J3.6 SHIP-BASED LIDAR MEASUREMENTS OF NOCTURNAL MEAN WINDS, MIXING HEIGHT AND BOUNDARY LAYER DYNAMICS AND CORRELATION TO HOUSTON OZONE MEASUREMENTS DURING TEXAQS II

Sara C. Tucker*[1,2], Wm. Alan Brewer[2], Janet L. Machol[1,2], Robert M. Banta[2], Christoph J. Senff[1,2], Wayne M. Angevine[1,2], Eric J. Williams[1,2], Brian M. Lerner[1,2], and R. Michael Hardesty[2]

[1]Cooperative Institute for Research in Environmental Sciences, University of Colorado at Boulder;
[2] NOAA Earth System Research Laboratory, Boulder, Colorado

1 Introduction

During the 2006 intensive operating period of the Second Texas Air Quality Study (TexAQS 2006), NOAA's Earth System Research Laboratory deployed a suite of air-quality research instruments on the research vessel Ronald H. Brown. From August 1 to September 11, 2006, the ship traversed areas that included the Houston Ship Channel, Galveston Bay, and the Gulf of Mexico. From the aft deck of the Brown, NOAA's High Resolution Doppler Lidar (HRDL) performed continuous scanning measurements of boundary-layer winds and relative aerosol backscatter. The lidar data were used to derive 15-minute profiles of boundary layer horizontal mean wind speed and direction, velocity variance σ_V^2, and uncalibrated aerosol backscatter, from the surface up through the top of the aerosol boundary layer. The HRDL data also provide information about coastal boundary layer dynamics, including low level jets (LLJ), shear, turbulence strength, and boundary layer mixing heights (MH).

Visual observations of the lidar data acquired when the ship was near Houston revealed that the presence of strong, nocturnal Deep, Southerly Low Level Jets (DSLLJ) extending to altitudes of 1km or more correlates with low ship-measured ozone levels at the time of the jet and during the following afternoon. When the nighttime jet winds were weaker and/or shallower (i.e. under 600 m), wind speeds tended to be lower the following afternoon, and peak ozone values were correspondingly higher. The objective of this short study is to understand the relationship between the DSLLJ, ozone and ozone precursor concentrations during the night, and peak ozone concentrations the following day.

*Corresponding author address: Sara C. Tucker, NOAA CSD3, 325 Broadway, Boulder, CO, 80305. 303-497-4684; e-mail: sara.tucker@noaa.gov

2 Instrumentation

HRDL is a 2 µm wavelength Coherent Doppler lidar that provides half-second updates of line-of-sight wind velocity estimates with 30 m range resolution and 20 cm/s velocity precision. The maximum range is 2-8 km, depending on scan geometry and aerosol conditions. HRDL's motion-compensated full-hemispherical scanning capability allows implementation of conical azimuth scans at various elevations, vertical-slice (elevation) scans, and zenith stares, in order to acquire data for the aforementioned profiles.

During the 42 day ship-based portion of TexAQS 2006, Houston's ozone network detected nine days that had an 8-hour ozone exceedence of the 84 ppbv National Ambient Air Quality Standard. For the rest of this study period, hourly averaged ozone concentrations in the Houston network, and on the ship, showed maxima between 30 and 75 ppbv. In addition to ozone, the quasi-conserved (on short time-scales) summation $Ox = O_3 + NO_2$ is used here to separate the effect of local source titrations from meteorological influences.

Most of the comparisons in this study are between HRDL horizontal mean wind profiles and in-situ ozone or Ox measured when the ship was at one of two ship locations: Barbour's Cut (at the north end of Galveston Bay) and the Houston Ship Channel. Both of these locations are close to Houston and experience land influences. Barbour's Cut is close to the shores of Galveston Bay and is thus an ideal location for high temporal and vertical resolution observations of sea breeze or bay breeze cycles generated by the contrast between land and water conditions (Nielsen-Gammon[1] 2002; Banta[2] 2005; Darby[3] 2005).

3 Meteorology and ozone in Houston

Some of the effects of meteorological conditions on high-pollution events in the Houston area have been well described in Banta et. al. (2005) where the authors presented a case-study of a high-pollution event observed during TexAQS 2000. Darby (2005) presented a thorough analysis of the surface winds and their impact on ozone levels in Houston during the same 2000 study. Both papers note that high ozone days typically displayed periods of offshore flow, followed by stagnant conditions in the mid-day to mid-afternoon, and then a sea breeze. Nielsen-Gammon (2002) discussed the role of the LLJ in the nighttime dispersion of the Houston plume as well as its relationship to the sea breeze. The author also mentions the role of the balanced relationship between the coastal diurnal oscillation and the Bermuda high in causing the stagnation events which lead to high ozone episodes. Based on mesoscale pressure maps, one finds that the nocturnal LLJ forms when the Bermuda high dominates the coastal diurnal oscillation and the post-sunset changes in convective turbulence lead to frictional decoupling, allowing the jet to form and grow.

