Final Report

Task F19: Evaluation of Houston Sea Breeze and Circulation of Pollutants

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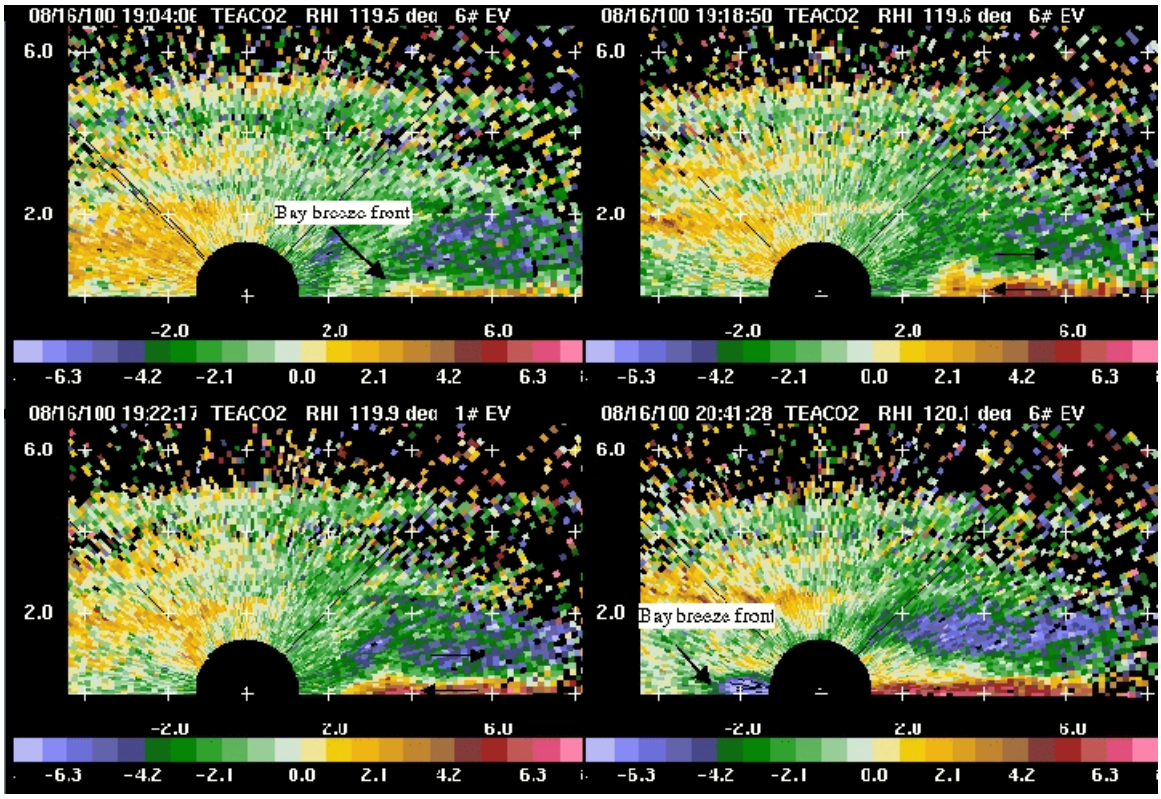


1. Introduction

a. Background

The National Oceanic and Atmospheric Administration's Environmental Technology Laboratory (NOAA/ETL) deployed 2 ground-based lidars at the LaPorte, TX Municipal Airport for the TexAQS 2000 study (Fig. 1). One lidar was a Doppler system that measures radial velocity and backscatter. The other lidar obtains profiles of ozone and aerosols. This report features results of our analyses of the Doppler lidar data for Task F19: Evaluation of Houston Sea Breeze and Circulation of Pollutants.

Of major concern is how the winds in Houston are influenced by either synoptic-scale or mesoscale forcing. The synoptic scale has a time scale of a few days and a horizontal scale of hundreds of km, while the mesoscale has a time scale of less than a day, and a horizontal scale of less than 100 km. An example of synoptically driven winds would be consistent flow from a single direction, all day long, due to a High or Low pressure system dominating the area. An example of mesoscale forcing would be a sudden increase in wind speed of several m s^{-1}, and possibly a wind direction shift, due to a thunderstorm outflow. The bay breeze and gulf breeze are also mesoscale circulations. The bay breeze and gulf breeze are thermally driven, i.e., are a result of the temperature difference between the land and Galveston Bay or the Gulf of Mexico, respectively.

The bay breeze or gulf breeze are likely to form when the large-scale pressure gradient is weak and insolation is high. At LaPorte, the bay breeze was primarily a southeasterly wind, (flow perpendicular to the coast of the bay, Fig. 1) whereas the gulf breeze would have a more southerly component and would be detected at LaPorte later in the day. A weak pressure gradient keeps the ambient winds weak, and strong insolation provides strong heating for the land mass. The weak winds and strong insolation allow the temperature contrast to become firmly established. During nighttime hours, when the temperature of the land is cooler than the water temperature, a land breeze may form (flow from land to water). It is important to note, however, that if the morning flow is offshore, it may not technically be a land breeze, it may be synoptically driven rather than thermally driven.

With weak ambient winds, the bay breeze is easily distinguishable in the wind data, particularly if the winds abruptly switch from offshore to onshore. Also, the onset of the bay breeze is indicated by a drop in temperature, rise in relative humidity, and possibly a rise in pressure coincident with the wind shift. Plenty of sunshine also enhances the photochemical production of ozone, while weak winds allow the ozone and its precursors to accumulate in the metropolitan and industrial areas.

A bay breeze may still form on days when synoptic-scale forcing dominates, and the morning winds are not necessarily offshore or weak. The bay breeze may not be as evident on these days as on days with stagnant conditions. In this case, the bay breeze will be detected by the onset of steady southeasterly flow and possibly an accompanying drop in temperature and increase in relative humidity.

b. Task F19

Key aspects of this task are as follows. The ground-based Doppler lidar wind data were analyzed to characterize the bay-breeze and gulf-breeze winds at the LaPorte site, focusing on several key elements of the wind flow. First of all, the classification of the morning wind conditions is essential for understanding the pre-bay-breeze pollutant transport. Are the morning winds onshore or offshore? How strong are the morning winds? Are there layers indicating speed

shear or directional shear? How do these winds relate to the synoptic scale conditions? Do these conditions enhance or impede the formation of a bay breeze or gulf breeze? The large-scale morning flow may affect the timing of the transition to bay-breeze flow, which could be a critical factor in determining the amount of pollutants over the bay that are available for recirculation back into the Houston metropolitan area.

The type of transition to onshore flow may also play a role in the pollutant transport. For instance, an abrupt transition from northwesterly to southeasterly flow may have a stronger impact on the air quality than a slow veering of the winds from northwesterly or northeasterly to southeasterly throughout the day. Examples of both types of day will be shown in this report.

c. Analysis strategy

Our analysis strategy was to first look at the Doppler lidar wind profiles and assess the winds in the lowest few hundred meters of the atmosphere. Days were classified according to the predominant daytime wind direction in this layer. The next step was to look at the synoptic weather maps to determine what role the synoptic situation played in the morning wind direction, the absence or presence of the thermally driven circulations, and the afternoon wind direction. Associating the behavior of ozone concentrations at LaPorte with the predominant wind direction was the next step in our analyses. Results from six days, each representing a different category of daytime wind flow, will be shown in Section 2.

The results at LaPorte may not necessarily reflect what happened across the rest of the Houston network of measurements. For example, days that were not exceedance days at LaPorte may have been exceedance days elsewhere. In Section 2 we include some information regarding the area covered by the TNRCC network of sensors by comparing what happened at LaPorte to other stations, and finally, using airborne data, we will assess the regional impacts of the wind direction and synoptic scale weather patterns on the ozone exceedances that occurred inside and outside the Houston area (this goal overlaps with other ETL tasks).

