P1.11 THE IMPACT OF RESIDUAL LAYER OZONE ON SURFACE OZONE LEVELS IN HOUSTON, TEXAS DURING TEXAQS II

Bonne Ford[1*], Gary A. Morris[2], Elizabeth Thompson[1], Bernhard Rappenglueck[3], Barry Lefer[3], Daewon Byun[3], Xiangshang Li[3], Ryan Perna[4], Renee Boudreaux[3], Bridget McEvoy-Day[3], Leonardo Pedemonte[3], and Aaron Chow[3]

1) Dept. of Geography & Meteorology, Valparaiso University, Valparaiso, IN 46383, USA
2) Dept. of Physics & Astronomy, Valparaiso University, Valparaiso, IN 46383, USA
3) Dept. of Geoscience, University of Houston, Houston, TX 77204, USA
4) Texas Commission on Environmental Quality, Houston, TX 77023, USA

1. INTRODUCTION

This study presents data collected from ozonesonde launches conducted in Houston from July 2004 through August 2007. On twelve days, two ozonesondes per day were launched with one in the early morning (around 12Z) and another in the early afternoon (around 18Z) in an attempt to examine the impact of the nighttime residual layer on the mid-afternoon ozone concentrations.

Although our data set is too small to reach specific conclusions, three specific days are examined as case studies: September 2, 2006, September 25, 2006, and August 11, 2007. These case studies provide examples of the type of information and subsequent analysis that ozonesonde data provide.

In addition to the ozonesondes, measurements taken at the continuous ambient monitoring site (CAMS) in downtown Houston as managed by the Texas Commission on Environmental Quality (TCEQ) were referenced for comparison and data validation. NOAA's HYSPLIT model (Draxler and Hess, 1997) was also used to compute back trajectories that assist in understanding air mass origins. This study provides evidence for the impact of the residual layer on the surface ozone concentrations as well as impacts from air masses with stratospheric characteristics that are advected into the lower free tropopsphere.

2. CHARACTERISTICS OF THE RESIDUAL LAYER

Around sunset, solar heating of the ground ceases, allowing for turbulence decay. Without turbulence, the surface layer is no longer well-mixed. Instead, radiational cooling leads to the formation of a stable boundary layer.

However, not all of the previous day's convective mixed layer is dissipated; instead, it survives as the residual layer (RL). With near neutral stability, this "left over" layer remains above the stable nocturnal boundary layer (NBL) and has the same properties of the previous day's mixed layer. The RL exists as a storage area for moisture and pollutants, so long as it remains decoupled from the surface. This isolation of the RL from the NBL is strongest with clear skies and weak, non-turbulent surface winds. Such conditions are usually found in post frontal regions or areas with anticyclonic influences (Chung, 1977).

TCEQ wind profiler data from LaPorte, TX show that for the three case studies presented, the surface winds near Houston were weak (< 5-10 knots).

Surface analysis (as referenced through Unisys) for 12Z on September 2, 2006, shows cold fronts to the east and to northwest of Houston. The 12Z analyses for September 25, 2006 and August 11, 2007 also show cold fronts to the east. On September 25th a high is in place to the west of Houston; while on August 11th highs are found over the Gulf of Mexico and to the northwest of Houston.

In the morning, solar heating generates turbulent eddies that will blend the NBL upwards, forming a new, growing convective mixed layer (ML). When the height of the mixed layer meets the bottom of the RL, pollutants from the RL are re-entrained into the ML, often leading to rapid changes in surface pollution concentrations.

An example of this diurnal cycle from September 1st-2nd, 2006 is depicted in Figure 1, which shows a time series of surface ozone readings from CAMS-81in downtown Houston (data courtesy TCEQ). On the first, sunset occurred at 7:43PM CDT (Hour 19.43) and sunrise at 6:58AM CDT (Hour 30.58) on the second.

