J1.5 COASTAL BOUNDARY LAYER TRANSPORT OF URBAN POLLUTION IN NEW ENGLAND

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1. INTRODUCTION

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. During pollution episodes, the air over land in daytime is warmer than the sea surface, so air transported from land over water becomes statically stable and separates into possibly several layers, each transported in a different direction. This presentation describes the atmospheric boundary layer processes involved in pollutant transport. Observations and a three-dimensional mesoscale model are used to examine two different cases, one dominated by large-scale transport (22-23 July 2002) and one with important mesoscale effects (11-14 August 2002). A detailed examination of the observations will be published as Angevine et al. (2004).

In both cases, the pollutants that affected coastal New Hampshire and coastal southwest Maine were transported over coastal waters in stable layers at the surface. These layers were at least intermittently turbulent, but retained their chemical constituents. The lack of deposition or deep vertical mixing on the overwater trajectories allowed pollutant concentrations to remain strong. The polluted plumes came directly from the Boston area. In the 22-23 July case, the trajectories were relatively straight and dominated by synoptic-scale effects, transporting pollution to the Maine coast. On 11-14 August, sea breezes brought polluted air from the coastal waters inland into New Hampshire.

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Why is overwater transport important? Why is it different than transport over land? In northern New England, air transported from land encounters a cooler, smoother surface; convective mixing therefore decreases. A persistent pool of cold water exists offshore in the northern and eastern Gulf of Maine and the Bay of Fundy, with warmer water inshore. Another factor is the lack of chemical deposition; ozone and most of its precursors are essentially not deposited to water surfaces, but are rapidly deposited to leaf surfaces. Finally, the reduction of convective mixing allows for differential advection, when polluted air at different heights is transported in different directions.

The New England Air Quality Study (NEAQS 2002) (http://www.al.noaa.gov/neaqs) 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 ship carried a suite of atmospheric chemistry instrumentation, a lidar measuring vertical profiles of ozone and aerosol, and a radar wind profiler. Scientific staff onboard launched radiosondes.

Ozone episodes in northern New England occur during periods of moderate synoptic forcing, as opposed to the more well-known situation of stagnation. The most prominent synoptic feature of all episodes is a low pressure system over northern Ontario and/or Quebec, producing the requisite southwesterly flow. Episodes are terminated by the passage of cold fronts associated with those lows.

2. CASE STUDIES

2.1 22-23 July

Trajectories computed from the wind profiler network data (figure 1) indicate that polluted air reaching the Atlantic near Cape Ann came along the urban corridor over major source areas including New York City and Boston in the 24 hours previous

Figure 1: Twelve-hour back trajectory at 300 to 400 m ASL ending at the position of the Ronald H. Brown at 1800 UTC on 23 July.

to 18Z on 23 July. These trajectories were calculated from a regional network of eight fixed, land-based wind profilers and a mobile wind profiler deployed on the RV *Ronald H. Brown*. The land-based wind profilers were located at Appledore Island, NH (ADI); Concord, NH (CCD); Orange, MA (ORE); Pease International Tradeport, NH (PEA); Pinnacles State Park, NY (PSP, location not shown in figure 1); Plymouth, MA (PYM); Rutgers University, NJ (RUT); and Schenectady, NY (SCH). The hourly wind profiler data were first averaged in the vertical between 300 and 400 m above sea level (ASL) and from these a weighted average of wind speed and direction was computed at the trajectory locations. The data from each individual profiler were weighted according to the inverse squared distance between the trajectory and the profiler location. These trajectories are generally consistent with trajectories computed from the operational Eta model (not shown). Surface winds were slightly more southerly than winds aloft throughout the episode. The alignment of sources along the trajectories contributes to the large ozone mixing ratios and is part of the reason that they are localized along the coast north of Boston rather than inland. Trajectories arriving off Cape Ann at times from 0300 UTC 22 July through the episode have similar directions. Transit times from Boston to the Isles of Shoals are approximately 2-3 hours throughout the episode, and transit times from the New York City area are approximately 12 hours.