In Section 3 we use examples of Doppler lidar data and surface meteorological and ozone data to characterize the pre- and post-bay breeze conditions on days with an offshore to onshore flow reversal. In Section 4 we will examine ozone 'excursions', either strong decreases, increases, or variability that occurred at LaPorte while Doppler lidar data were being taken. Doppler lidar data may show wind features that explain these excursions. For instance, we show Doppler lidar measurements of a gust front passage (01 September), and show the variability in ozone that occurred with its passage. We also have a summary of our results and an appendix including Doppler lidar wind profiles from all days that we took data.

d. Data

During TexAQS 2000 our Doppler lidar scanner experienced a slow upward drift in the elevation angle on some days. We have implemented a correction algorithm to our program that calculates the profiles from the constant-elevation-angle scans. This algorithm accounts for the slow elevation angle drift. For each day of lidar data, this problem was either corrected, or it was determined that significant drift did not occur.

2. Categorization of the lidar data

Vertical profiles of the horizontal wind were derived from Doppler lidar constant-elevation-angle scans, using the VAD technique of Browning and Wexler (1978). A sample time series of Doppler lidar wind profiles is shown in Fig. 2. Profiles from constant-elevation-angle scans ranging from 1E to 10E above the horizon were plotted in this manner for each day, showing the winds from as low as ~20 m above ground level (AGL) to ~500 m AGL. (The vertical range of

the profiles derived from low elevation angle scans varied from day to day, and perhaps from hour to hour, depending upon the amount of scatterers in the atmosphere, and the range of elevation angles for each day.) Based on these profiles, the days were divided into the following categories: [a] transition from westerly to southeasterly (8 days); [b] transition from southwesterly to southeasterly (5 days); [c] offshore flow most of day (2 days); [d] onshore flow most of day (3 days); [e] transition from weak northerly to southeasterly (2 days); and [f] slow veering from westerly to southeasterly (1 day). Table 1 shows the dates of lidar data and the mean wind direction as indicated in the lidar profiles. All days except for the 2 offshore-flow days (1 and 3 September 2000) had a transition to southeasterly flow that may be considered a bay breeze. This transition was more apparent on some days than others, and was usually supported in the surface meteorological data with an increase in relative humidity and a drop in temperature.

This categorization relies exclusively on the lidar data, which did not operate 24 hours per day. The typical hours of operation were from pre-dawn until early evening, after the bay breeze was established. These categorizations reflect daytime winds only, and do not account for nighttime events. There were, however, some nighttime Doppler lidar measurements. Also, these categorizations may or may not be representative of the regional-scale winds.

Representative time series of Doppler lidar wind profiles will be shown for each of the categories, along with synoptic maps that represent the large-scale meteorological influences for each category. The behavior of daytime ozone concentrations at LaPorte will also be discussed for each category. While the focus of this report is LaPorte, the number of exceedances measured in the Houston metropolitan network will be mentioned for each category, and airborne ozone lidar data will be referred to when appropriate. Some nighttime trajectories derived from the network of 915-MHz profilers deployed for TexAQS 2000 will also be shown.

a. Transition from westerly to southeasterly (offshore to onshore) flow

Figure 3 is a time series of wind profiles derived from Doppler lidar 1 - 10E constant-elevation-angle scans taken on 30 August 2000. From 0300 CST to 1300 CST the winds from 20 m AGL to the top of the profiles were from the west to northwest. A period of light and variable winds occurred between 1300 CST and 1500 CST as the transition to bay breeze (southeasterly) flow occurred. Figure 4 shows profiles from scans with an elevation angle of 20E to 30E for the same day.

Ozone and meteorological variable time series from 30 August 2000 are shown in Fig. 5. The intrusion of a new airmass is seen in the abrupt increase in relative humidity coinciding with the onset of the bay breeze, along with an increase in wind speed and a slight drop in temperature at ~1530 CST. The ozone time series had a very dramatic jump in ozone of ~95 ppbv associated with the wind shift, bringing the already high ozone concentrations at LaPorte to values greater than 200 ppbv.

On the synoptic scale, this day was dominated by high pressure at the surface (Fig. 6). The clear skies and stagnant conditions associated with this high pressure system provided ample sunlight for photochemistry and little transport away from the Houston area, allowing pollutants to accumulate in the metropolitan area. The limited transport of pollutants that did occur was due to light westerly to northwesterly winds, resulting in an accumulation of pollutants over Galveston Bay. When the bay breeze ensued, the pollutants over Galveston Bay were transported inland, significantly increasing the ozone concentrations along the coast of the bay. These higher ozone concentrations were eventually advected landward, including into the city of Houston. For more details on this day, see Banta et al. (2002).

Figure 7 is a Doppler lidar scan showing the vertical structure of the bay breeze during its developmental stage at LaPorte, just before the surface wind measurements indicated the shift from offshore to onshore. Overlying the decaying layer of offshore flow, above ~2 km AGL, was a layer of flow with an easterly component (as also seen in the profiles (Fig. 4)).

The events of 30 August show how the thermally-driven bay breeze contributed to the high ozone values seen at LaPorte. But, how representative is this day of all days with a flow reversal at LaPorte? The ozone time series for all other days with an offshore to onshore transition indicated that the bay breeze alone was not necessarily enough to cause a large increase in ozone *at LaPorte*. Other factors to consider are the timing of the onset of the bay breeze, the direction and speed of the wind before the transition to bay breeze, and the depth of the bay breeze. For instance, on 20 August 2000, a clear transition from offshore to onshore flow at ~1300 CST (Fig. 8) was accompanied by a distinct increase in surface ozone concentration of ~25 ppbv. This increase was about one-fourth the increase seen on 30 August when the bay breeze began, and the pre-wind shift concentrations were also significantly less than on 30 August 2000. A similar situation existed on 29 August, with a definite switch from offshore to onshore flow and an increase in surface ozone (Fig. 9), yet it also was not an exceedance day at Laporte. More details on the differences between Aug. 20th, Aug. 29th and Aug. 30th will be discussed in Section 3. Our analysis indicates that the timing of the bay breeze onset and the depth of the onshore flow on 30 August, compared to the other days, appear to play a role in the differences in the ozone concentrations among these three days at LaPorte. Also, the number of exceedances that occurred on these and other flow reversal days in the Houston/Galveston/Brazoria TNRCC surface network (HGB network) will be discussed in Section 3. 30 and 31 August 2000, both flow reversal days, were the highest ozone days in Houston during the Texas 2000 experiment. Both days had ozone concentration > 200 ppbv. 30 August is a classic example of the bay breeze severely hampering the air quality at LaPorte, and elsewhere, it is not representative of all hot summer days with a transition from offshore to onshore flow.

b. Southerly flow days

The time series of 11 September 2000 Doppler lidar wind profiles (Fig. 10) showed winds with a southerly component throughout the morning and afternoon, except for a period of easterlies at the lowerest levels from 0800 CST to 1100 CST. The temperature and relative humidity time series (Fig. 11) indicated a drop in temperature and a rise in relative humidity just after ~1000 CST, associated with the onset of fairly steady winds from the southeast, indicating the onset of the bay breeze. The reason for the sudden drop in relative humidity, increase in temperature, and gusty winds ~1 hour later is undetermined at this time.

The synoptic scale setting on 11 September 2000 was quite different from 30 August 2000. The synoptic-scale southerly flow was a result of the clockwise flow around high pressure centered on the Georgia and South Carolina border (Fig. 12). Clouds and rain showers were evident throughout the day around the Houston metropolitan area. The rainy, unsettled weather was associated with an upper-level trough (Fig. 13a), whereas on 30 August, subsidence at the surface was supported by a ridge aloft (Fig. 13b). The nighttime transport, late 10 September and early 11 September, was from south to north (Fig. 14), most of the day the winds at LaPorte were from the south (Fig. 10), and there were fewer sources of pollutants to the south of Houston. These facts, combined with the lack of subsidence, led to low ozone values with a maximum ozone concentration 41 ppbv at LaPorte on this day (Fig. 11). With southerly flow dominating, no pollutants emitted from the Houston metropolitan area were transported over Galveston Bay, and

therefore the onset of the bay breeze had little or no effect on the ozone levels at LaPorte. The four other days with southerly flow (27 and 28 August 2000, 10 and 12 September 2000) also had relatively low ozone values, with maximum ozone concentrations of 68.4, 61.6, 65.5, and 46.9 ppbv, respectively. According to the HGB network, no stations reached ozone values $125 ppbv on any of the southerly flow days. The airborne ozone lidar data for one of the southerly days, 28 August (not shown), indicates O_3 concentrations > 100 ppbv, with some small areas approaching 125 ppbv north of the HGB network. The only other southerly flow day with airborne lidar data is 12 September. Again, airborne measurements (not shown) indicated ozone values > 100 ppbv, but nothing > 125 ppbv. The higher values detected on 12 September were elevated.

