated in Figure 5 as derived from the SST field. Region (i) indicates the near shore waters where the SST ranged from 8C–12C. Region (ii) is the constant (15C) SST region between the oceanic near-shore and midshelf fronts. Region (iii) delineates the approximately constant (19C) SST region between the midshelf front and the Gulf Stream front. Region (iv) is the Gulf Stream region (SST = 22–23C). The Electra aircraft did not cross the Gulf Stream front. Approximately the same SST fields were observed from 90 m and 150 m altitude (Figure 5a) using the aircraft downward-looking PRT-5 radiometer.

A significant change in the wind field is easily distinguishable from the wind speed (Figure 5c) and direction (Figure 5b) traces at 50 m altitude. The winds are east-northeasterly (70–80 deg) over the cold waters and backed to westerly (260–280 deg) over mid-shelf waters (SST = 15C). Wind speed was a minimum ( $1$  to  $2 \text{ m s}^{-1}$ ) at location H (Figure 5c). Over the cold shelf waters, the winds increased to  $6 \text{ m s}^{-1}$  and towards the Gulf Stream over warm waters the winds increased to  $11 \text{ m s}^{-1}$ . Since Electra aircraft did not cross the Gulf Stream, the wind speeds over the Gulf Stream

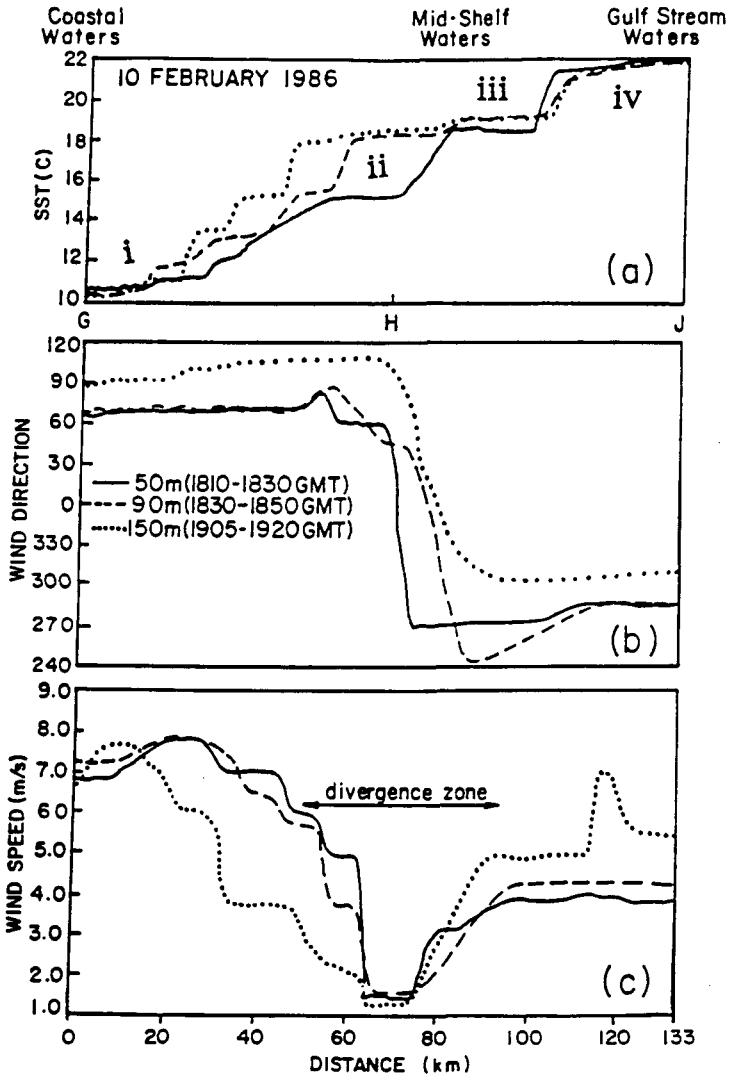


FIGURE 5 Spatial variation of a SST; b Wind Direction; c Wind Speed at 50 m, 90 m and 150 m altitudes. Data obtained from the Electra aircraft transect at G to J on 10 February. Data points are averaged for every 10 sec.

