Reprinted from JOURNAL OF CLIMATE AND APPLIED METEOROLOGY, Vol. 25, No. 1, January 1986
American Meteorological Society

Observations of the Marine Boundary Layer Thermal Structure over the Gulf Stream during a Cold Air Outbreak

S. SETHURAMAN, A. J. RIORDAN, T. HOLT, M. STUNDER AND J. HINMAN

Department of Marine, Earth and Atmospheric Sciences, North Carolina State University, Raleigh, NC 27695

(Manuscript received 10 November 1984, in final form 26 June 1985)

ABSTRACT

Thermal structure of the marine boundary layer (MBL) was studied during a five-day cruise over the coastal Atlantic Ocean off North Carolina. Three different synoptic conditions were present: ahead of a low moving along the coast, in the area of a frontal zone and during a cold air outbreak. The marine boundary layer height was deeper (approximately 1500 m) and more sharply defined during the cold air outbreak than when the flow was southwesterly with a long fetch over water; the height was only about 1000 m for the latter case. Latent heat fluxes were significantly larger than sensible heat, but during the cold air outbreak, sensible heat fluxes increased appreciably.

1. Introduction

The region comprising North and South Carolina is horizontally nonuniform. The east-facing slopes of the Appalachians, the rolling Piedmont, and the flat coastal plain each form zones 100 to 150 km wide, oriented northeast–southwest and aligned approximately parallel to the coast. Offshore, cold shelf waters extend to about 100 to 150 km seaward where they meet the meandering western edge of the Gulf Stream, which is also aligned roughly parallel to the coast. During cyclogenesis, the flow at low levels usually crosses these regional discontinuities resulting in a highly variable and evolving boundary layer structure. Cold air outbreaks are an important example of cross-boundary flow. Off the East Coast of the United States the fluxes of momentum and heat in the evolving boundary layer during cold offshore flow have been described in field studies such as MASEX (Chou and Atlas, 1982; Atlas *et al.*, 1983). The fluxes of heat and momentum are large during these events which often follow cyclone passage.

Ahead of a coastal cyclone, the surface wind may be easterly and could cross regional boundaries, particularly north of the warm front. Bosart (1981) describes some important modifications in the character of the boundary layer in this type of regime. In the warm sector of the cyclone, however, the wind typically remains southwesterly parallel to the Gulf Stream and shoreline. Here, by contrast, one would expect steady state conditions with little change in the surface fluxes along air parcel trajectories. From the perspective of the boundary layer, cyclone passage causes a changing sequence of events as the lower atmosphere adjusts to new flow regimes. The process, however, is nonlinear, since the boundary layer itself may profoundly affect the cyclone evolution. For example, upward heat flux from the oceans has long been recognized as an important contributor to the genesis of coastal cyclones and fronts (Winston, 1955; Reed, 1958; Gall and Johnson, 1971; Bosart, 1981).

The purpose of this paper is to compare observations of the thermal structure of the marine boundary layer and associated heat and momentum fluxes during prestorm southwesterly flow, cold frontal passage, and during a cold air outbreak which followed. These observations were made from a research cruise off the coast of North Carolina from 9 to 13 November 1983. Figure 1 illustrates the ship track and sea surface temperatures during the cruise. Dashed isotherms are inferred from satellite observations. Locations of miniradiosonde launches are also shown.

2. Synoptic conditions

A weak low-pressure system over central Florida on the morning of 9 November moved northward along the coast to eastern Virginia by 1800 GMT 10 November (Fig. 2) where it began to intensify rapidly as it merged with a larger system approaching from the Ohio Valley. At this time, winds off the North Carolina coast were southwesterly at about 5 m s^{-1}. Synoptic scale thermal advection was weak, as evidenced by the surface and 850 mb fields. The main cold front, characterized by strong cold advection below 500 mb, was still located well to the west, over eastern Tennessee and western Georgia at 1800 GMT. Its passage at 0900 GMT 11 November was marked by a windshift, dew point drop, and wind gusting to gale force at the ship position 80 km southeast of Cape Fear.