4 Ship-based observations: TexAQS 2006

Using the HRDL mean wind profile data, those days in August and September that exhibited strong winds (> 8 m/s peak) with a jet shape between 0 and 12 UTC (1900 to 0700 LST) were selected. These days are listed in Table 1. Note that all these DSLLJ events took place in August. By September, most of the jet-like events were weaker, shallower, and less likely to have a southerly component.

Most of the DSLLJs reached “peak” speeds of between 9 and 13 m/s, and their vertical extent was typically about 1500 m. An example of the wind speed profiles from one of the DSLLJ, observed while the ship was in the Houston Ship Channel after 0300 UTC on 13 August, is shown in Figure 1. Note the high wind speeds in yellow, above low (1-3 m/s) surface wind speeds. Ozone and Ox are both plotted on the mean wind direction display; and mixing height and Ox are both plotted on the velocity variance display. The black line on the speed profile plot indicates the solar flux.

The DSLLJ events had the following characteristics in common:

- They were usually southerly (moving from southwesterly to southeasterly throughout the night) winds extending from near the surface up to 1000-1800 m, with peak speeds between 9 and 13 m/s.
- During the jets the strong shear near the surface induces mechanical turbulence that forms a shallow mixing layer of 150-250 m depth, as observed in the HRDL turbulence profiles like those shown in Figure 1 and discussed in Tucker et. al.[4]
- On average the shear-induced turbulence at the surface during DSLLJs was stronger than surface-turbulence on weak jet nights or nights without a jet.
- Ship-measured in-situ ozone and Ox concentrations were very low at these times, and tended to remain low the rest of the day.
- Surface horizontal mean wind speeds were not necessarily higher than on weak jet nights or nights without a jet.

Table 1. UTC Days that started with a deep southerly nocturnal low-level-jet

Date	Peak jet speed (m/s)	Peak ship ozone (ppbv)	Peak Houston ozone (ppbv) and location
8/3	9.7	20	70 – Conroe
8/11	10.2	50	66 – Conroe
8/12	11.2	25	51 – Conroe
8/13	10.0	20	48 – Conroe
8/14	9.1	30	73 – Crosby Library
8/15*	9.2	59	98 – Wallisville Rd
8/26	11.1	30	32 – Kingwood Library
8/27	12.7	25	36 – Conroe, Atascocita, and Bunker Hill
8/28	11.1	20	47 – Atascocita

*August 15 demonstrated a fairly strong peak speed in the jet, but with a maximum height below 500 m. Therefore, it is not included among the DSLLJ events used in this analysis.

Figure 2 (top) shows a scatter plot of nocturnal Ox concentration versus wind speed measured near the surface. Data points are colored according to whether or not there was a DSLLJ observed during the night (i.e. between 1900 and 0700 LST). The plot does not demonstrate a strong relationship between Ox levels and surface mean wind speeds. Plotting surface ozone versus average horizontal mean wind speed for a higher altitude bin (i.e. 650-700m AGL), however, does demonstrate a clearer relationship (bottom of Figure 2).

