8.7 COASTAL BOUNDARY LAYER INFLUENCE ON POLLUTANT TRANSPORT IN NEW ENGLAND

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1. INTRODUCTION

Much of the air pollution in northern New England comes from sources near coasts and is transported along the coast, either over land or across the near-shore waters. Strong pollutant concentrations are transported in shallow layers near the cool sea surface. The New England Air Quality Study (NEAQS 2002) was conducted in July and August 2002. Many of the study sites and instruments, however, were active for a longer period. The core components of the study were four surface chemistry sites operated by the University of New Hampshire, six radar wind profilers and a Doppler lidar of NOAA, and the NOAA Research Vessel Ronald H. Brown. The Brown carried a suite of atmospheric chemistry instrumentation, a lidar measuring vertical profiles of ozone and aerosol, and a radar wind profiler; radiosondes were launched from the ship.

A previous field campaign in this area, the North Atlantic Regional Experiment 1993 Intensive (NARE 1993), explored many of these issues and produced extensive documentation. Angevine et al. (1996) give an overview of the mesoscale meteorological situation and the state of understanding of the coastal boundary layer that was then current. Ray et al. (1996) showed measurements from coastal Maine and described the circumstances leading to high ozone episodes there. Strong layering of the atmosphere caused by the cold water offshore was a theme of many of the papers, including those analyzing aircraft observations (Buhr et al. 1996; Daum et al. 1996; Kleinman et al. 1996).

Considerable work has been done since NARE 1993 on coastal, stable (nocturnal), and transitional boundary layers. For example, the Risø Air Sea Experiment (RASEX) data have been used to test and adapt the theoretical framework for stable boundary layers (Mahrt et al. 1998a, 2001). Long-term measurements in the Kattegat between Denmark and Sweden were analyzed by Sempreviva and Gryning (2000). Spatially resolved measurements of turbulence in flow of warm air over cold water at the coast of North Carolina were reported by Vickers et al. (2001). Aircraft measurements in the Baltic were reported by Källstrand et al. (2000) showing the behavior of the internal boundary layer in two cases; one with a stronger geostrophic wind and no sea breeze, and one with a sea breeze and weaker large-scale winds. Smedman et al. (1997) combined theory, modeling, and measurements to show a pattern of internal boundary layer development consisting of a stable layer at short overwater transport times followed by development of a near-neutral layer at longer transport times. A thorough discussion of offshore flow in general can be found in Mahrt et al. (2001). Žagar et al. (2003) give useful scaling arguments for fluxes near shore. The recent and ongoing Baltic Sea Experiment (BALTEX) (http://w3.gkss.de/baltex/baltex_home.html) is being carried out in that area, which has a similar situation to the east coast of the U.S.

Nocturnal boundary layers over land have features that are relevant to the coastal problem. Mahrt et al. (1998b) draw a distinction between weakly stable and very stable boundary layers and discuss the difficulties inherent in measurements and interpretation in very stable cases. These issues are explored further by Mahrt and Vickers (2002) using data from the Cooperative Atmosphere-Surface Exchange Site 1999 (CASES-99) experiment, which also yielded many other interesting results (Coulter and Doran 2002; Poulos et al. 2002). An interesting perspective on intermittent turbulence is provided by Van de Wiel et al. (2002). The afternoon transition from convective to stable boundary layer over land, which is analogous to the coastal transition, has been described by Grimsdell and Angevine (2002). Key findings are that the afternoon transition is a gradual reduction in the intensity and vertical extent of turbulence, not a sudden collapse, and that the transition begins as early as several hours before sunset.

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2. OBSERVATIONS

During pollution episodes, large-scale winds near the surface were from the southwest (Merrill and Moody 1996). Near-surface air temperatures were warmer over land than offshore at almost all times of day and night. Soundings from the ship just off the New Hampshire coast showed a statically stable layer near the surface (e.g. figure 1), a few tens of meters deep. The figure also shows the advected continental mixed layer, about 500 m deep at 1354 UTC and 1300 m deep at 2014 UTC. Profiles of bulk Richardson number (not shown) indicate that the shallow surface-based layer was dynamically unstable (very small or slightly negative bulk Richardson number). The turbulence produced by shear-driven instability allows for some of the mixing that cools the layer -- if no turbulence were present at all, the layer cooled by contact with the water would only be on the order of 1 m deep. During the night, the land-sea temperature difference is small, and the dynamically unstable layer deepens; during the day, the land-sea temperature difference increases, the static stability increases, but advected turbulence is available to enhance mixing. We cannot distinguish the effects of locally-produced shear-driven turbulence and advected turbulence with the data we have available.