Soundings from the RV *Ronald H. Brown* in the area between Cape Ann and Isles of Shoals at several times on 22 and 23 July showed a statically stable layer near the surface (figure 2), a few tens of meters deep. An advected continental mixed layer, up to about 500 m deep at 1354 UTC and 1300 m deep at 2014 UTC, lies above the stable marine layer. In the earlier sounding, a near-neutral residual layer with similar water vapor content extends to approximately 1.5 km, and a statically stable layer with decreasing water vapor lies atop that. In the later (2014Z) sounding, the transition between the advected mixed layer and the stable layer above 1.3 km is smooth, without a pronounced temperature inversion, and the transition is more easily seen in the water vapor profile. Profiles of bulk Richardson number (not shown) indicate that the shallow surface-based layer is dynamically unstable (very small or slightly negative bulk Richardson number). The basic structure shown in these soundings was quite typical; all soundings in offshore flow had surface-based statically stable layers.

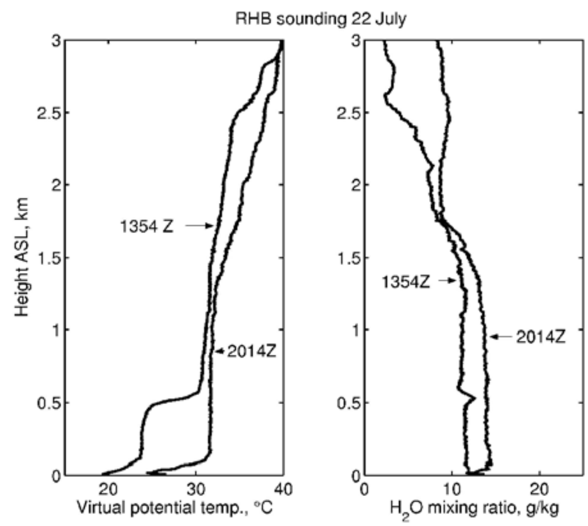

Figure 2: Potential temperature and water vapor mixing ratio from radiosoundings launched from the ship at 1354 UTC and 2014 UTC 22 July.

Three-dimensional numerical simulations were performed with the COAMPS version 2 atmospheric model, developed at the US Naval Research Lab, Monterey, CA (Hodur 1997). It is a primitive equation compressible Boussinesq model with terrain-following vertical coordinate. The turbulent kinetic energy is one of the prognostic variables and provides the input to the level 2.5 turbulence closure (Mellor and Yamada 1974). The diabatic part of the model includes explicit moist physics computation (Rutledge and Hobbs 1983) and at very high

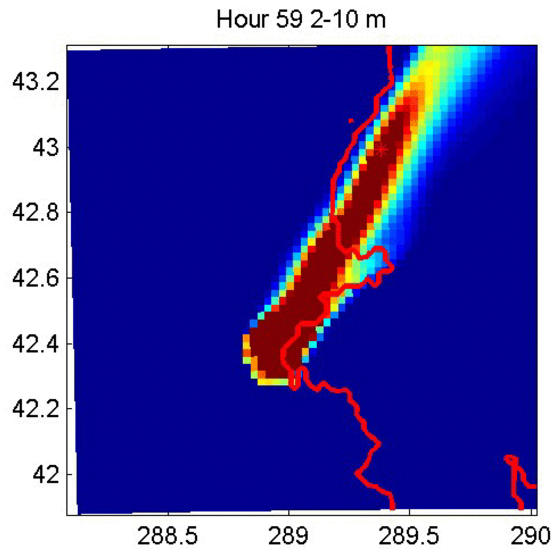

Figure 3: Top view of Boston tracer plume at 0600 EST (1100 UTC) 23 July.

