P1.1 AN INSIGHT INTO THE VERTICAL STRUCTURE OF THE ATMOSPHERE DURING TEXAQS-II: UNDERSTANDING THE EFFECT OF THE UPPER-LEVEL METEOROLOGY ON HOUSTON'S SURFACE OZONE LEVELS

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1. INTRODUCTION

Despite reductions in automobile and industrial emissions, Houston continues to be designated as a non-attainment area for ozone (O_3). This study focuses on ozone episodes where the peak 8 hour average exceeded 85 ppb which occurred in August/September 2006 during the Texas Air Quality Study-II (TexAQS-II) and addresses upper-level synoptic maps and vertical atmospheric temperature structures associated with Houston's ozone episodes.

2. METHODS AND DATA USED

In order to address the common patterns for O_3 episodes in August and September 2006, composite maps were created using the National Climatic Data Center's web interface for episode days and non-episode days. The 500hPa and 850 hPa levels were considered for this upper-level analysis. To observe the weather conditions that create elevated ozone levels in the Houston area, 850 hPa maps were further analyzed and placed in "clusters" based upon the classifications of Ngan and Byun [2007]. The cluster analysis was applied to classify synoptic patterns associated with high background O_3 levels as determined using surface ozone data of selected sites of the Continuous Ambient Monitoring Site (CAMS) network (Fig. 1). Frontal passages were investigated in more detail in order to identify the conditions that may raise Houston's background levels of ozone.

Using rawinsonde data made at the University of Houston (UH) campus (Fig. 1) during the months of August and September 2006, the height and development of the PBL was determined and the effect of inversions on Houston's ozone concentration investigated.

Radiosondes were launched twice per day at 0700 and 1900 CDT (Central Daylight Time). Intensive observational periods (IOPs) were scheduled on days forecasted to have high ozone levels (ozone 8-hr averages > 85 ppbv). To capture the temporal and vertical development of the PBL height on IOPs, rawinsondes were also launched at 0500, 1000, 1300, 1600, and 2200 CDT.

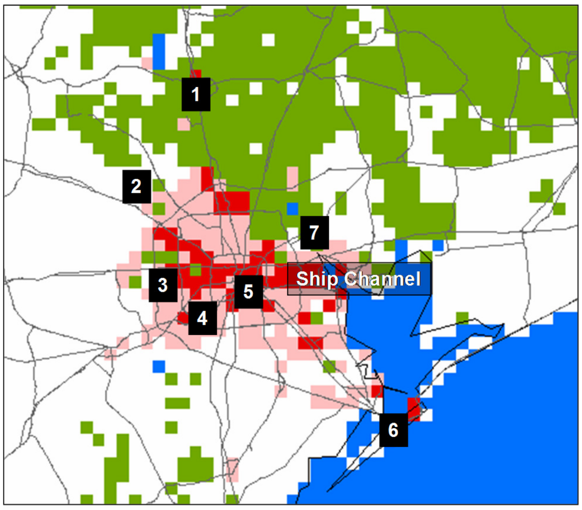

FIG. 1. Location of radiosonde site on UH main campus and CAMS stations used to determine 8-hr background ozone: (1) Conroe, (2) Northwest Harris County, (3) Westhollow, (4) Croquet, (5) UH Main Campus, (6) Galveston, and (7) Crosby. In addition the location of the Ship Channel is indicated. Color coding reflect some major land use types: water bodies (blue), forests (green), urbanized area (light red) and densely urbanized area (red). No color indicates rural areas with shrub-like vegetation.