Two major pollution episodes differed by the importance of mesoscale flow. On 22-23 July, the pollutants were transported by large-scale flow along the coast, having the greatest impact on coastal Maine. Model trajectories indicate that polluted air reaching the Atlantic near Cape Ann came along the urban corridor over several major source areas (Washington DC, New York City, and Boston) in the 24 hours previous to 1800 UTC on 23 July. This alignment of sources along the trajectories contributed to the large ozone mixing ratios and is part of the reason that they were localized along the coast north of Boston rather than inland. Transit times from Boston to the Isles of Shoals were approximately 2 hours throughout the episode, and transit times from the New York City area were approximately 12 hours. The winds as measured by profilers at Portsmouth and Isles of Shoals have interesting similarities and differences. The wind speed at Portsmouth below 1 km was near 10 ms^{-1}, and the wind speed at Isles of Shoals was consistently 3-4 ms^{-1} faster than at Portsmouth during the day. Wind directions were very consistent between the two sites except below 300 m. The wind direction profiles at Portsmouth at midday were nearly constant with height up to about 1.2 km, indicating a deep mixed layer, which does not exist at Isles of Shoals.

On 11-14 August, a sea breeze brought very polluted air inland to areas within 50 km of the New Hampshire coast. Winds during the most polluted period (12-14 August) were lighter than during the 22-23 July episode, but never fell below 2 ms^{-1} in the profiler observations (above 100 m AGL). Diurnal vector-averaged wind magnitudes were about 2 ms^{-1} at 150 m AGL on 14 August, the day of lightest overall winds, indicating that the airmass near and offshore was never stagnant but always had some net motion. Transport times from Boston are rather uncertain, but could have been a substantial fraction of a day, and transport times from other source areas were likely more than a day. The profiler observations show a sea breeze layer (southeasterly wind direction) of varying depth. The layer was only about 300 m deep at 1530 UTC when it was first observed at Portsmouth on 13 August and deepened to about 400 m by 1930 UTC. It was deeper on 14 August, approximately 600 m between 1500 and 1800 UTC, then shallower and less well-defined later in the day (figure 2). Surface observations and the timing of the ozone peaks at Thompson Farm (approximately 20 km inland) indicate that a sea breeze carried the ozone onshore. The sea breeze onset is clear in the meteorological measurements, especially wind direction, at Thompson Farm on 12 and 14 August but not as clear on 13 August. Surface winds inland were very light at night on 12 and 13 August. Trajectories derived from the Eta model analysis do not capture the sea breeze pattern.

To summarize, the coastal boundary layer influences pollutant transport in northern New England by producing thin, stable layers over water that carry pollutants, relatively undiluted and with minimal deposition, to distant (20-200 km) areas on other parts of the coast. The sea breeze modifies the large-scale flow to select the particular sites that receive polluted air. Layers that do not impact the coast again transport polluted air very long distances (200-2000 km).

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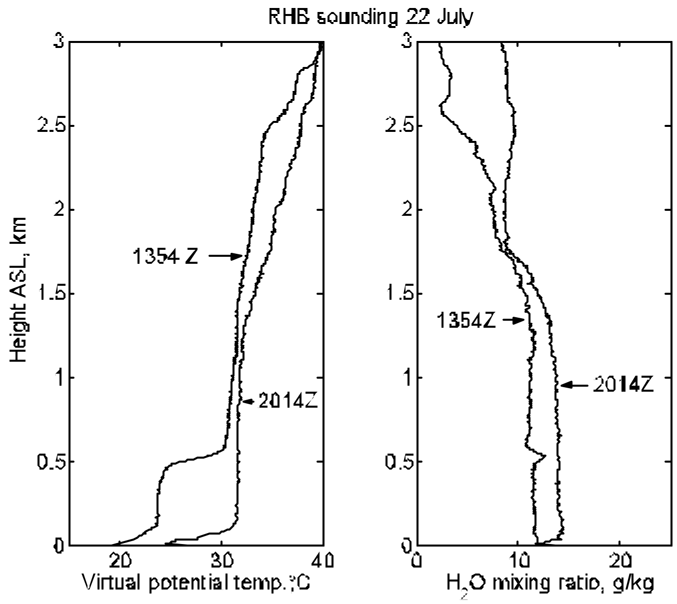

Figure 1: Potential temperature and water vapor mixing ratio from radiosoundings launched from the ship at 1354 UTC and 2014 UTC 22 July.