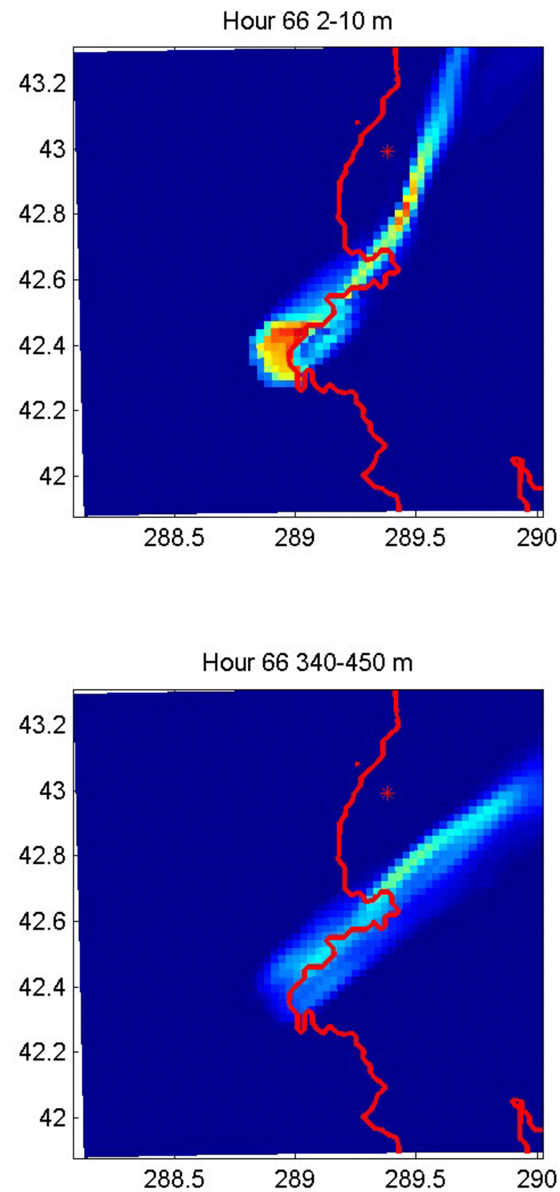

Figure 4: Top view of Boston tracer plume at 1300 EST (1800 UTC) 23 July.

resolution it effectively becomes a cloud-resolving model. Subgrid convection at coarser resolutions (greater than 10 km grid spacing) is parameterized using a version of the Kain-Fritsch flux scheme (Kain and Fritsch 1993). Transfer and absorption of radiation is treated as in Harshvardan et al. (1987). The ground surface temperature is computed taking into account different land classes with pre-defined albedo (for snow-free surface), while the soil moisture and water content are computed using a force-restore scheme. The initial and lateral boundary conditions in our simulations were provided using the ECMWF analyses and the Davies relaxation scheme (Davies 1976). Sea surface temperatures were also from the ECMWF analyses. Lateral boundary conditions were updated every 6 hours. No other data were assimilated. Consecutive static nesting was used in the simulations. Successive grids were at spacings of 67.5, 22.5, 7.5, and 2.5 km. The vertical resolution, on the other hand, did not change between the nests. Forty vertical levels were used in the simulations. They were very densely distributed in the planetary boundary layer (13 levels within the lowest 1 km, 5 within lowest 100 m, the two lowest levels at 1 m and 5 m above surface). Land use data was from the

United States Geological Survey database at 1 km resolution, and terrain height from the (U.S.) National Imagery and Mapping Agency Digital Terrain Elevation Data level 0, also at 1 km resolution. For the 23 July results shown, the model was initialized at 0000 UTC 21 July. For the 14 August case, initialization was at 0000 UTC 11 August.

A tracer was emitted from the Boston area. The tracer was emitted in the three lowest model levels (at 1, 5, and 17 m AGL) at the constant rate of 2 units per time step over the area classified as urban land use, and at 1 unit per time step in a ring of 1 grid box around that area. No deposition or reactions affected the tracer.

