

SPATIAL AND TEMPORAL CHARACTERISTICS OF WINDS AND MIXING DURING TEXAQS-II

**FINAL REPORT
STI-907101-3344-FR**

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**Prepared for:
Texas A&M University
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April 10, 2008

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1. INTRODUCTION

Sonoma Technology, Inc. (STI) completed mixing height derivation and quality control of wind and virtual temperature (T_v) data from May 19, 2005, through October 15, 2006, as part of the Texas Air Quality Study II (TexAQS-II). Twelve 915-MHz radar wind profilers (RWP), seven 404-MHz RWPs, nine Radio Acoustic Sounding Systems (RASS), two sodars, and one ship-based lidar were operated during the study. **Figure 1-1** shows the profiler, RASS, and sodar sites. Data from these instruments were collected by the Texas Commission on Environmental Quality (TCEQ), National Oceanic and Atmospheric Administration (NOAA) – Physical Sciences Laboratory (PSL), and STI.

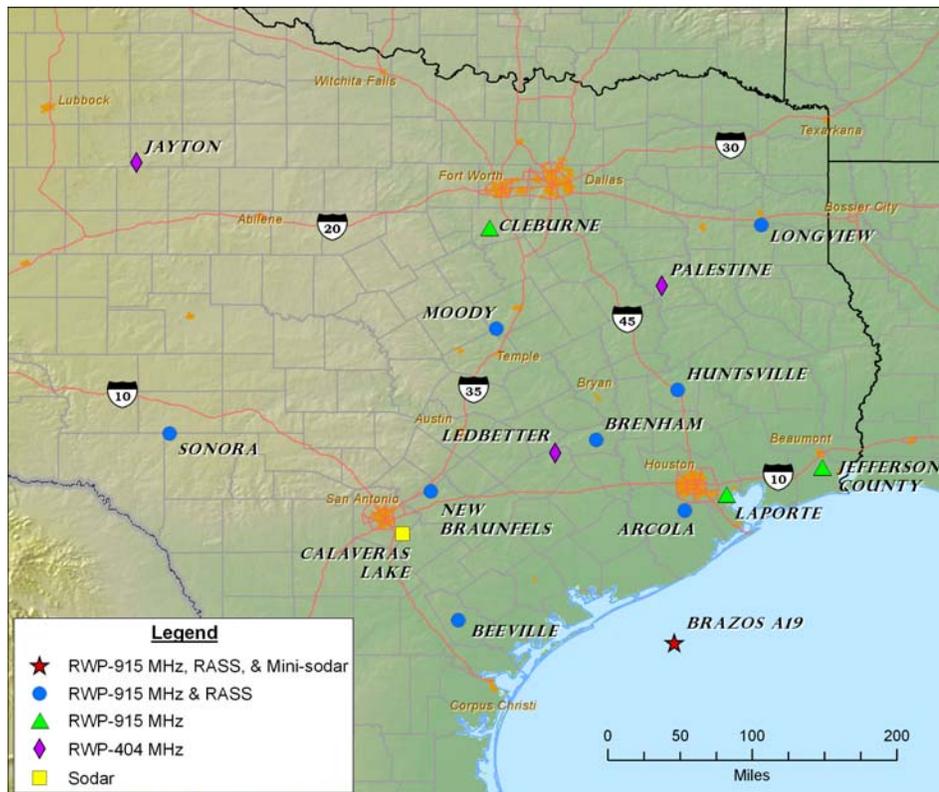


Figure 1-1. RWP, RASS, and sodar sites used for the TexAQS-II study. (Haskell, Oklahoma; Purcell, Oklahoma; Winnfield, Louisiana; and DeQueen, Arkansas not shown)

Using this data, STI performed a limited investigation of the characteristics of winds and mixing heights for the study period. In particular, we performed a climatological analysis of the wind and mixing height data collected and several case study investigations of RWP data and their relationship to ozone.

For the climatological analyses, we focused on the Houston, San Antonio-Austin, and Dallas-Fort Worth metropolitan areas. In particular, we investigated the spatial and temporal characteristics of wind and mixing height data for these three areas. We determined how these characteristics vary by season and synoptic weather pattern. We also investigated the

relationship between wind and mixing heights and regional and local ozone conditions for these three locations, focusing on the data collected from May through October, 2005 and 2006. We analyzed several mixing height characteristics, including peak mixing heights, time of peak mixing, average morning mixing heights, morning mixing height growth rates, and diurnal mixing height patterns. We also investigated the relationship between transport statistics (including transport distance, transport direction, and ventilation index) and air quality.

The following subsections describe the methods we used in our analyses and the analysis results.

1.1 METHODOLOGY

1.1.1 Climatological Analysis

We calculated seven wind and mixing parameters (listed below) and then grouped them by daily synoptic pattern, season, episode day, and non-episode day. A day was characterized as an episode day if any site in the metropolitan area (Dallas-Fort Worth, San Antonio-Austin, and Houston areas) exceeded 100 on the U.S. Environmental Protection Agency (EPA) Air Quality Index (AQI) for ozone, which is the equivalent of 84 ppb. For each area, synoptic patterns were identified. These synoptic patterns included ridge, trough, broad high, weak ridge, zonal flow, and low (weak low). Examples of each pattern are shown in Appendix A. We calculated the following seven parameters:

Diurnal Mixing Heights

Diurnal mixing heights were calculated by season and by synoptic pattern for May 19, 2005, through October 15, 2006. Comparisons were made between sites by season and synoptic pattern. Selected comparisons are discussed in Section 1.2.1.

Peak Mixing Heights

Peak mixing heights were calculated for each day, for May through October, 2005 and 2006. The peak mixing heights were then averaged by episode and non-episode days and comparisons were made between sites.

Time of Peak Mixing

The time of peak mixing was calculated for May through October, 2005 and 2006. If the peak mixing height occurred at multiple times during a day, the first occurrence was used. The time of peak mixing was then averaged by episode and non-episode days and comparisons were made between sites.

Average Morning Mixing Height

The average morning mixing height was calculated for the 9:00 a.m. CST through 12:00 p.m. CST hours for May through October, 2005 and 2006. The average morning mixing height was then averaged by episode and non-episode days and comparisons were made between sites.

Morning Mixing Height Growth Rate

The morning mixing height growth rate was calculated for the 9:00 a.m. CST through 12:00 p.m. CST hours for May through October, 2005 and 2006. The morning mixing height growth rate was then averaged by episode and non-episode days and comparisons were made between sites.

Diurnal Average Daytime Ventilation Statistics

Diurnal average daytime ventilation statistics at 400-500 m agl were calculated for the 9:00 a.m. CST through 12:00 p.m. CST hours for May through October, 2005 and 2006, by multiplying the average wind speed at 400-500 m agl by the average mixing heights. The diurnal average daytime ventilation statistics were then averaged by episode and non-episode days and comparisons were made between sites.

Daily Average Transport Statistics

Daily average transport statistics at 400-500 m agl were calculated for the 24-hour period from 6:00 a.m. CST the prior day to 6:00 a.m. CST on the current day for episode and non-episode days, for May through October, 2005 and 2006. These statistics were then used to create transport roses, which show the direction and transport distance on a chart similar to a wind rose. These comparisons are discussed and illustrated in Section 1.2.1.

1.1.2 Case Study Analysis

To provide additional insight into the spatial and temporal variability of the mixing height data, we conducted limited case study analyses for the following ten Houston days, which are a focus of TCEQ modeling efforts:

- June 22-25, 2005
- July 31 – August 2, 2005
- August 31 – September 2, 2006

To characterize the meteorology on the episode days, we analyzed selected available data and organized them into the following topics.

Large-Scale Aloft Weather: The height of the 500-mb constant pressure level and winds at 500-mb as depicted on the National Weather Service Daily Weather Maps were used to characterize the aloft large-scale weather patterns that existed at 6:00 a.m. CST on each day. Locations and strengths of ridges, troughs, and circulation patterns were noted, along with their

probable influence on mixing and cloud cover in the Houston area. Selected weather maps are shown in Section 1.2.2 and Appendix B contains weather maps for all case studies.

Large-Scale Surface Weather: The large-scale surface pressure patterns and regional winds as depicted on the National Weather Service Daily Weather Maps were used to characterize the large-scale surface flows that existed at 6:00 a.m. CST on each day. General locations of surface highs and lows were noted, along with their probable influence on local flows in the Houston area.

Local Flows: The diurnal and spatial changes in the local flow patterns were characterized by reviewing 24-hour back trajectories generated by the AIRNow-Tech Navigator website. The trajectories were calculated using the latest North American Model (NAM) model run obtained from the National Oceanic and Atmospheric Administration (NOAA) ending at the site with the highest 8-hour ozone concentration. Hourly RWP wind and reflectivity data collected at LaPorte were reviewed. The existence, timing, and strength of synoptic winds, the land breeze, the Bay breeze, and the Gulf breeze were noted, along with their relationships to the vertical mixing at LaPorte, the large-scale pressure pattern, and cloud cover.

Vertical Mixing: The hourly height of the daytime surface-based mixed layer was estimated from the LaPorte radar profiler reflectivity data for all episode days. Reflectivity data were not of sufficient quality to estimate mixing heights on June 23 and 24, 2005, and August 2, 2005. The mixing height data were used to determine the characteristics of the daytime mixed layer including the period of Convective Boundary Layer (CBL) growth, the maximum height of the CBL, the time of maximum height of the CBL, and any undercutting of the CBL by the Bay and/or Gulf boundary layers.

Cloud Cover: Quarter-hourly visible satellite images of southeast Texas were reviewed to characterize the spatial and temporal variations in cloud cover and its probable impact on photochemistry. The existence and movement of clouds associated with large-scale systems, convective activity, the land breeze front, the Bay breeze front, and the Gulf breeze front were noted.

Ozone Patterns: Spatial and temporal ozone patterns were analyzed by reviewing spatial plots of 8-hour ozone data collected at continuous ambient monitoring stations (CAMS) sites in the Houston and Galveston Bay area. The ozone plots were reviewed in conjunction with the meteorological data discussed above.

1.2 RESULTS

1.2.1 Climatological Analyses

Spatial and Temporal Characteristics of Winds and Mixing:

Figures 1-2 through 1-4 show the average diurnal mixing heights for the Dallas-Fort Worth, San Antonio-Austin, and Houston metropolitan areas. Mixing heights at San Antonio-Austin and Dallas-Fort Worth were lowest during the winter, between 500 m agl during the

morning hours, and 1500 m agl at their peak. Mixing heights at San Antonio-Austin, and Dallas-Fort Worth were highest during the summer, between about 500 m agl during the morning, and about 2000 m agl at their peak. The higher boundary layer is reflective of the warmer temperatures during the summer. Houston's highest mixing heights occurred in the spring, averaging about 600 m agl during the morning hours and reaching about 1650 m agl at their peak, while the peak mixing heights for the other three seasons were similar, ranging between about 500 m agl and 1200 m agl.

San Antonio had the highest peak mixing heights on average (about 2100 m agl during the summer) compared to other sites for all seasons and Houston had the lowest (about 1200 m agl during the summer) except for fall. The high mixing heights were likely due to San Antonio's inland and southern location. The limited seasonal variation in mixing heights at Houston is likely due to the moderating influence of the Gulf of Mexico.

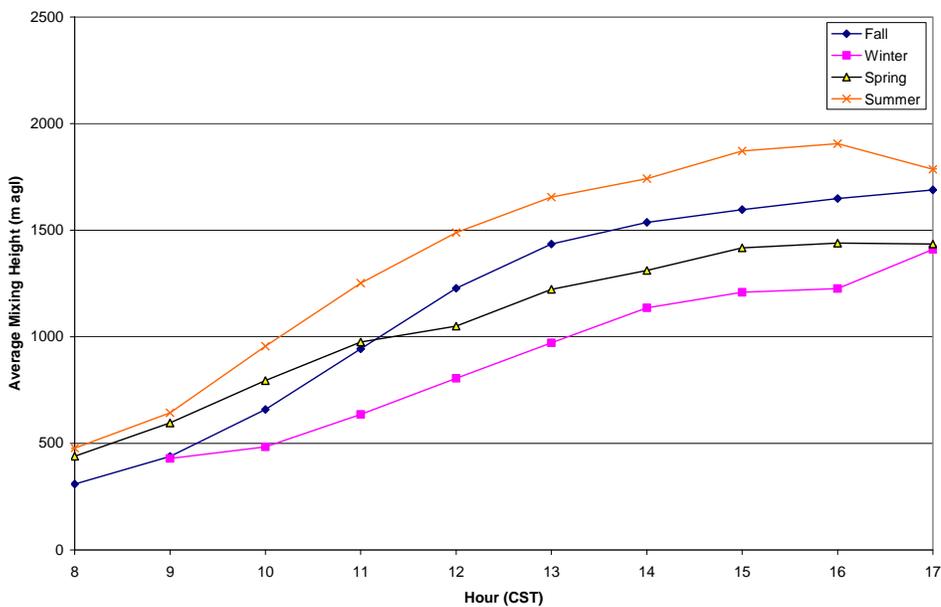


Figure 1-2. Average hourly daytime mixing heights for Dallas-Fort Worth metropolitan area based on RWP data collected at the Cleburne RWP site.