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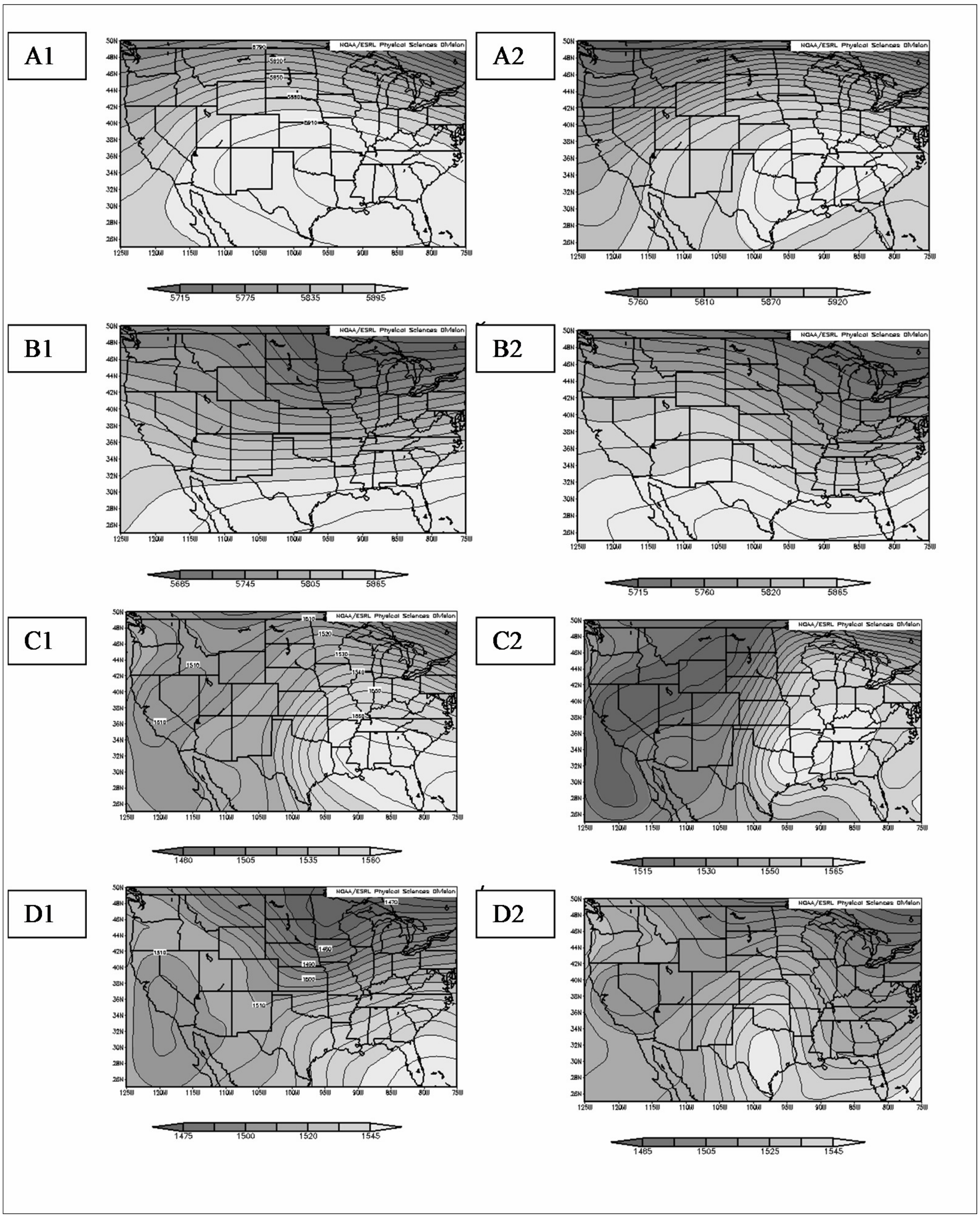

FIG. 2. 500 hPa composite maps of geopotential heights for August 2006 (A1: non-episode days; A2: episode days) and for September 2006 (B1: non-episode days; B2: episode days]); C1 and C2 show corresponding plots for August, (D1 and D2 for September) but this time for 850 hPa levels.

3. RESULTS AND DISCUSSION

3.1. *Synoptic conditions for Houston's ozone episodes*

Composite synoptic maps were created using the National Climatic Data Center's composite map web interface (Figure 2). The 500 hPa composite map for non-episode days during August 2006 (Figure 2-A1) reveals a center of an upper-level High to the northeast of the Houston area that may have helped support the southeasterly flow that Houston experienced over much of the month of August 2006. In contrast, the 500 hPa composite map for ozone episode days (August 16-18) during August 2006 (Figure 2-A2) shows a stronger than average upper-level High centered over northeastern Texas and Arkansas, resulting in northeasterly flow in Houston.

Figure 2-B1 shows the composite map for non-episode days in September 2006. The average flow for the month of September is mostly zonal. Figure 2-B2 shows the average 500 hPa flow for the ozone episodes of September 2006. Note the ridge located to the west of the Houston area and a trough to the east. This scenario is typically associated with a recent cold frontal passage and a Low system moving to the east of the Houston area.

The composite maps for non-episode days of August 2006 at 850 hPa are shown in Fig. 2-C1. The non-episode day composite reveals an upper-level High centered to the east of Houston, possibly contributing to southerly flow that tends to suppress ozone levels due to the advection of relatively ozone-depleted marine air. However, the composite map for ozone episodes reveals an upper-level High centered to the northeast of Houston (indicative of the episode of August 16-18) that contributes to the easterly flow over the area. This flow may have increased the ozone precursor concentration over the Houston area, since it brings air from the ship channel region east and southeast of the Greater Houston area into the central urban area.