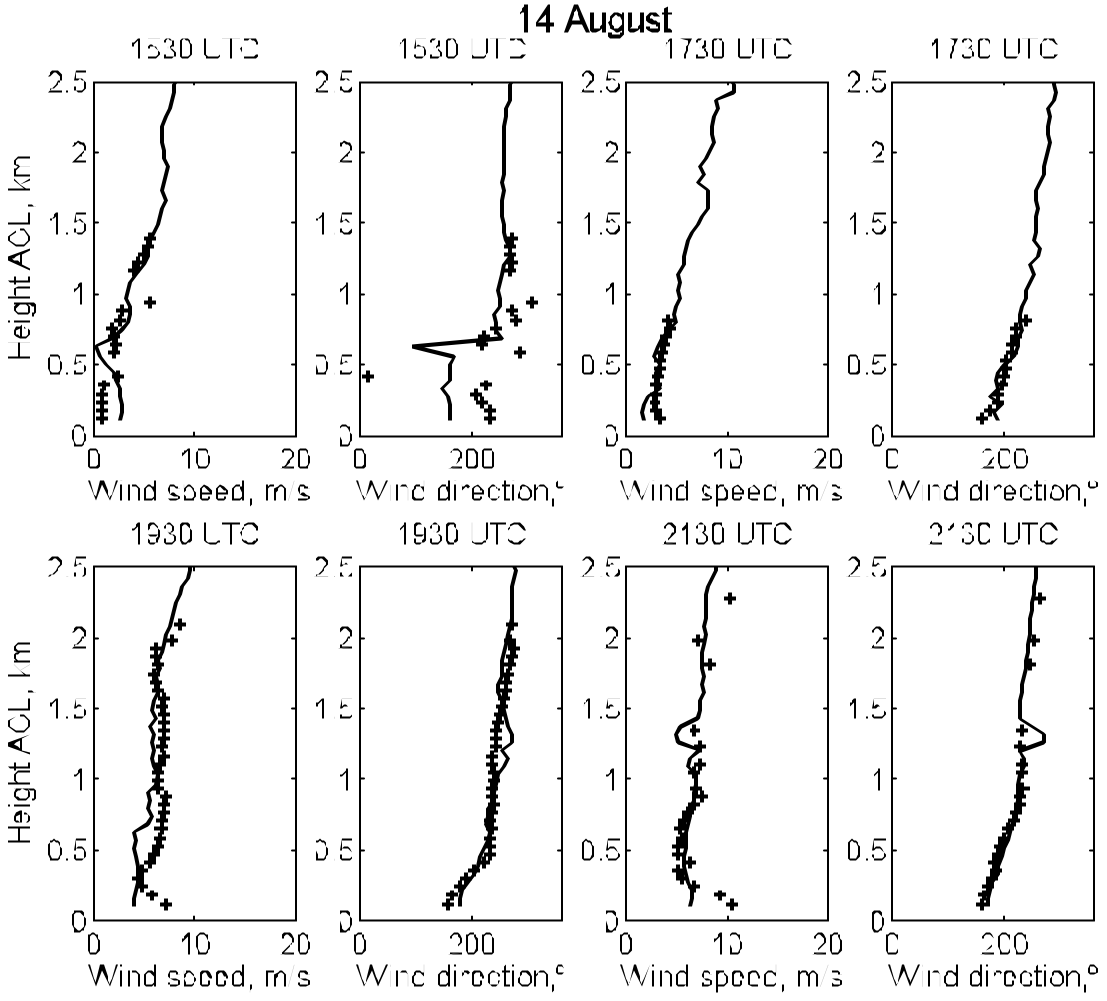

Figure 2: Wind speed and direction measured by wind profilers at Portsmouth (solid) and Isles of Shoals (plus signs) on 14 August showing the sea breeze development.