

MEASUREMENTS IN THE MARINE BOUNDARY LAYER NEAR A COASTAL FRONT

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Abstract. Measurements taken from aboard ship and from nearby fixed sites during a March 1985 research cruise near Cape Hatteras document some interesting boundary layer features of the coastal front which have been largely unexplored. The front, although commonly associated with the development of coastal cyclones is nevertheless shallow and often difficult to detect due to the scarcity of routinely available observations off-shore.

During the particular case described, the coastal front, undetected by routine analyses, divides air masses of quite different character. To the east of the surface wind shift line a warm, statically unstable boundary layer is associated with strong fluxes of latent heat from the sea surface. To the west, however, the boundary layer is cold and stable with negligible air-sea heat exchange. A low-level jet in the frontal zone carries the warm moist air westward toward eastern North Carolina. Subsequent moderate precipitation and cyclone passage may be associated with the frontal boundary.

Introduction

Several investigators have provided evidence that the shallow baroclinic zone termed the coastal front is of major importance in precipitation enhancement and consequent latent heat release along the East Coast of the United States [Marks and Austin, 1979, Bosart, 1975]. Fluxes of latent and sensible heat from the ocean may be sizeable near developing storms in this region, and together with nearby frontal processes, the energy-enriched air may contribute to cyclogenesis. For example, Bosart and Lin [1984] re-examined the much-studied Presidents' Day storm of February 1979 and calculated latent and sensible heat fluxes of 500 to 1000 W m^{-2} and 300 W m^{-2} respectively, in onshore air flow over the warm Gulf Stream waters prior to coastal front development. They provided considerable evidence of flux convergence of water vapor in the boundary layer as moist air moved southwest toward the coast. Coastal frontogenesis was shown to be accompanied by highly ageostrophic convergent flow in the boundary layer which provided an environment highly favorable to subsequent cyclogenesis.

In other case studies, the low-level flow in the moist unstable Planetary Boundary Layer (PBL) forms a distinct mesoscale jet ahead of the synoptic-scale frontal zone. Termed the conveyor belt [Harrold, 1973, and Browning and Pardoe, 1973], the jet may be a key contributor to synoptic-scale precipitation in cyclones [Harrold, 1973, and Carlson, 1980].

A research cruise near Cape Hatteras, North Carolina on 21-22 March 1985 aboard the R/V Cape Hatteras has provided some interesting boundary-layer measurements near a developing coastal front. In this case, the encounter with the front was totally unexpected since little evidence of its existence was discernable from routine data or analysis from the National Meteorological Center (NMC).

Figure 1 illustrates the synoptic regime as discerned from routinely available observations. Near Cape Hatteras at 0000 GMT on 22 March, a moderate pressure gradient of roughly $1.3 \times 10^{-3} \text{ Pa m}^{-1}$ supported a geostrophic wind of 15 m s^{-1} from the east at the surface. An east-west stationary front extending offshore at the surface was analyzed some 300 km to the south. Northeast winds of 8 m s^{-1} were observed at Cape Hatteras. Comparison of the surface and upper-air analyses at 0000 GMT shows moderate low-level warm advection over much of the Southeast. NMC surface analyses, essentially reproduced in Figure 1 depict the northwest propagation of the frontal zone toward the coastline. However, as suggested by the wind-shift at Hatteras by 0600 GMT, and as described here, a separate frontal zone, namely, the coastal front, already existed offshore for at least 6 hours prior to 0600 GMT.

Results of Detailed Observations

Figure 2a illustrates observed temperatures and winds at three selected times near 0000 GMT on 22 March when the coastal front was encountered. Together with ship observations (S), those from the National Weather Service Office at Hatteras (HAT) and the NOAA C-MAN observations from Diamond Shoals Light Tower (DSLNL) are also plotted. For reference, the analysis of seasurface temperatures as monitored by the ship depict the location of the western edge of the Gulf Stream.

At 2300 GMT the wind-shift line is west of but very near DSLNL, since the ship, located only a few kilometers away appears to be in a different wind regime. By 0100 GMT, however, winds at the two sites are again in very close agreement.