The composite 850 hPa map for non-episode days during September 2006 shown in Fig. 2-D1 is inconclusive with the exception of some cold advection occurring over the north-central portion of the country and a tendency for southerly flow over the Houston area. However, the composite 850 hPa map for September ozone episodes shown in Fig. 2-D2 clearly shows an upper-level High center to the west of Houston, again indicative of a recent frontal passage. Such a meteorological regime is found to be the leading cluster for Houston's ozone episodes for September (see the next section). The position of this upper level High brings dry flow from the continent giving Houston both clear skies (a prerequisite for enhanced photochemistry) and an increased background ozone. The higher background levels are mostly due to the transport of both aged air masses with elevated ozone levels produced by regional emissions of anthropogenic and biogenic precursors, and air masses that have fresh entrainment of primary pollutants along the trajectory. The light northerly flow regime is also associated with increased subsidence, and counters the sea breeze resulting in increased stagnation, both of which may enhance ozone concentrations

3.2. *Classification of Synoptic Patterns for Ozone Episodes*

To better define the weather conditions that create elevated ozone levels in the Houston area, 850 hPa maps were visually inspected, analyzed, and placed in clusters based upon classifications according to Ngan and Byun [2007]. The classifications are as follows: Cluster I is characterized by northerly flow with a high pressure system to the west of Houston (the "post-frontal" category); Cluster II is characterized by easterly flow with a high pressure system to the north; Cluster III is characterized by southeasterly flow with a high pressure system to the northeast; Cluster IV is characterized by southerly flow from the Gulf with a high pressure system to the east of Houston; Cluster V is characterized by southwesterly flow with a high pressure system in the Gulf; and Cluster VI occurs when Houston is under the direct influence of a tropical storm (which did not happen in 2006).

	I	II	III	IV	V	VI
Episode days	5	6	0	1	0	0
Non-episode days	10	6	9	12	12	0
Average background ozone [ppb]	52.4	41.6	31.0	20.6	28.0	n/a

Table 1. Cluster frequency during ozone episodes and non-episode days (for definitions of cluster I-VI see text). Last row indicates the background ozone mixing ratios associated with the different clusters.

Table 1 illustrates the frequency of the clusters for ozone episode and non-episode days. The data in

Table 1 demonstrate that Clusters I and II are the most common scenarios for ozone episodes in August and September 2006. The majority of cluster I days are post-frontal and often precede an ozone episode. In fact, nearly every ozone episode in September 2006 occurred in a post-frontal environment with a light northerly flow that opposes the inland propagation of clean marine air with sea breeze and/or brings with it elevated continental background levels. The non-episode days in this cluster were related to cold fronts with strong northerly winds (about 8 m/s) that suppress ozone concentrations by blowing pollutants away from the Houston area. Precipitation frequently accompanies frontal passages and would serve to clean out pollutants, resulting in decreased ozone levels. While an equal number of episode and non-episode days can be found in Cluster II, 50% of all episode days are found in Cluster II and only 12% of all non-episode days are in Cluster II.

In September, Cluster II was common after a frontal passage as high pressure passed to the north of the Houston area. Cluster II conditions can result in elevated ozone levels due to winds carrying precursors from the ship channel region.

The cluster analysis is also applied to classify synoptic patterns associated with high background ozone concentration as determined using surface ozone data from the Continuous Ambient Monitoring Site (CAMS) network. Several CAMS stations on the perimeter of the network far from power plants or chemical refineries were chosen as representative sites with limited effects of NO titration (shown in Fig. 1). The background ozone was defined as the minimum of the 8-hr mean ozone values among all background stations following Nielsen-Gammon et al. [2005a]. The same 6 cluster classifications previously discussed were also applied in the post-frontal environment to determine the effect of the background concentration on Houston.

As indicated in Table 1, Cluster I has the highest background values and is associated with a high pressure system to the west of Houston, bringing in northerly flow from the continental United States. This cluster is very common in the wake of a cold front. Cluster II also has high background values typical of easterly flow coming into the Houston area. This cluster can have a slight northerly component that would help to bring in continental air and thus increase the background ozone level. Back trajectory analyses for the ozone episodes of September 2006 indicated that all trajectories on Cluster I and II days came from either northern Texas or from the northeast in Louisiana, which is in agreement with the synoptic analysis above. On Cluster I and II days, therefore, Houston was under the influence of a continental air mass, as would be expected in the post-frontal environment.

3.3. *The Role of Frontal Passages*

It is well known that high pressure situations favor the build-up of ozone in the PBL over a time scale of a couple of days due to stagnant air that is repeatedly exposed to solar radiation under clear sky conditions. However, the Houston case is unique since frontal passages that precede these high pressure systems are associated with a significant change in background ozone levels (as seen Table 1), providing elevated ozone levels to which local and regional photochemistry will produce further enhanced peak 1-hr and 8-hr ozone values. Enhanced background O_3 is likely to be related to the transport of continental air and/or subsidence occurring behind the front.