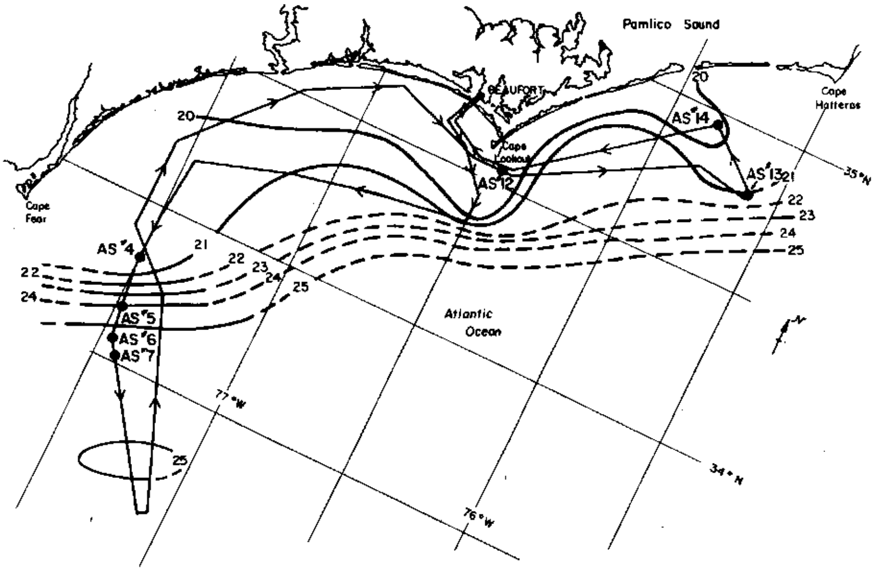

FIG. 1. Ship track for the cruise from 9–13 November 1984. Also shown are the surface temperature contours obtained from ship data (solid line) and estimated from satellite (dotted line).

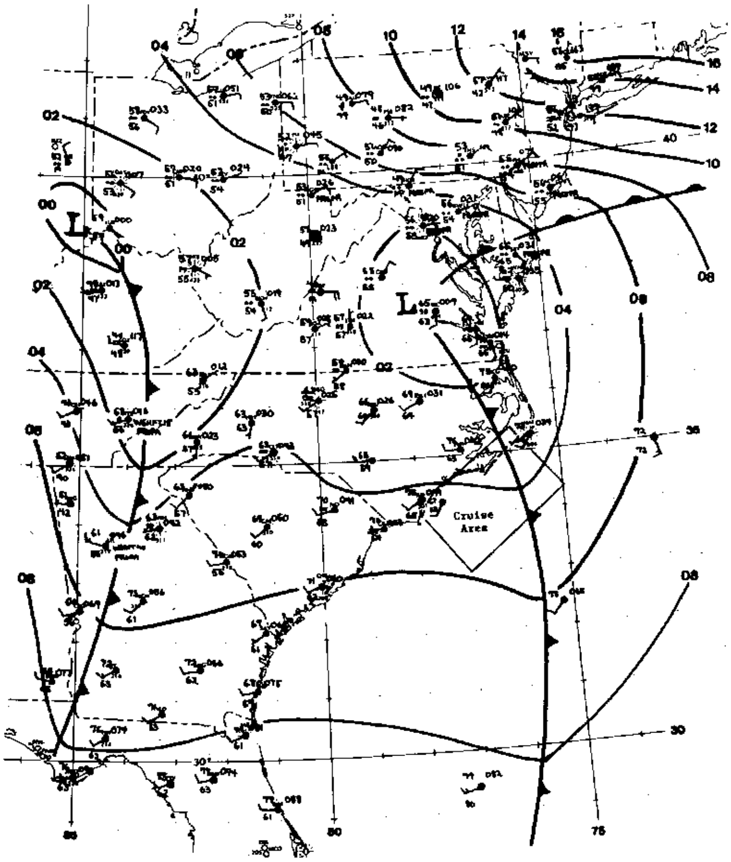

FIG. 2. Synoptic surface map for 11 November 1983 (1800 GMT) for the East Coast. Isobars are labeled in tens of millibars. The ship observation is plotted at the ship position within the cruise area.

By 1800 GMT 12 November, the low pressure complex had moved northeast and had evolved into a large, deep low centered over the Canadian Maritime Provinces. Cold advection and synoptic-scale subsidence were well established over the coastal area as can be seen in Fig. 3. By late afternoon, diurnal cooling over the coastal plain had intensified the cold advection over the coastal waters.

