5.4 DEVELOPMENT OF THE COASTAL BOUNDARY LAYER IN OFFSHORE FLOW FROM NEW ENGLAND

Wayne M. Angevine[1,2]*, J.E. Hare[1,3], C.W. Fairall [3], and D.E. Wolfe [3]

[1]Cooperative Institute for Research in Environmental Sciences (CIRES), University of Colorado, Boulder, Colorado
[2]NOAA Aeronomy Laboratory, Boulder, Colorado
[3]NOAA Environmental Technology Laboratory, Boulder, Colorado

1. INTRODUCTION

When warm air from land flows over colder water, a stable internal boundary layer is formed. The column spanning the depth of the continental boundary layer separates into possibly several layers, which are then advected in different directions. Analysis of data and modeling of scenarios from the 2002 New England Air Quality Study (Angevine et al. 2004a,b) showed that the details of the coastal boundary layer transition were important in understanding ozone pollution episodes in New Hampshire and Maine. An outstanding question is how the stable internal boundary layer develops, specifically what the surface flux magnitudes are; whether the fluxes are continuous or intermittent; and how the temperature profile evolves. Measurements in 2004 addressed these questions as part of the International Consortium for Atmospheric Research on Transport and Transformation (ICARTT) study. Instruments on the NOAA Research Vessel *Ronald H. Brown* measured surface heat and moisture fluxes and temperature profiles in the coastal waters at varying distances from the coast. Here, we report on the analysis of those measurements and relate them to model results.

Concentrations of ozone exceeding regulatory standards are regularly observed along the coasts of New Hampshire and Maine in summer. These events are primarily caused by transport of pollutants from urban areas in Massachusetts and farther south and west. Pollutant transport is most efficient over the ocean because deposition is minimal and deep vertical mixing does not take place.

The 2004 New England Air Quality Study (NEAQS 2004) was conducted in July and August 2004 as part of the larger ICARTT study. The measurements presented here come primarily from instruments aboard the NOAA Research Vessel *Ronald H. Brown*. The ship carried a comprehensive package of instruments for measuring air-sea fluxes (REF), a suite of atmospheric chemistry instrumentation, two lidars measuring ozone, aerosols and winds, and a radar wind profiler. Scientific staff onboard launched radiosondes.

2. RESULTS

From 2000 UTC 15 July until 1200 UTC 16 July, the ship was nearly stationary approximately 10 km northwest of Cape Ann. The wind direction at the ship was initially from the southeast, and changed to southwest by 0000 UTC 16 July. Thus two thirds of the diurnal cycle was sampled in one position with flow from the land. Figures 1 and 2 show that the sea-air temperature difference, wind speed, and heat fluxes are strong functions of time of day. The wind speed was lowest during the day when turbulent mixing over land retarded the wind, and increased rapidly in the evening. The sea-air temperature difference was largest in magnitude during the day also, because the air coming off the land was strongly heated. Its magnitude decreased slowly in the evening. The difference in rate of change of wind speed and temperature difference resulted in the maximum (negative) sensible and latent heat fluxes occurring in the early evening. Soundings at 2300 UTC 15 July and 1100 UTC 16 July (figure 3) show strong surface-based inversions, but the 2300 UTC sounding has an inversion strength of approximately 10° C over 100 m while the 1100 UTC sounding the next morning has a weaker (7° C) and shallower surface-based inversion with a layer of distinctly different (but still very stable) lapse rate above, from 50-250 m. Strong surface-based inversions 50-150 m deep are universal in all soundings taken in this region in summer when the flow is offshore.

---

* Corresponding author address: Wayne M. Angevine, NOAA Aeronomy Lab R/AL3, 325 Broadway, Boulder, CO 80304 USA; e-mail Wayne.M.Angevine@noaa.gov