In a post-frontal environment, the soundings on ozone days had several features in common. One of these features was a strong elevated inversion, significantly limiting the growth of the mixed layer. Since an elevated inversion was present during most of the high ozone days (especially in September), an attempt was made to analyze the different characteristics of the air masses associated with these inversions.

Elevated inversions for each sounding at 0700 CDT and 1900 CDT were categorized by the strength of inversion (i.e., the amount of temperature increase), moisture, and height to find the possible role that elevated inversions play on Houston's 8 hour ozone peak. Inversions less than 0.3°C were ignored. The results of the 0700 CDT analysis are shown in Fig. 3. The strongest elevated inversions are not correlated with the highest ozone values. However, the dry air masses aloft (see back corner of the diagram) are associated with frontal passages that occurred in the days preceding ozone episodes. The figure indicates that the highest O_3 averages occurred when the relative humidity of the air mass was rather low and the inversion itself may not have been very strong. Although the inversion still exists, it is getting weaker as instability gradually increases in the post-frontal environment. Fig. 3 also shows that moist inversions typically do not occur on episode days. Moist inversions are usually associated with cloud layers that inhibit the photochemical O_3 formation.

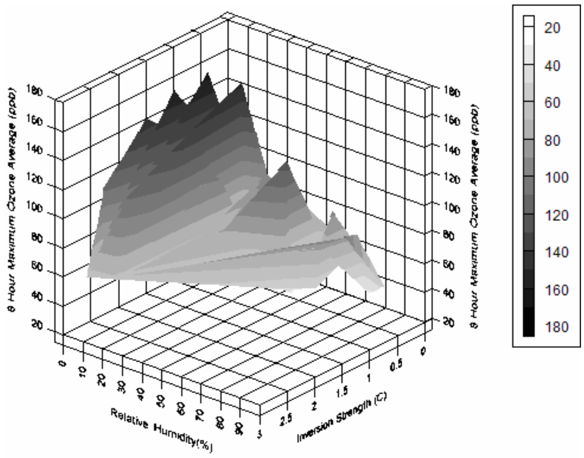

Fig. 3. 8-hr average ozone peak compared with elevated inversion strength (℃) and relative humidity (%) at the top of the inversion.

3.4. *The Effect of the PBL Height*

Figure 4 shows the average rate of PBL development on episode vs. non-episode days. The development of the PBL in the morning may be slower on O_3 episode days due to the fact that most of the episode days occurred in a post-frontal environment with relatively cool morning temperatures, resulting in a delay in boundary layer development.

The aforementioned PBL observations may be typical for O_3 episode days, but will not necessarily be the cause for afternoon O_3 peaks. There are certainly also other factors that can influence O_3 concentration. These include the degree of stagnation, the intensity of solar radiation, wind direction, presence/absence of precipitation, and temperature, and chemical properties of the air masses such as their photochemical history and the rate of freshly entrained precursor emissions. Variations of the PBL height may only play a minor role.

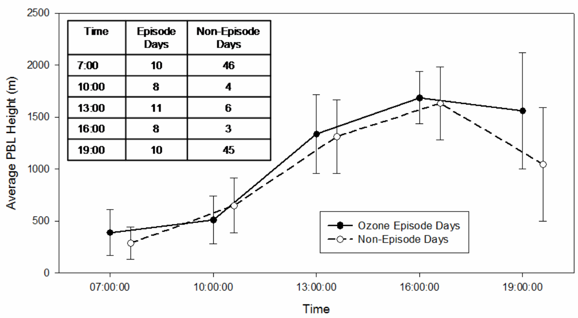

Fig. 4. The average growth of the PBL on O_3 episode days and non-episode days. Times in CDT.

4. CONCLUSION

The overall results for the Houston-Galveston area indicate that large scale northerly flows, often initiated by frontal passages, will lead to a rapid and significant change in background ozone levels due to the shift in wind direction and associated change of source areas for air masses (continental vs marine). The higher background levels are mostly due to the transport of both aged air masses with elevated ozone levels produced by regional emissions of anthropogenic and biogenic precursors, and air masses that have fresh entrainment of primary pollutants along the trajectory. Post-frontal subsidence will most likely lead to an additional O3 increase. As the front departs the area and high pressure settles in, local and regional photochemistry will produce ozone on top of the already enhanced background levels, which will eventually lead to an ozone episode. An analysis of the PBL structure and development indicated that a delay in the development of the PBL could be associated with higher ozone peaks in the afternoon. This study showed that the morning PBL height had little effect on peak ozone concentration.

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