Plots of the tracer plumes from COAMPS are our primary tool for displaying the transport phenomena. Figure 3 shows plan views of the plume at two levels for 0600 EST (1100 UTC) 23 July. The tracer emitted from Boston has been blown to the northeast directly over Isles of Shoals after leaving the land northwest of Cape Ann, the prominent cape at approximately 42.6°N, 289.5°W. Having been emitted into the nocturnal boundary layer, the plume is less than 300 m deep. It does not come ashore again within the 2.5 km domain, but is headed for the coast of Maine. Later in the day (figure 4), the plume is deeper, up to 800 m, and therefore less concentrated. At the surface, it does not precisely hit Isles of Shoals (as it did in reality) because the model wind direction is slightly too westerly. At a higher level, the plume has moved more to the east. This type of wind shear with height was very

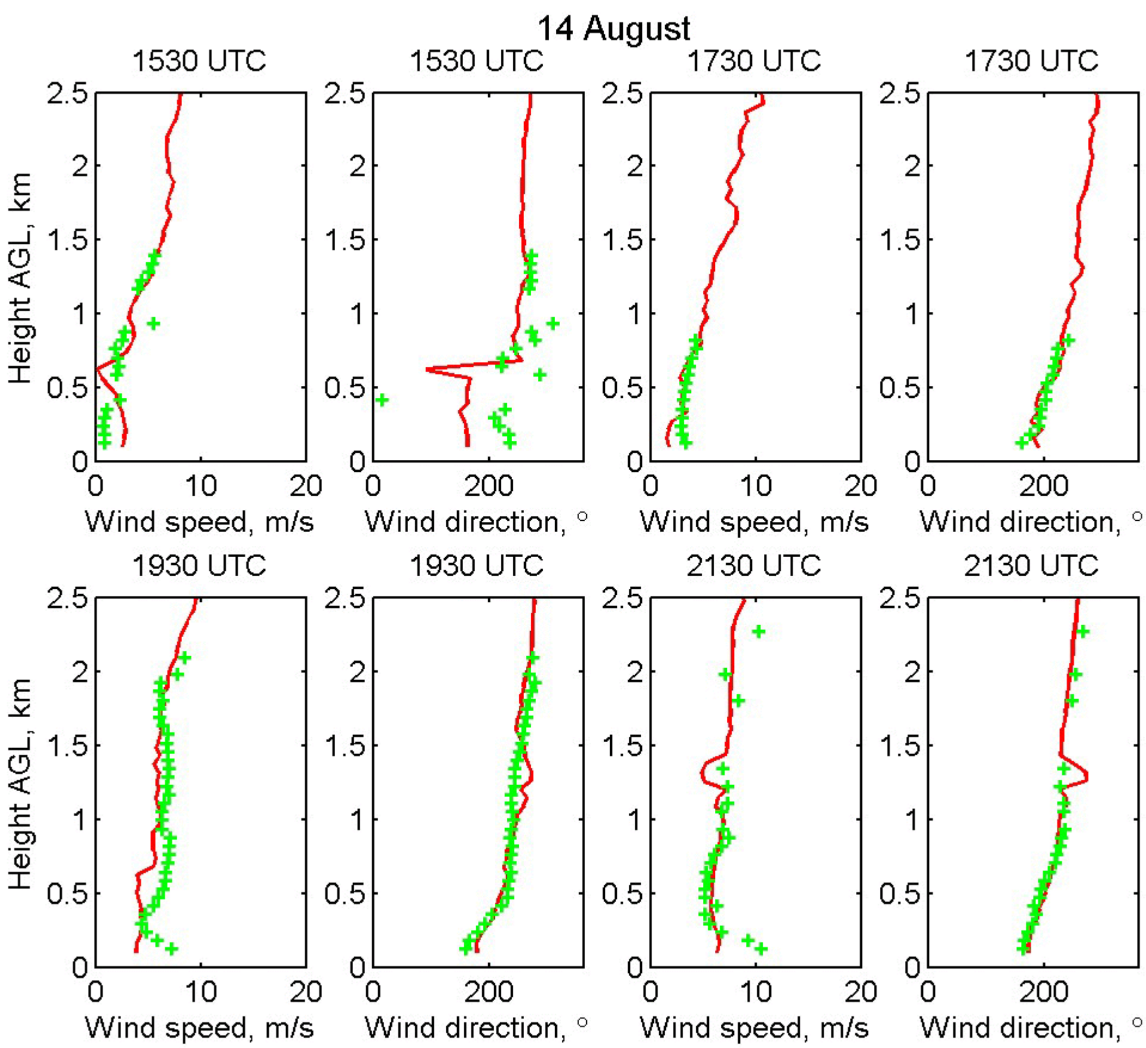

Figure 5: Wind speed and direction measured by wind profilers at Portsmouth (solid red) and Isles of Shoals (green plus signs) on 14 August showing the sea breeze development.