3. Methodology

The 41-m NSF Research Vessel (RV) *Cape Hatteras* was used as a mobile platform to investigate the thermal structure of the marine boundary layer (MBL) and the fluxes of momentum and heat across the air–sea interface in the vicinity of the Gulf Stream off the North Carolina Coast. A total of ten successful minisonde launches provided layer temperature and dew point profiles up to a height of about 3 km. The minisonde system consisted of a receiver station located inside the ship along with a sensor package to measure pressure and dry and wet bulb temperatures. Helium filled balloons were used to deploy the sensor package. Data were transmitted to the receiving station by radio telemetry and recorded on magnetic tapes. The choice of launch location was based on the mesoscale weather situation present and the proximity of the Gulf Stream.

Hourly meteorological surface observations on board the ship began upon leaving the home port of Beaufort, North Carolina (Fig. 1) and continued until the return to port. Wind measurements were made with a vortex anemometer mounted on the top of the superstructure at a height of about 18 m above water. Wind speed was then corrected to its 10 m value using a logarithmic profile relationship and assuming an appropriate roughness length (SethuRaman and Raynor, 1975).

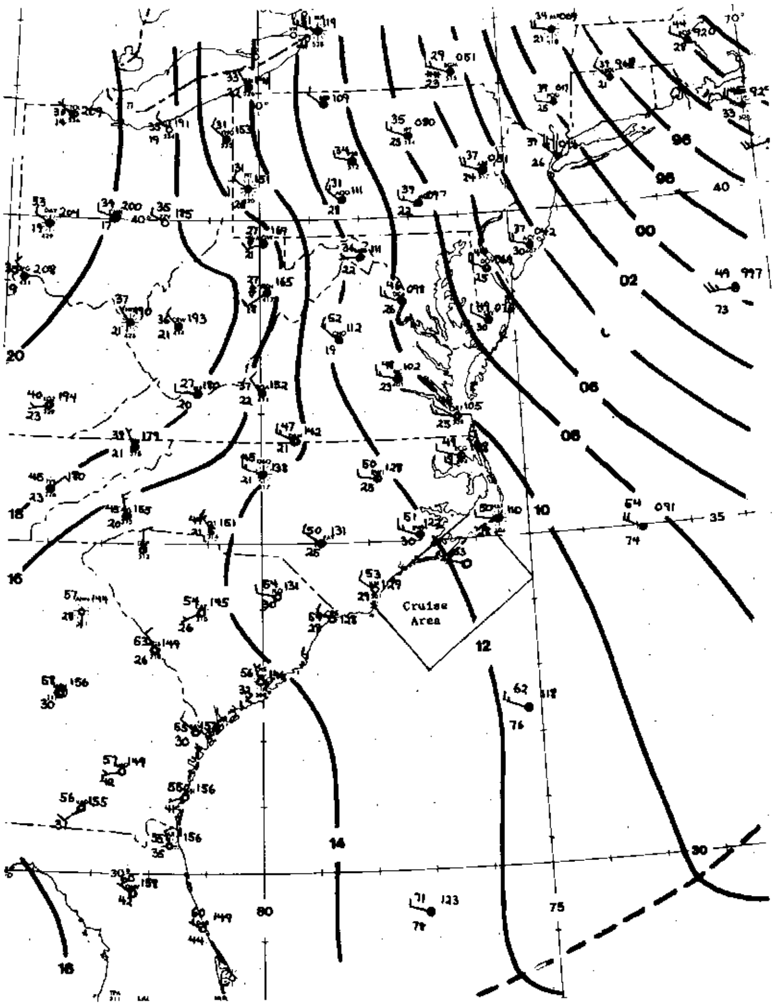

FIG. 3. Surface weather map for 12 November 1983 (1800 GMT) for the East Coast. Isobars are labeled in tens of millibars. Note cold air outbreak in the cruise area. The ship observation is plotted at the ship position within the cruise area.

Ten-min averages of wind direction and speed were determined relative to the ship and corrected for the ship heading and course. The direction and speed were then recorded manually. Air temperature was determined using a thermistor mounted at a height of approximately 10 m on the superstructure. The temperatures, obtained hourly, were averaged over 10 min.

Dew point temperatures were determined from a wet bulb thermometer at a height of about 10 m on the superstructure. Both the dry and wet bulb thermometers were cleaned regularly to avoid salt spray contamination. A hand held IR thermometer was used at a height of about 3 m as one method of determining the sea surface temperature (SST). In addition, a thermistor was used to measure ship intake water temperature. The intake was located midships at a depth of about 2 m. The difference between the IR and ship intake sea temperature averaged about ±0.5°C.