A Doppler lidar scan at approximately the same time and direction as the scan shown previously for 30 August is shown in Fig. 15. A much deeper layer of onshore flow existed at this time on 11 September as compared to the shallow bay breeze seen on 30 August (Fig. 7). This deeper, cleaner layer of onshore flow was in stark contrast to the shallow, polluted onshore flow layer that occurred on 30 August.

c. Offshore flow most of day

Doppler lidar wind profiles from 1 September 2000 are shown in Fig. 16. Early morning profiles indicated a westerly low-level jet (LLJ), with winds up to 12 m s^{-1}, below 1 km AGL. The LLJ dissipated by late morning, but the flow continued from a westerly (offshore) direction, and remained westerly throughout the day until the passage of a thunderstorm outflow after 1645 CST. Winds behind the outflow boundary are indicated by the north to northeast winds in the profiles after 1700 CST. With surface temperatures > 100E F (38E C) for several hours during the afternoon (Fig. 17), there was an ample temperature contrast between the land surface and water to promote a bay breeze or gulf breeze, but the large-scale pressure gradient (Fig. 18) was such that the winds remained synoptically driven at LaPorte in the afternoon rather than thermally driven.

The ozone time series for this day (Fig. 17) showed a rise in ozone from zero in the early morning to a maximum of 99 ppbv in the afternoon. The wind shift, drop in temperature, and rise in relative humidity and surface pressure due to the thunderstorm outflow passage is seen at ~1645 CST. Along with the gust front passage came much variability in the ozone concentration time series (discussed in more detail in Section 4). With the exception of this variability, the ozone time series took a normal course of rising in the morning and afternoon, and then falling in the late afternoon after photochemical production of ozone had decreased, and then leveling off to low levels after sunset. Thus, while the daytime ozone levels were not low, this day (as well as 3 September, also an offshore flow day with a similar synoptic situation) was not an exceedance day at LaPorte. There were exceedances recorded by the HGB network, however, on these offshore days (2 stations/3 hours on 1 September and 1 station/1 hour on 3 September). The continuous offshore flow advected pollutants to the east throughout the day, as measured by the airborne ozone lidar, which detected large areas of ozone $125 ppbv between the HGB and Beaumont/Port Arthur network. Exceedances were also recorded in the Beaumont/Port Arthur network (3 stations/6 hours).

Figure 19 is an example of a Doppler lidar range-height scan from 1 September 2000. This scan was taken at approximately the same time of day as the scan shown for 30 August (Fig. 7) and 11 September (Fig. 15). The deep offshore flow (the yellow to red layer below 2 km AGL) was quite well established (as also indicated in the profiles), whereas on 30 August, the winds at this time of day were light and transitional in preparation for the onset of the bay breeze (Fig. 7).

d. Easterly-component flow (onshore flow with respect to LaPorte) most of day

Like the offshore-flow days discussed in Section 2c, the synoptic-scale meteorology dominated eastern Texas weather on the onshore flow days of 6, 7, and 8 September 2000. With high pressure covering the eastern half of the United States, and low pressure in the Gulf of Mexico, winds with an easterly component (ranging from northeasterly to southeasterly) were the case for 6, 7, and 8 of September (Fig. 20a is a surface synoptic map for 6 September). The easterly-component flow was also supported at upper levels, as indicated by the 6 September, 1200 UTC 500 mb map (Fig. 20b).

Figure 21 shows the Doppler lidar wind profiles for 6 September 2000. The winds slowly veered from northeasterly to southeasterly throughout the day. The ozone time series (Fig. 22) looked similar to the ozone time series for the offshore flow day (Fig. 17), that is, there was a normal rise and fall of ozone associated with daytime photochemistry. With the slow veering of the wind direction with time, a point was reached when the local flow at LaPorte became onshore with respect to the main body of Galveston Bay (~125E azimuth). In the absence of a distinct windshift from offshore to onshore flow, in addition to pollutants not being advected to the southeast during the day, as on 30 August, no sudden increases in ozone occurred with the intrusion of marine air signified by the onset of steady southeasterly winds and an increase in relative humidity (~1500 CST). In fact, ozone started a slight decline shortly after the marine air intrusion. While 6 September was not an exceedance day at LaPorte, there was 1 station in the HGB network that recorded 4 hours of O_3 $125 ppbv.

Nighttime trajectories (Fig. 23) showed that over the previous night the pollutants were transported well to the southwest of Houston, and this transport pattern continued with the two subsequent days of onshore (easterly) flow. Daytime airborne ozone lidar measurements (not shown) for 6 September showed the Houston daytime urban plume was transported to the southwest of Houston as well. Lidar-measured ozone concentrations were high enough (~160 ppbv) to indicate that violations were occurring at the surface, but oustide the network (see Banta et al. report, Task #21). During the two subsequent days of onshore flow, ozone concentrations dropped at Laporte, (Fig. 24), and no exceedances were reported in the HGB network on these days (7 and 8 September). The airborne lidar data from 7 September (not shown) indicated that ozone was still being transported to the southeast, but ozone levels overall were lower, and no values $125 ppbv were detected on these two days.

Figure 25 is 6-panel plot of east-west range-height scans on 6 September. The winds below 1 km AGL remained onshore all day, but the vertical structure of the wind speeds in this layer varied quite a bit as seen in this series of scans. Near 0400 CST, a low-level jet, indicated by the elevated layer of purple and red radial velocities centered about 600 m AGL, was well established. A layer of opposing flow was seen above this LLJ between 2 and 3 km. With time the LLJ dissipated, the layer of opposing flow had eroded away, and the winds weakened considerably in the lowest 1 km. By late afternoon the strongest winds were above 2 km AGL.

e. Transition from weak northerly to southeasterly flow

Figure 26 is a time series of Doppler lidar wind profiles from 25 August 2000. The profiles show a transition from offshore to onshore flow. However, the surface station data (Fig. 27) show that the early morning surface winds were light and north to northeasterly in direction, which is different from the offshore to onshore flow days presented in Section 2a, when the morning offshore flow clearly extended to the surface. Thus, 25 August is in a different category. Two notable features in the ozone time series (Fig. 27) are the large increase in ozone between 0700 and 0800 CST, and the sudden drop in ozone that occurred coincident with the bay breeze at

1100 CST. It is suspected that the northerly flow in the early morning transported pollutants from the ship channel (about 10 km north of LaPorte) to LaPorte or polluted air was mixed downward as the boundary layer grew after sunrise. As the morning low-level flow became northeasterly, a new air mass did enter LaPorte at ~0830 CST, as indicated by a drop in temperature and increase in relative humidity. This is probably due to the veering surface winds, since it appears that a true bay breeze does not set up until 1100 CST. High pressure dominated the region on this day, as indicated on the surface synoptic map (Fig. 28). The stagnant conditions before the bay breeze allowed urban pollutants to accumulate in the Houston area, which were subsequently transported across the TNRCC network from east to west by the bay breeze, resulting in high ozone concentrations on the west side of Houston (Fig. 29a). Twleve stations in the HGB network reported a total of 22 hours of O_3 exceedances. Airborne lidar data from this day (not shown) indicate there was little ozone over the main body of Galveston Bay on this morning, so the transition to bay breeze flow actually brought cleaner air into LaPorte (as indicated in the ozone time series (Fig. 27)). As the bay breeze moved westward, transporting the higher-ozone air westward, cleaner air replaced the high-ozone air (Fig. 29b).