---

* Corresponding author address: Bonne Ford, Dept. of Geography and Meteorology, Valparaiso University, 1809 Chapel Dr., Kallay-Christopher Hall, Valparaiso, IN 46383; email: Bonne.Ford@valpo.edu

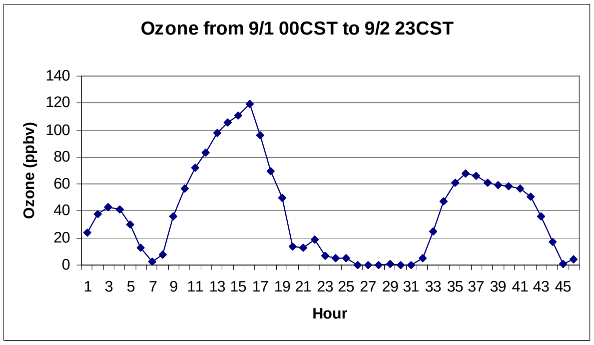

Figure 1. Time Series for surface ozone concentration from 00CST on September 1, 2006 to 23CST on September 2, 2006 as measured by CAMS 81 (Houston Regional Office) (TCEQ)

Figure 2, which depicts wind speeds measured for the same time period, shows increased values during the first night (Hours 1 – 4) that could explain the peak in ozone concentrations at the same time. A burst of turbulence in the NBL can cause intermittent mixing down from the RL.

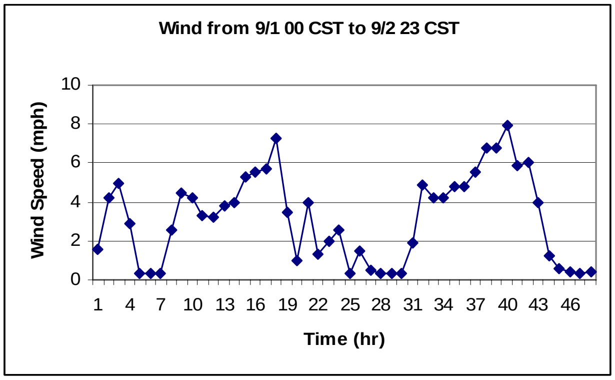

Figure 2. Time Series for surface wind speeds (mph) from 00CST on September 1, 2006 to 23CST on September 2, 2006 as measured by CAMS 81 (Houston Regional Office) (TCEQ)

While high concentrations of ozone usually result from increased photochemical production (sunlight causing volatile organics compounds to react with nitrogen oxides to form ozone), vertical mixing and advection from other regions also play important roles (Morris et al., 2006). Neu et al. (1994) and Kleinman et al. (1994) both suggested that this re-entrainment of ozone particles from the residual layer can actually account for up to 50-70% of the day's maximum surface concentration.

3. IDENTIFICATION OF THE RESIDUAL LAYER

Vertical profiles of ozone are strongly linked to the growth of the mixed layer (Zhang and Rao, 1999). However, determining the depth and evolution of the mixed layer as it relates to air pollution can be quite complicated (e.g., Berman et al., 1997).

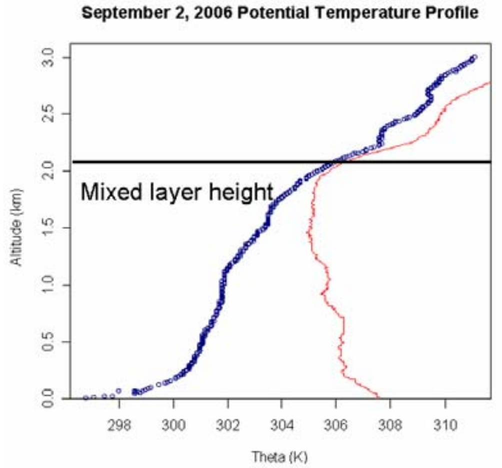

Figure 3. Potential temperature (K) profiles for a 1201Z launch (blue) and a 1837Z launch on September 2, 2006.

However, atmospheric soundings permit the identification of the RL due to its near neutral stability and frequently enhanced levels of pollutants. The top of the RL, much like the daytime convective mixed layer, is marked by a capping inversion.

Figure 3 shows potential temperature data derived from temperature and pressure measurements of two soundings on September 2, 2006. The base of the RL is found in the morning profile (blue) below 0.5 km kilometer, where the vertical potential temperature gradient noticeably decreases. By comparison, the mixed layer height later from the afternoon launch (red) is found ~2.1km, with the mixed layer below identified by its nearly constant potential temperature.

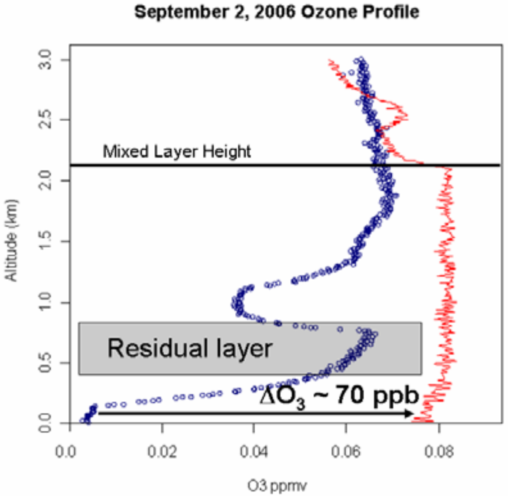

Figure 4. Ozone profiles for a 1201Z launch (blue) and a 1837Z launch (red) on September 2, 2006.