Computations of relative humidity and sea surface fluxes were derived from the routine shipboard meteorological data. Shipboard radar and operational weather maps from the National Meteorological Center provided quick dissemination of regional weather data. Post-cruise mesoscale data analysis included examination of hourly weather observations from central and eastern North Carolina, with particular emphasis placed on the observations of the Cape Hatteras, Wilmington, New Bern and Cherry Point weather stations. Data from the Cape Hatteras (near water) and Greensboro (overland) daily radiosonde launches were obtained for comparison purposes with the shipboard minisonde data.

An early operational decision was made based on satellite-derived Gulf Stream analysis received on 9 November for the ship to proceed southeasterly to the Gulf Stream at a point about 50 km offshore of Cape Fear, North Carolina (Fig. 1). The sail time between Morehead City, North Carolina and the Gulf Stream eddy interception point was used to perfect the mechanics of minisonde shipboard launches. Upon arriving in the Gulf Stream area on 10 November, four minisondes were lauched to allow exploration of both the temporal and spatial variation of the MBL near the Gulf Stream. However, heavy seas very early on 11 November resulted in the ship turning toward shore and pursuing a north-northwesterly course for the next day. Observations for the rest of the cruise period concentrated on the study of the MBL during a cold air outbreak.

4. Discussion of results

a. Thermal structure of the MBL with southerly flow

The virtual potential temperature θ_v is often used to identify the mixed and cloud layers in the marine boundary layer (e.g., LeMone, 1980; Rao and Haney, 1982). The θ_v profiles obtained from miniradiosonde data before encountering the Gulf Stream (AS 4) and while over the Gulf Stream are shown in Fig. 4. The profile of θ_v outside the Gulf Stream (solid line) is approximately 3°C cooler near the surface than the profiles over the Gulf Stream (AS 5–AS 7). The surface winds at this time were directed roughly parallel to the edge of the Gulf Stream as air flowed northeastward ahead of an approaching cold front. Thus, although the two profiles, AS 4 and AS 6, were measured only 28 km from one another, they sampled air of two different overwater histories. The strongly stable layer throughout the boundary layer evident in the θ_v profile outside the Gulf Stream is absent for locations over the warmer water. There, a well-mixed layer had developed up to approximately 900 mb (1 km) due to the presence of the warmer surface as seen in the nearly constant θ_v profile.

b. Thermal structure of the MBL during a cold air outbreak

The case of the cold air outbreak over the warm waters off the North Carolina coast on 12 November 1983 provided an excellent situation for study of the thermal structure of the MBL during air mass modifications. Figure 3 for 1200 GMT 12 November illustrates well the strong north-northwest flow and the associated cold air advection over the coastal waters. Figure 5 shows the time history of air and sea surface temperatures. Decreases in air temperature of approx-

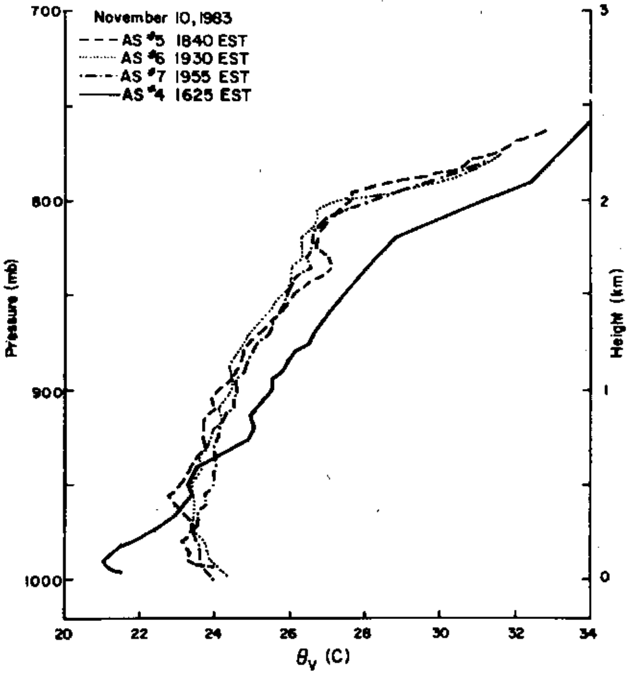

FIG. 4. Profiles of virtual potential temperatures for southwesterly flow with a long fetch over water. Note a mixed layer of about 1000 m capped with two layers of increasing stability.