were obtained from King Air data. A divergence zone appears to exist (Figure 5b) over the mid-shelf waters (SST = 13–14°C) which was approximately 60–70 km off the Carolinas. Existence of this divergence zone is confirmed by the stream line analyses to be discussed later. A divergence ( $\partial u/\partial x + \partial v/\partial y$ ) of  $4.6 \times 10^{-5} \text{ s}^{-1}$  was estimated over this region. Two convergence zones existed on either side of this divergence zone, one further offshore near the Gulf Stream (further east of Region (iv)) and one near the coast line (Region (i)). The low-level convergences in Region (i) and Region (iv) were observed

to be  $3.1 \times 10^{-5} \text{ s}^{-1}$  and  $2.0 \times 10^{-5} \text{ s}^{-1}$  respectively. This type of convergence/divergence zone offshore parallel to the east coast near the Carolinas with a divergence zone over cold shelf waters and a convergence zone near the Gulf Stream were also observed by Riordan (1990) and Holt and Raman (1990) and modeled using a three-dimensional numerical model by Huang and Raman (1992).

The dashed line in Figure 5b shows the wind direction trace at 90 m altitude. West of the divergence zone, the winds were east-northeasterly (70–90 deg) backing to a westerly (260–300 deg) direction east of the divergence zone towards the warmer waters further confirming the convergence/divergence zone at 90 m altitude. The dashed line in Figure 5c shows the time series of the wind speeds at 90 m altitude. This figure once again shows significant changes in the wind speeds across the divergence zone. Wind speeds increased with height on both sides of the divergence zone compared to the lower level transect (50 m altitude, Figure 5c). Over cold waters (i.e., the convergence zone near the coast) the winds increased from  $6 \text{ m s}^{-1}$  at 50 m to  $7 \text{ m s}^{-1}$  at 90 m altitude indicating the presence of a low-level jet in the coastal convergence zone. A local maximum in wind speeds at 150 m altitude was also observed in this region as will be presented in a later section.

Time series of the wind direction at 150 m altitude again shows easterly (80–100 deg) winds west of the divergence zone and westerly winds (300–310 deg) east (dotted line in Figure 5b) once again indicating two convergence zones, one near the coast and the other towards the warmer Gulf Stream waters. At an altitude of 200 m (not shown), it was difficult to pinpoint the convergence/divergence zones because the changes in wind direction were not as sharp as those observed at lower levels. The wind direction data at 320 m and above did not show any marked changes. Hence, the time series of wind direction at different altitudes indicate that a mesoscale circulation existed near the Gulf stream approximately 30–50 m west of the Gulf Stream and this circulation was shallow and extended up to only 250 m. A comparison between the changes in the wind direction with respect to SST fields at different altitudes indicates a shallow front sloping towards the Gulf Stream from the divergence zone. Thus the observations made by the Electra aircraft (1800 UTC), east of the divergence zone (Region (iv)), and west of the filament also indicate the existence of the circulation. This indicates the mesoscale circulation to be present over a broader area. The King Air data across the filament presented earlier showed this circulation to extend vertically up to at least 300 m.

Winds along isentropic surfaces obtained from the King Air and the Electra aircraft, ship and CLASS data at 1200–1800 UTC on 10 February are shown schematically in Figure 6. A cyclonic flow is apparent over the Gulf Stream filament. The winds are turning from northeasterly over mid-shelf waters (west of the filament) to northwesterly over the filament (almost at right angles to the filament) to southwesterly over the cold core waters indicating a cyclonic flow (290 K contour was obtained from the King Air). This cyclonic flow is closed by easterly winds at RVC located at the core of the Gulf Stream. This closed cyclonic flow extended up to at least 300 m as observed from the King Air aircraft. Mesoscale analysis at G (Figure 7), close to the coast indicated strong onshore flow. Electra aircraft data over a region about 150 km southwest of the filament indicated two convergence zones (Figure 7b, heavy solid lines), one near the western edge of the Gulf Stream and the other very near to the coast with a divergence