Surface fluxes of sensible and latent heat were estimated using bulk aerodynamic methods to study their variation in the vicinity of the Gulf Stream during various synoptic conditions. The sensible heat flux H was estimated from the bulk aerodynamic method:

$$H = \rho c_p C_H U_{10} (T_s - T_{10}) \quad (1)$$

where the subscript "10" denotes values measured at 10 m, "s" denotes surface values, ρ is air density, c_p the specific heat of air at constant pressure and C_H the heat exchange coefficient.

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Paper number 5L6663.

0094-8276/85/005L-6663\$03.00

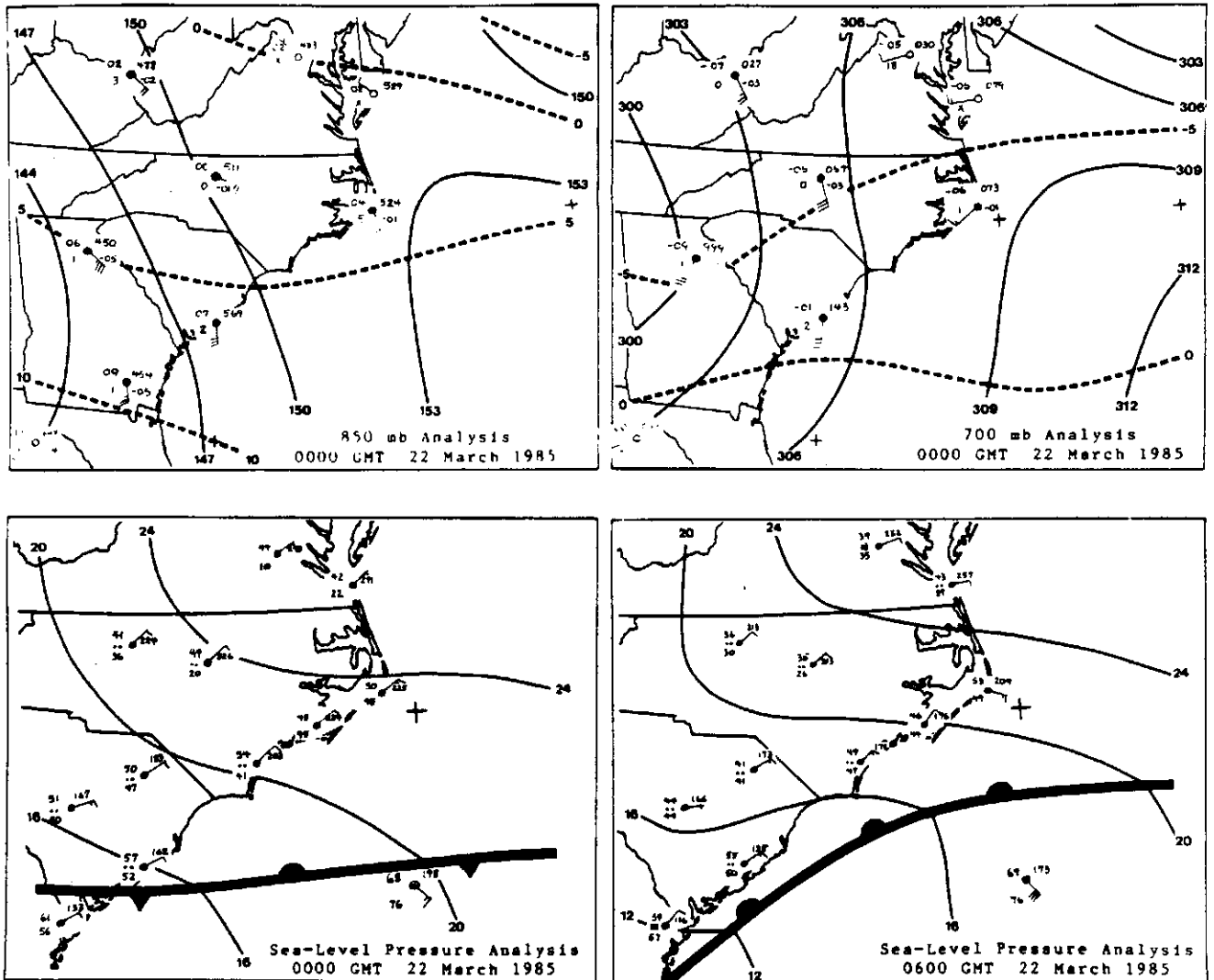


Fig. 1. Analysis of surface and upper air features for 0000 to 0600 GMT 22 March 1985 over the Southeast Coast of the United States. The analyses are redrawn from routine National Meteorological Center charts with heights of 700 and 850 mb surfaces (solid, dm) isotherms (dashed, $^{\circ}C$); and sea-level isobars in whole millibars (i.e. 24 = 1024 mb).