22 August 2000 was also a day with light and variable winds in the morning and onshore flow in the afternoon. The synoptic scale setting was quite different on this day. Low pressure in the Gulf dominated rather than high pressure (not shown). Thus, the wind patterns on these two days, although similar, were for different reasons. Consequently, the ozone behavior at LaPorte on 22 August, a day without subsidence, was different, with a maximum reading of 70 ppbv, and no stations in the HGB network reporting exceedances. There were no airborne ozone flights on 22 August 2000.

f. Slow veering from westerly to southeasterly flow

Wind profiles from 04 September 2000 are shown in Fig. 2, featuring synoptically driven offshore to onshore flow, with the onshore flow enhanced by the local bay breeze circulation. The 1500 UTC the surface synoptic map (not shown) shows low pressure to the northwest of Houston, with surface winds converging into the low, resulting in westerly flow in the Houston area. By 1800 UTC (Fig. 30) stations surrounding the Houston area had east to northeast winds. There were two marine air mass intrusions at LaPorte on this day as the winds slowly veered with time. The onset of easterly flow at ~1330 CST (Fig. 2) coincided with a drop in temperature and increase in relative humidity (Fig. 31), and likewise at ~1530 CST with the onset of strong southeasterly flow (Fig. 2 and Fig. 31). No exceedances were recorded at Laporte on this day, but 2 stations in the HGB network reported exceedances for one hour each. There were no airborne ozone flights on 4 September 2000.

3. Characterization of the bay breeze and gulf breeze using Doppler lidar data

a. Transition from westerly to southeasterly (offshore to onshore) flow

Figure 32 is a time series of range-height scans taken along the 120/300E radials that show the progression of a bay breeze front and the development of the onshore flow on 16 August 2000. The start time of the scan appears in the upper left corner of the plot (UTC = CST + 6 hours). In Fig. 32a (1904 UTC, 1304 CST), the leading edge of the bay breeze is seen just beyond 3 km range from the lidar. Since the bay breeze flow is in opposition to the ambient westerly flow, it is easy to distinguish. Just 15 min later, Fig. 32b, the bay breeze layer had gained strength and depth, attaining the characteristics of a density current (Darby et al. 2002). By 2041 UTC (1441 CST) the bay breeze front had passed through the LaPorte site, with wind speeds greater than 7 m s^{-1} in the onshore layer. The onshore flow continued to increase in depth (Fig. 32e and 32f). These

characteristics were common among the other days with the development of a bay breeze in opposing ambient winds (not shown).

b. Properties of the pre- and post bay breeze conditions at LaPorte for offshore to onshore flow days

The ozone maxima at LaPorte had the most variability on days with a clear transition from offshore to onshore flow, with some days having much higher surface ozone concentrations than others. A key difference between the days with very high ozone (August 30 and 31) and the rest of the flow reversal days (16, 17, 19, 20, 21, and 29 August) was the timing of the bay breeze onset. On August 30 and 31 the bay breeze began at LaPorte at 1530 and 1500 CST, respectively, one to five hours later than the other flow reversal days. To further investigate this relationship between the timing of the bay breeze onset and surface ozone behavior, it was decided to investigate properties of the bay breeze and pre-bay breeze conditions for the offshore to onshore flow days, beginning with the day of the earliest bay breeze onset (21 August 2000) to the day with the latest onset (30 August). The properties of interest are surface wind speed and direction, and depth of offshore and onshore flows.

The starting point for this analysis was to first determine the time of the bay breeze onset, using the surface station data, and rounding the time to the nearest half hour. The bay breeze onset was clearly indicated on these days by the initiation of steady southeasterly flow coinciding with a drop in temperature and an increase in relative humidity (see, for example, Fig. 5). To characterize the pre-bay breeze conditions, we extracted the wind speed and direction and ozone concentration from the surface time series two hours before the bay breeze onset. On one day (16 August), there were no surface data two hours before the bay breeze onset, so a lidar 2E quasi-horizontal scan, closest in time to two hours before the onset, was used to determine the wind speed and direction to characterize the pre-bay breeze conditions. To determine the depth of the pre-bay breeze offshore flow, we looked at range-height scans closest in azimuth to the pre-bay breeze surface wind direction and closest in time to two hours before onset. The top of the layer of offshore flow was determined as the height where the flow reversed to a non-offshore component. Lidar wind profiles (such as the profiles shown in Section 2) were used as a double-check on the flow depths, and in some instances these profiles were the only way to determine the heights of the flow layers.

To characterize the post-bay breeze conditions, similar measurements were gathered (surface ozone concentrations, surface wind speed and direction, and depth of onshore flow) one hour after the bay breeze onset. The results of this analysis are shown in Table 2. The days are arranged in order of bay breeze onset, from earliest to latest.

It was of interest to determine whether the timing of the bay breeze onset was related to other characteristics of the bay breeze. The wind direction, wind speed, depth, and ozone values from Table 2 were plotted against time of bay breeze onset, and a linear fit applied (Figs 33, 34, 35, and 36). The results of this small sampling are as follows. The wind direction tended to be slightly north of west for days with a later bay breeze onset (Fig. 33), but the scatter in the measurements and the closeness of all measurements to 270E precludes us from making a strong statement regarding the pre-bay breeze wind direction. The post-bay breeze line indicates that the later the bay breeze onset, the more southeasterly the bay breeze direction became. It is not clear how this trend impacts ozone at LaPorte. The next step in our analysis will be to assess the wind direction and speed throughout a column, using profiles derived from Doppler lidar data. Perhaps this type of analysis will yield trends that are more reliable.

The plot comparing the depths of the offshore and onshore flows (Fig. 34) indicates that the later the bay breeze onset, the deeper the pre-bay breeze offshore flow, but the scatter in the measurements was large. The bay breeze depth tended to be shallower with a later onset, but again, there is scatter in the measurements. The 2 days with the earliest bay breeze onsets have post-bay breeze depths similar to the latest 2 days, and this turns out to be important, as will be shown later. If the air over Galveston Bay is ozone-rich, shallower bay breeze depths will keep ozone transported from the bay to the shore confined to a shallower layer, resulting in higher concentrations of ozone nearer the ground.

On some days, the winds were weak before the bay breeze onset (Fig. 35). These weaker winds allow more ozone and ozone precursors to accumulate near the shore. This is supported by the results in Fig. 36 which shows the ozone trends pre- and post-bay breeze. The later the bay breeze onset, the higher the surface ozone concentrations tended to be at LaPorte, both before and after the bay breeze onset.

How relevant are these results at LaPorte to the rest of the Houston network? Figure 37 shows the number of stations with exceedances (ozone concentrations > 125 ppbv) in the Houston/Galveston/Brazoria network (pink line), the number of hours with exceedances across the network (blue line), and the number of hours of exceedances at the TNRCC LaPorte station (green line). At LaPorte, only the flow reversals that occurred after 1400 CST led to exceedances in ozone, while the timing of the bay breeze onset appears to have less of an effect on the network stations as a whole. For example, the day with the earliest bay breeze onset at LaPorte (21 August 2000) had 14 hours meeting exceedance criteria at 9 stations, but it was a relatively low ozone day at LaPorte. On the other hand, the days with the latest bay breeze onset (30 and 31 August) were high ozone days at LaPorte, as well as 9 more stations on 31 August and 6 more stations on 30 August, indicating that a late bay breeze onset is likely to affect many stations within the network, as well as LaPorte. The points shown in Fig. 37 indicate that the presence of a distinct transition between offshore and onshore flow does not mean that there will be ozone exceedances in the Houston metropolitan area. There are two days (16 and 20 August) that had a distinct transition, but no exceedances measured in the metropolitan area. There were also no exceedances reported in the Beaumont/Port Arthur network on these two days. Airborne measurements have not been investigated at this time to determine if high ozone concentrations were measured outside the network on 20 August (there were no airborne measurements on 16 August).