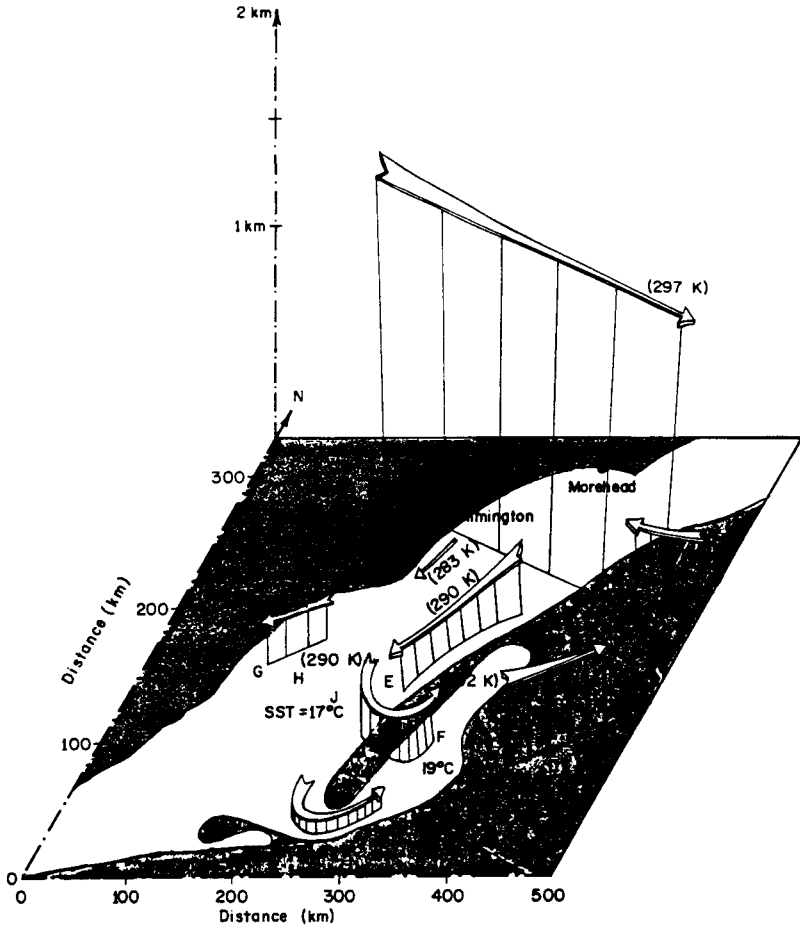


FIGURE 6 Three dimensional view of the wind flow along the isentropic surfaces over the observational region on 10 February at 1800 UTC (King Air and Electra aircraft data, CLASS and ship data are used here). (see color plate I at the end of this issue).

(heavy dashed line) region in between. The winds over the convergence zone, *J* near the Gulf Stream (for location see Figure 1) were westerly and turned to southwesterly over the Gulf Stream (Figure 7) as observed by the King Air aircraft indicating a cyclonic flow at this location. This cyclonic flow observed aircraft extended up to 250 m. Electra aircraft data further confirmed that this circulation was not only restricted to the Gulf Stream filament but extended over a broader area at least 150 km southwest of the filament. This three-dimensional atmospheric circulation appears also to have been associated with a front-like feature over the Gulf Stream (Figure 7).

The northeasterly onshore winds over coastal waters was due to a high pressure system over northeastern United States. This synoptic feature could have led to the formation of a weak shallow coastal front observed by the aircraft near the Gulf Stream. The synoptic analysis on 10 February at 1800 UTC (Figure 2e) indicated