Friehe and Schmitt (1976) found that C_H , the sensible heat coefficient can be approximated as:

$$C_H = 0.97 \times 10^{-3} \quad \text{if } 0 < U_{10}(T_s - T_{10}) < 25 \text{ m s}^{-1} \text{ K} \quad (2)$$

$$C_H = 1.46 \times 10^{-3} \quad \text{if } U_{10}(T_s - T_{10}) > 25 \text{ m s}^{-1} \text{ K}$$

For conditions in which $T_s < T_{10}$, $C_H = 0.86 \times 10^{-3}$. Latent heat flux LH was calculated from:

$$LH = L_v C_E U_{10} (q_s - q_{10}) \quad (3)$$

where L_v is the heat of vaporization and q_s and q_{10} are the absolute humidities at the surface and 10 m respectively. Air was assumed to be saturated at the surface. C_E , the latent heat coefficient, was taken to be 1.32×10^{-3} after Friehe and Schmitt (1976).

Fluxes in the cold air, as for example at S on 2200 GMT are very small due to small air-sea temperature differences. Evidently the flow, orient-

ed parallel to sea-surface isotherms, has allowed a near thermal equilibrium between the air and sea. By contrast, however, east of the front over the Gulf Stream there is a 4 to 5 $^{\circ}C$ air-sea temperature difference and low humidity accompanied by 15 m s^{-1} winds. Here the latent and sensible heat fluxes reach 600 and 130 W m^{-2} respectively.

A series of 5 mini-radiosonde launches were begun on the ship starting at 0100 GMT as the ship proceeded north-northeast toward 30 $^{\circ}$ 30' N, 75 $^{\circ}$ 00' W. Except in the lowest 300 m, the profiles of virtual potential temperature and specific humidity are all quite similar and can readily be compared to the routine radiosonde profile in the cold air at HAT. Figure 3 compares the 0330 GMT ship profiles with the 0000 GMT Hatteras profiles.

At the ship the lapse rate is absolutely unstable from the sea surface to about 300 m becoming slightly stable to about 1.6 km, above which an inversion, present at the same level on subsequent soundings, marks the top of the PBL. A con-