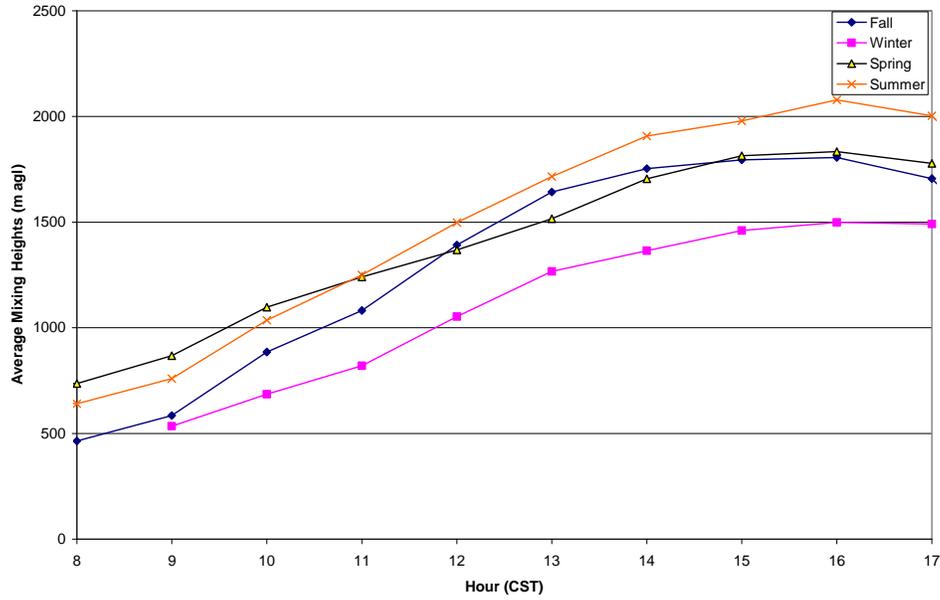


Figure 1-3. Average hourly daytime mixing heights for San Antonio-Austin metropolitan area based on RWP data collected at the New Braunfels RWP site.

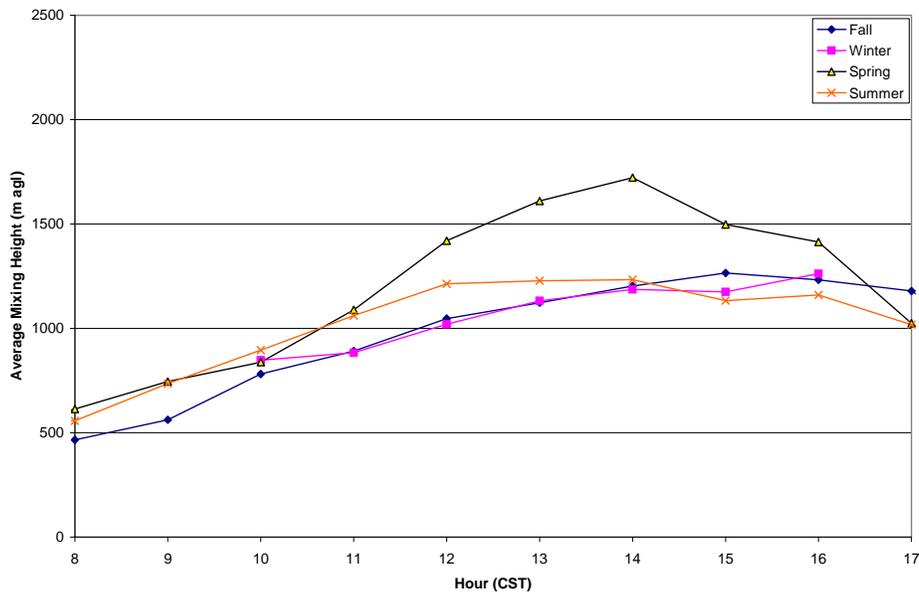


Figure 1-4. Average hourly daytime mixing heights for the Houston metropolitan area based on RWP data collected at the LaPorte RWP site.

Figures 1-5 through 1-7 show the average hourly daytime mixing heights sorted by synoptic pattern for the Houston, San Antonio-Austin, and Dallas-Fort Worth metropolitan areas. Mixing heights in Houston were highest (~1600 m agl) on days with a ridge of high pressure located over Texas. These days had abundant sunshine and greater daytime heating, which would have caused the boundary layer to grow more rapidly and to higher levels, despite warm aloft temperatures.

Mixing heights peaked earlier in the day when there was a weak ridge or broad high pressure system across the southern third of the United States. Mixing heights were lowest (~800 m agl at their highest) on days with a weak low pressure system over the Houston area.

In both the San Antonio-Austin and Dallas-Fort Worth areas, mixing heights were highest (~2000 m agl) on days when a broad high pressure system covered the southern third of the United States. The lowest mixing heights (between about 300 and 1600 m agl) were observed on days when aloft flow over Texas was classified as zonal (West to East).

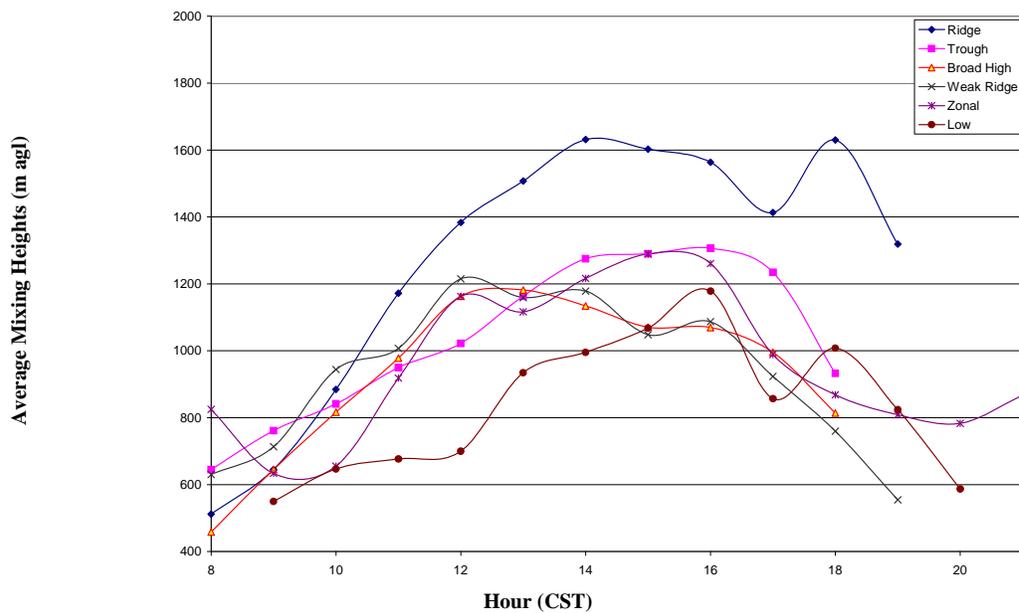


Figure 1-5. Diurnal mixing heights for the Houston metropolitan area for May 2005 through October 2006, by synoptic type.

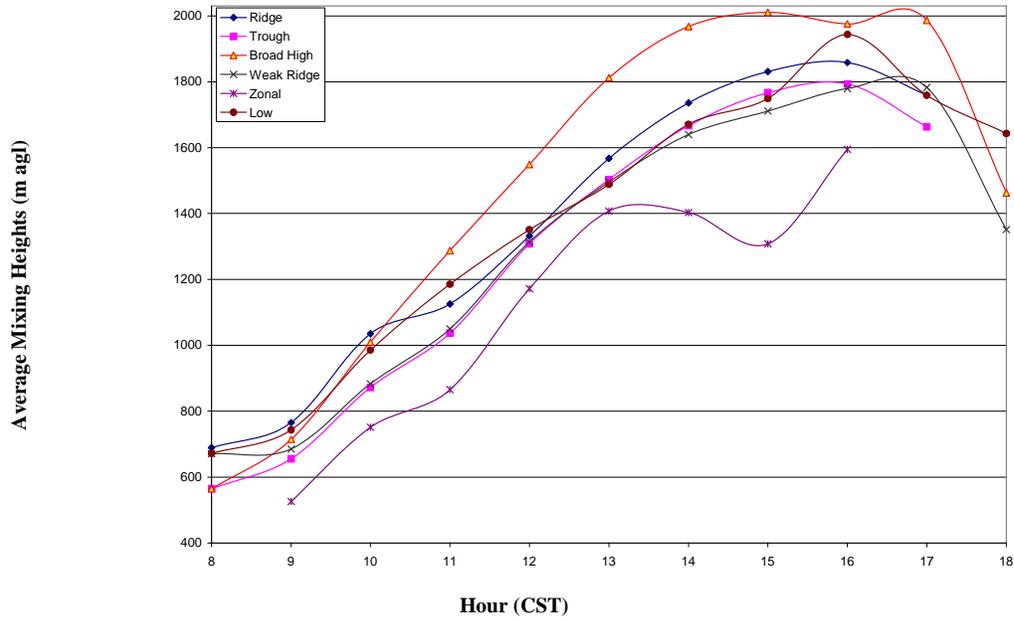


Figure 1-6. Diurnal mixing heights for the San Antonio-Austin metropolitan area for May 2005 through October 2006, by synoptic type.

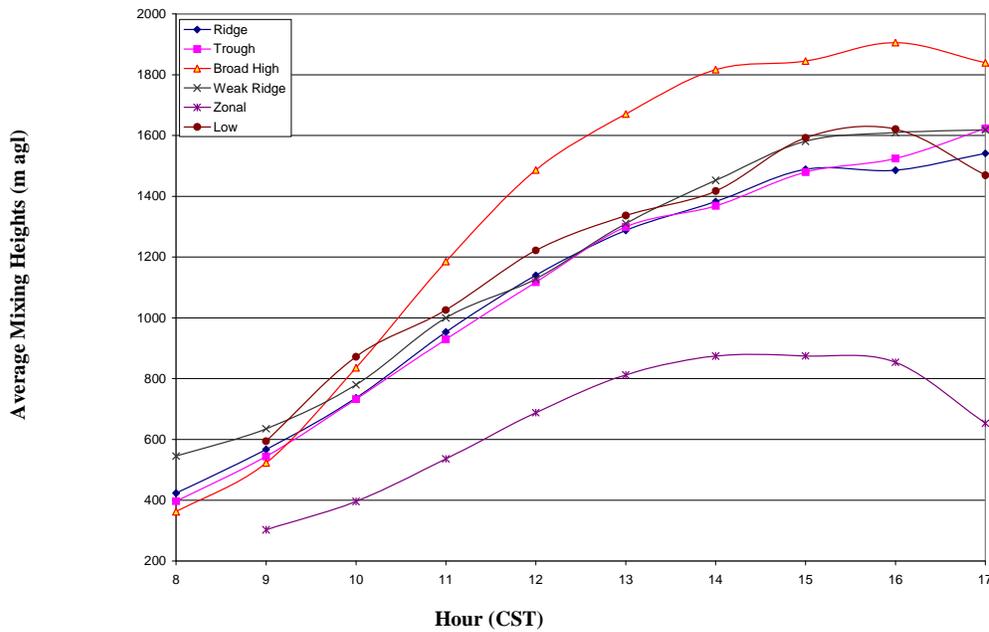


Figure 1-7. Diurnal mixing heights for the Dallas-Fort Worth metropolitan area for May 2005 through October 2006, by synoptic type.

Relationship Between Wind, Transport, Mixing Heights, and Air Quality

Figure 1-8 shows the average peak mixing heights for episode and non-episode days for May through October, 2005 and 2006. The peak mixing heights were about 20% higher on episode days at Dallas-Fort Worth and San Antonio, while they varied little between episode and non-episode days at Houston, which may be due to the influence of the Gulf of Mexico.