common during southwesterly flow.

2.2. 11-14 August

Surface observations and the timing of the ozone peaks at Thompson Farm indicate that a sea breeze carried the ozone onshore during this episode. The sea breeze onset is clear in the meteorological measurements, especially wind direction, at Thompson Farm on 11, 12 and 14 August but not as clear on 13 August. Surface winds inland were very light at night on 12 and 13 August.

The profiler observations show a sea breeze layer (southeasterly wind direction) of varying depth during the days. The layer is only about 300 m deep at 1530 UTC when it is first observed at Portsmouth on 13 August and deepens to about 400 m by 1930 UTC. It is deeper on 14 August, approximately 600 m between 1500 and 1800 UTC, then shallower and less well-defined later in the day (figure 5).

The Boston tracer plume in the model at 1000 EST (1500 UTC) in the morning of 14 August (figure 6) looks rather similar at the surface to that seen on 23 July (figs. 3 and 4 above). The flow overnight and into the morning hours was southwesterly as on 23 July, although somewhat weaker. By 1600 EST (2100 UTC) in the afternoon, however, the plume looks completely different (figure 7). Near the surface, the plume is now inland, impacting areas in New Hampshire including Thompson Farm. Note that the tracer plume should not be interpreted as a trajectory; in fact, the trajectory of the air reaching Thompson Farm at the surface goes from Boston out to sea, then turns and comes inland on the sea breeze (not shown). At higher levels, the tracer plume continues to move to the northeast over the water. The sea breeze layer is 300-400 m deep, consistent with the observed winds. The cool sea breeze layer has apparently not been subject to deep convective mixing while moving inland over the warm land, probably because it came inland late in the day.

3. DISCUSSION

In the episodes examined above, transport of polluted air to coastal New Hampshire and coastal southwest Maine occurred in a layer in contact with the surface. The lowest portion of this layer was turbulent despite being strongly statically stable. It was evidently turbulent because it cooled during the transport; without turbulence there would have been little or no cooling. The transport was definitely not isentropic, as assumed by Angevine et al. (1996) and Dye et al. (1995). The fact that the layer contained large pollutant concentrations justifies the assumption of Lagrangian transport, that is, the cooling could not have been due to temperature advection. The polluted layer was 400-600 m deep in both cases studied. The turbulently cooled portion of the layer was less than 100 m deep in the 22-23 July case where we have vertical profiles.

There were other layers, equally or more polluted, above the surface. They affected areas of the coast farther northeast, such as Acadia National Park, and contributed to long-range transport.

To summarize, the coastal boundary layer influences pollutant transport in northern New England by allowing for 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. Elevated layers transport polluted air very long distances (200-2000 km).