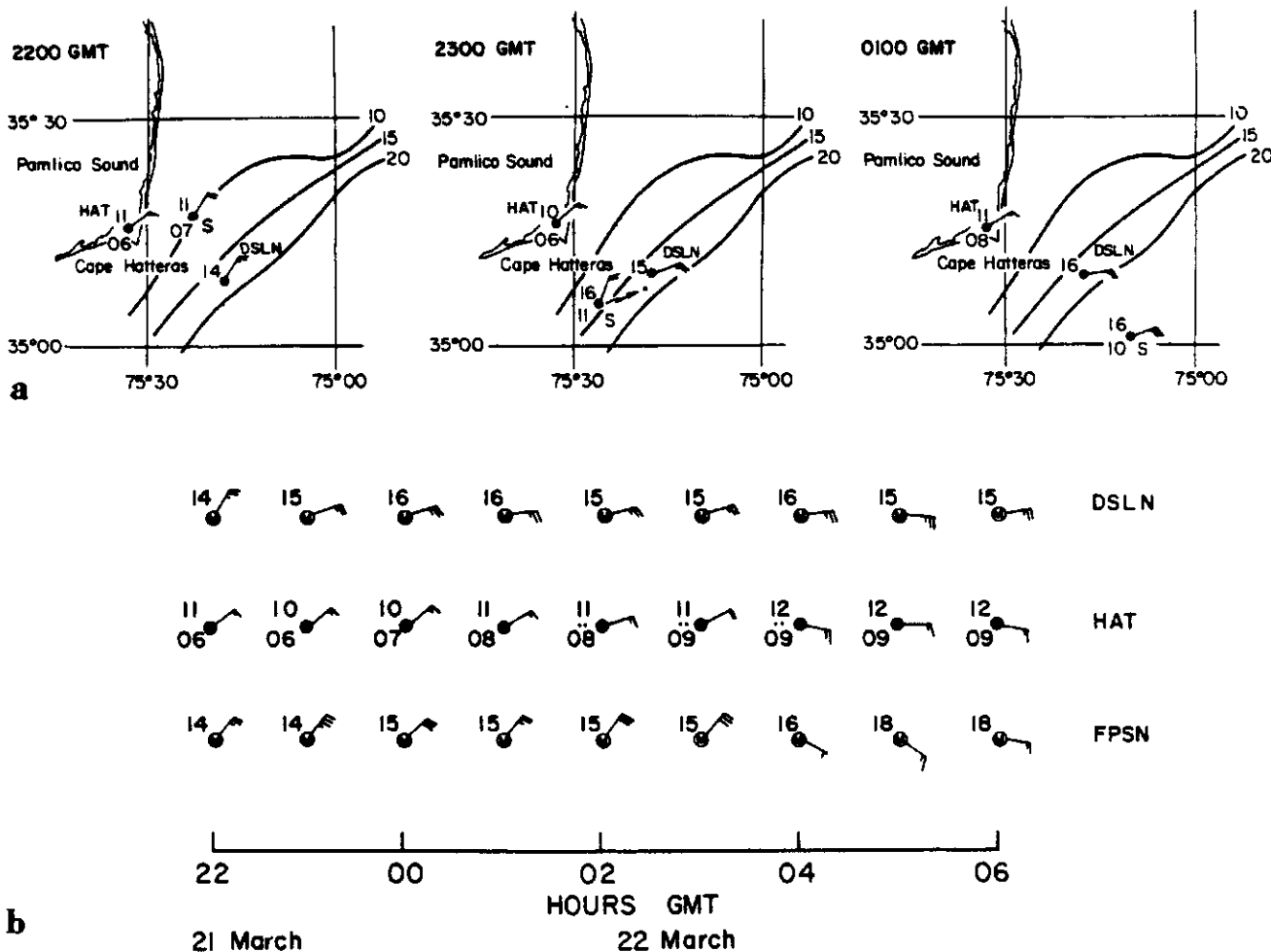


Fig. 2. Coastal front passage near Cape Hatteras, North Carolina as evidenced by surface observations: (a) Plots of wind velocity (wind speed in $m s^{-1}$ with whole flags for each $5 m s^{-1}$) temperature ($^{\circ}C$) and dew point ($^{\circ}C$, where available) at the NWS office at Cape Hatteras (HAT), the Research Vessel (S), and Diamond Shoals Light Tower (DSLNL). Sea-surface isotherms ($^{\circ}C$) are also included, and (b) a meteorogram of wind velocity, temperature and dew point from 2200 GMT on 21 March 1985 through 0600 GMT on 22 March 1985 at Diamond Shoals (DSLNL), the NWS station (HAT), and Frying Pan Shoals (FPSN).

vective marine boundary layer seems well-established over the Gulf Stream. At HAT, however, the PBL is quite stable. Surface temperatures of 274 K are at least 16 K colder than at the ship. Earlier ship measurements over the cold shelf water at 2200 GMT (Figure 2a) confirm that the cold surface air is truly characteristics of the marine environment west of the front and is not due to nocturnal terrestrial cooling at the cape.

The wind profile also in Figure 3 shows a well-defined low-level jet from the east-northeast at $15 m s^{-1}$ above HAT. After frontal passage at HAT at 1200 GMT, winds at 500 m are from about 110° . Above 1 km wind speeds then remain more nearly constant while directions continue to veer with height. Judging from the surface winds at the ship at 0100 GMT, such a wind regime probably also is characteristic of the boundary layer in the warm air at that time. The veering winds and direction of low-level flow strongly suggest that the unstable moist air in the PBL is directed westward toward the frontal zone.

