APPLICATION OF AIRBORNE AND SHIP-BASED LIDARS FOR CHARACTERIZING TRANSPORT AND MIXING OF OZONE OVER THE COLD OCEAN

R. Michael Hardesty[1,2], Christoph J. Senff[2], W. Alan Brewer[1], Raul J. Alvarez[1], Scott P. Sandberg[1], Sara C. Tucker[2], Janet M. Intrieri[1], Robert M. Banta[1], Lisa S. Darby[1]

[1]NOAA/ESRL Chemical Sciences Division
[2]Cooperative Institute for Research in Environmental Sciences, University of Colorado
325 Broadway, Boulder, CO 80305 USA, Email: mike.hardesty@noaa.gov

ABSTRACT

An airborne ozone lidar and shipboard Doppler lidar were applied during summer 2004 to study ozone production over Boston and plume transport along the New England coast. Estimates of ozone production agreed reasonably well with model predictions. A probable vertical mixing event over the Gulf of Maine was identified, in which high ozone air from aloft was mixed down to the surface by turbulence. Observations confirmed that once over the ocean pollution can be transported within thin layers over significant distances.

1. INTRODUCTION

The New England region of the United States is often plagued by poor air quality during the warm summer months. Most air quality pollution events during this period are associated with transport of polluted air from the large urban areas along the Atlantic coast by weak southwesterly flow associated with the frequently-occurring Bermuda high. During such events, pollution levels can reach high levels even in areas, such as coastal Maine, that are well-separated from major sources of pollutants.

Forecasting air quality events and concentrations in these regions can be particularly challenging because the plumes are often advected directly along the coast. The New England coast is an area of high horizontal thermal contrast because cold ocean temperatures are directly adjacent to warmer land surface temperatures. When a plume is transported from the land into the stable atmosphere over cold water, it may be distributed into layers which become decoupled from other parts of the plume and independently transported. Under such conditions, knowledge and understanding of both horizontal transport and vertical mixing processes is essential for accurate forecasting of local air quality.

During the summer of 2004 we deployed an ozone and aerosol profiling lidar system on an aircraft, as well as ozone and Doppler lidars on a NOAA research vessel, to study mixing and transport processes as part of the International Consortium for Atmospheric Research on Transport and Transformation (ICARTT). This paper presents estimates of ozone production as a pollution plume passed over Boston, illustrates the transport of pollution over the cold ocean, and describes an event in which an increase in turbulent mixing in the marine boundary transported high ozone levels to the surface.

2. INSTRUMENTATION

The NOAA UV Airborne Ozone DIAL [1] instrument was deployed on a DC-3 aircraft during ICARTT to measure ozone and aerosol profiles in the boundary layer and lower troposphere. In order to characterize the fine-scale structure and evolution of plumes, the lidar returns were processed to provide horizontal resolution of 600 m and vertical resolution of 90 m. Precision of the measurements ranged from 5-15 ppb, depending on the total optical depth between the aircraft and the specific range gate.

Along with the airborne DIAL, we also deployed the NOAA High Resolution Doppler Lidar (HRDL [2]) and the NOAA Ozone Profiling Atmospheric Lidar (OPAL [3]) on the NOAA research ship Ronald H. Brown to investigate the structure of ozone, aerosol, and winds over the cold ocean. The lidars operated in a scanning mode to produce high vertical resolution profiles, which provided context for the numerous onboard *in situ* measurements of meteorological, chemical and aerosol parameters.

The ICARTT observational network included wind profiling radars deployed at several locations across New England and on the Ron Brown. For ICARTT we developed and applied an analysis tool to incorporate data from the profiler network, along with buoy data over the ocean, to compute both back- and forward-trajectories from specified locations. This was very useful in identifying source locations and analyzing plume transport.

3. OZONE PRODUCTION OVER BOSTON

On July 30, a large region of high ozone originating south of New England advected northward over Boston

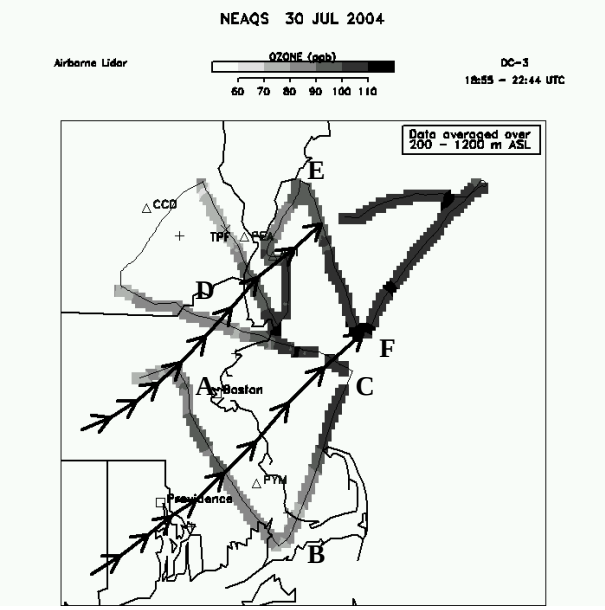

Fig. 1. Flight track of DC-3 on July 30, showing average ozone concentration between 200 and 1400 m. Back trajectories from leg EF are shown, each arrow signifies one hour of transport.