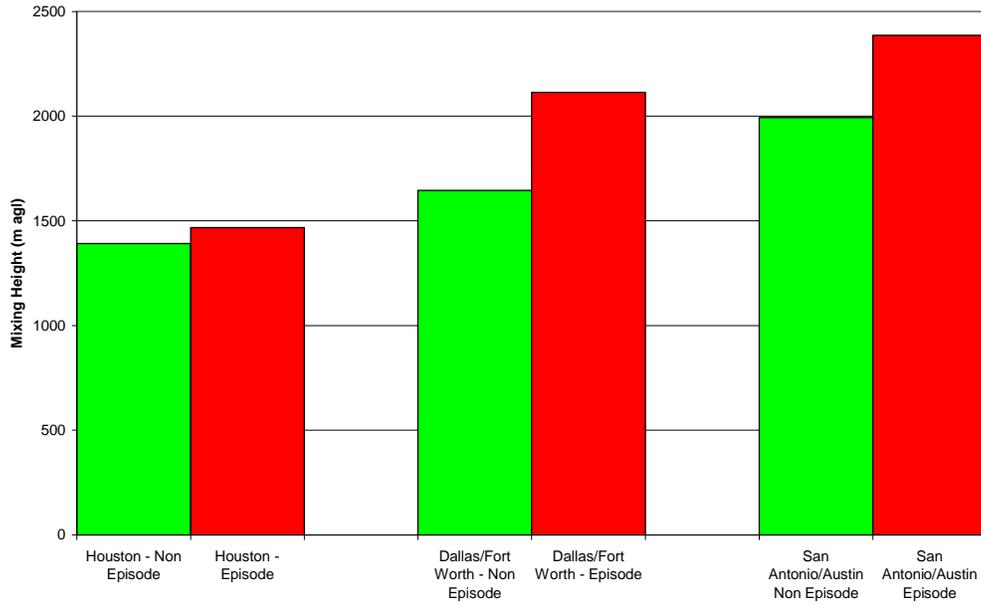


Figure 1-8. Average peak mixing heights for episode and non-episode days for May through October, 2005 and 2006 for the Houston, Dallas-Fort Worth, and San Antonio-Austin metropolitan areas.

Figure 1-9 shows that the time of peak mixing was similar for episode and non-episode days for all three areas. However, the peak mixing heights were observed around 2:00 p.m. CST at Houston, compared to around 3:00 p.m. CST at Dallas-Fort Worth and San Antonio-Austin. This difference in the time of peak mixing is likely due to the Bay and Gulf breeze undercutting the convective boundary layer in Houston.

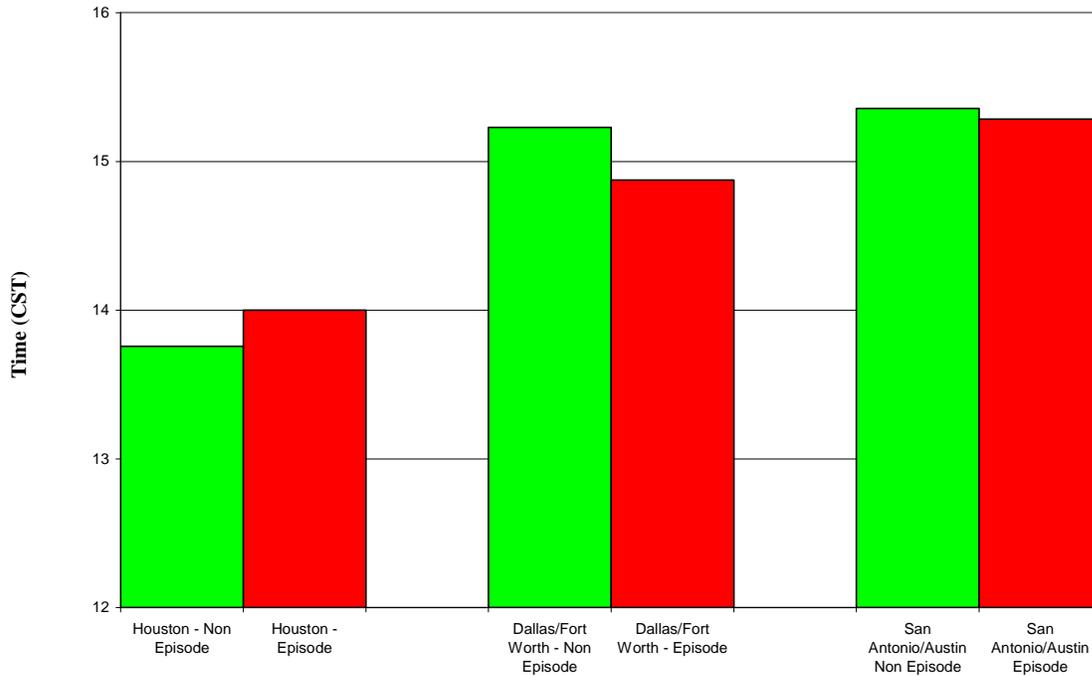


Figure 1-9. Average time of peak mixing for the Houston, Dallas-Fort Worth, and San Antonio-Austin metropolitan areas for May through October, 2005 and 2006, for episode and non-episode days.

Figure 1-10 shows the average morning mixing heights in each area for episode and non-episode days. In Houston, the average morning mixing heights were lower on episode days (about 810 m agl as opposed to nearly 1000 m agl on non-episode days), whereas, in Dallas-Fort Worth and San Antonio-Austin, they were higher on episode days (about 1150 to 1300 m agl).

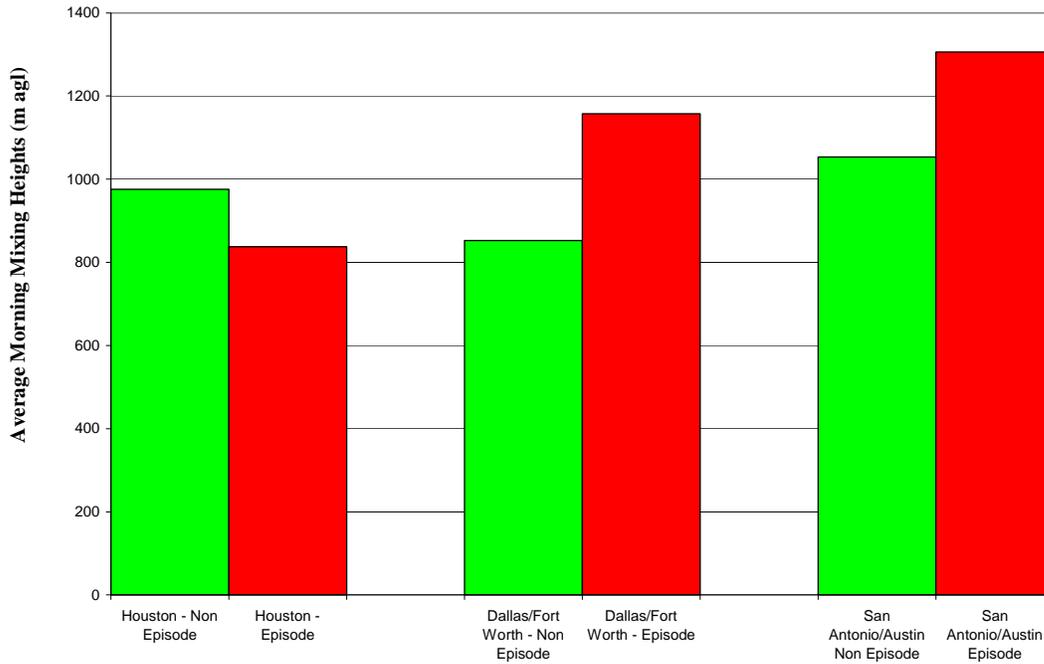


Figure 1-10. Average morning mixing heights (9:00 a.m. to 12:00 p.m. CST) for the Houston, Dallas-Fort Worth, and San Antonio-Austin metropolitan areas for May through October, 2005 and 2006, for episode and non-episode days.

Figure 1-11 shows the average morning mixing height growth rates (MGR) in each area for episode and non-episode days. The lowest MGR occurred on non-episode days at all sites. In Houston, the MGR were slightly higher on episode days, about 210 m over a three-hour period compared to about 180 m on non-episode days; whereas, the MGR were significantly greater at Dallas-Fort Worth on episode days (about 380 m) compared to non-episode days (about 220 m) and at San Antonio-Austin on episode days (about 405 m) compared to about 245 m on non-episode days.

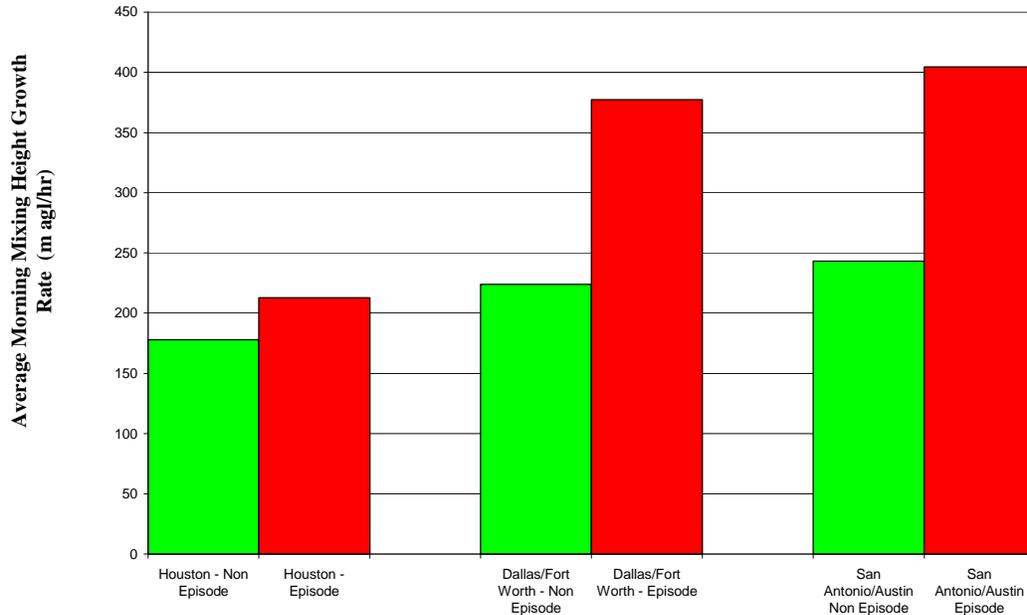


Figure 1-11. Average morning mixing height growth rates (9:00 a.m. to 12:00 p.m. CST) for the Houston, Dallas-Fort Worth, and San Antonio-Austin metropolitan areas for May through October, 2005 and 2006, for episode and non-episode days.

Figure 1-12 shows the 24-hour 6:00 a.m. CST to 6:00 a.m. CST transport roses for the Brazos A19, LaPorte, New Braunfels, and Cleburne RWP sites. **Tables 1-1** and **1-2** summarize the transport distances and directions shown in Figure 1-12. In general, winds were primarily out of the south-southeast on non-episode days with larger transport distances. On episode days, winds were spread over more directions with shorter distances. These results suggest that weaker horizontal dispersion may offset the dilution effect caused by higher mixing heights during episodes. In addition, the frequent south-southeast-easterly wind flow on episode days suggests that transport from Houston to cities from the north through west occurs.

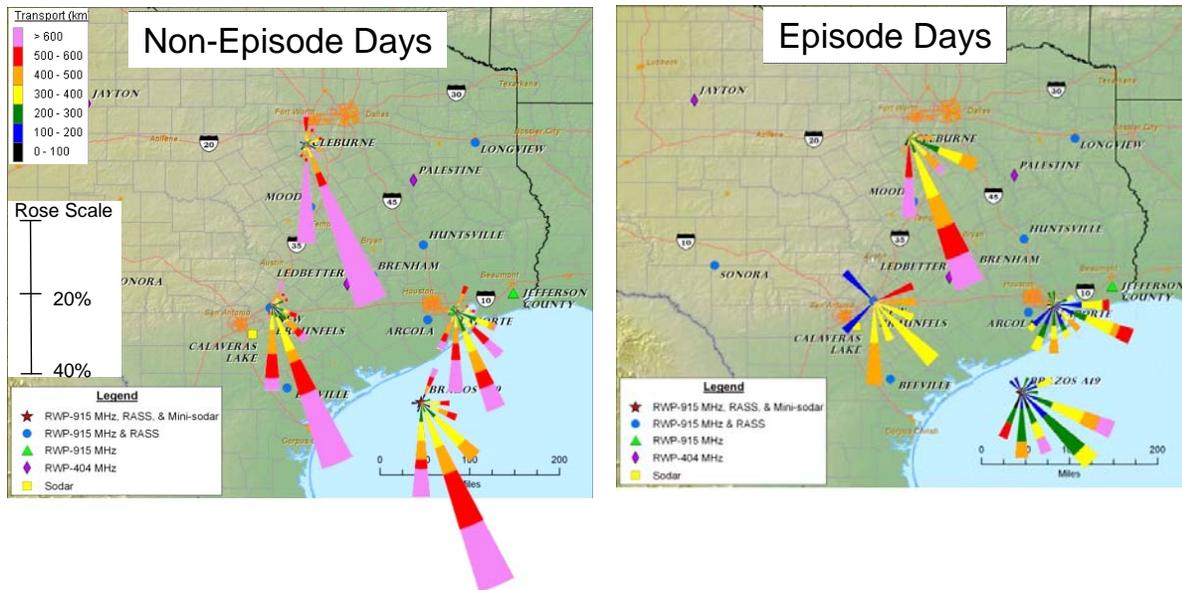


Figure 1-12. Transport roses for non-episode and episode days at the Brazos A19, LaPorte, New Braunfels, and Cleburne RWP sites for May through October, 2005 and 2006, at 400-500 m agl.