What does 21 August, the day with the earliest bay breeze onset, yet many hours of exceedances across the TNRCC network, have in common with 30 and 31 August? As mentioned above, the depth of the bay breeze on 16 August is similar to the depth of the bay breeze on 30 and 31 August (Fig. 34), whereas 16 and 20 August have deeper bay breezes with no exceedances measured. Figure 38 is a plot of the same data shown in Fig. 37, but plotted against the depth of the bay breeze rather than time of onset. Clearly, days with a bay breeze that measured < 700 m one hour after onset were the days with the most exceedances.

4. Using Doppler lidar data to explain rapid changes in ozone concentrations

Figure 39 shows two lidar scans at a constant elevation angle and two scans at a constant azimuth angle. The pre-gust front westerly flow is indicated in the top two plots, as well as the approaching thunderstorm outflow boundary, which had winds up to 15 m s^{-1} behind it. The bottom two plots are vertical slices through the gust front, showing its depth. Airborne ozone lidar data and TNRCC network plots (not shown) indicated that higher ozone concentrations were measured at the surface and aloft to the northeast of Laporte, and the gust front approached LaPorte

from the northeast. Therefore, the variations in ozone at LaPorte that occurred with the gust front passage (Fig. 16) may have been due to horizontal transport of ozone. Other studies have indicated that much vertical mixing can occur with the passage of the gust front, bringing ozone-rich air downward to the surface (e.g., Darby et al., 2002).

5. Summary

The mean lidar wind direction at LaPorte was determined for all days that Doppler lidar measurements were taken. For all days but one, the wind direction time series from the surface station matched the lidar winds in the lowest few hundred meters of the profiles, indicating that the winds at the surface were coupled to the winds just above the surface. 25 August was the day when the surface winds were different from the profiles at the lowest levels (weak, shallow northerly flow at the surface underlying offshore (westerly) flow). The Doppler lidar days were categorized according to the wind direction in the lowest few hundred meters of the lidar wind profiles (Table 1), and were then analyzed by category. Representative days for each category were presented in detail, including Doppler lidar wind profiles, high-resolution meteorological surface station and ozone data, synoptic weather maps, and a select Doppler lidar scan. Supplemental information included data from the TNRCC network and forward trajectories derived from profiler winds. Each section ended with a brief reference to how many TNRCC stations reached exceedances, and for how many hours. Table 3 lists all Doppler lidar days, grouped by mean wind flow, and the number of exceedances in the Houston/Galveston/Brazoria network, including total hours across the network, and total hours at LaPorte. Airborne ozone lidar data were not shown, but if relevant information was available for the days under discussion, the data were mentioned in the report.

Important results include:

- The mean wind direction at LaPorte has an influence on the behavior of ozone at LaPorte (Section 2).

- Meteorological and pollution conditions at LaPorte are related to those in the rest of the TNRCC network for certain types of days. For instance, days with synoptically-driven southerly flow were relatively low ozone days at LaPorte, as well as the rest of the network (Table 3; Section 2).

- The number of exceedances in the network are related to mean wind direction at LaPorte (Table 3).

- Days with a flow reversal from offshore to onshore flow (a bay breeze) tended to have exceedances somewhere in the network, but not necessarily at LaPorte (Table 3).

- The timing of the bay breeze onset appeared to influence whether LaPorte experienced ozone exceedances, or not, on a flow reversal day (Fig. 37). The later the onset, the more likely the chances of exceedances.

- The depth of the onshore flow one hour after bay breeze onset influenced the chance of

exceedances happening somewhere in the network, rather than the timing of the onshore flow reversal as at LaPorte. Days with bay breeze depths less than 700 m were exceedance days (Fig. 38).

- Days with offshore flow (including offshore flow just above the surface, as on 25 August), regardless of whether or not there was a reversal to a bay breeze, tended to have exceedances (Table 3) when compared to days without offshore flow.

- The bay breeze may bring cleaner air into Houston, or higher-ozone air into Houston, depending on the pre-bay breeze transport. As in the case of 25 August, the bay breeze air had less ozone, but the leading edge of the bay breeze transported higher ozone air across the network, resulting in exceedances at several TNRCC stations (Figures 27 and 29). In contrast, on 30 August, the onset of the bay breeze caused ozone at LaPorte to increase by ~95 ppbv (Fig. 5).

- Synoptic conditions (high vs. low pressure systems) play a role in the amount of ozone found in Houston. High pressure leads to stagnant conditions which allow ozone and precursors to linger. Low pressure days may include clouds and showers that will keep ozone production down or reduce the ozone in the boundary layer (Section 2).

- Synoptic conditions that lead to consistent flow in one direction for one or more days lead to long-range transport of ozone to other regions, and across areas that do not have a surface station network (Section 2).

- Steady flow from one direction for more than one day will also have an effect on the local ozone concentrations. For example, 6, 7, and 8 September (easterly component flow days) had lower ozone concentrations at LaPorte with each successive day (Fig. 24). Airborne ozone lidar data indicate that this effect was regional (Section 2).

- Doppler lidar is an excellent instrument for detecting the vertical structure of the bay breeze, particularly when the bay breeze forms in opposing ambient flow (Fig. 32).

Date	Aug. 16, 17, 19, 20, 21	Aug. 22, 25	Aug. 27, 28	Aug. 29, 30, 31	Sep. 1, 3	Sep. 4	Sep. 6, 7, 8	Sep 10, 11, 12
Doppler lidar winds at LaPorte	Offshore to onshore transition	Light and variable, then onshore	Southerly flow most of day	Offshore to onshore transition	Offshore most of day	Slow veering - offshore to onshore	Onshore most of day	Southerly flow most of day

Table 1: Doppler lidar days categorized by mean wind.

Date	Bay Breeze Onset (CST)	Pre-Bay Breeze (2 hours before onset)				Post-Bay Breeze (one hour after onset)			
		Speed (m s^{-1})	Dir (degrees)	Depth (m)	O_3 (ppbv)	Speed (m s^{-1})	Dir (degrees)	Depth (m)	O_3 (ppbv)
Aug 21 Monday	1000	3	300E	1050	40	2.25	80E	575	110
Aug 19 Saturday	1130	4.5	220E	2000	65	6	100E	600	90
Aug17 Thursday	1200	8	270E	1000	no O_3 data	10	110E	1000	no O_3 data
Aug 20 Sunday	1300	2.5	300E	1500	50	5.5	120E	800	70
Aug 16 Wednesday	1400	2	255E	2500	no O_3 data	11	110E	645	110
Aug 29 Tuesday	1400	2	310E	1500	50	5	150E	640	90
Aug 31 Thursday	1500	1	310E	1300	140	1	115E	480	90
Aug 30 Wednesday	1530	0.5	260E	1350	140	4	120E	600	210

Table 2: Pre- and post-bay breeze characteristics.

Date	Mean wind at LaPorte	Exceedances Number of stations/number of hours	Number of hours of exceedances at Laporte
August 16	Offshore to onshore flow reversal days	0 / 0	0
August 17		1 / 2	0
August 19		1 / 4	0
August 20		0 / 0	0
August 21		9 / 14	0
August 29		3 / 7	0
August 30		7 / 18	5
August 31		10 / 21	3
August 22	Light and variable to onshore days	0 / 0	0
August 25		12 / 22	0
August 27	Southerly flow days	0 / 0	0
August 28		0 / 0	0
September 10		0 / 0	0
September 11		0 / 0	0
September 12		0 / 0	0
September 1	Offshore flow days	2 / 3	0
September 3		1 / 1	0
September 4	Slow veering day	2 / 2	2
September 6	Onshore flow days	1 / 4	0
September 7		0 / 0	0
September 8		0 / 0	0

Table 3: Doppler lidar days arranged by mean wind flow. Number of exceedances in the Houston/Galveston/Brazoria network, number of hours of exceedances in the Houston/Galveston/Brazoria network, and the number of hours of exceedances at LaPorte.

Figure 1: Map of Houston area with key locations labeled. The NOAA/ETL Doppler lidar was stationed at LaPorte, Tx.