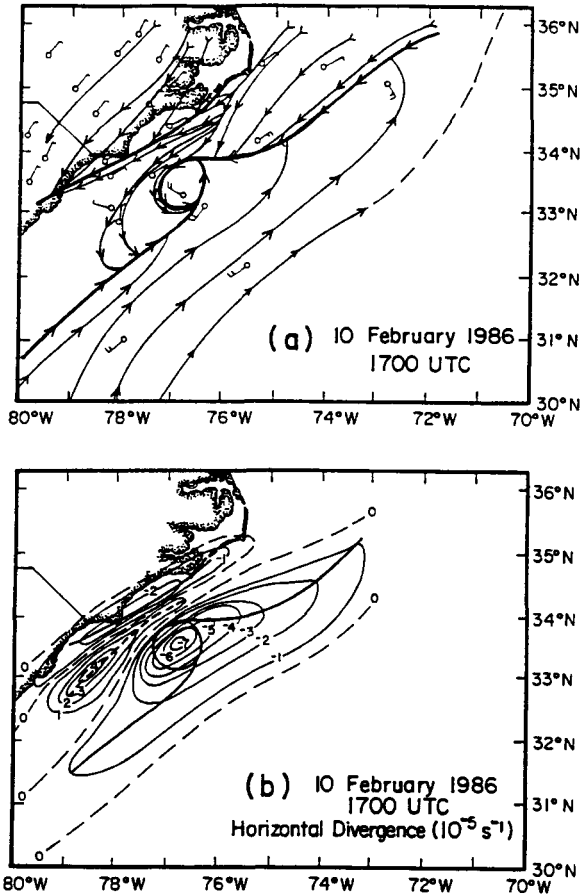


FIGURE 7 Mesoscale analysis on 10 February, 1986 at 1700 UTC. Data from PAM stations, GALE and NOAA buoys, ships and King Air and Electra aircraft are used. **a** Streamline analysis. Solids lines indicate the stream lines. A meso-low can be seen over the filament and a front along the Gulf Stream. **b** Horizontal divergence ( $10^{-5} \text{ s}^{-1}$ ). Heavy solid lines indicate the convergence and divergence zones and heavy dashed lines indicate the zero lines.

a mesoscale front at this location. Comparing these observations with those of Holt and Raman (1990) and Riordan (1990) indicates that the frontal features were quite different. The wind flow observed by Holt and Raman (1990) and others indicated a more north-northeasterly flow west of the convergence zone and easterly or east-southeasterly flow east of the convergence zone. In the present case study, easterly winds are observed west of the front and southwesterly winds of the front. This cyclonic flow is believed to be a part of an offshore meso-low over this region.

The synoptic analysis on 11 February at 1200 UTC (Figure 2f) indicated the deepening of the surface meso-low into a midlatitude cyclone. In general, when a meso-low formed due to low level forcing and is in phase with an upper level disturbance, cyclogenesis could result (Holt and Raman 1990 and Uccelleni, et al. 1987). The 500 mb analysis on 11 February indicated a mid-tropospheric trough over

the eastern United States coastline. Alignment of this trough with the meso-low may have led to the offshore development and intensification of the cyclone.

Cione, Raman and Pietrafesa (1993) showed that nearer the Gulf Stream to the coastline, more frequently are the development of the storms because of increased boundary layer baroclinicity. The formation of a filament decreases the distance between the western edge of the Gulf Stream and the coastline can be seen in Figure 1 and thus would increase the boundary layer baroclinicity.

#### 4.4 Mean Vertical Structure in the Convergence Zone

Mean vertical profiles up to a height of 15 km were obtained over the ocean every three hours using CLASS soundings. However, for the present paper, data are plotted only up to 2 km to investigate the marine atmospheric boundary layer structure over the Gulf Stream and over the coastal waters. The only CLASS sounding over water was from the Research Vessel Cape Hatteras, (34 N, 75.5 W) located over the Gulf Stream during this experiment.

It will be of interest to look at the air mass modification associated with the mesoscale circulation across the Gulf Stream filament and other SST discontinuities. The vertical soundings of wind direction, wind speed, air temperature and absolute humidity taken by Electra aircraft over cold coastal waters (SST = 12C) is shown in Figure 8. The vertical profiles indicate a moist, stable atmosphere up to a height of about 1 km. Air temperature at 50 m altitude was 12.5C which is slightly larger than the underlying SST (12.0C) for the cool, northeasterly flow, indicating stable stratification near the coast. Northeasterly surface winds veered almost linearly with height to southwesterly (230 deg) at 1.2 km indicating a convergence zone near the coast line.