Table 1-1. Summary of 24-hour transport distance and direction for non-episode days.

Site	Predominant Transport Distance (km)	Average Transport Distance (km)	Predominant Transport Direction
Houston	> 600	~450	South-Southeast
Dallas-Fort Worth	> 600	~620	South-Southeast
San Antonio-Austin	> 600	~490	South-Southeast

Table 1-2. Summary of 24-hour transport distance and direction for episode days.

Site	Predominant Transport Distance (km)	Average Transport Distance (km)	Predominant Transport Direction
Houston	100-200	~267	Southeast
Dallas-Fort Worth	Evenly Distributed	~450	Southeast
San Antonio-Austin	300-400	~330	Southeast

Figure 1-13 shows the average ventilation indices for Dallas-Fort Worth, San Antonio-Austin, and Houston on episode and non-episode days. At all sites, the ventilation index was lower on episode days (~30% lower on episode days at all three sites).

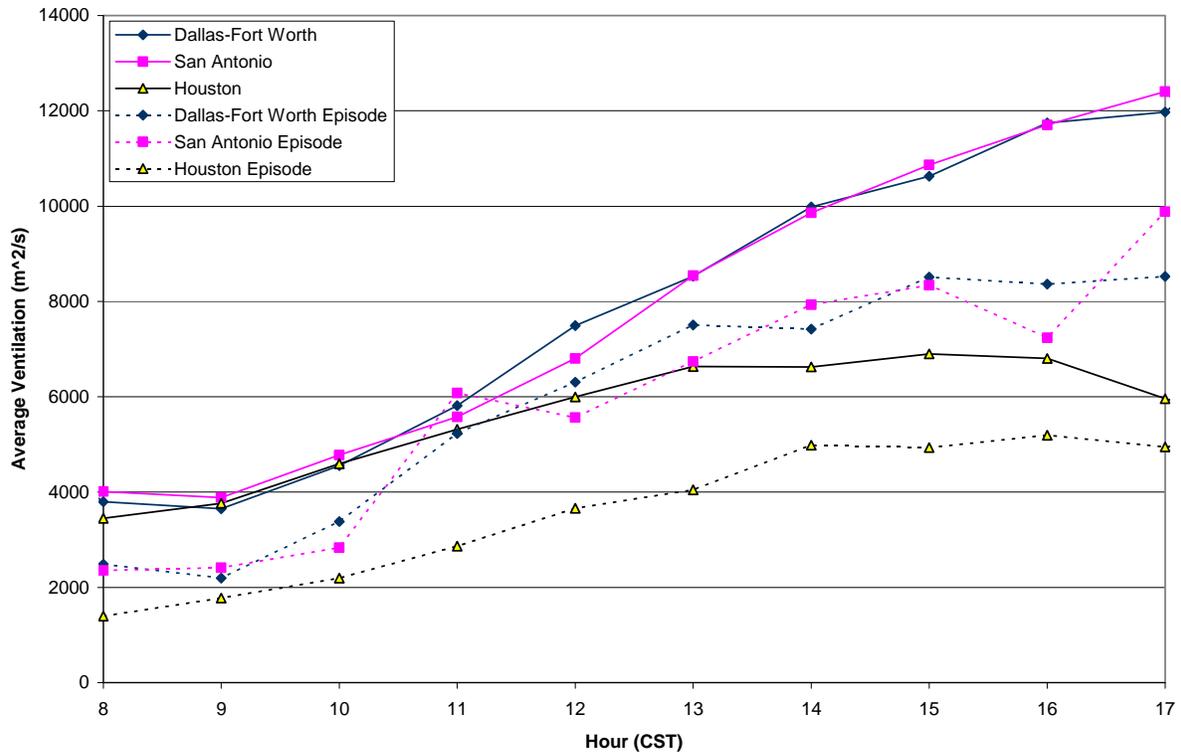


Figure 1-13. Average ventilation indices for episode and non-episode days at Dallas-Fort Worth, San Antonio-Austin, and Houston for May through October, 2005 and 2006, at 400 to 500 m agl.

In summary, mixing heights were generally higher on episode days. However, wind speeds were found to be lower on episode days. The mixing height and wind speed statistics were combined to form the ventilation index, which was lower on episode days at all sites. The lower ventilation indices indicate that less horizontal dispersion counteracted the enhanced vertical dilution created by the higher mixing heights on episode days.

1.2.2 Case Study Analyses

This section summarizes the important meteorological and ozone characteristics for the days listed in **Table 1-3**. Table 1-3 provides a brief summary of the key phenomenon responsible for the air quality on each day. The details of each case study follow.

Table 1-3. Summary of Case Studies.

Date	Peak 1-hr Ozone (ppb)	Peak 8-hr Ozone (ppb)	Key Phenomenon
6/22/2005	123	104	<ul style="list-style-type: none"> • Weak Surface Pressure Gradient Leads to Bay/Gulf Breeze Cycle • Few Clouds
6/23/2005	138	96	<ul style="list-style-type: none"> • Light Southeasterly Winds Limit Dispersion • Mostly Sunny Skies
6/24/2005	104	91	<ul style="list-style-type: none"> • Bay/Gulf Breeze Circulation Leads to Recirculation • Upper-level High Limits Mixing
6/25/2005	93	82	<ul style="list-style-type: none"> • Moderate Gulf Breeze Enhances Dispersion • Cloud Cover Limits Ozone Formation
7/31/2005	86	72	<ul style="list-style-type: none"> • High Mixing Heights • Northerly Flow
8/1/2005	140	93	<ul style="list-style-type: none"> • Low Mixing Heights • Bay/Gulf Breeze Forces Highest Ozone Concentrations Over Northwestern Houston
8/2/2005	135	104	<ul style="list-style-type: none"> • Recirculation of Pollutants Results in Highest Ozone Concentrations Over Western and Southern Houston
8/31/2006	147	127	<ul style="list-style-type: none"> • Bay/Gulf Breeze Circulation Leads to Recirculation • No Clouds • Low Mixing Heights
9/1/2006	161	121	<ul style="list-style-type: none"> • Land/Bay/Gulf Breeze leads to Recirculation • Upper-level High Limits Vertical Mixing
9/2/2006	90	80	<ul style="list-style-type: none"> • Cold Front passing through, which enhances vertical mixing, which lowers ozone concentrations

June 22, 2005

High ozone concentrations existed throughout the Houston area, with the exception of the northwest sector of Houston where the ozone concentrations were Moderate on the AQI. High ozone concentrations were associated with a weak surface pressure gradient that allowed the Land/Bay/Gulf breeze to occur, resulting in recirculation of air in the Houston area.

- **Large-Scale Aloft:** An aloft high pressure system centered over the Kansas/Colorado region expanded over all of Texas, increasing the likelihood of subsidence in Houston.
- **Large-Scale Surface:** There was a surface high pressure system centered over northern Mississippi. This high-pressure system led to a weak pressure gradient in the Houston area that allowed local flows to dominate.
- **Local Meteorology:** There was a Bay/Gulf breeze cycle in the afternoon, with a period of northerly flow in the morning.
 - Transport and Surface Winds:
 - The 50 m and 300 m 24-hour backward trajectory ending at 10:00 a.m. CST on June 22 showed that the air flow came from the south-southeast and then shifted to the northwest, then came from the north-northwest during the last six hours.
 - At 700 m, the trajectories show that the air flow came from the northeast during the last six hours.
 - Time/height Structure:
 - From 5:00 a.m. CST to 9:00 a.m. CST, a northerly offshore flow was apparent between the surface and about 600 m (see **Figure 1-14**).
 - At around 11:00 a.m. CST, an easterly Bay breeze developed, lasting until at least 3:00 p.m. CST.
 - Following the Bay breeze there was a Gulf breeze, though the exact time shift is not clear in Figure 1-14 due to a couple of hours of missing data. The Gulf breeze continued for the rest of the night.
 - No mixing height data were available for this day.
- **Cloud Cover:** Clouds did not significantly influence ozone concentrations. There were scattered clouds throughout the morning and afternoon, with clearing in the evening around 5:30 p.m. CST.
- **Ozone Patterns:** Ozone levels were high in the Galveston Bay region (above 100 ppb) early in the day; ozone levels were high in western Houston in the afternoon. By 6:00 p.m. CST the ozone levels in the Houston region dropped below 100 ppb.

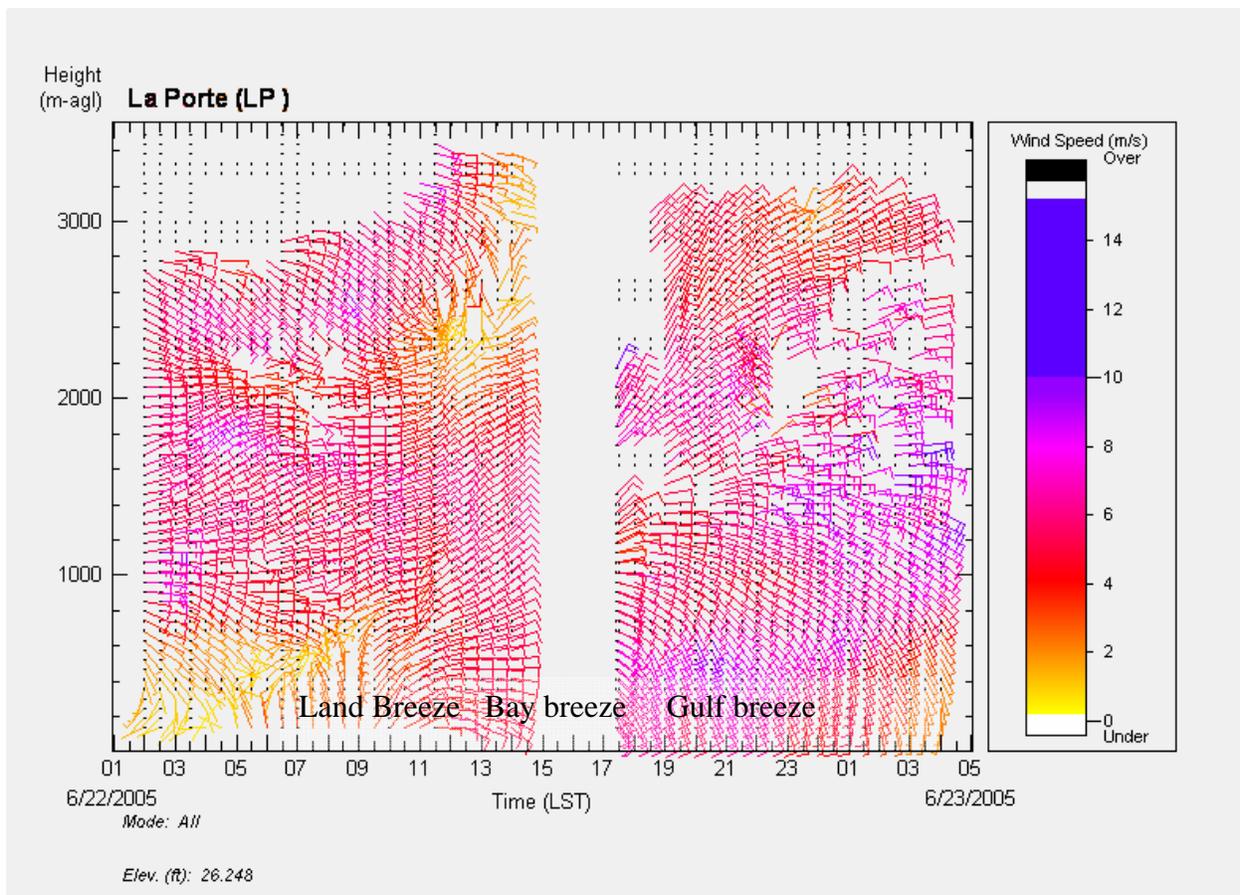


Figure 1-14. RWP winds at LaPorte from 1:00 a.m. CST on June 22, 2005, through 4:00 a.m. CST on June 23, 2005.