Figure 4 shows the ozone profiles from the same soundings presented in Figure 3. Ozone value in the NBL for Houston fall to near zero each morning due to titration, an effect indicated in the morning profile (blue) below 0.2 km where ozone values are < 5 ppbv. A residual layer is clearly present between 300 and 600 m, with elevated ozone amounts > 60 ppbv. In the afternoon profile (red), ozone values are nearly constant in the mixed layer with values around 80 ppbv from the surface up to 2.1 km. The ozone profiles frequently depict sharp gradients at such dynamical boundaries such as the top of the ML. Additional analyses of this and two other case study days are provided below.

4. SEPTEMBER 2, 2006

Surface ozone concentrations in Houston exceeded 100 ppbv on September 1, 2006, an unhealthy air quality day. The RL that formed that evening preserved some of the day's high ozone concentrations. As seen in the ozone profile from the next morning (blue) in Figure 4, the RL had a maximum ozone concentration of 71 ppbv. The measured surface ozone concentration increased from 4 to 74 ppbv in the 6.5 hours between launches. Entrainment of elevated ozone from the RL provided a catalyst for additional photochemical production on September 2nd, resulting in a convective mixed layer with ~80 ppbv of ozone by the time of the afternoon sounding (red in Figure 4).

HYSPLIT Model back trajectories (Figure 5) show that the air mass at 10m AGL (red trajectory) has been in the Houston area for the previous 24 hours, suggesting that these high surface concentrations are not due to long range transport. However, the slight ozone maximum seen in the afternoon (red) profile at ~2.5 km could be attributed to transport from the Midwest, as shown in the green trajectory in Figure 5. Transport from nearby Louisiana is shown at 200 m by the blue trajectory, suggesting that short-range transport could also have affected the ozone concentration levels near the surface.

5. SEPTEMBER 25, 2006

On September 24, 2006, a cold front passed through the Houston area, and maximum surface ozone levels remained below ~50 ppbv throughout the day, with CAMS-81 recording a maximum reading of 45 ppbv. Figure 6 shows the potential temperature data from the two soundings on September 25, 2006 while Figure 7 shows the corresponding ozone profiles.

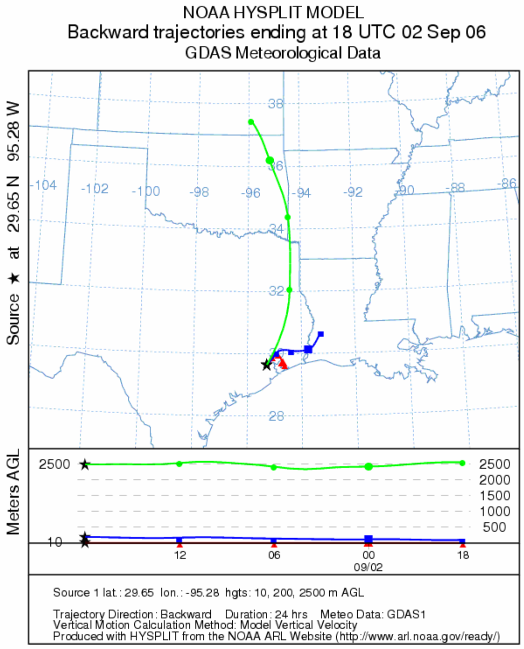

Figure 5. 24-Hour Backward Trajectories computed for Houston running from September 1, 2006 1800UTC to September 2, 2006 1800UTC using NOAA's Hysplit Model. Green shows the transport at 2500m, blue for 200m, and red for 10m AGL.