The temperature profile over the cold shelf waters (Figure 8c) showed the existence of two stable boundary layers indicating two different air masses. The first stable layer up to 400 m is believed to have been caused by the advection of warm air from the mid-shelf region over the relatively cooler coastal waters. This warm air advection was also confirmed from the wind direction profile where the winds are turning anti-cyclonically from northeasterly at the surface to southerly at 400–500 m height. A low-level jet formed at a height of about 150 m causing strong wind shear (Figure 8b). This turning of winds (Figure 8a) could have been in response to the differential surface forcing at different levels. The absolute humidity profile indicates a moist layer below 500 m (Figure 8d), with a relative humidity of 100% (not shown) indicating clouds in this region. The convergence below the cloud layer at altitudes between 200 m and 400 m can be seen from the acceleration of the winds (Figure 8b). The second less stable air mass from 500 m to 1000 m could have been due to the dry overland air. In contrast, the leg-averaged values of the mean temperatures at the location *J* (Figure 1) close to the Gulf Stream (not shown) indicated a well mixed, convective boundary layer.

Vertical profiles of air temperature, wind direction, wind speed and absolute humidity observed by the King Air aircraft at *D* (Figure 1), east of the Gulf Stream (33N, 75W) are shown in Figure 9. These profiles approximately reflect the conditions over the Gulf Stream because the SST does not decrease significantly east of the Gulf Stream (Wayland and Raman, 1989). All profiles show a well mixed boundary layer 600 m deep (Figures 9a and 9b) with a cloud layer extending from 900 m to 1300 m as indicated by

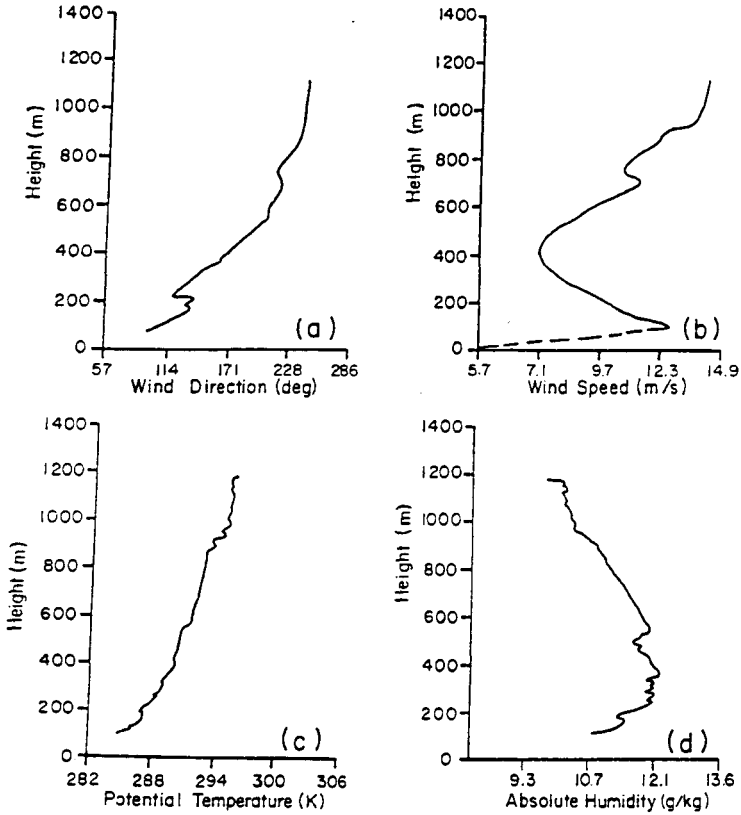


FIGURE 8 Vertical profiles of **a** Wind Direction; **b** Wind Speed; **c** Potential Temperature, and **d** Absolute Humidity over the cold coastal waters (at G) on 10 February, 1986. Data obtained from the Electra aircraft at 1800 UTC.