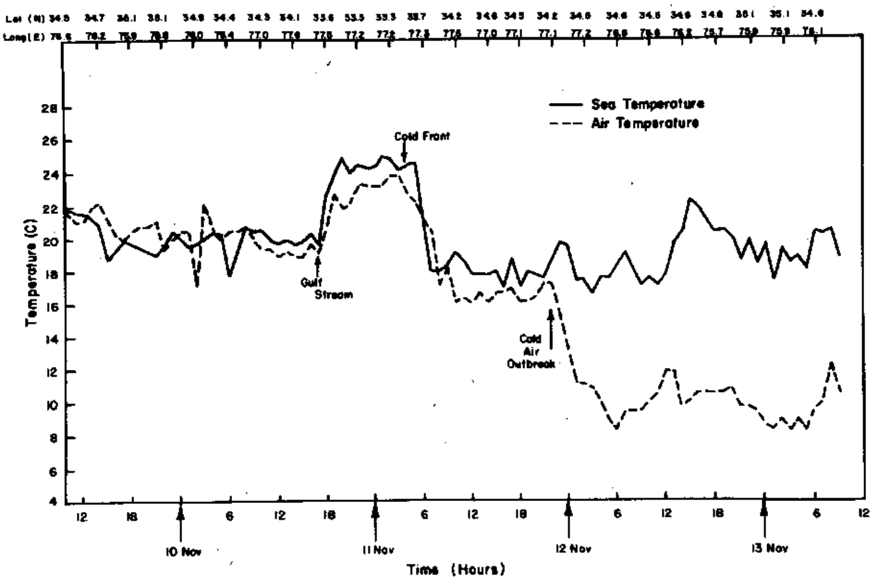

FIG. 5. A temporal and spatial history of air and sea surface temperatures.

imately 6°C from 2200 EST 11 November to 0100 EST 12 November delineate the onset of the cold air outbreak. The vertical variation of θ_v shown in Fig. 6 indicates the effect of the air–sea temperature difference on the boundary layer depth. The solid line indicates the profile obtained approximately 12 hours after the onset of cold air outbreak and the dashed line almost 9 hours later. Overwater fetch was close to 13 km for AS 12 and 55 km for AS 13. The well-mixed boundary layer grows approximately 500 m, from 1 km to about 1500 m, and warms by close to 3°C over this temporal and spatial interval. The layer is capped by a strong inversion.

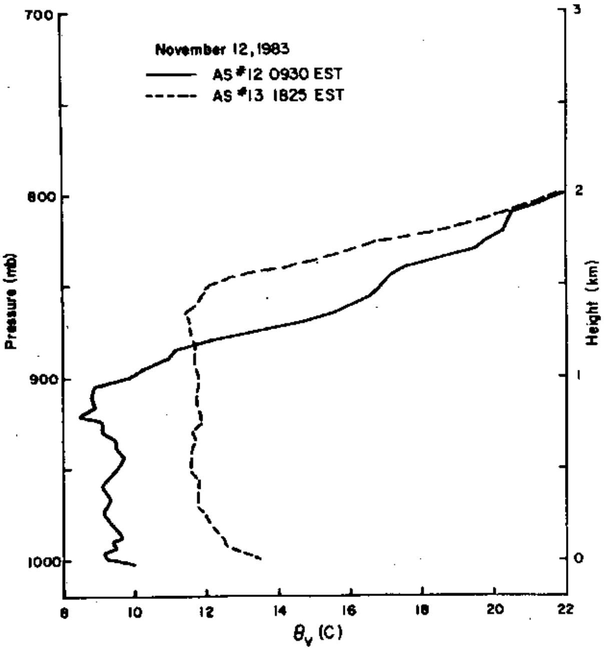

FIG. 6. Profiles of virtual potential temperatures during cold air outbreak. A larger height of mixed layer was observed farther downwind from the coastline.

c. Variation of sensible and latent heat fluxes

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 bulk aerodynamic method:

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

where the subscript 10 denotes values measured at 10 m, s surface values, ρ air density, c_p the specific heat of air at constant pressure and C_H the heat exchange coefficient. Friehe and Schmitt (1976) found that C_H, the sensible heat coefficient can be approximated as

$$C_H = \begin{cases} 0.97 \times 10^{-3} & \text{if} \quad 0 < U_{10}\,(T_S - T_{10}) \\ & \qquad < 25 \text{ m s}^{-1}\text{ K} \\ 1.46 \times 10^{-3} & \text{if} \quad U_{10}\,(T_S - T_{10}) \\ & \qquad > 25 \text{ m s}^{-1}\text{ K} \end{cases} \qquad (2)$$

for conditions in which $T_S < T_{10}$, $C_H = 0.86 \times 10^{-3}$.