and then out over the Gulf of Maine. Fig. 1 shows the flight track of the DC-3 for that day, along with average ozone concentration computed over the layer between 200 m and 1200 m ASL. Also shown are trajectories computed from the wind network. Each barb represents one hour of advection. The trajectories indicate that wind speed and direction were relatively constant during the flight and that the plume passed directly over Boston. Because the flight legs appeared to cross the plume roughly orthogonal to the flow both upwind and downwind of Boston, we computed the average ozone concentration measured across each of 3 flight legs between the two trajectory tracks, shown as AB, CD, and EF on the figure, in an attempt to quantify ozone production as the plume passed over Boston. We then applied interpolated wind speed data from the wind profiler network to estimate the ozone flux across each of the three legs.

Table 1 shows the results of our flux calculations for the three legs. Also shown in the table are the 36-hour forecasts of ozone concentration and ozone fluxes for each leg computed using the Community Multiscale Air Quality/ETA (CMAQ-ETA) forecast model, one of several air quality forecast models tested during the 2004 study.

Both lidar and model results indicate increased ozone concentrations and fluxes downwind from Boston, as are also evident in Fig. 1. The apparent decrease in flux density observed along Leg CD of the lidar measurements is somewhat puzzling. As can be seen in Fig. 1, the highest concentrations downstream of Boston

Table 1: Lidar estimates of ozone concentration upwind and downwind of Boston on July 30, compared with CMAQ/ETA 36-hour forecast

	Concentration $*10^{18}$ mol m^{-3}		Flux density $*10^{19}$ mol m^{-2} s^{-1}	
	Lidar	Model	Lidar	Model
Leg AB	2.11	1.96	2.0	2.52
Leg CD	2.19	2.2	1.8	2.80
Leg EF	2.45	2.0	2.1	2.65

seem to be slightly offset from the paths defined by the trajectories. This is also observed in Fig. 2, which shows the time-height ozone cross-section for the flight.

The apparent shift in plume position may be due to errors in the wind field introduced by interpolation across the profiler network. Another possibility is that inhomogeneities were present in the plume in the along-wind direction, such that the concentrations sampled by the lidar on the upwind legs were not consistent with plume characteristics a few hours earlier, when the air sampled on the downwind legs passed through leg AB. Also, the data are somewhat more sparse along leg CD (see Fig. 2), increasing the possibility of sampling error. Despite the questions, these data indicate that lidar estimates of ozone production over large source regions should be useful, given more careful flight planning and better estimates of wind fields.

4. VERTICAL MIXING OVER THE OCEAN

Because of the stable boundary layer present over the cold ocean off New England, sharp gradients associated with layering in the vertical structure of pollution can exist near the surface. Under such conditions, strong turbulence-induced vertical mixing can potentially

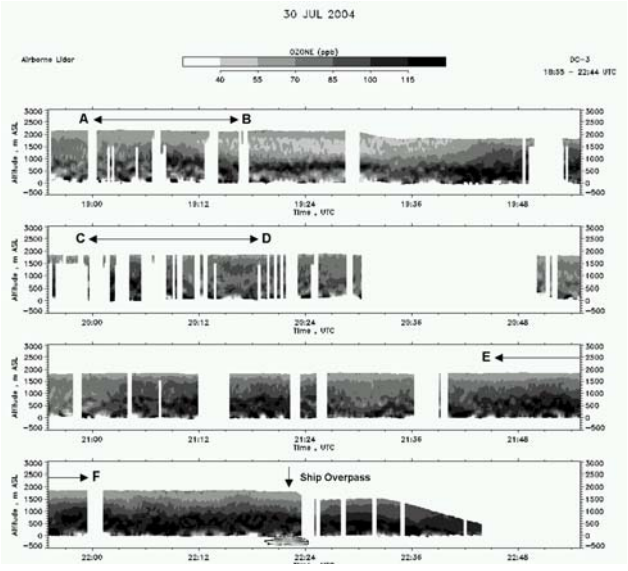

Fig. 2. Time-height cross section for flight of July 30, showing flux legs and Ron Brown overpass.