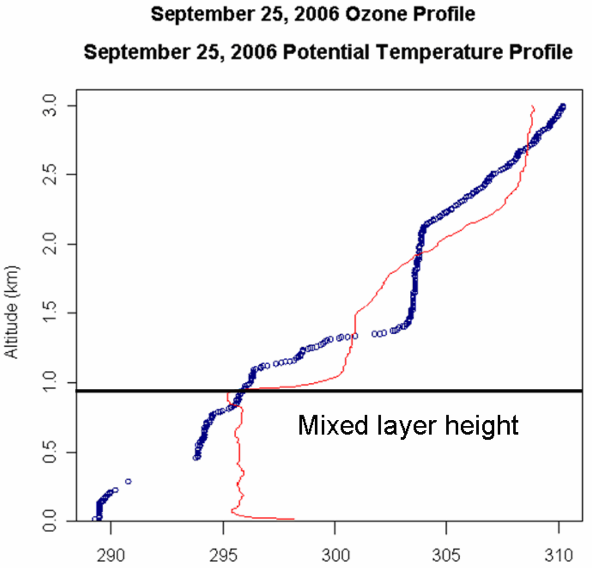

Figure 6. A graph of potential temperature (K) and altitude (km) for a 1200Z launch (blue) and a 1803Z launch on September 25, 2006.

The morning potential temperature profile (blue) seen in Figure 6 indicates two air masses with nearly constant potential temperature. The

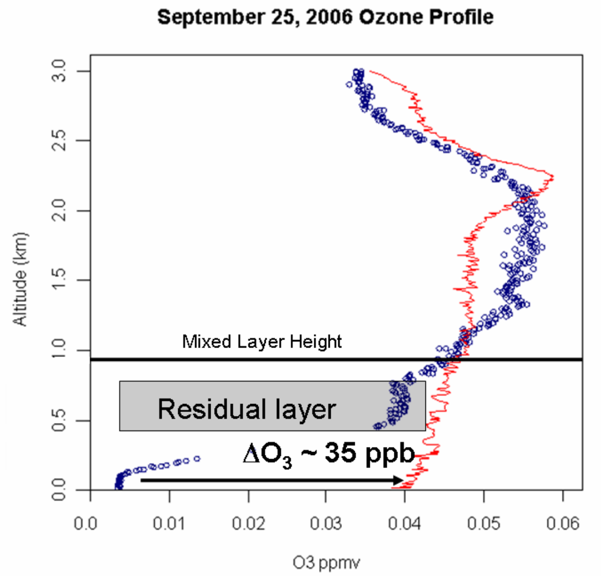

Figure 7. A graph of ozone (ppmv) and altitude (km) for a 1200Z launch (blue) and a 1803Z launch (red) on September 25, 2006. The data gap is attributed to a short loss of signal between the receiver and radiosonde.

lower (500 – 800 m) corresponds to the RL and contains about 38 ppbv of ozone, as seen in Figure 7. The upper (1300 – 2100 m) contains ~55 ppbv of ozone and is associated with a region of relatively dry air (relative humidity < 20%). As the convective mixed layer grew on the 25th, it first encountered enhanced ozone levels in the RL, then later the enhanced ozone levels in the higher air mass. By the time of the afternoon profile (red), ozone shows only a small vertical gradient from the surface up to 2.0 km, with a mean value ~45 ppbv. A sharp gradient in potential temperature seen in Figure 6 is found near 1.0 km, indicating the top of the convective mixed layer.

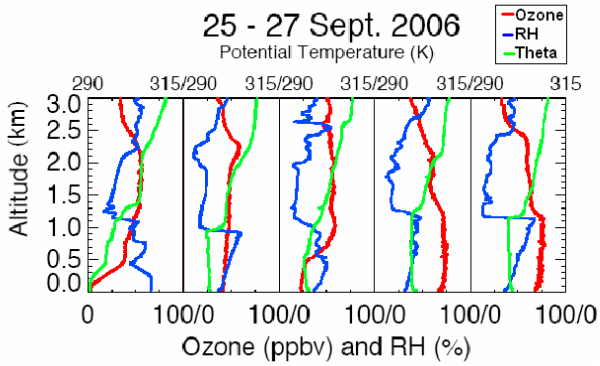

Figure 8. Profiles of Relative Humidity (blue), Potential Temperature (green), and Ozone (red) for 9/25 1203Z, 9/25 1803Z, 9/26 1540Z, 9/26 1916Z, and 9/27 1801Z launches.

To better understand the origin of this higher ozone layer in the morning profile, back trajectories were again run using HYSPLIT, as shown in Figure 9. The two lower trajectories (10 m in red and 200 m in blue) have origins in Michigan and Ontario with paths through the Midwest. However, the back trajectory started at 2250 m shows origins in Arizona and rapid descent – just 24 hours earlier, the air parcel was above 5000 m. Given this trajectory and the relative humidity and ozone associated with this air mass, as indicated by the morning sounding; it is reasonable to conclude that this air mass has been influenced by stratospheric air brought down through the troposphere behind the cold front.