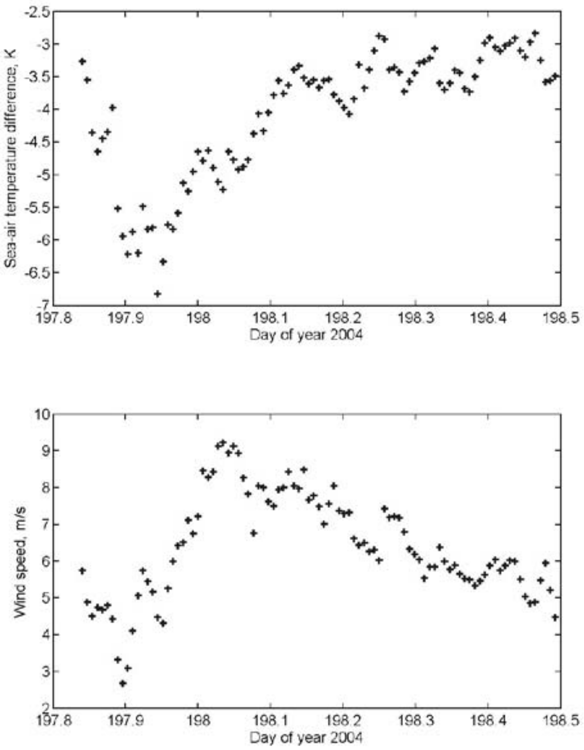

Figure 1: Sea-air temperature difference (upper panel) and wind speed (lower) measured on the ship from 2000 UTC 15 July through 1200 UTC 16 July.

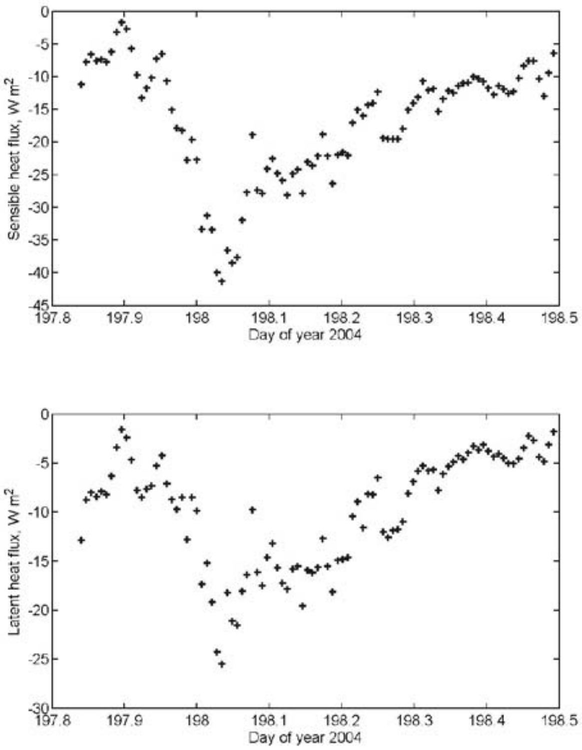

Figure 2: Sensible (upper) and latent (lower) heat fluxes measured by the gradient method on the ship from 2000 UTC 15 July through 1200 UTC 16 July.

On 30 July, the ship sampled a plume from Boston and vicinity at varying distances downwind of the sources. Carbon monoxide (CO), a reliable tracer of anthropogenic pollution, remained strong (250-300 ppb) all day. The strongest surface ozone of the entire experiment, approximately 105 ppb, was observed around 2000 UTC, well offshore and about 100 km downwind of Cape Ann. Four radiosondes were launched during the day, at 0500, 1100, 1700, and 2000 UTC. All four showed typical surface-based inversions. At 2000, the ship was in an area of somewhat warmer water (~19° C) than at other times of the day, when the water temperatures were 16-17° C. The near-surface air temperature was approximately 20.5° C, also at the warmer end of the range for the day. The inversion based at the surface and extending up to approximately 100 m had a magnitude of over 6° C. The sensible heat flux averaged for 2 h around the sounding time was -10 W m^{-2} . Similar averages around the other sounding times gave sensible heat fluxes of -7.5, -7.2, and -19 W m^{-2} . The latter, around 1700 UTC, was in a region near the Maine coast. No obvious dependence on downwind distance is apparent when examining the fluxes. The local wind speed was 5-7 m s^{-1} throughout the day. Trajectories computed using the operational mesoscale wind analysis (EDAS) show transport times from land (Boston vicinity) of approximately 7 hours for the 1100 and 1700 UTC sounding locations, and 12 hours for the 2000 UTC location.