an increase in turbulence. This cloud layer is clearly evident from the absolute humidity profile (Figure 9d). The relative humidity is 100% in this cloud layer with a slightly drier layer (600 m–900 m) below it. The wind direction profile indicates a southwesterly (220 deg) flow below the boundary layer and westerly flow (260 deg) above. This westerly flow in the cloud layer indicates that the clouds were advected from the west. Thus the boundary layer height (600 m) observed by the King Air aircraft was close to the one observed by RVC at 1500 UTC (750 m height). The increase of 150 m in the boundary layer height at RVC could be due to the increased convection over the Gulf Stream. The wind speeds were about  $11 \text{ m s}^{-1}$  in the boundary layer again showing a mixed layer. The humidity profiles also showed the characteristics of a well-mixed, convective boundary layer (Figure 9d). Two different boundary layer structures were observed in the potential temperature and the absolute humidity profiles over the cold shelf waters and over the eastern edge of the Gulf Stream. The mean boundary layer temperature increased from 284 K over the cold shelf waters (Figure 8c) to 293 K over the warm Gulf Stream waters (Figure 9c) and the absolute

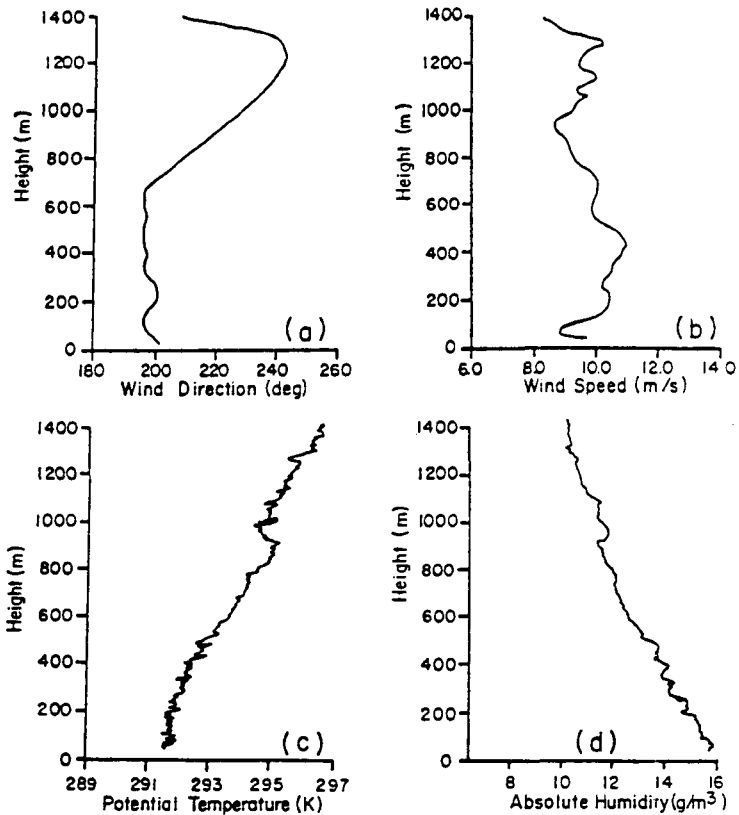


FIGURE 9 Vertical profiles of **a** Potential Temperature; **b** Wind Direction; **c** Wind Speed, and **d** Absolute Humidity over the Gulf Stream (at *D*) observed by the King Air aircraft at 1330 UTC on 10 February, 1986.

humidity increased by  $4.5 \text{ g kg}^{-1}$  from cold waters (Figure 8d) to warm waters (Figure 9d). These profiles are characteristic of a convective marine boundary layer (Wayland and Raman 1989). However, location *D* is a relatively undisturbed region with no significant low-level circulations. The profiles do not show any low-level jet (Figure 9b) and no vertical variation in wind direction with height (Figure 9a). Also, location *D* is far from the region where the meso-low existed.