June 23, 2005

Ozone concentrations were high on this day, but lower than they were on June 22. High ozone concentrations were confined to northwest Houston and were influenced by mostly sunny skies and light southeasterly winds that limited dispersion.

- **Large-Scale Aloft:** An aloft surface high pressure system was over New Mexico. In addition, there was weak anticyclonic circulation over the Houston area, leading to subsidence over Houston.
- **Large-Scale Surface:** The surface high pressure system over Mississippi broadened and moved west, encompassing eastern and central Texas. Like on the previous day, there was still a weak pressure gradient that allowed local flows to dominate in Houston.
- **Local Meteorology:** No wind data were collected from 3:00 a.m. CST to 8:00 a.m. CST at the LaPorte profiler. Mixing height data were also unavailable.

- Transport and Surface Winds:
 - The 50 m, 300 m, and 700 m 24-hour backward trajectory ending at 11:00 a.m. CST on June 23 (see **Figure 1-15**) showed that air flow came from the Freeport region, south of Houston.
- Time/height Structure:
 - From 3:00 a.m. CST to 8:00 a.m. CST the boundary layer flow shifted from southerly to northerly.
 - No mixing height data were available for this day.
- **Cloud Cover:** Clouds did not significantly affect ozone concentrations. There were scattered clouds from 11:00 a.m. CST to 5:00 p.m. CST, with clear skies for the rest of the day.
- **Ozone Patterns:** Ozone levels started the day elevated in the northern suburbs of Houston. As the day progressed, the higher ozone concentrations moved south into the western and north central areas of Houston. By 3:00 p.m. CST, ozone concentrations were above 100 ppb and had moved back into the northern suburbs of Houston.

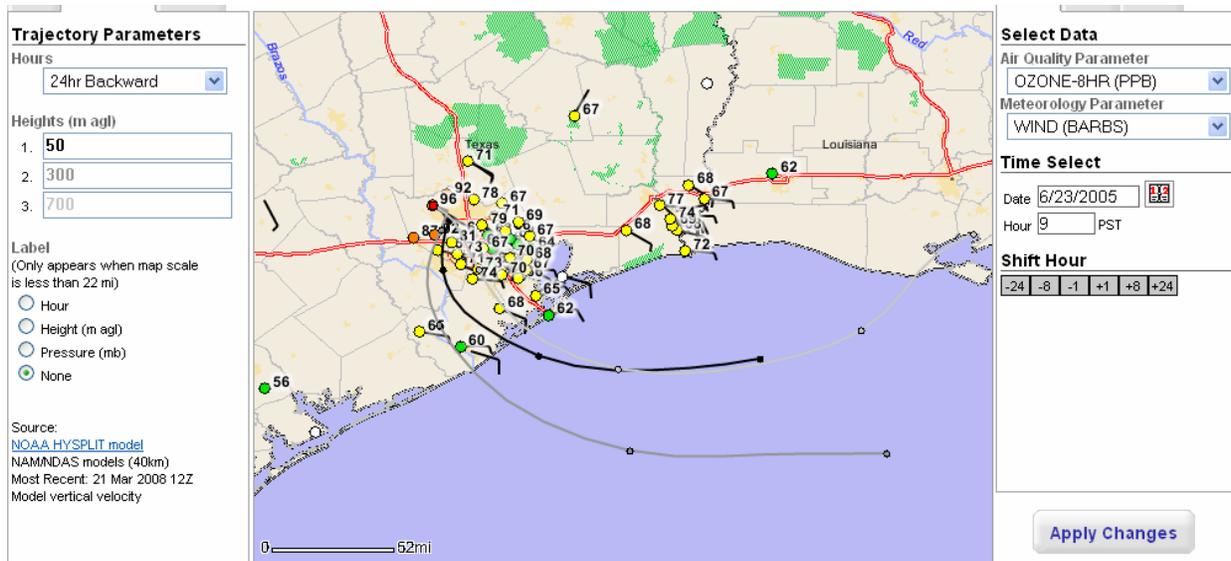


Figure 1-15. 24-hour backward trajectories ending at 11:00 a.m. CST calculated using the AIRNow-tech Navigator software.

June 24, 2005

Ozone concentrations were high, but lower than on June 22 and 23. High ozone concentrations were confined to northwest Houston, influenced by recirculation and an upper-level high that limited mixing.

- **Large-Scale Aloft:** The high pressure system that covered Houston weakened and moved out of the area. As a result, subsidence over Houston was likely weak.

- **Large-Scale Surface:** The high-pressure system from June 22 and 23, moved east over the mid-Atlantic states. However, similar to the previous two days, local flows dominated on this day.
- **Local Meteorology:** Wind data from the LaPorte profiler were missing before 10:30 a.m. CST. The rest of the day the boundary layer flow was southeasterly with easterly flow aloft.
 - Transport and Surface Winds:
 - The 50 m 24-hour backward trajectory ending at 10:00 a.m. CST on June 24 (see **Figure 1-16**) showed that air flow re-circulated north of Houston in the last six hours.
 - The 300 m and 700 m air flow came from the Galveston area and traveled to the northwest.
 - Time/height Structure:
 - A Gulf breeze from 2:00 p.m. CST to 8:00 p.m. CST occurred in the lower 1000-1200 m agl, as shown in **Figure 1-17**.
 - Winds were easterly throughout the day above 1200 m agl.
 - No mixing height data were available for this day.
- **Cloud Cover:** Clouds were not significant. There were clear skies for most of the day with a few clouds in the afternoon.
- **Ozone Patterns:** Hourly ozone concentrations above 100 ppb were limited to a few stations northwest of Houston. The higher ozone values were limited to between 11:00 a.m. CST and 1:00 p.m. CST.

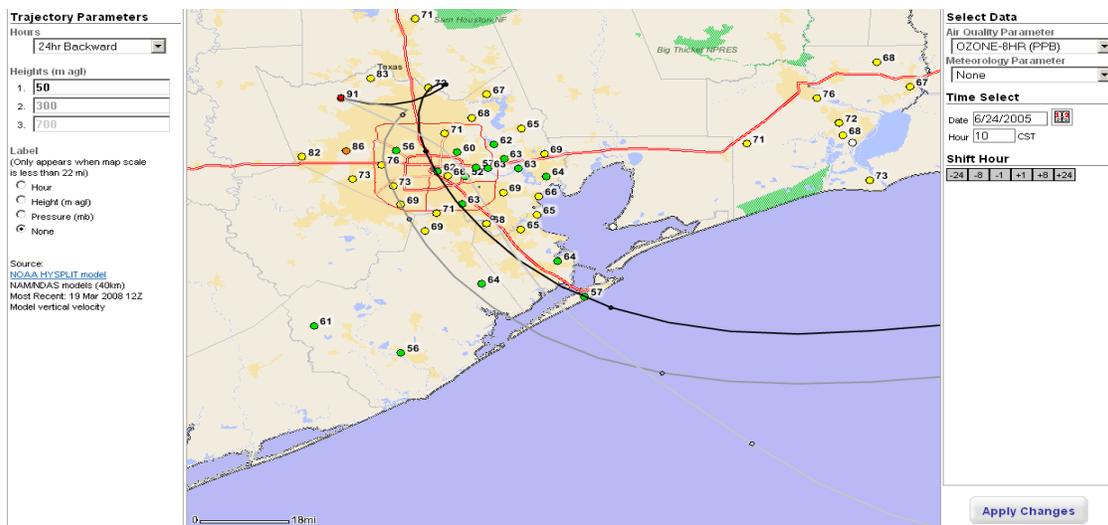


Figure 1-16. 24-hour backward trajectories ending at 10:00 a.m. CST calculated using the AIRNow-tech Navigator software.

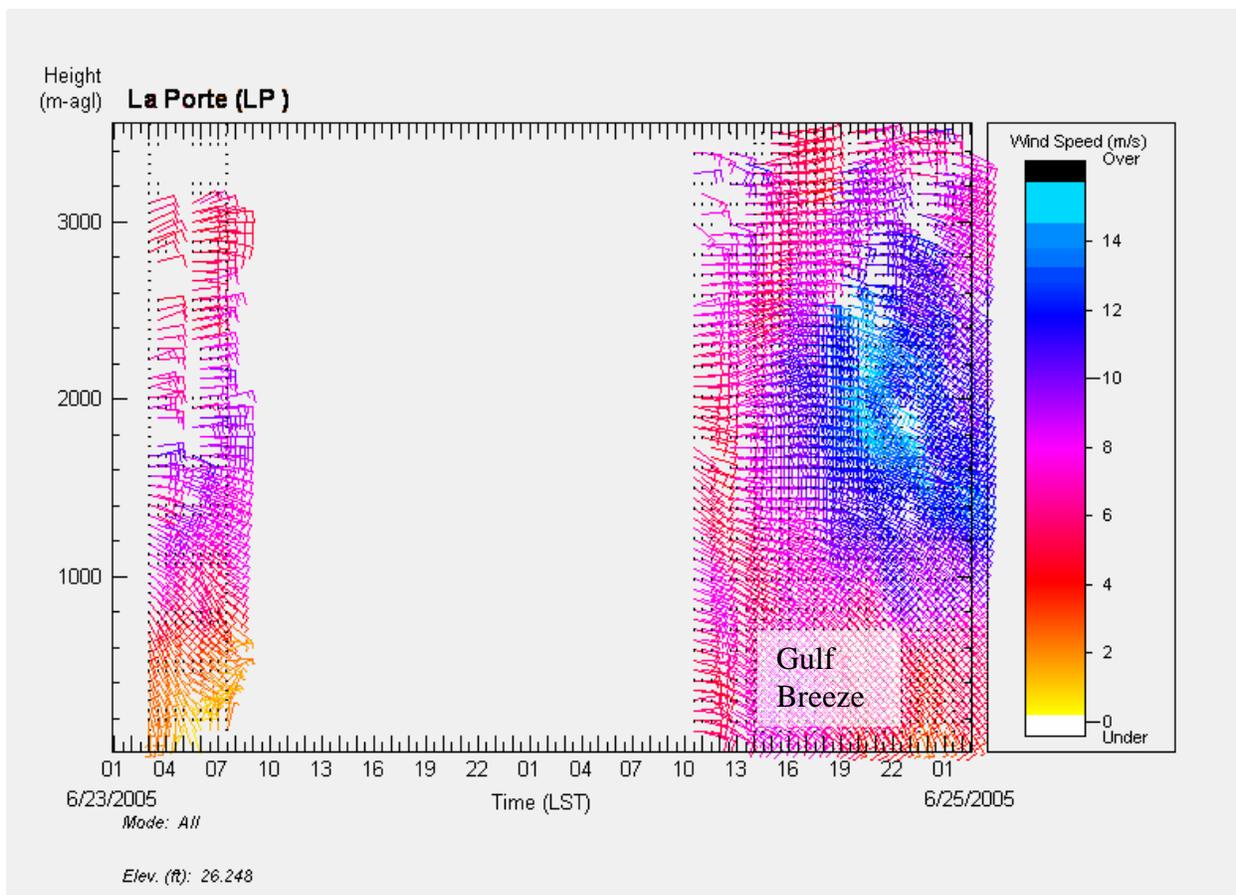


Figure 1-17. RWP winds at LaPorte from 2:00 a.m. CST on June 23, 2005, through 2:00 a.m. CST on June 25, 2005. No wind data were collected between 8:00 a.m. CST on June 23, 2005, and 10:00 a.m. CST on June 24, 2005.

June 25, 2005

Low ozone concentrations were associated with a moderate Gulf breeze that enhanced dispersion and cloud cover, limiting ozone formation.