This is further emphasized by Figure 8, which shows ozone (red), potential temperature (green), and relative humidity (blue) profiles for the period of the 25th-27th of September 2006. The progression of relative humidity profiles shows the intrusion of drier air on the 25th (after frontal passage) which then gets mixed downward with the growth of the ML (shown by the potential temperature profiles) over the next two days. As this stratospheric air, which naturally contains higher levels of ozone, is mixed downward; the surface ozone concentrations increase. As a result, vertical mixing can not only re-entrain the previous day's pollution from the RL but also entrain old stratospherically influenced air.

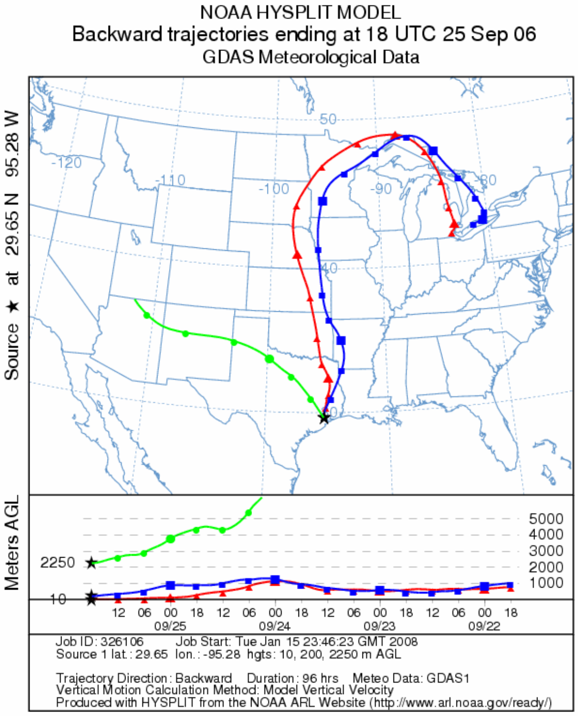

Figure 9. 96-Hour Backward Trajectories computed for Houston running from September 23, 2006 1800UTC to September 25, 2006 1800UTC using NOAA's Hysplit Model. Green shows the transport at 2250m, blue for 200m, and red for 10m AGL.

6. AUGUST 11, 2007

The third case study examines data from August 11, 2007. The potential temperature data (Figure 10) indicates the base of the RL for the morning profile (blue) at ~0.5 km, while the height of the convective mixed layer for the afternoon profile (red) can be found ~1.6km. The ozonesonde launched the previous afternoon (not shown) found a maximum ozone concentration of 76 ppbv in the mixed layer, while the nearby CAMS stations, #81 and #411, had maximum daily surface readings of 87 and 111 ppbv respectively. The 1206Z morning launch (blue in Figure 11) measured a maximum ozone concentration of 58 ppbv in the RL. Maximum CAMS ozone measurements on August 11, 2006 were 55-60 ppm. The 1831Z afternoon launch (red) indicated a maximum ozone concentration in the mixed layer of 76 ppbv. The surface ozone concentration increased from ~5 to ~65 ppmv between launches.

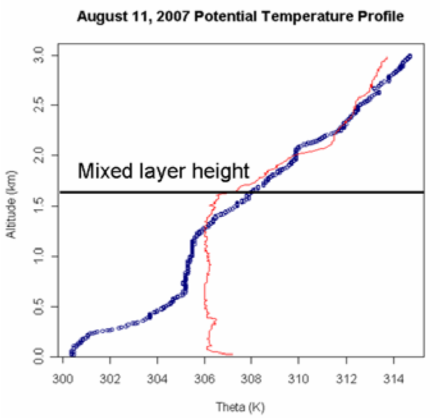

Figure 10. Potential temperature (K) profile for a 1206Z launch (blue) and an 1831Z launch (red) on August 11, 2007.

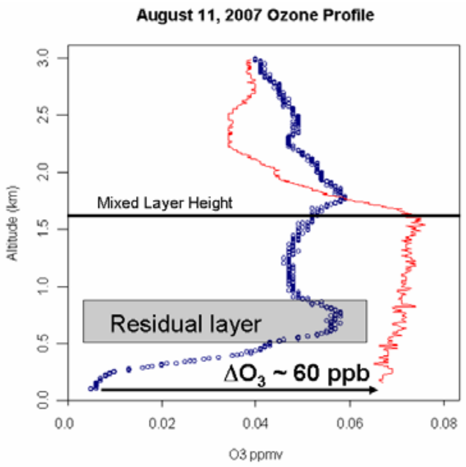

Figure 11. A graph of ozone (ppmv) and altitude (km) for a 1206Z launch (blue) and a 1831Z launch (red) on August 11, 2007.