Latent heat flux LH was calculated from:

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

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. The latent heat coefficient C_E was taken to be 1.32×10^{-3} after Friehe and Schmitt (1976).

Figure 7 shows the time history of latent and sensible heat flux for the five-day cruise calculated from the foregoing formulations. The SST remains approximately constant at about 20°C until 0600 EST on 11 November (see Fig. 5). However, from 1700 to 2000 EST, the ship crossed into the Gulf Stream and the SST warmed 4°–5°C. Figure 7 for this time period over the Gulf Stream shows a marked increase in latent heat (from 60 W m^{-2} to 350 W m^{-2}) due primarily to the warmer SST. Sensible heat flux remains fairly constant during this time period over the Gulf Stream because of a corresponding increase in air temperature. A local maximum of approximately 50 W m^{-2} at 2000 EST on 10 November appears to have been caused mainly by a sharp decrease in air temperature.

Synoptic conditions play an important role in the dynamics near the surface. The passage of the cold front associated with a weak surface low at 0400 EST on 11 November and the accompanying squalls with gale force winds and substantial decrease in dew point temperature greatly affected the surface fluxes. Latent and sensible heat flux values showed a substantial increase due to the cold front passage. The fact that the cold front passage and the ship's departure from the Gulf Stream approximately coincided (Fig. 5) makes it difficult to distinguish which had a greater effect on the surface fluxes. The cold front passage (approximately 0300 EST 11 November) and its associated increase in wind speeds and decrease in air temperature caused an obvious increase in both sensible and latent heat flux near the surface. However, departure from the Gulf Stream (approximately 0600 EST 11 November) and the consequent drop in SST caused a decrease in surface heat fluxes. Thus, the fact that the SST and near-surface air temperature decreased at approximately the same rate (but for different reasons) led to nearly constant sensible and latent heat fluxes from approximately 0700 to 2200 EST 11 November.

After the frontal passage, a secondary surface trough, still associated with the deepening surface low centered far to the north, temporarily blocked the arrival of colder continental air until approximately 2200 EST 11 November. With the arrival of this colder drier air, temperatures dropped from approximately 17°C at 2200 EST 11 November to 8°C at 0600 EST 12 November. Wind speeds increased slightly from about 10 to 14 m s^{-1} while the relative humidity remained essentially constant (60%) after having dropped significantly with the passage of the front. Accordingly, sensible heat flux values increased from 25 W m^{-2} at 2200 EST 11 November to 210 W m^{-2} 0800 EST 12 November. Latent heat fluxes during this time period showed an initial increase to a maximum of about 425 W m^{-2} at 0800 EST on 12 November and then a general decrease. Average wind speed was approximately 12 m s^{-1}. It appears that the increase in heat fluxes is due to the appreciable cooling of the air associated with the cold air outbreak.

Total heat flux values of about 700 to 800 W m^{-2} were observed (Murty, 1976) during the Air Mass Transformation Experiment (AMTEX). Present values of about 600 W m^{-2} compare well with the AMTEX values. Heat fluxes during intensive cold air outbreaks in winter could be even higher.

d. Variation of momentum flux

The bulk aerodynamic method was used to compute the surface momentum flux. Variations of the surface