- **Large-Scale Aloft:** The aloft surface high pressure system moved over eastern New Mexico, which caused the anticyclonic circulation to move west of Houston.
- **Large-Scale Surface:** The high pressure system from previous days moved east of Houston. A low-pressure system in northern Mexico produced easterly flow in the Houston area.
- **Local Meteorology:** There were easterly winds throughout the morning with a Gulf breeze in the late afternoon and evening.
 - Transport and Surface Winds:

- The 300 m and 700 m 24-hour backward trajectory ending at 10:00 a.m. CST on June 25 showed that air flow came from the Texas City area, southeast of Houston.
- The 50 m air flow came from the Galveston area until the last 6-12 hours. During the last 6-12 hours, the transport went north of downtown Houston, and then shifted back to the downtown area, before heading west.
- Time/height Structure:
 - From about 5:00 a.m. CST through 2:00 p.m. CST there was easterly flow in and above the boundary layer.
 - At 3:00 p.m. CST, a Gulf breeze was observed in the boundary layer, lasting until about 9:00 p.m. CST (see Figure 1-18).
 - No mixing height data were available for this day.
- **Cloud Cover:** Clouds were present beginning about 1:30 p.m. CST over eastern Houston, and the over entire Houston area by 2:00 p.m. CST. The clouds were probably associated with the low-pressure system and not the Gulf breeze.
- **Ozone Patterns:** Ozone levels were low. The ozone concentrations were uniform around the Houston area throughout the day with no major spikes in the hourly concentrations.

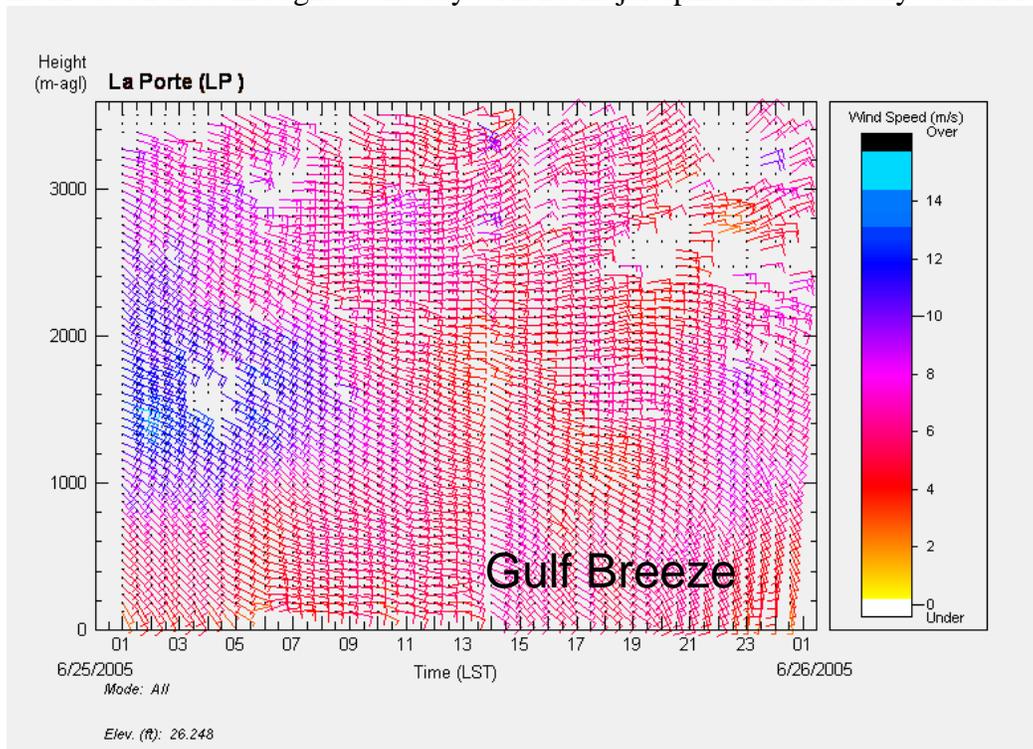


Figure 1-18. RWP winds at LaPorte for 1:00 a.m. CST on June 25, 2005, through 1:00 a.m. CST on June 26, 2005.

July 31, 2005

Ozone concentrations were low due to the high mixing heights and northerly flow.

- **Large-Scale Aloft:** There was a broad high pressure system centered over Kansas/Colorado, likely producing weak subsidence over the Houston area.
- **Large-Scale Surface:** A broad high-pressure system was located in northern Arkansas. This high-pressure system led to a weak pressure gradient in the Houston area that allowed local flows to dominate.
- **Local Meteorology:** The air flow was from the northeast, which allowed for cleaner air to move into the Houston area, keeping ozone levels low.
 - Transport and Surface Winds:
 - The 50 m, 300 m, and 700 m 24-hour backward trajectory ending at 10:00 a.m. CST on July 31 showed that air flow came from the north-northwest for most of the day.
 - Time/height Structure:
 - The CBL grew to the highest level of all episode days reviewed. In addition, the northerly wind seen in RWP data collected at LaPorte enhanced horizontal dispersion, keeping ozone levels low. At the end of the day, there was a short and shallow Bay/Gulf breeze.
 - The maximum height of the CBL occurred at 5:00 p.m. CST at a height of 3061 m agl (see **Figure 1-19**).
 - The growth of the CBL from 9:00 a.m. CST to 12:00 p.m. CST was 1910 m.
 - From 1:00 a.m. CST to 5:00 a.m. CST the winds in the lower 600 m agl shifted from easterly to northerly (see Figure 1-19).
 - The boundary layer flow was northeasterly from 6:00 a.m. CST to 5:00 p.m. CST.
 - A shallow Bay breeze occurred from 5:00 p.m. CST to 8:00 p.m. CST in the lower 400 m agl.
 - A Gulf breeze came in from 8:30 p.m. CST to 11:30 p.m. CST below 600-800 m agl.
 - The winds were easterly from 11:00 a.m. CST through the end of the day above 2000 m agl.
- **Cloud Cover:** There were clear skies until about 10:30 p.m. CST when a thunderstorm developed over Galveston Bay. The thunderstorm was very short and dissipated rapidly.
- **Ozone Patterns:** The ozone levels were the lowest of the episode. The highest one-hour values of the day were in the afternoon in southern Houston, while northern Houston's values remained low.

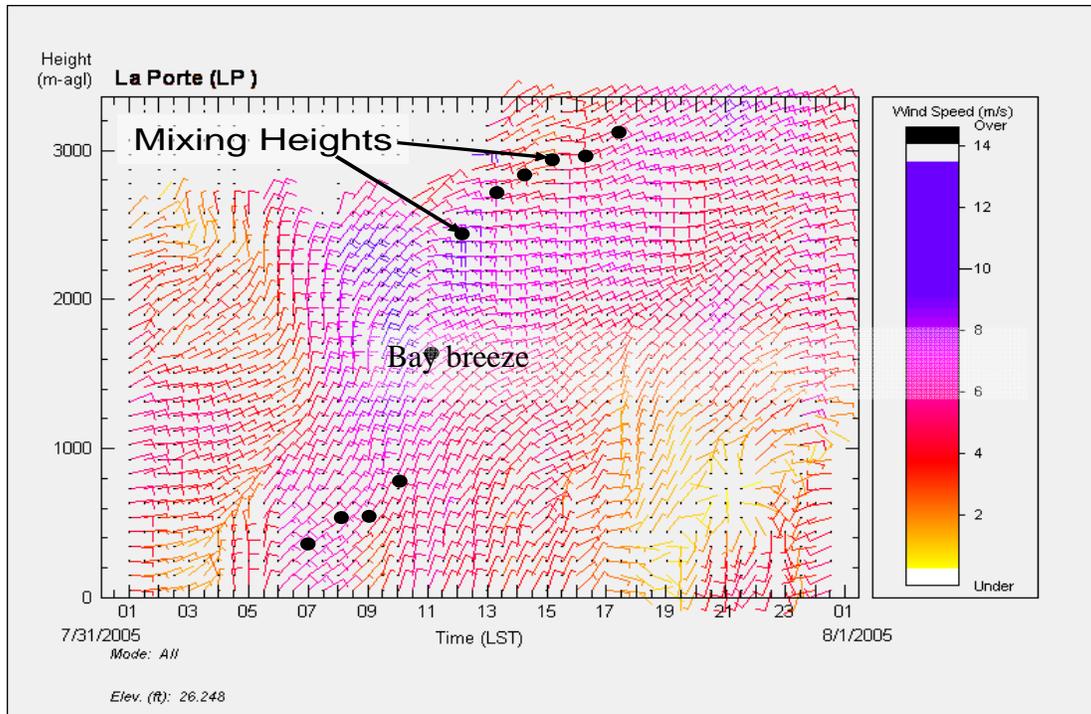


Figure 1-19. RWP winds and mixing heights (black dots) at LaPorte from 1:00 a.m. CST on July 31, 2005, through 1:00 a.m. CST on August 1, 2005.

August 1, 2005

Ozone concentrations were high due to low mixing heights and the Land/Bay/Gulf breeze circulation

- **Large-Scale Aloft:** The high pressure system from July 31 expanded eastward; while Houston was on the edge of the system, likely resulting in weak subsidence in the area.
- **Large-Scale Surface:** The high pressure system moved over West Virginia, while the pressure gradient remained weak over Houston, allowing local flows to dominate.
- **Local Meteorology:** There was a Land/Bay/Gulf breeze circulation in the boundary layer.
 - Transport and Surface Winds:
 - The 50 m and 300 m 24-hour backward trajectory ending at 10:00 a.m. CST on August 1 showed that air flow re-circulated northeast of Houston and then flowed back over western Houston.
 - The 700 m air flow came from the northeast.
 - Time/height Structure:
 - From 12:30 a.m. CST to 8:00 a.m. CST the boundary layer flow shifted from westerly to northwesterly, then to northerly (see **Figure 1-20**).
 - At 9:00 a.m. CST a Bay breeze up to 600 m agl blew until 3:30 p.m. CST.

- A Gulf breeze up to about 800 m agl started to blow at 3:30 p.m. CST.
- **Cloud Cover:** Clouds and convective activity were significant in the afternoon and evening. The convective activity that occurred at 3:00 p.m. CST was associated with the Bay and Gulf breeze.
- **Ozone Patterns:** Higher ozone levels started in central Houston and moved westward throughout the afternoon. One-hour ozone levels in the middle of Houston were very high, above 130 ppb, from 11:00 a.m. CST to 1:00 p.m. CST. At 2:00 p.m. CST higher ozone levels were in western Houston and by 5:00 p.m. CST ozone levels were down below 80 ppb in Houston.

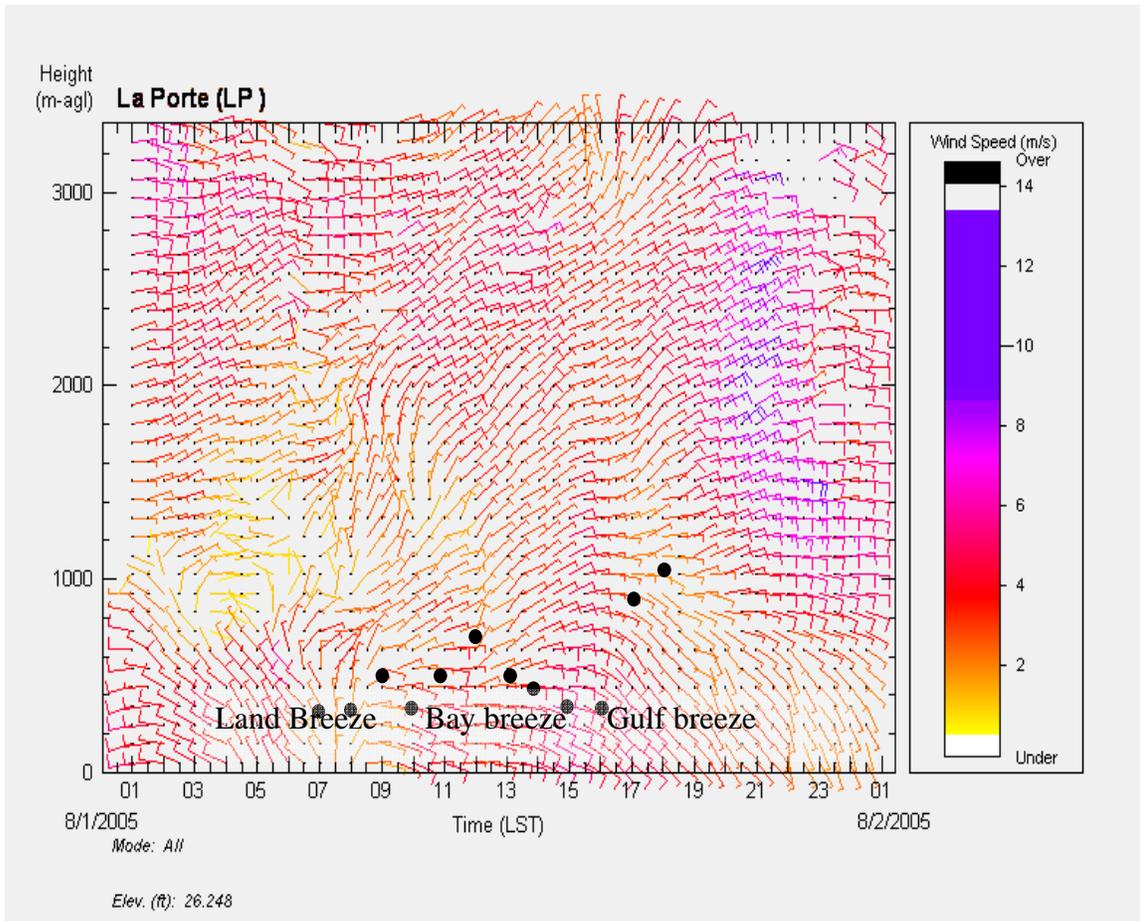


Figure 1-20. RWP winds and mixing heights (black dots) at LaPorte for 1:00 a.m. CST on August 1, 2005, through 1:00 a.m. CST on August 2, 2005.