Again using the Hysplit Model (Figure 12) to compute trajectories, it is evident that lower-level air masses (10m and 200m) have remained in the Houston area for the previous 24 hours. At 2500m, the air mass that was over Louisiana a day ago traveled over the Gulf of Mexico before arriving in Houston.

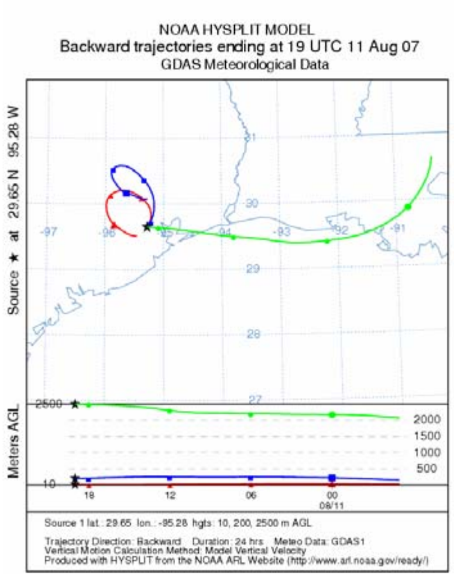

Figure 12. Back Trajectory for air at 10m (red), 200m (blue), and 2500m (green) computed for August 11, 2007 ending at 1900UTC.

8. SUMMARY AND FUTURE WORK

The ozonesonde data presented in the three case studies described here demonstrate the impact that ozone stored in the RL overnight can have on following day's surface ozone levels. The data also indicate the possibility of influence from stratospheric air masses on surface concentrations subsequent to the passage of cold fronts through the Houston area. Unfortunately, statistically quantifying the magnitude of these impacts cannot yet be determined from our limited dataset of 12 days.

Kleinman et al. (1994) found that in rural Georgia, the impact of the RL on increasing surface ozone concentrations was important on days with high ozone concentrations but played almost no role on days with low ozone concentrations. In Houston, however, multiple launches were only conducted on days for which high ozone levels were forecast. There is therefore no comparison for the impact of the residual layer on days with low ozone concentrations. As a result, additional days with morning and afternoon launches are needed. Furthermore, an experiment with launches every couple of hours throughout the night and morning hours would provide insight into the growth and re-entrainment of the RL. Finally, a series of successive double-launch days over an extended period would provide insight into the intensification of surface ozone pollution during stagnant meteorological conditions.

REFERENCES

Berman, S., J.Y. Ku, J. Zhang, and S.T. Rao, 1997: Uncertainties in estimating the mixing depth-comparing three mixing depth models with profiler measurements. *Atmospheric Environment*, **31**, 3023-3039.

Draxler, R.R., and G.D. Hess, 1997: Description of the Hysplit_4 modeling system. *NOAA Technical Memorandum ERL ARL-224*, 24p.

Chung, Y.-S., 1977: Ground-level ozone and regional transport of air pollutants. *Journal of Applied Meteorology*, **16**, 1127-1136.

Kleinman, L.K. and Coauthors, 1994: Ozone formation at a rural site in southeastern United States. *Journal of Geophysical Research*, **99**, 3469-3492.

Morris, G.A., S. Hersey, A.M. Thompson, O.R. Cooper, A. Stohl, P.R. Colarco, W.W. McMillan, J. Warner, B.J. Johnson, J.C. Witte, T.L. Kucsera, D.E. Larko, and S.J. Oltmans, 2006: Alaskan and Canadian forest fires exacerbate ozone pollution over Houston, Texas, on 19 and 20 July 2004. *Journal of Geophysical Res*earch, 111, D24S03 doi:10.1029/2006JD007090.

Neu, U. et. al., 1994: On the relation between ozone storage in the residual layer and daily variation in near-surface ozone concentration- a case study. *Boundary Layer Meteorology*, **69**, 221-247.

Zhang, J., and S. T. Rao, 1999: The role of vertical mixing in the temporal evolution of ground-level ozone concentrations. *Journal of Applied Meteorology*, **38**, 1674-1691.