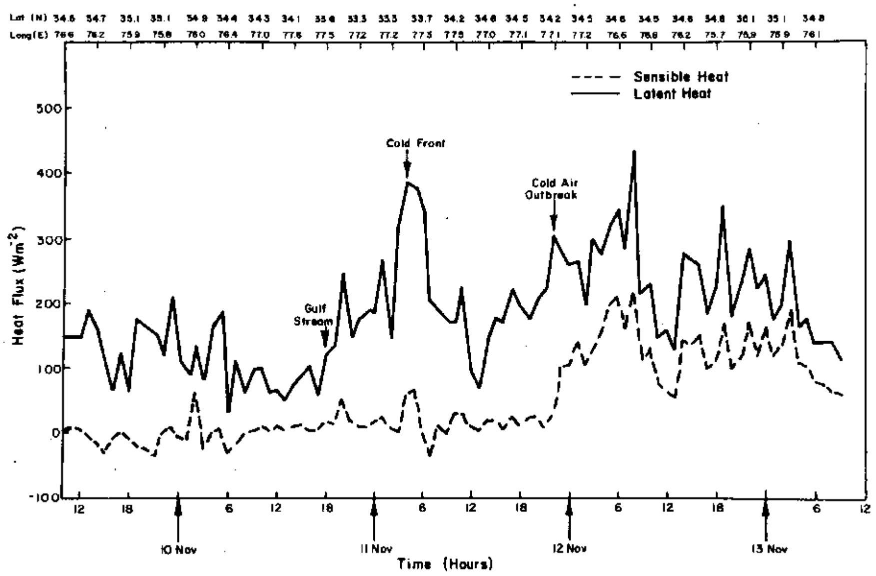

FIG. 7. A temporal and spatial history of the sensible and latent heat fluxes.

flux of momentum in the vicinity of the Gulf Stream during various synoptic conditions were then studied. Values of wind stress τ were obtained using the drag coefficient formulation given by Large and Pond (1981),

$$\tau = \rho[0.49 + 0.065U_{10}] \times 10^{-3} U_{10}^2, \qquad (4)$$

where U_{10} is the wind speed at 10 m. Effect of stability on the surface drag coefficient was assessed by using a formulation suggested by Kondo (1975):

$$C_D = (1 + 0.47S^{1/2})C_{DN}, \quad S > 0$$

where

$$S = (\theta_s - \theta_a)/U^2(1 + \log 10/z)^2 \qquad (5)$$

and θ_s and θ_a are sea surface and air temperatures, respectively; C_{DN} is the drag coefficient for neutral conditions incorporated in Eq. (5). Air temperature was measured at a height (z) of 10 m. With a mean wind speed of about 10 m s^{-1} and a temperature difference of about 10°C during cold air outbreak, the correction factor amounts to about 15%. This is within the general errors associated with C_D computation and hence were not taken into account in Eq. (5). Other investigators also found the effect of stability on surface drag coefficient to be negligible (SethuRaman and Raynor, 1975). With the passage of the cold front (0400 EST on 11 November) and the subsequent increase in wind speeds, momentum flux near the surface increased significantly from about 0.05 N m^{-2} at 0200 EST on 11 November to 0.60 N m^{-2} at 0400 EST 11 November as shown in Fig. 8. The arrival of the colder continental air at approximately 2200 EST 11 November also caused an increase in momentum flux. Calculations for the time period 2200 EST 11 November to 0800 EST 12 November showed average values of approximately 0.20 N m^{-2} as opposed to average values of 0.05 N m^{-2} before and after this time period. Values of momentum flux over the Gulf Stream varied from 0.05 to 0.15 N m^{-2}.

5. Conclusions

A five-day training cruise has given some valuable information about the thermal structure and surface fluxes in the marine boundary layer over the coastal Atlantic Ocean off North Carolina. Three sets of synoptic conditions existed during the time period of the study: southwesterly flow ahead of a coastal low, passage of a cold front, and a cold air outbreak.

Thermal structure of the marine boundary layer was significantly different for southerly flow with a long fetch over water as against northwesterly flow associated with cold air outbreak. The boundary layer was shallow (~1000 m) over the Gulf Stream for the southerly flow ahead of the coastal low. The virtual temperature profile over the Gulf Stream indicated a well-mixed layer up to about 1000 m. Outside the Gulf Stream, stable conditions existed throughout the boundary layer. Sweet *et al.* (1981) observed values ranging from 500 to 700 m over the Gulf Stream. Heights reached values of about 1500 m for cold air outbreak case when strong convective conditions were present. The marine boundary layer was also better defined with a strong inversion above.