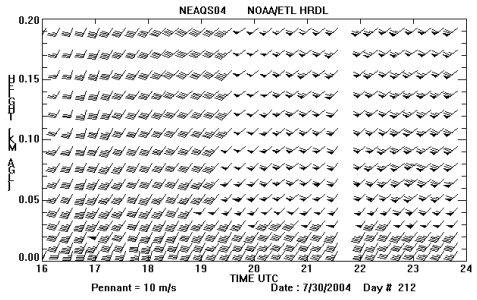

Fig. 3. Low level winds measured by Doppler lidar from the Ron Brown showing increase in shear during the ozone mixing event.

result in rapid changes in pollution levels measured at the surface as dirty air is mixed into clean air (or vice-versa). One apparent example of such an event is seen in airborne and ship data from July 30. On this day, sensors on the Ron Brown measured a sudden sharp increase in ozone at around 2000Z while steaming eastward across the Gulf of Maine, approximately 60 miles off the New Hampshire coast. Trajectory analyses did not trace this area of high surface ozone, which exceeded 100 ppbv, back to an obvious ozone source; however measurements from the airborne ozone lidar indicated an extended deep layer of high ozone, extending from roughly 1500 m to just above the surface (Fig. 2.). Temperature soundings from the ship showed strong stability in the boundary layer prior to the high ozone event on July 30, which likely inhibited mixing of the elevated high ozone air. However, coincident with the ozone increase, the ship entered a region of higher sea surface temperatures, which likely decreased stability in the layers near the ocean.

Stability also decreased at this time as a result of an increase in wind speed in the layer beginning at 50 m above the surface. Fig. 3 shows a time height sequence of low level wind velocities measured by the Doppler lidar from the deck of the Ron Brown at the time that the high ozone concentration was observed. The profiles, obtained by processing very low angle conical scans, show that the winds above 50 m increased sharply beginning at about 2000Z, roughly coincident with the beginning of the high ozone event. We hypothesize that the resulting increase in shear, in combination with the increase in sea surface temperature, initiated turbulent mixing between the elevated ozone layer and the surface, leading to the rapid increase in surface ozone. Fig. 4 shows profiles of gradient Richardson number Ri, an indicator of dynamic stability and the formation of turbulence, computed from a temperature sounding at 0000Z and the lidar-measured wind profile. Flow becomes dynamically unstable and turbulent when Ri falls below a critical

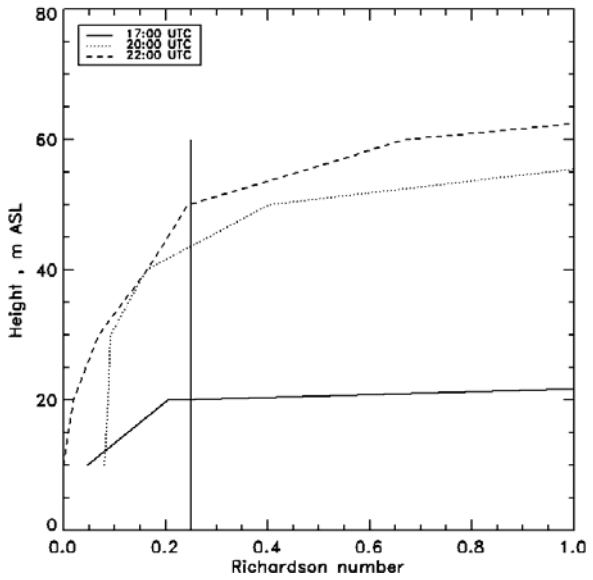

Fig. 4. Richardson number profiles computed from lidar winds and ship soundings during July 30 mixing event.

value Ri_c, which is typically about 0.25. Fig. 4 shows that the height at which $Ri<Ri_c$ increased to about 50 m as shear increased over the period, which likely enhanced downward mixing of ozone from the elevated layer that was present just above the surface.

Downward mixing of ozone over the Gulf of Maine has little impact on the general population, However, once pollution makes its way to the surface it can be transported toward the coast and reduce air quality for nearby residents. This appeared to be the case for the July 30 downward mixing event. Forward trajectories computed from the location of the Ron Brown indicated that the ozone was transported toward Portland, Me., where localized high ozone levels were reported.

5. POLLUTION TRANSPORT ALONG THE MAINE COAST FROM BOSTON

Air quality along the coast of Maine is also affected by transport over the water of pollution from Boston and beyond. As noted earlier, when a plume is transported within the stable atmosphere over the water, vertical mixing is minimized and concentrations can remain high for extended distances. Such was the case on August 3, 2004, when an extended offshore plume parallel to the coast was predicted by the CMAQ/ETA model. The DC-3 flight plan for that day was designed to cross the coast at several locations extending to beyond Bar Harbor, in order to examine the differences in the structure of the plume over land and water.