August 2, 2005

The high ozone concentrations were associated with the recirculation of pollutants over western and southern Houston.

- **Large-Scale Aloft:** High pressure north of Texas likely produced weak subsidence over Houston.

- **Large-Scale Surface:** A weak pressure gradient over the area allowed local flows to dominate.
- **Local Meteorology:** There was a Land/Bay/Gulf breeze cycle.
 - Transport and Surface Winds:
 - The 50 m, 300 m, and 700 m 24-hour backward trajectory ending at 11:00 a.m. CST on August 2, 2005, showed that air flow re-circulated in the Houston area in the prior twelve hours (see **Figure 1-21**).
 - Time/height Structure:
 - **Figure 1-22** shows a northwesterly land breeze up to about 700 m agl from 7:00 a.m. CST to 8:30 a.m. CST.
 - A northeast wind occurred between 8:30 a.m. CST and 12:00 p.m. CST in the lower 600 m agl.
 - A Bay breeze occurred from 12:00 p.m. CST to 5:00 p.m. CST in the lower 600 m agl.
 - A Gulf breeze occurred from 5:00 p.m. CST to 9:00 p.m. CST in the lower 600 m agl.
 - Aloft winds were easterly above 2000 m agl.
- **Cloud Cover:** Clouds and convective activity were significant in the afternoon. Around 3:30 PM CST there was convective activity in the northeast suburbs of Houston.
- **Ozone Patterns:** Ozone levels peaked for the July 31 through August 2, 2005, episode. By 12:00 p.m. CST one-hour ozone levels were above 100 ppb in southern Houston. At 3:00 p.m. CST many sites in southern and western Houston reported ozone values of over 120 ppb.

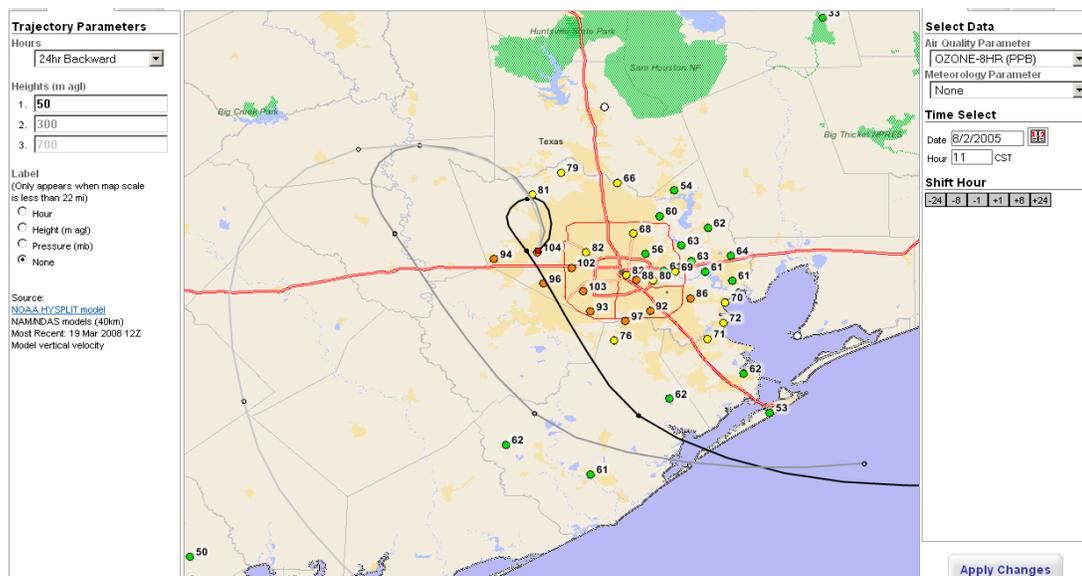


Figure 1-21. 24-hour backward trajectories ending at 11:00 a.m. CST calculated using the AIRNow-tech Navigator software.

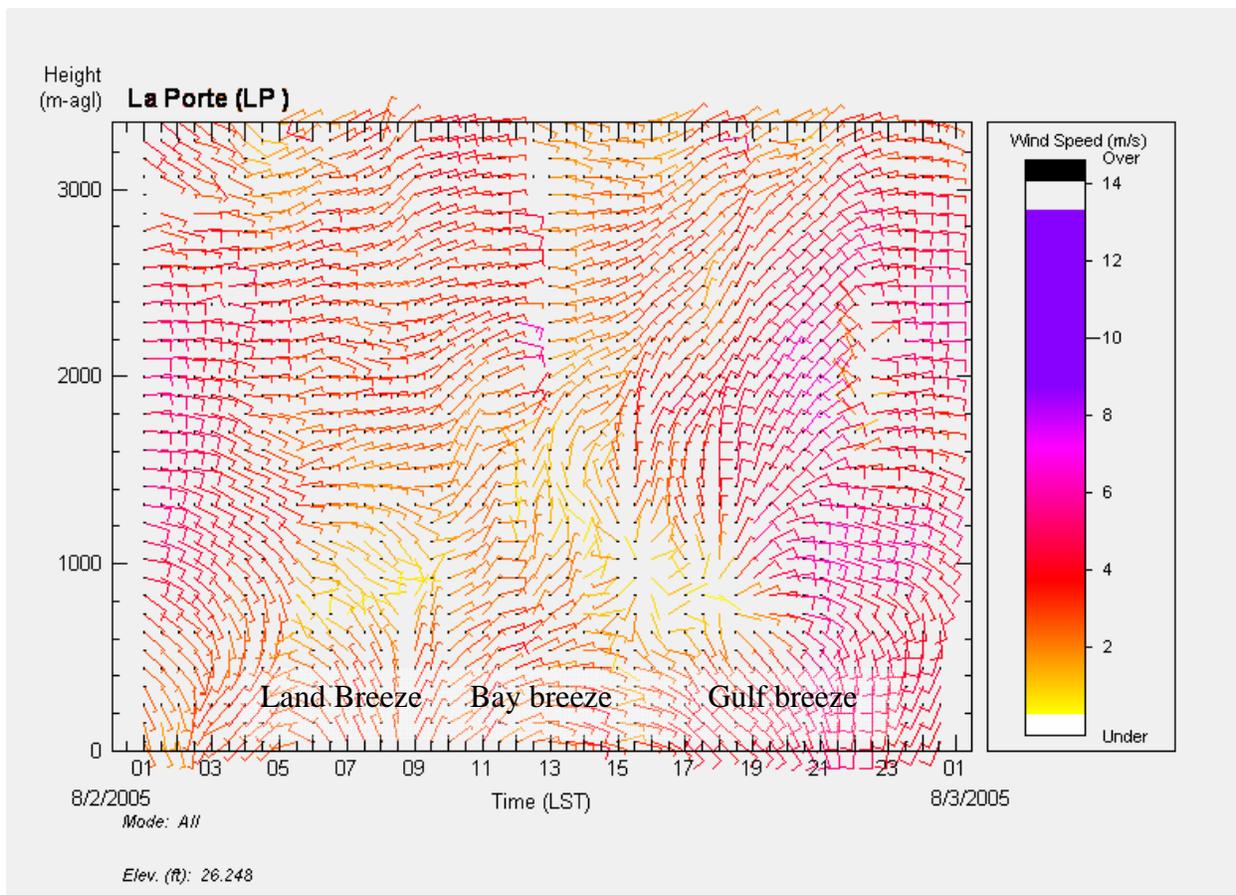


Figure 1-22. RWP winds at LaPorte from 1:00 a.m. CST on August 2, 2005, through 1:00 a.m. CST on August 3, 2005.

August 31, 2006

Ozone concentrations were high because of the influence of the Bay/Gulf breeze that led to recirculation, relatively low mixing heights, and no clouds.

- **Large-Scale Aloft:** The high-pressure system was centered over northeastern Mexico, and only the edge of the system was over the Houston area. In addition, there was weak anticyclonic circulation over Houston.
- **Large-Scale Surface:** A surface high-pressure system was centered over the border of Colorado and New Mexico and a departing low-pressure system was east of Houston in southeastern Alabama. The very weak pressure gradient between these two systems allowed local flows to dominate.
- **Local Meteorology:** The flow was dominated by a Bay breeze until midday when there was a Gulf breeze. There was no Land breeze on this day.

- Transport and Surface Winds:
 - The 50 m 300 m and 700 m 24-hour backward trajectory ending at 11:00 a.m. CST on August 31 showed that air flow came from the northeast.
 - In the last six hours the 50 m trajectory showed that the air flow went from the north edge of downtown Houston to western Houston.
 - Surface winds were light northeasterly in the early morning until 8:00 a.m. CST when they shifted to an easterly Bay breeze.
 - From 12:00 p.m. CST to 6:00 p.m. CST surface winds were primarily southeasterly in the Houston area.
 - At 7:00 p.m. CST surface winds shifted to southerly in the Houston area.
- Time/height Structure:
 - The Bay breeze occurred from 7:00 a.m. CST to 11:00 a.m. CST (see **Figure 1-23**).
 - A Gulf breeze from 12:00 p.m. CST to 10:00 p.m. CST occurred below a height of 400 m agl.
 - Aloft winds were strong, around 20 m/s, and northerly above about 1500 m agl.
 - Mixing heights were low with very slow CBL growth. From 9:00 a.m. CST to 12:00 p.m. CST, the CBL grew 562 m agl (see Figure 1-23). At 9:00 a.m. CST the CBL started at a height of 265 m agl. By 1:00 p.m. CST, the CBL reached its peak at 1202 m agl. The low mixing heights probably played a large role in the high ozone concentrations.
- **Cloud Cover:** There were no clouds in the Houston area; therefore, clouds did not inhibit the production of ozone in the area. The lack of clouds in Houston was related to the anticyclonic flow aloft and resulting subsidence.
- **Ozone Patterns:** Ozone concentrations on this day were higher than any other episode day, with several sites reporting hourly concentrations above 130 ppb. The highest one-hour ozone concentration was 147 ppb in western Houston. The high ozone concentrations started at 11:00 a.m. CST over the downtown Houston area. By 12:00 p.m. CST the high ozone concentrations were over central and western Houston. Ozone concentrations remained above 100 ppb in the Houston area until 7:00 p.m. CST.