Estimation of turbulent surface fluxes of sensible and latent heat was made using the bulk aerodynamic method. Sensible heat flux was almost negligible for the southerly flow ahead of coastal low, approximately an order of magnitude smaller than the latent flux when the cold front passed, but roughly half the value of the

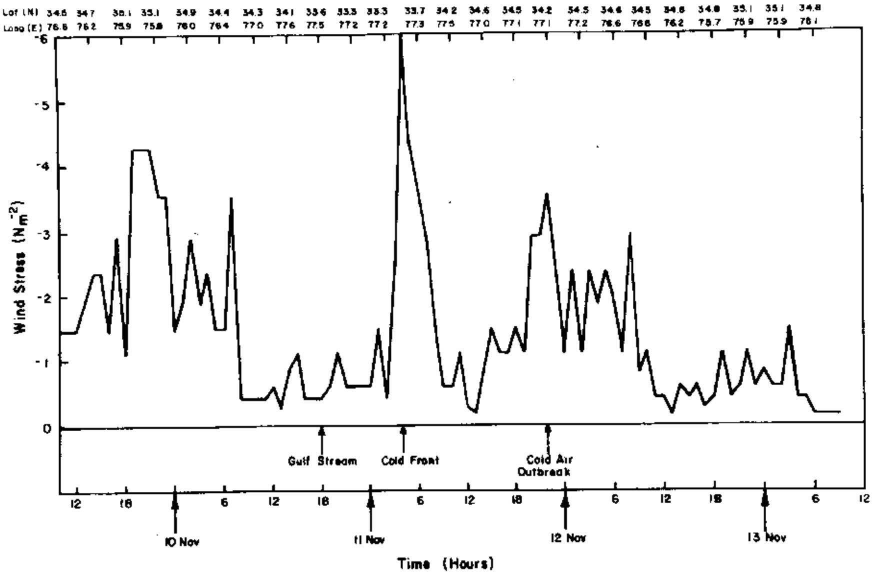

FIG. 8. Variation of surface shear stress with space and time.

latent heat flux following a substantial increase during the cold air outbreak.

Acknowledgments. Part of 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.

REFERENCES

Atlas, D., S.-H. Chou and W. P. Byerly, 1983: The influence of coastal shape on winter mesoscale air-sea interaction. *Mon. Wea. Rev.*, **111,** 245–252.

Augstein, E., 1978: The atmospheric boundary over the tropical oceans, Meteorology over tropical oceans. *Roy. Meteor. Soc.*, 105–132.

Bosart, L. F., 1981: The President's Day snowstorm of 18–19 February 1979; a sub-synoptic-scale event. *Mon. Wea. Rev.*, **109**, 1542–1566.

Chou, S-H., and D. Atlas, 1982: Satellite estimates of ocean–air heat fluxes during cold air outbreaks. *Mon. Wea. Rev.*, **110**, 1434–1450.

Friehe, C. A., and K. F. Schmitt, 1976: Parameterization of Air–Sea Interface Fluxes of Sensible Heat and Moisture by the Bulk Aerodynamic formulas. *J. Phys. Oceanogr.*, **6**, 801–809.

Gall, R. L., and D. T. Johnson, 1971: The generation of available potential energy by sensible heating; A case study. *Tellus*, **23,** 465–482.

Kondo, J., 1975: Air–sea bulk transfer in diabatic conditions. *Bound.-Layer Meteor.*, **9,** 91–112.

Large, W. G., and S. Pond, 1981: Open ocean momentum flux measurements in moderate to strong winds. *J. Phys. Oceanogr.*, **11,** 324–336.

LeMone, M. A., 1980: The marine boundary layer, Workshop on the Planetary Boundary Layer, American Meteorological Society, Boston, MA, 182–246.

Murty, L. K., 1976: Heat and moisture budgets over AMTEX area during AMTEX'75, *J. Meteor. Soc. Japan*, **54,** 370–381.

Rao, G. V., and J. L. Haney, 1982: Kinematic and thermal structures of two surges of flow in the northern Mozambique Channel area. *Quart. J. Roy. Meteor. Soc.*, **108,** 957–974.

Reed, R. J., 1958: A graphical prediction model incorporating a form of nonadiabatic heating. *J. Meteor.*, **15,** 1–8.

SethuRaman, S., and G. S. Raynor, 1975: Surface Drag Coefficient Dependence on Aerodynamic Roughness of the Sea Surface. *J. Geophys. Res.*, **80,** 4983–4988.

Sweet, W., R. Felt, J. Kerling and P. La Violette, 1981: Air–sea interaction effects in the lower troposphere across the north wall of the Gulf Stream. *Mon. Wea. Rev.*, **109,** 1042–1052.

Winston, J. S., 1955: Physical aspects of rapid cyclogenesis in the Gulf of Alaska. *Tellus*, **7,** 481–500.