3. DISCUSSION

We started with the question of how the stable boundary layer is formed after air leaves the coast. The answer depends on the time of day and therefore the relative temperature of air and water. If 15-16 July can be taken as paradigmatic, we see the following scenario. During the summer afternoon, the air coming off the land is substantially warmer than the water, so much so that the temperature difference between air at 2 m and water is as large as 6° C. The wind is fairly light, slowed by strong turbulent mixing over land. The temperature

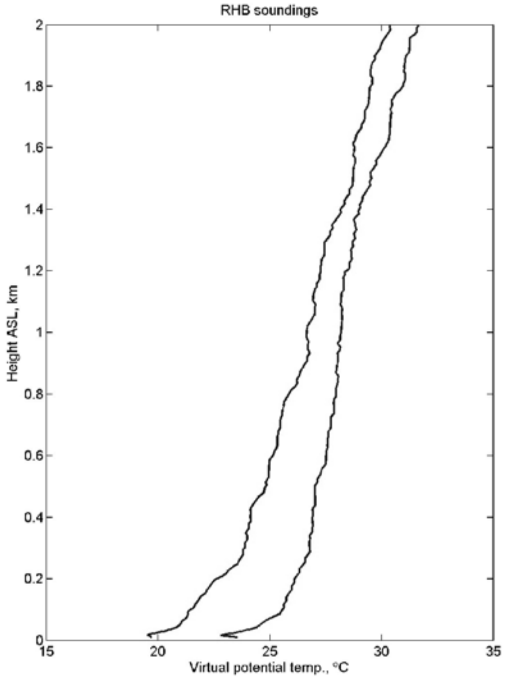

Figure 3: Soundings launched at 2300 UTC 15 July (warmer) and 1100 UTC 16 July (cooler) from the ship.

profile is neutral at the coast. The combination of strong temperature difference and light wind produces moderate negative heat flux, which in the absence of any other contributions would cool a layer roughly 100 m deep at approximately 0.3 degrees per hour. This is insufficient to explain the strong inversion observed in the 2300 UTC sounding if we assume that the locally observed wind speed governs the transport time from the coast. The wind speed at the coast could be substantially slower, but even half the speed give insufficient time.

Later in the evening, after turbulent mixing decreases, the wind speed increases rapidly but the air cools slowly. The increased wind speed combines with a still substantial air-sea temperature difference to produce a large (negative) heat flux. Finally, as the night goes on, the air-sea temperature difference decreases, the wind speed moderates, and the heat flux magnitude decreases.

At longer distances downwind, as on 30 July, the heat flux seems to depend primarily on the local water temperature. The varying ship positions, times of day, and transport times complicate interpretation. The rough similarity of soundings at all times and locations suggests that some combination of processes produces similar soundings regardless of the time of day that the air left the coast and the distance downwind. If we attempt to assume that the local heat flux and wind speed have prevailed since the air left the coast, we always find too little cooling to account for the inversion strength. However, if the transport time from the EDAS-based trajectories is used, the local cooling rate is consistent with the observed inversion strength.

A plausible scenario is the following: When the air is warmest (late afternoon), the heat flux and cooling rate just offshore are very large, supported by the large air-sea temperature difference and advected turbulence. By contrast, in the early morning, the air from the land surface is relatively cool and non-turbulent, and the heat flux is smaller. In other words, the flux near shore adjusts to whatever is needed to produce a roughly 100 m thick surface-based inversion layer within 10 km of the coast. The sea surface temperature and the temperature at the middle of the daytime boundary layer (say 1 km above ground) are both roughly constant during a synoptically undisturbed period. The result is a roughly constant inversion strength even at 10 km offshore.

This presents a difficult challenge for measurements and modeling. If most of the action that creates the inversion layer happens very near the coast, a model must be able to produce that layer in a few grid points even if it has grid spacing of order 1 km. It will also be difficult to make measurements in the region of strong heat flux and rapid inversion growth because the atmosphere will likely not be in local equilibrium and stationarity may not hold.

References

Angevine, W.M., C.J. Senff, A.B. White, E.J. Williams, J. Koermer, S.T.K. Miller, R. Talbot, P.E. Johnston, S.A. McKeen, and T. Downs, 2004a: Coastal boundary layer influence on pollutant transport in New England. J. Appl. Meteorol., in press.

Angevine, W.M., M. Žagar, M. Tjernström, C.J. Senff, and A.B. White, 2004b: Coastal boundary layer transport of urban pollution in New England. Preprints, 16th Symposium on Boundary Layers and Turbulence, Portland, Maine, 9-13 August 2004.