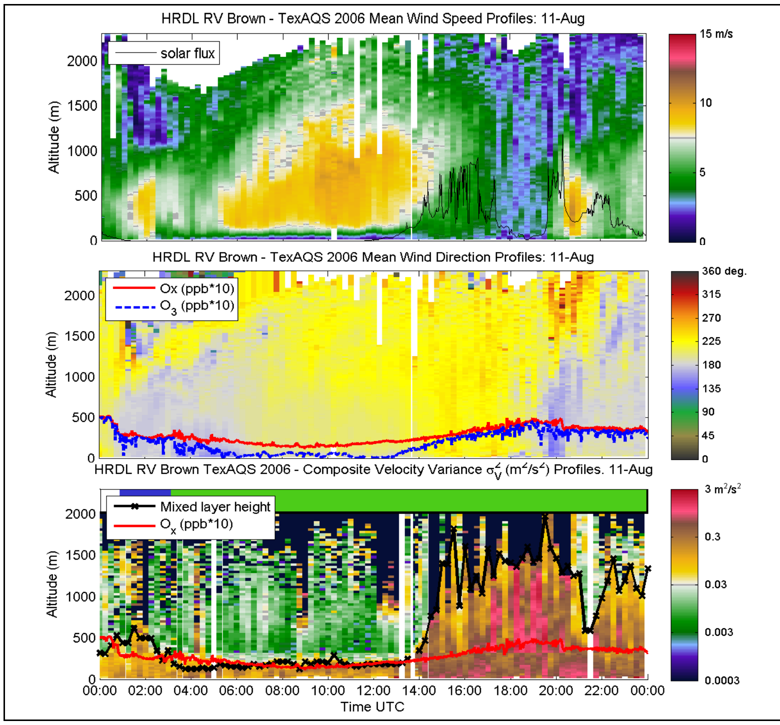

Figure 1. HRDL-derived profiles of horizontal wind speed overplotted with solar flux (top) wind direction overplotted with Ox and O_3 (middle) and velocity variance overplotted with Ox and mixing height (bottom) for August 11, 2006. The ozone and Ox scales are 1/10 of the altitude scale (An ozone point at 500 m corresponds to 50 ppbv). The deep LLJ appears as a yellow "blob" in the wind speed profiles. Note that the ozone concentrations are the lowest around 1200 UTC when surface wind speeds are the slowest and when morning rush hour contributes additional titrating CO and NO. During the LLJ the boundary layer mixing height drops down to 200-250 meters corresponding to height at which the jet wind speed shear diminishes to a level that generates negligible mechanical turbulence.

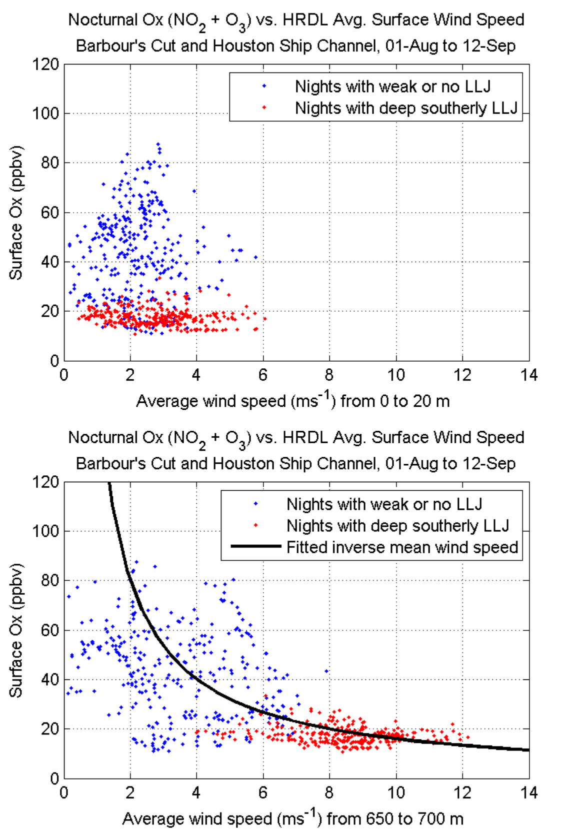

Figure 2. Ship-measured surface Ox versus HRDL-measured average horizontal mean wind speed between 0 and 20 meters AGL (Top) and between 650 and 700 meters AGL (Bottom).

The 650-700 m AGL altitude bin was chosen because it represents an average height range for the vertical center of most of the observed DSLLJs. Relative to weak or no jet days, lower ozone concentrations on DSLLJ days becomes clearer when the Ox concentrations are compared to winds aloft. The bottom panel of Figure 2 also contains a fit of an inverse-mean-wind-speed curve, demonstrating and inverse or "dilution" relationship between wind speeds aloft and surface Ox concentrations. At higher wind speeds (9-12 m/s) the Ox levels do not continue to decrease according to the inverse-mean-wind-speed curve but rather they level out around 15-22 ppbv which corresponds to the background ozone and Ox levels of 15-28 ppbv measured in the Gulf of Mexico during TexAQS 2006.

5 Nocturnal LLJ and afternoon air quality

The previous section discussed the observed effects of nocturnal wind speeds aloft on concurrent surface ozone concentrations – and the difference between nights with a DSLLJ and other nights. The question of how these winds correlate to data the following afternoon is addressed by comparing nocturnal jet characteristics and the peak ozone value measured the following day. Figure 3 contains a plot of the maximum ozone measured on the ship (red-circles) and the maximum ozone measured anywhere in the Houston monitoring network (blue diamonds) versus the maximum speed of the jet V_{max} (m/s) measured during the previous night. All ozone peaks appeared between local noon and 1800 LST. The Houston area measurements are for any location in the Houston network, which covers an area of ~48000 km^2, and so it is possible that the nocturnal winds and conditions measured at the ship were uncorrelated from peak ozone measurements at more distant locations.