The frontal zone and perhaps some of the associated features may extend farther southwest of the area shown in Figure 2a. For example, the frontal passage evident between 0300 and 0400 GMT at HAT in Figure 2b is roughly coincident with a much more dramatic frontal passage at Frying Pan Shoals Light Tower (FPSN) located some 250 km to the southwest, although this passage may have been the synoptic-scale warm front.

Later surface observations and radar analyses showed a persistent broad area of precipitation over land west of the stationary coastal front during 22 March. Rainfall totals over eastern North Carolina for the system ranged from 2 to 4.5 cm. Later, a weak cyclone formed just offshore and moved northeast roughly along the coastal front boundary, passing west of HAT at about 0600 GMT on 23 March.

Conclusions

Although this case is not characterized by heat fluxes, precipitation or dramatic cyclogenesis

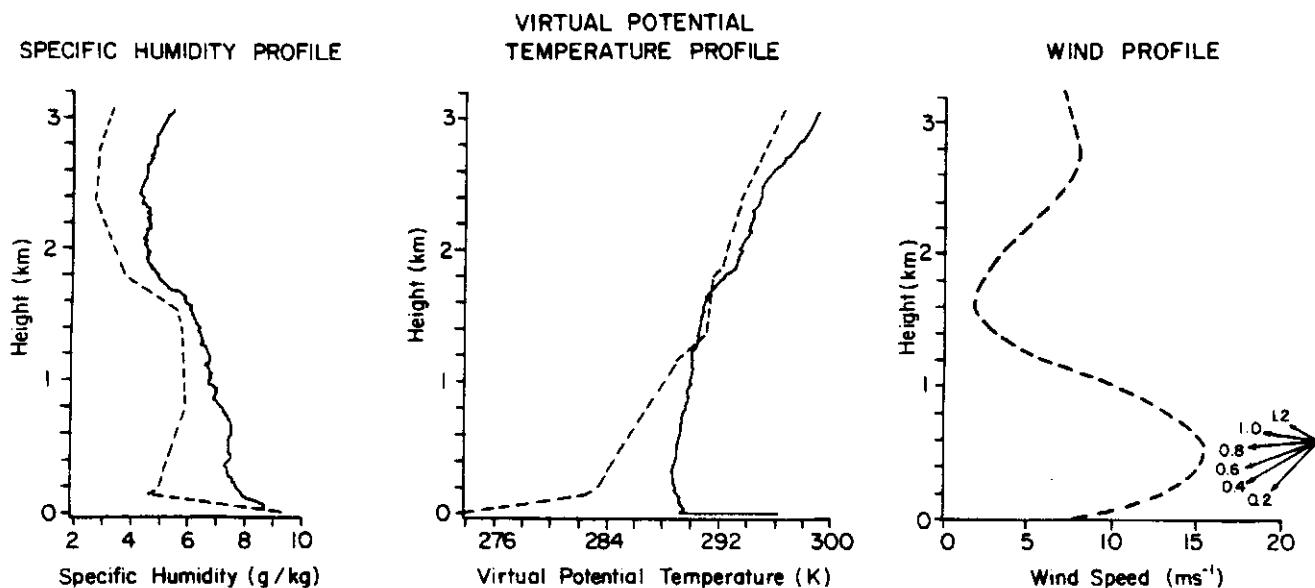


Fig. 3. Profiles of specific humidity, virtual potential temperature and wind speed at 0000 GMT 22 March 1985 at the NWS station at Cape Hatteras (dashed) and at 0330 GMT at the Research Vessel (solid). Included with the wind profile is the hodograph of wind vectors from 0.2 to 1.2 km in the low-level jet.

comparable to the Presidents' Day cyclone, the measurements presented here suggest that coastal fronts, undetected by routine analysis, may nevertheless be important in the frequent smaller weather disturbances of the area. In the case discussed here the front marked a division between a warm, moist unstable PBL characterized by large latent heat fluxes and a dramatically cooler, stable regime with negligible fluxes. More measurements in such zones may provide clearer documentation of the low-level jet and its role in transporting moisture into the frontal zone. The role of the western boundary of the Gulf Stream in coastal frontogenesis also merits more attention.

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(Received August 2, 1985;
accepted August 14, 1985.)

Acknowledgements: This work was supported by the National Science Foundation under Grant ATM-83-11812 and Office of Naval Research under Contract N00014-84-K-0620.