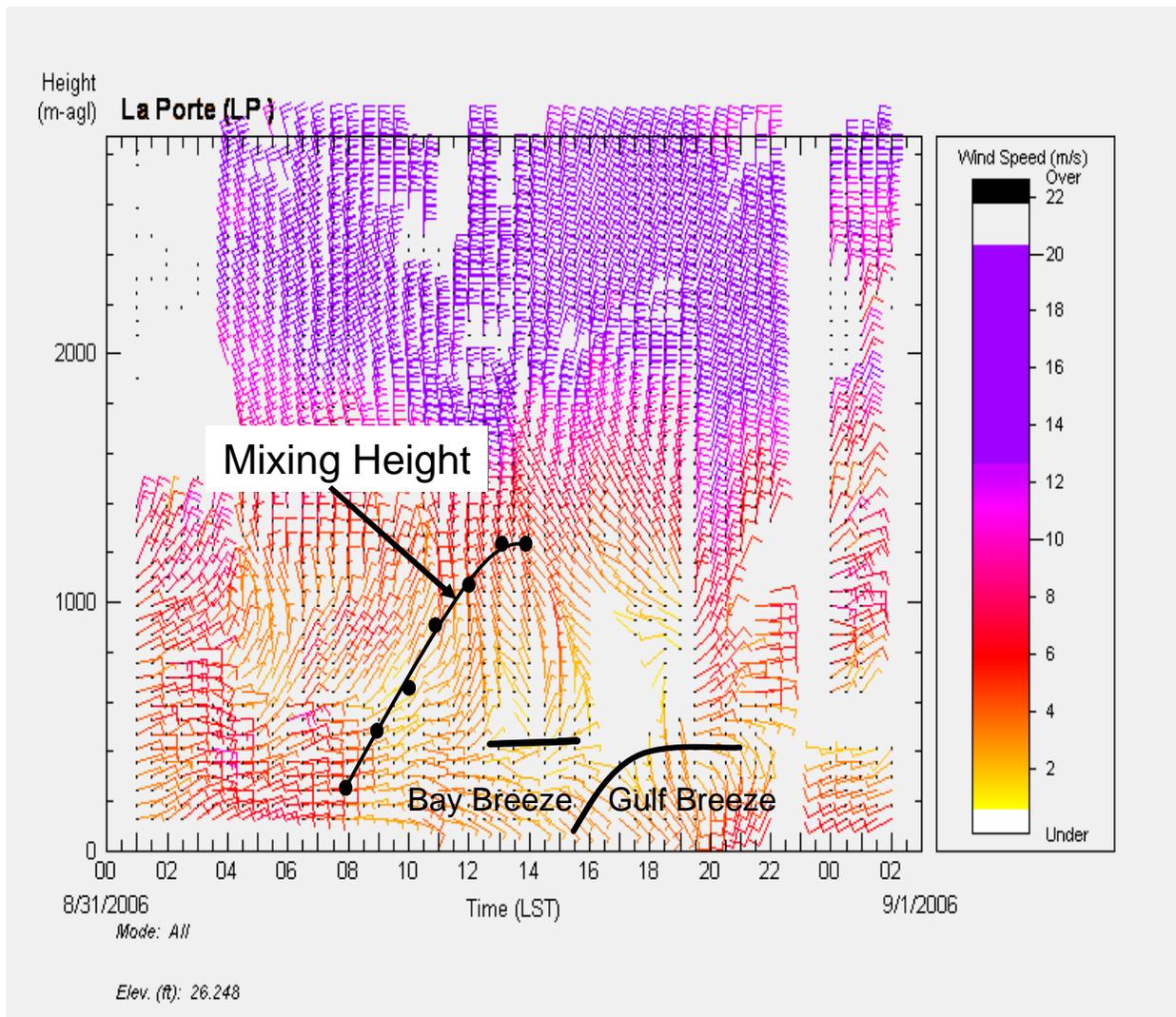


Figure 1-23. RWP winds and mixing heights (black dots) at LaPorte from 1:00 a.m. CST on August 31, 2006, through 2:00 a.m. CST on September 1, 2006. The black lines indicates the top of the Bay and Gulf Breeze.

September 1, 2006

The high ozone concentrations were related to recirculation associated with a Land/Bay/Gulf breeze circulation and an upper-level high pressure system that limited vertical mixing.

- **Large-Scale Aloft:** A high pressure system was centered over north-central Mexico and expanded over all of Texas, which increased the likelihood of subsidence over Houston.
- **Large-Scale Surface:** There was a very weak pressure gradient over Houston, allowing local flows to dominate.

- **Local Meteorology:** There was a Land/Bay/Gulf breeze cycle. Within this cycle between 7:00 a.m. CST and 11:00 a.m. CST winds were light westerly in the lowest 600 m agl.
 - Transport and Surface Winds:
 - The 50 m and 700 m 24-hour backward trajectories ending at 11:00 a.m. CST on September 2 showed that air flowed from the south and then northwest in the last six hours.
 - At 300 m air flow was from the southwest and west.
 - In the early morning, the surface winds were light and variable in the Houston area. At 8:00 a.m. CST the surface winds were westerly in Houston. The surface winds shifted to light and variable at 11:00 a.m. CST. At 3:00 p.m. CST the winds intensified and were from the south/southeast.
 - Time/height Structure:
 - There was a southwest-to-west boundary layer flow from 1:00 a.m. CST to 9:00 a.m. CST, which was consistent with the local surface winds (see **Figure 1-24**).
 - From 10:00 a.m. CST to 11:00 a.m. CST there was a period of stagnation.
 - The Bay breeze occurred from 12:00 p.m. CST to 2:00 p.m. CST in the lower 600 m agl. The Bay breeze then shifted to a Gulf breeze.
 - The aloft winds, above 2000 m agl, were strong, about 20 m/s, and from the north.
 - Between 9:00 a.m. CST and 12:00 p.m. CST the CBL grew 1188m, a little more than double the growth from the day prior. This is the greatest growth for the episode period. The maximum mixing height for the day occurred at 12:00 p.m. CST at a height of 1765 m. Soon after, the mixing height began to lower, coinciding with the onset of the easterly Bay breeze that undercut the CBL.
- **Cloud Cover:** At 12:00 p.m. CST, a few clouds started to form in the Houston area. By 2:00 p.m. CST convective clouds moved into the area, building up until 5:30 p.m. CST when a thunderstorm entered northeastern Houston. The clouds throughout the day were not associated with the Bay or Gulf breeze.
- **Ozone Patterns:** The highest one-hour ozone concentration (161 ppb) occurred at 3:00 p.m. CST in the Ship Channel. Unlike yesterday, the high ozone levels started in southeastern Houston along the Galveston Bay. Southeasterly winds transported ozone from Galveston Bay during the afternoon into central and northern Houston.

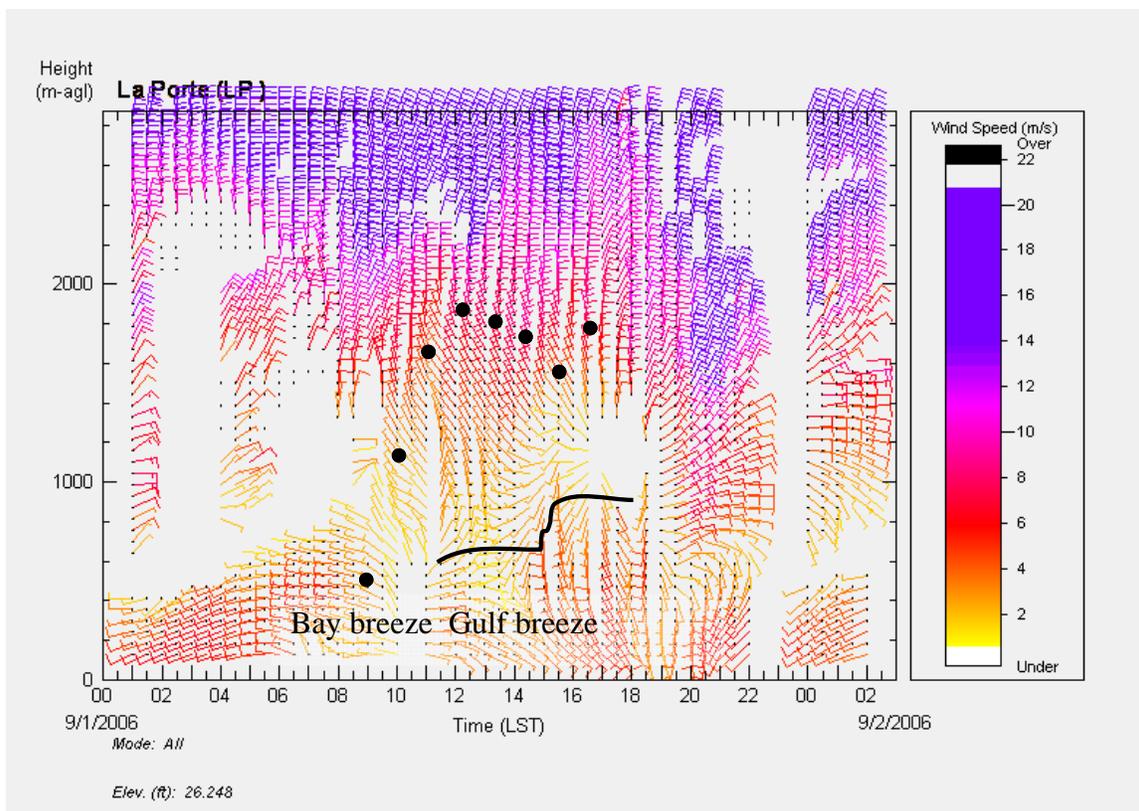


Figure 1-24. RWP winds and mixing heights (black dots) at LaPorte from 12:00 a.m. CST on September 1, 2006 through, 2:00 a.m. CST on September 2, 2006. The black line indicates the top of the Bay and Gulf Breeze.

September 2, 2006

Ozone concentrations were low because of a cold front that passed through Houston and high mixing heights that enhanced vertical mixing.

- **Large-Scale Aloft:** The high pressure system observed on September 1, 2006, moved slightly east and weakened.
- **Large-Scale Surface:** A cold front moved through the Houston area.
- **Local Meteorology:**
 - Transport and Surface Winds:
 - The 50 m and 300 m 24-hour backward trajectories ending at 10:00 a.m. CST on September 2 showed air flow coming from the south and then shifting to the northwest in the last six hours, similar to the previous day.
 - In the early morning, the winds were generally light and from the northeast.
 - At 9:00 a.m. CST, the winds picked up slightly and were from the north.
 - Throughout the late morning and afternoon the winds were from the east.

- The winds remained easterly until 9:00 p.m. CST, and then became light and variable.
 - Time/height Structure:
 - The boundary layer flow was westerly from 12:00 a.m. CST to 4:00 a.m. CST (see **Figure 1-25**).
 - From 6:00 a.m. CST to 10:00 a.m. CST the boundary layer flow shifted from northwesterly to northeasterly, and then transitioned to a Bay breeze.
 - At 3:00 p.m. CST the boundary layer flow shifted back to northeasterly and remained northeasterly for the remainder of the day.
 - The CBL reached the peak for the episode on this day. The peak CBL height of 2265 m occurred at 2:00 p.m. CST and 4:00 p.m. CST (see Figure 1-25). Between 9:00 a.m. CST and 12:00 p.m. CST the CBL grew 1041 m, the second greatest growth of the episode.
- **Cloud Cover:** There was minimal cloud cover.
- **Ozone Patterns:** This day had the lowest ozone levels of the episode. The peak one-hour ozone (90 ppb) occurred at 3:00 p.m. CST south of Houston. Unlike the previous two days, the ozone concentrations were fairly uniform around the Houston area.

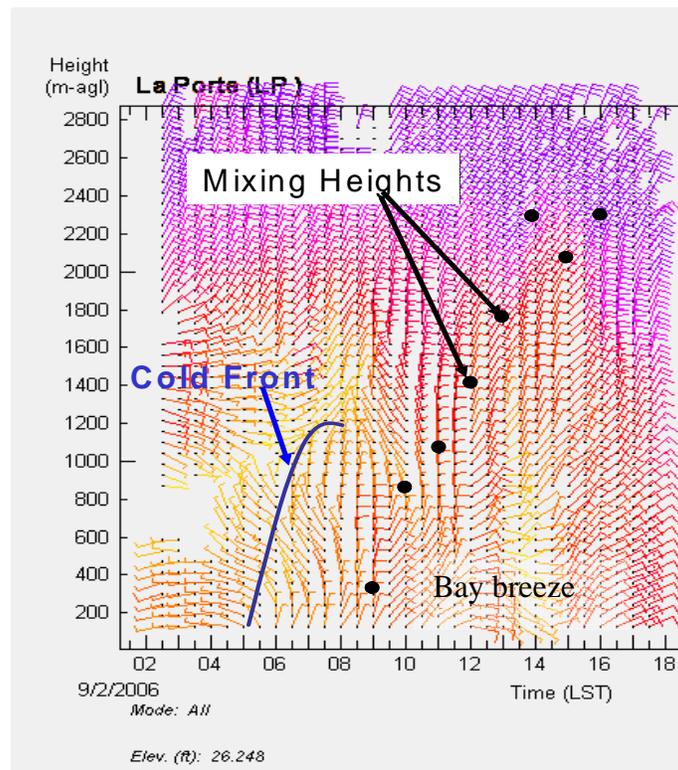


Figure 1-25. RWP winds and mixing heights (black dots) at LaPorte from 2:00 a.m. CST, through 6:00 p.m. CST on September 2, 2006.