Now the marine boundary layer structure in the region of the meso-low will be investigated and compared with the relatively undisturbed MBL structure (Figure 9) presented above. This location is identified as the disturbed region due to meso-low development just south (50 km) of this point. Figure 10 shows the vertical profiles of wind speed, wind direction, air temperature and specific humidity at 1500 UTC obtained from RVC situated at the core of the Gulf Stream (34N, 75.5W) 50 km north of the filament. The wind speed profile shows an easterly low-level jet at 300 m which coincides with the sharp changes in wind direction at that height. The wind direction is east-northeasterly in the boundary layer and westerly above the boundary layer. The humidity profile shows a well mixed layer up to 1000 m consistent with the depth above



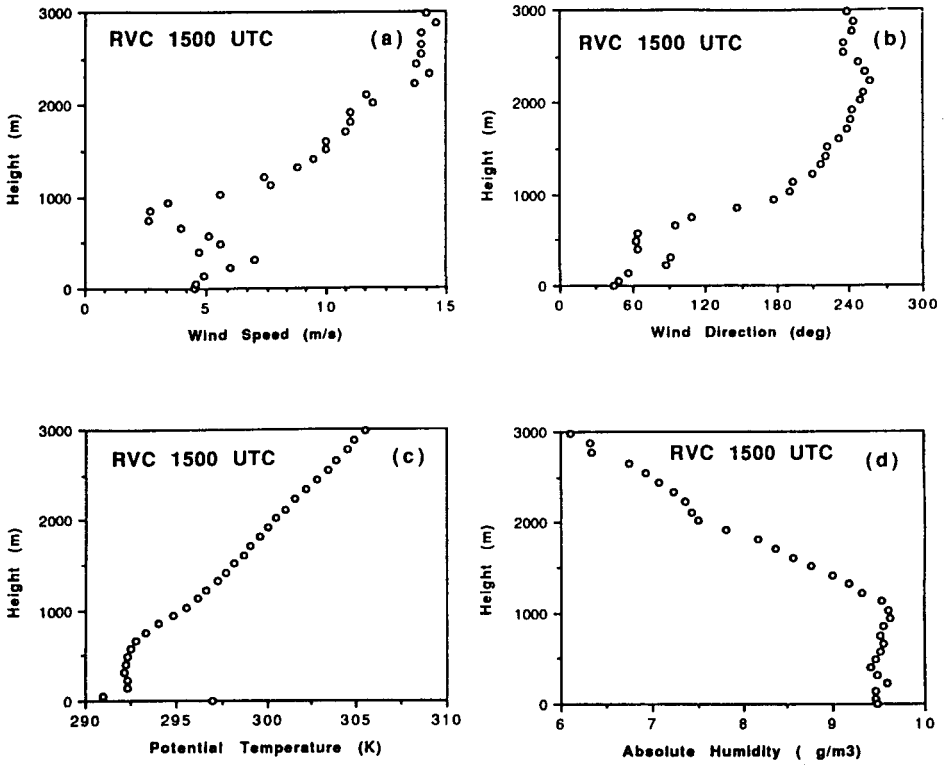


FIGURE 10 Vertical profiles of **a** wind speed; **b** wind direction; **c** potential temperature and **d** absolute Humidity at RVC situated at the core of the Gulf Stream at 1500 UTC.

which significant changes in wind speed and direction occur. The potential temperature profile indicates a mixed layer of about 700 m and a change in vertical temperature gradients at 1000 m. The profiles in general indicate two different air masses, one moist and affected by surface conditions (up to 1000 m) and the other unaffected.

Vertical air mass modification across the Gulf Stream filament is shown in Figure 11 using the observations from the King Air aircraft at 1630 UTC along the low-level wind trajectory. The data plotted are one minute leg-averaged values upwind of the filament (Region I of Figure 3) and at the edges of the filament (Regions II–III of Figure 3) from the transect *E-F*. Dotted lines indicate the profiles over the colder waters upwind of the filament. Solid lines indicate the profiles near the eastern edge of the filament. Upwind of the filament, winds were light ( $5 \text{ m s}^{-1}$ ) from a northeasterly direction. As the cold air moved over the relatively warmer filament, the air was modified significantly in terms of the wind speed, direction, potential temperature and humidity as can be seen in Figure 11. The wind speeds increased by a factor of 1.7 at lower levels and air temperature ( $\theta$ ) increased by 3 K. The modification extended to a height of at least 300 m above the surface.