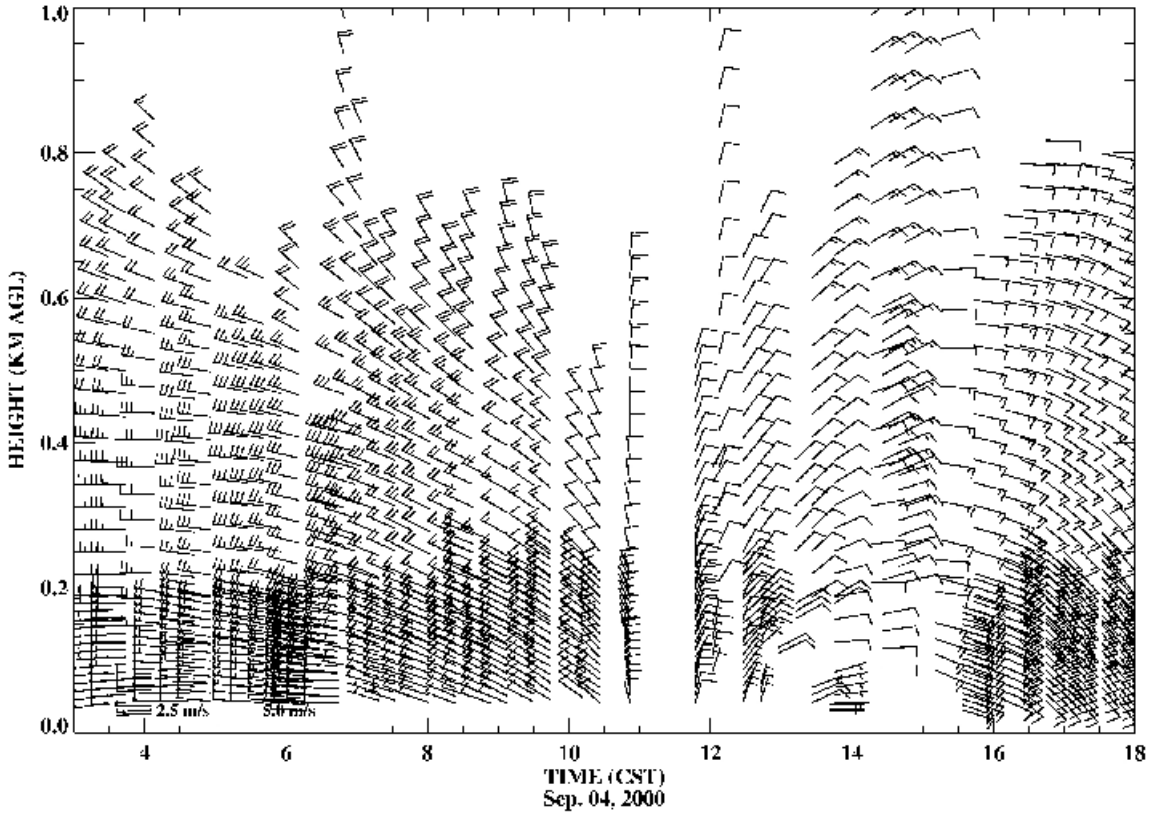


Figure 2: Vertical profiles of the horizontal wind derived from Doppler lidar constant-elevation-angle scans taken between 1E and 10E elevation above the horizon for 04 September 2000. The long barb points into the wind. A half-barb represents 2.5 m s^{-1} and a full barb represents 5 m s^{-1}. Time (Central Standard Time (CST)) runs from left to right. Heights are km above ground level (AGL).

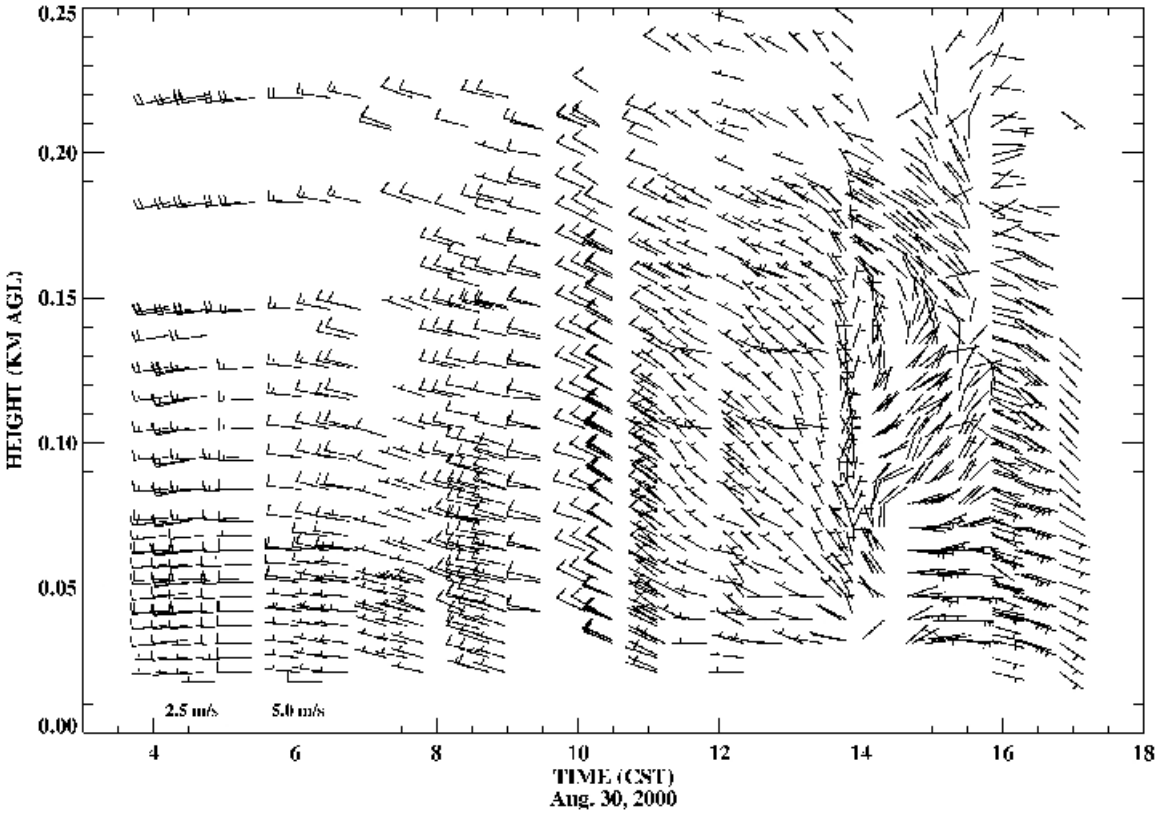


Figure 3: As in Figure 2, except for 30 August 2000.