Fig. 5 shows a 3-dimensional cross section of the lidar measured ozone profiles along the coast. Low ozone

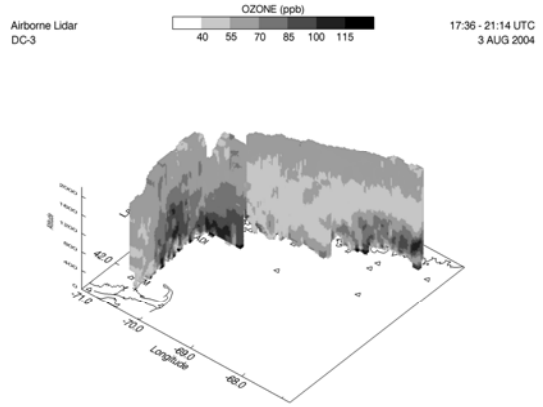

Fig. 5. Flight track for August 3 showing high ozone concentrations near Bar Harbor and Portland, Me.

levels were measured by the plane as it flew northward until it arrived just east of Bar Harbor, where a layer of high ozone concentrations extending from the surface to approximately 500 m was observed. Surface ozone readings above 80 ppb were measured at an elevated site on Mt. Desert Island, near Bar Harbor, at this time. Given the forecast and the lack of observed ozone in the area southwest of Bar Harbor, this elevated ozone reading was initially somewhat puzzling - where did this ozone come from? Trajectory analyses (Fig. 6), provided an apparent answer, indicating that the ozone observed at Bar Harbor likely was a shallow portion of the previous day's plume from Boston, which had been advected well off the coast before its arrival at Bar Harbor and was not well represented in the CMAQ/ETA forecast.

As the aircraft turned and returned to the southeast, ozone levels again dropped until the vicinity of Portland, when a shallow layer with high ozone concentrations, similar to that encountered at Bar Harbor was observed. The trajectory analysis (Fig. 7) indicated that this was the current day's Boston plume, consistent with the forecast, which had also traveled over the water before coming ashore. As the plane continued south, closer to Boston, the high-ozone layer deepened as the Boston plume was observed closer to its source region with less over-water transport.

For all flights during ICARTT we compared lidar observations of ozone vertical structure with the 36 hour ozone forecasts from the CMAQ/ETA model. The lidar observations provide significantly more information than surface station readings for assessing model performance in that they show such features as vertical distribution and plume dimensions. Direct comparisons showed mixed results; the model typically represented general features quite well, but often erred on such features as plume location and depth.

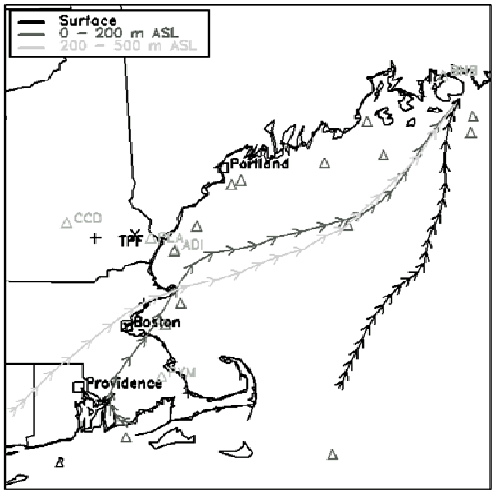

Fig. 6. 24-hour back trajectories for plume observed near Bar Harbor, Me. on August 3.

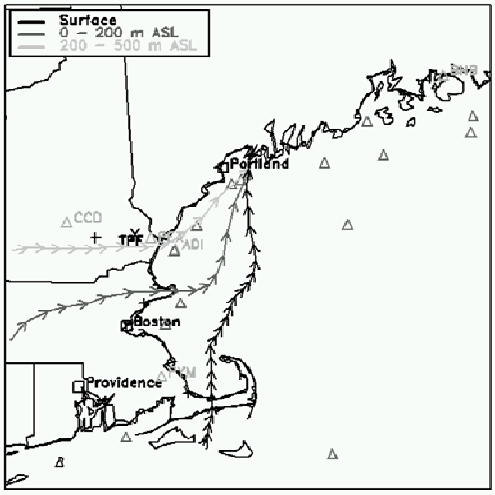

Fig. 7. 24 hour back trajectories for plume observed near Portland, Me., on August 3.

6. FUTURE PLUME TRANSPORT RESEARCH

During late summer 2006, we will deploy ozone and Doppler lidars to investigate local and regional air pollution in the Houston, Texas, area. A new solid state transmitter will replace the current excimer laser in the airborne instrument for the Houston study. Doppler and DIAL lidars will again be mounted on the Ron Brown, which will operate in the Gulf of Mexico, Galveston Bay, and the Houston ship channel during the campaign.

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