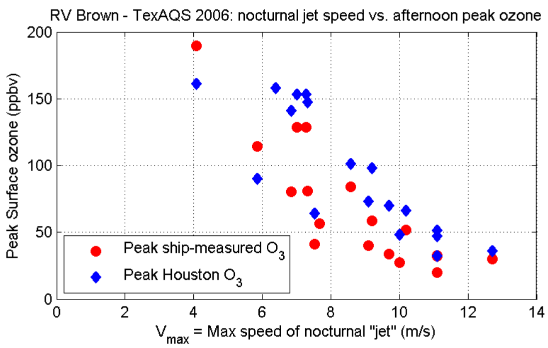

Figure 3. Peak ozone (ppbv) as measured in the Houston network (blue diamonds) and at the ship (red circles) versus maximum speed (m/s) of the "jet" the preceding night

To simplify the analysis, the data are limited here to just those measurements made from the ship platform when in Barbour's Cut or the Houston Ship Channel. A jet "area parameter", $A_{jet} = V_{max} x H_{max}$, ($m^2 s^{-1}$) was generated where H_{max} is the altitude of V_{max} in m. The daytime peak ozone values demonstrate an inverse relationship to this area parameter as shown in Figure 4. Stronger and deeper nocturnal jets correlate to lower peak ozone the following day.

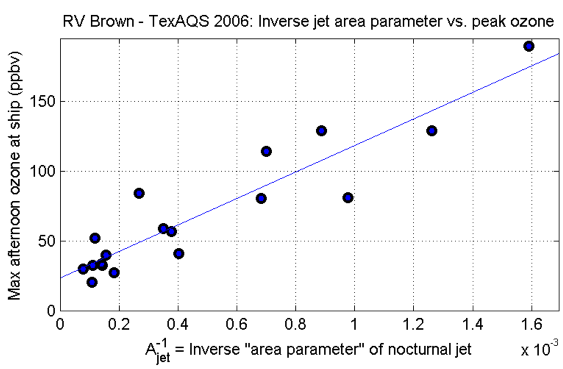

Figure 4. Ship-measured peak ozone versus the inverse of the nocturnal jet area parameter A_{jet}.

The data show a correlation of 0.93. The ~23 ppbv offset for the line fit in Figure 4 corresponds to measured background levels in the Gulf of Mexico (also see Figure 2). Note, however, that ozone values downwind of the Houston network may be higher as discussed by Senff et. al.[5]

6 Summary

HRDL Doppler lidar measurements provide evidence that the DSLLJ plays a large role in reducing nocturnal ozone concentrations in the Houston area. The nocturnal DSLLJs near Houston have a strong southerly component that advects relatively clean marine air from the Gulf of Mexico. The shear induced by the jet generates mechanical turbulence that permits some mixing of the marine air down to the surface and mixing up of near-surface ozone precursors generated during the night or left over from the previous day into the jet where they are dispersed by the high wind speeds. Later in the day, when convective mixing increases and the jet mixes out, there are less ozone and ozone precursors aloft to be mixed down. In addition, slightly stronger and more southerly horizontal winds in the afternoons following DSLLJs prevent buildup of ozone in the measurement area. Horizontal mean wind speeds at the surface during a DSLLJ are usually similar to those on weak/no jet nights. Therefore, comparison of winds at higher altitudes corresponding to the center of stronger jets demonstrates a better dilution relationship with corresponding in-situ surface ozone or Ox levels than do surface wind speeds. Finally, peak ozone concentrations measured each day in the near-Houston ship locations appear to have an inverse relationship to the "area parameter" of the jet from the previous night - suggesting possible forecast information.

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[1] Nielsen-Gammon, J., 2002: Validation of Physical Processes in MM5 for Photochemical Model Input: The Houston 2000 Ozone Episode, 2002 MM5 meeting, UCAR.

[2] Banta, R. M., C. J. Senff, J. Nielsen-Gammon, L. S. Darby, T. B. Ryerson, R. J. Alvarez, S. P. Sandberg, E. J. Williams, and M. Trainer, "A bad air day in Houston," *Bull. Am. Met. Soc.*, **86**, 657-669, (2005).

[3] Darby, L. S., "Cluster Analysis of Surface Winds in Houston, Texas, and the Impact of Wind Patterns on Ozone," *J. Appl. Met.*, **44**, 1788-1806, (2005).

[4] Tucker, S. C., W. A. Brewer, C. J. Senff, R. Banta, S. P. Sandberg, D. Law, A. Weickmann, W. M. Angevine and R. M., Hardesty, "Doppler lidar estimates of mixing layer heights during TexAQS 2006," *AGU Fall Meeting*, San Francisco, California, USA, 10-14 December 2007.

[5] Senff, et. al., 2007: Ozone Flux and Production Downwind of Houston and Dallas, *AGU Fall Meeting*, San Francisco, California, USA, 10-14 December 2007.