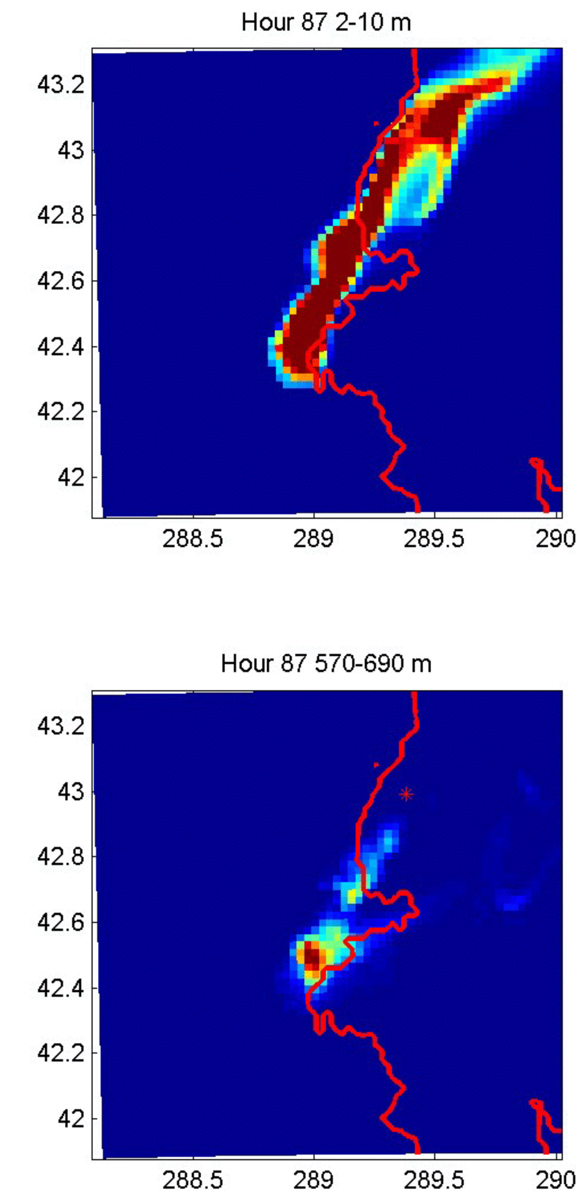

Figure 6: Top view of Boston tracer plume at 1000 EST (1500 UTC) 14 August.

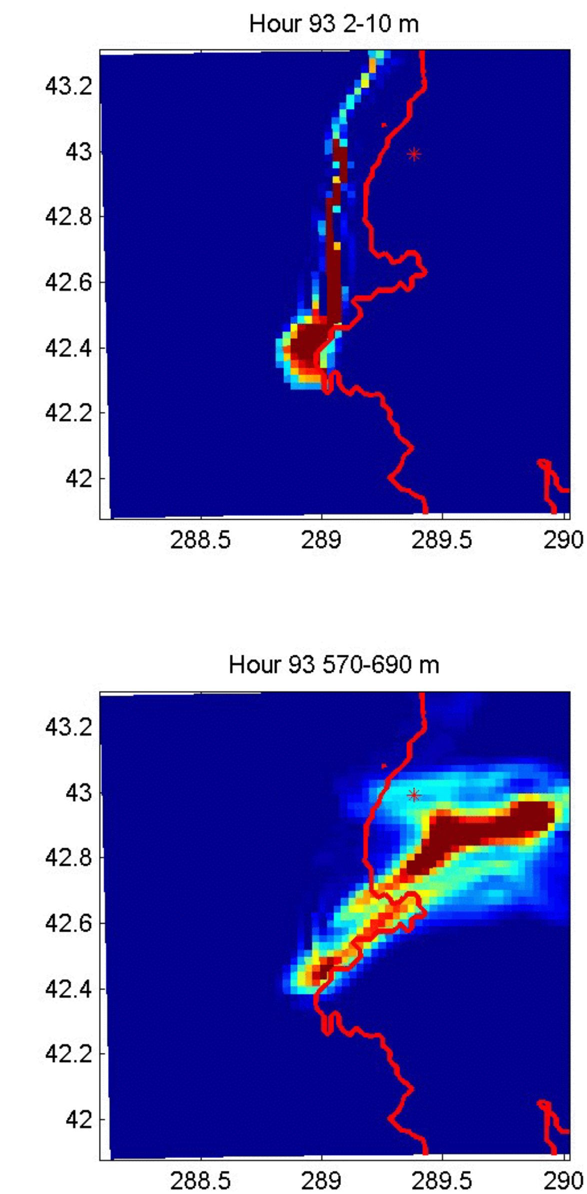

Figure 7: Top view of Boston tracer plume at 1600 EST (2100 UTC) 14 August.

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