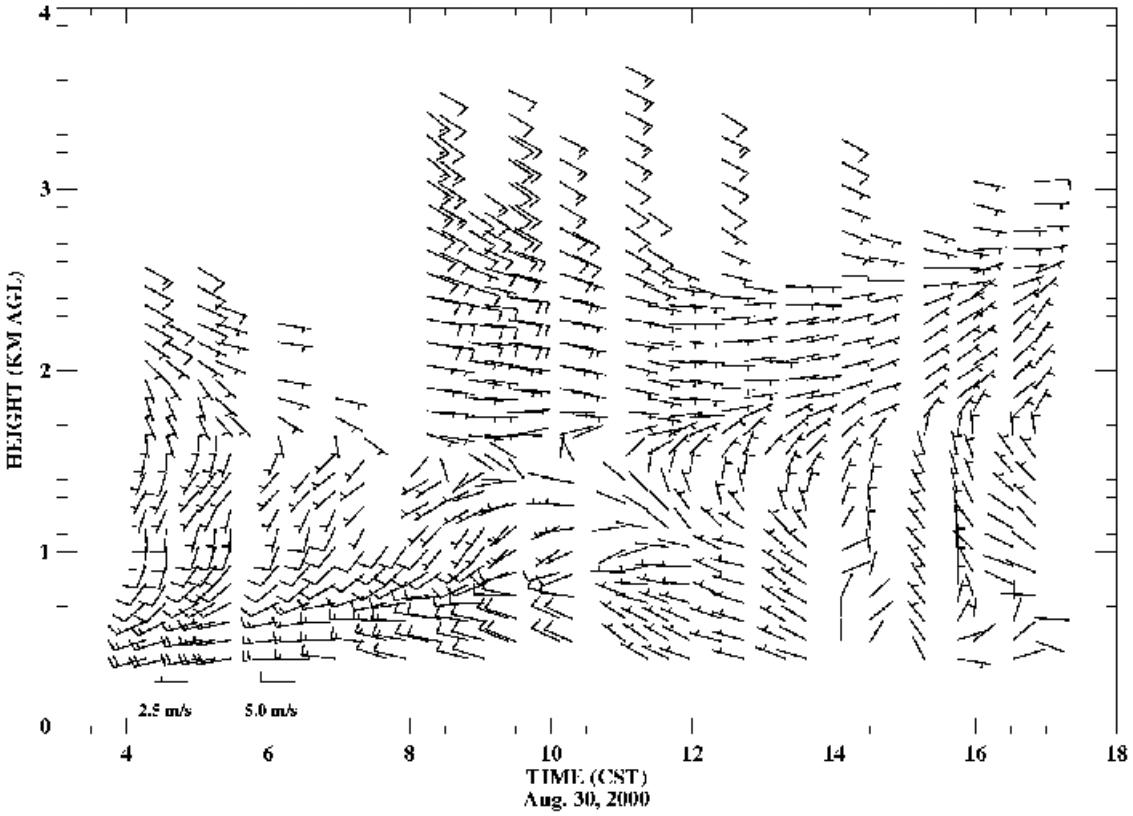


Figure 4: As in Figure 2, except for 30 August 2000, and these profiles were derived from scans taken between 20E and 30E elevation above the horizon.

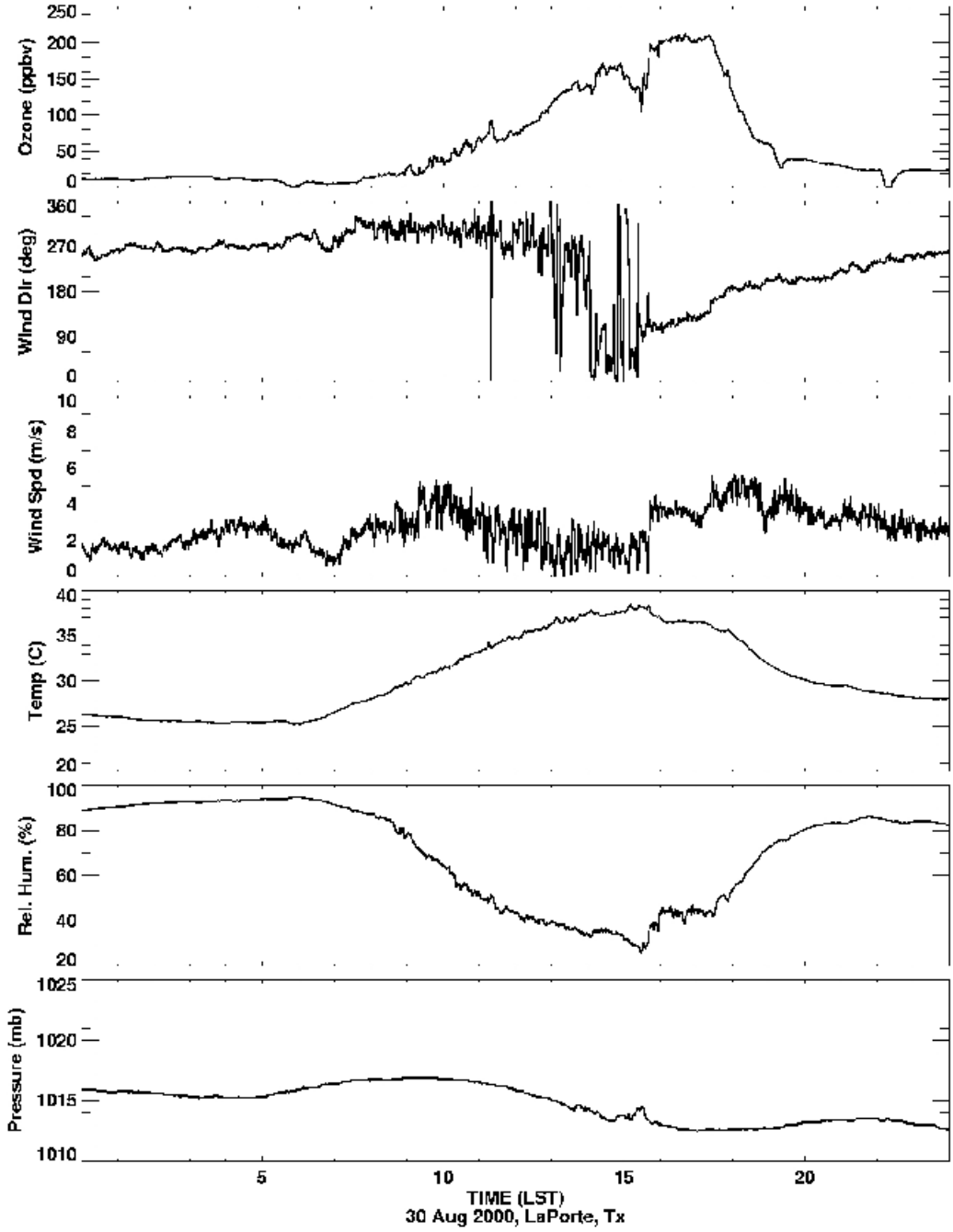


Figure 5: Time series of high-resolution surface chemistry and meteorological measurements taken at the LaPorte site (courtesy of Eric Williams, NOAA/Aeronomy Laboratory). From top to bottom: Ozone concentrations in ppbv; wind direction in degrees from north, wind speed in m s^{-1}; temperature in EC; relative humidity in percent, and pressure in mb. For 30 August 2000.