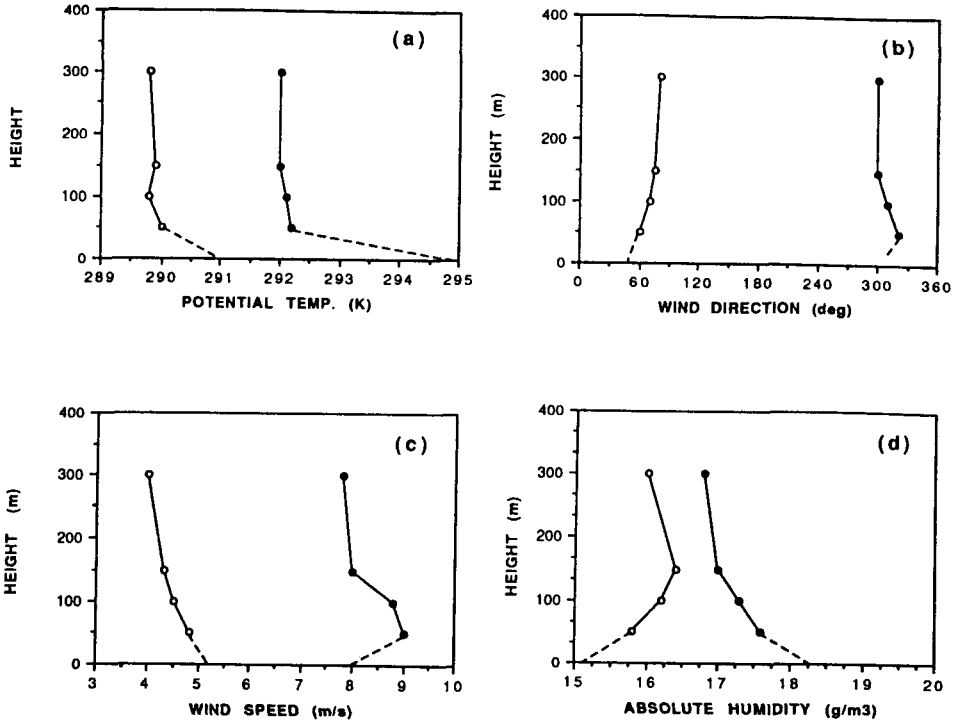


FIGURE 11 Mean vertical profiles of **a** Potential Temperature; **b** Wind Direction; **c** Wind Speed, and **d** Absolute Humidity upwind and over the filament (E-F) at 1630 UTC on 10 February, 1986. Open circles indicate data over the filament and closed circles indicate data upwind of the filament. The data presented are the leg-averaged values at various heights.

## 5. CONCLUSIONS

Observations from 9–11 February, 1986 obtained during the Genesis of Atlantic Lows Experiment (GALE 1986) are used to investigate the formation of a meso-low in the Gulf Stream region. This includes data from King Air and Electra aircraft, ships, buoys, CLASS and satellite imagery. These observations indicate that somewhat quiescent conditions existed on 9 February but a mesoscale circulation formed over a Gulf Stream filament on 10 February. This low intensified into a cyclone on 11 February.

Also the analysis of data over a Gulf Stream filament in the region indicated a significant increase in wind speed and a change in wind direction across the filament up to a height of about 300 m. Northeasterly ambient winds changed to a northwesterly direction, with winds almost at right angles to the filament. Vertical profiles of wind speeds over the filament indicated low-level acceleration of winds due to a mesoscale convergence. This in combination with the effects of the horizontal temperature gradients between the cold core adjacent to the filament and the Gulf Stream appears to have induced a closed mesoscale circulation leading to the generation of a meso-low. It is planned to conduct a numerical sensitivity study designed to investigate the processes associated with the formation of the meso-low on 10 February, 1986.

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