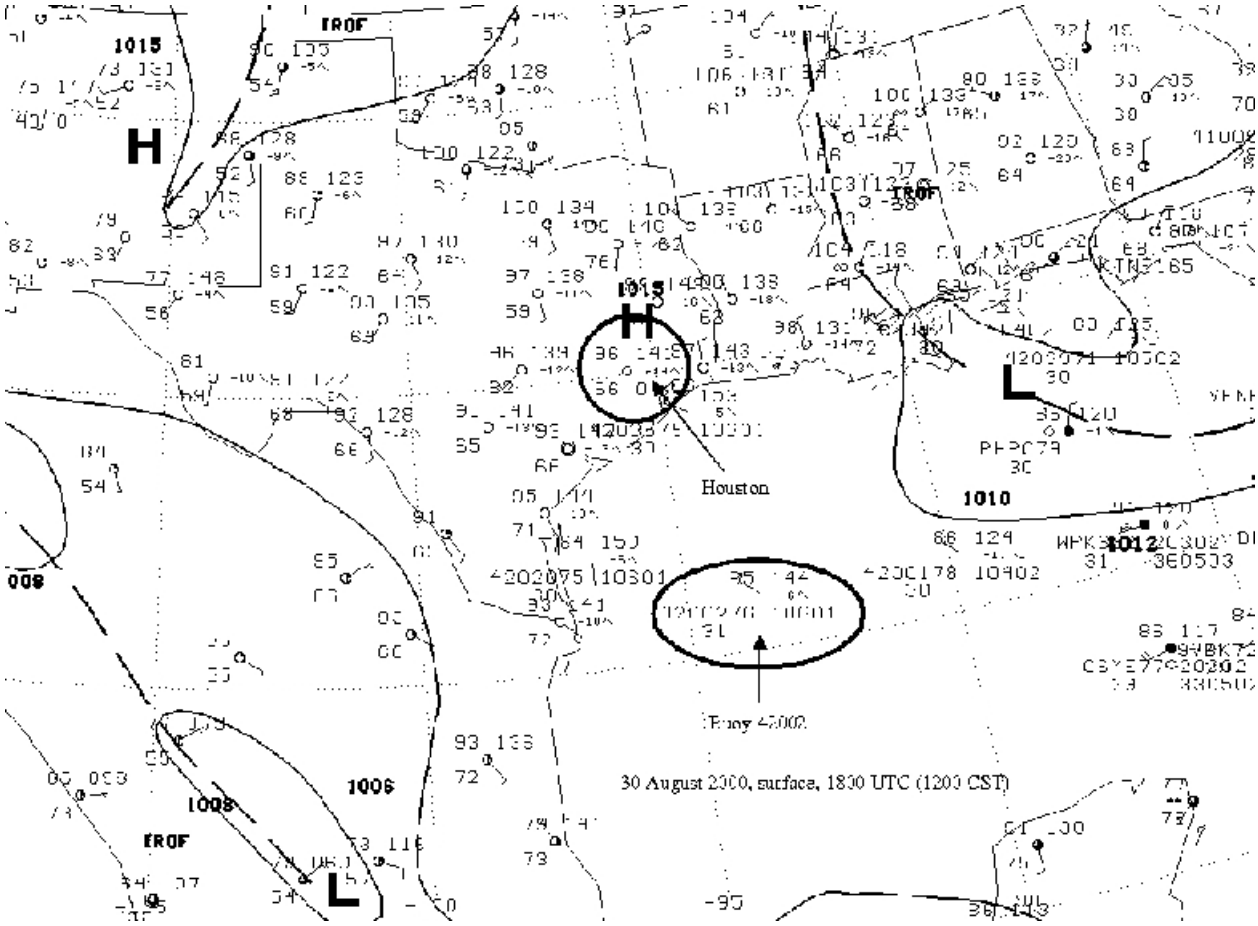


Figure 6: Surface synoptic weather map obtained from the NOAA/National Climatic Data Center, 30 August 2000, 1800 UTC (1200 CST). Buoy 42002 and the Houston surface station are circled.

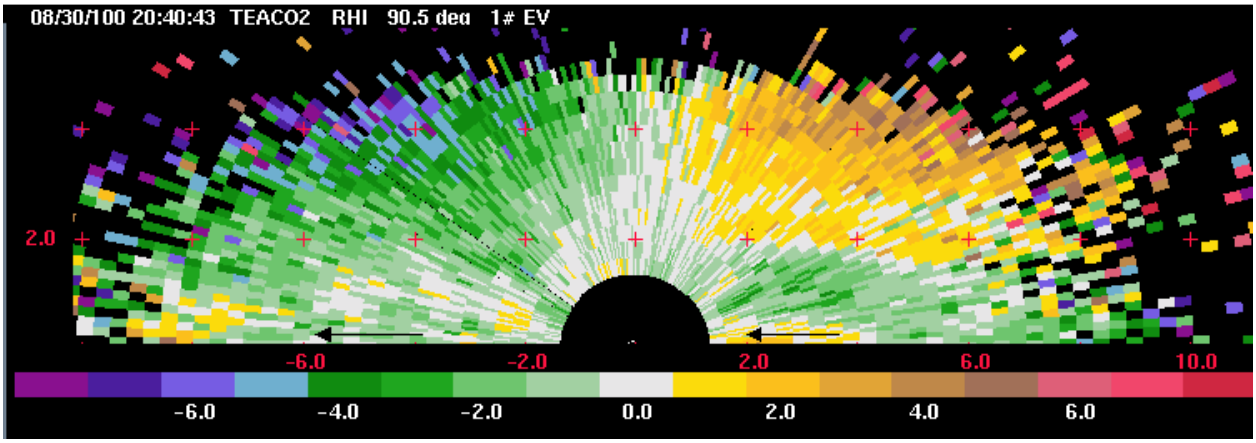


Figure 7: Doppler lidar scan from 30 August 2000. The lidar scanned along the 270/90E radials (west is on the left side of the scan, east is to the right). Time is 2040:43 UTC (1440:43 CST). The lidar is located at x = z = 0. Tick marks (red marks and numbers) are in 2 km increments. The scale at the bottom represents radial velocity in m s^{-1} (white numbers). Positive numbers indicate wind flow toward the lidar. Negative numbers represent flow away from the lidar. Black arrow are placed as reminders as to which way the radial wind was flowing and are not representative of the velocity.

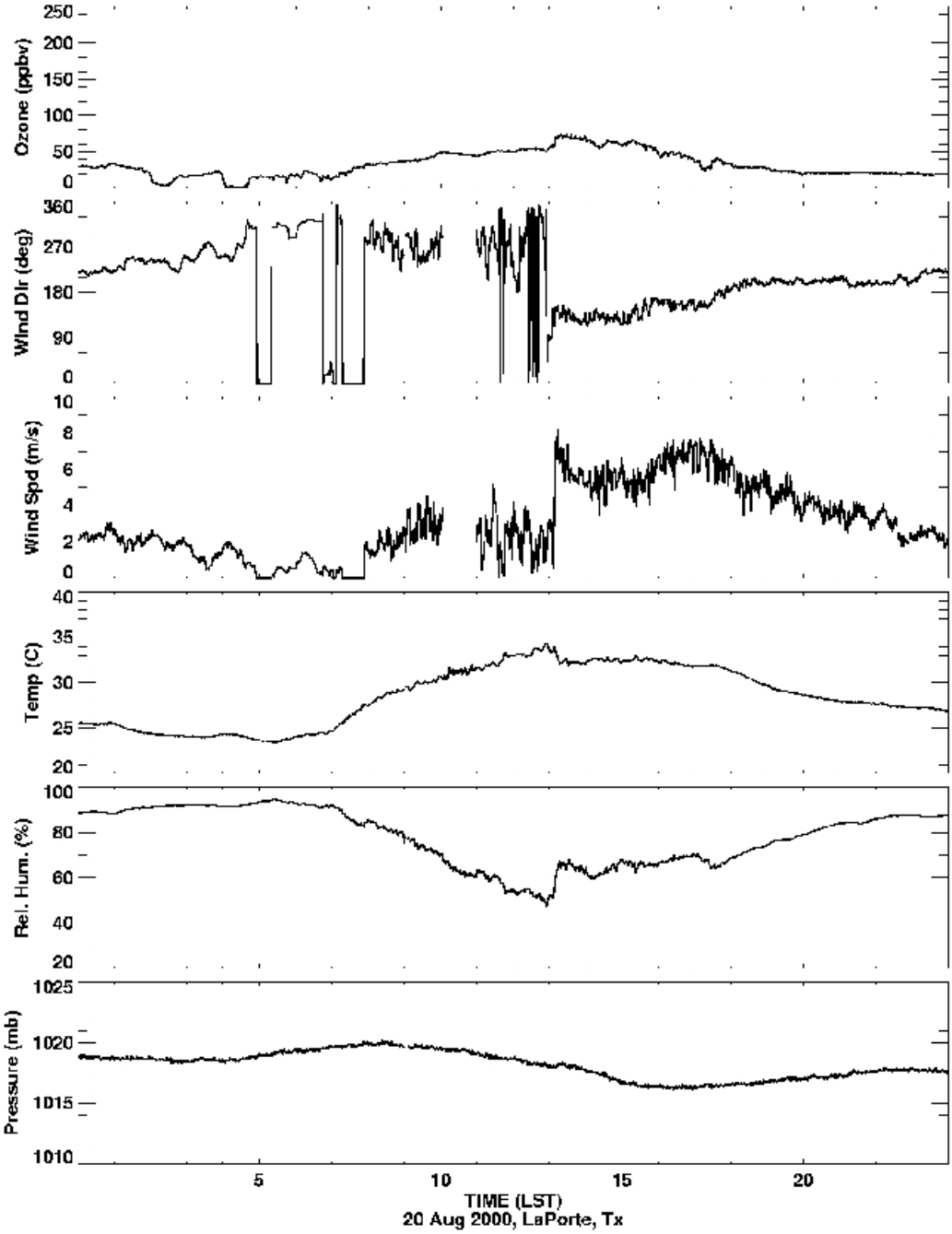


Figure 8: As in Figure 5, except for 20 August 2000.

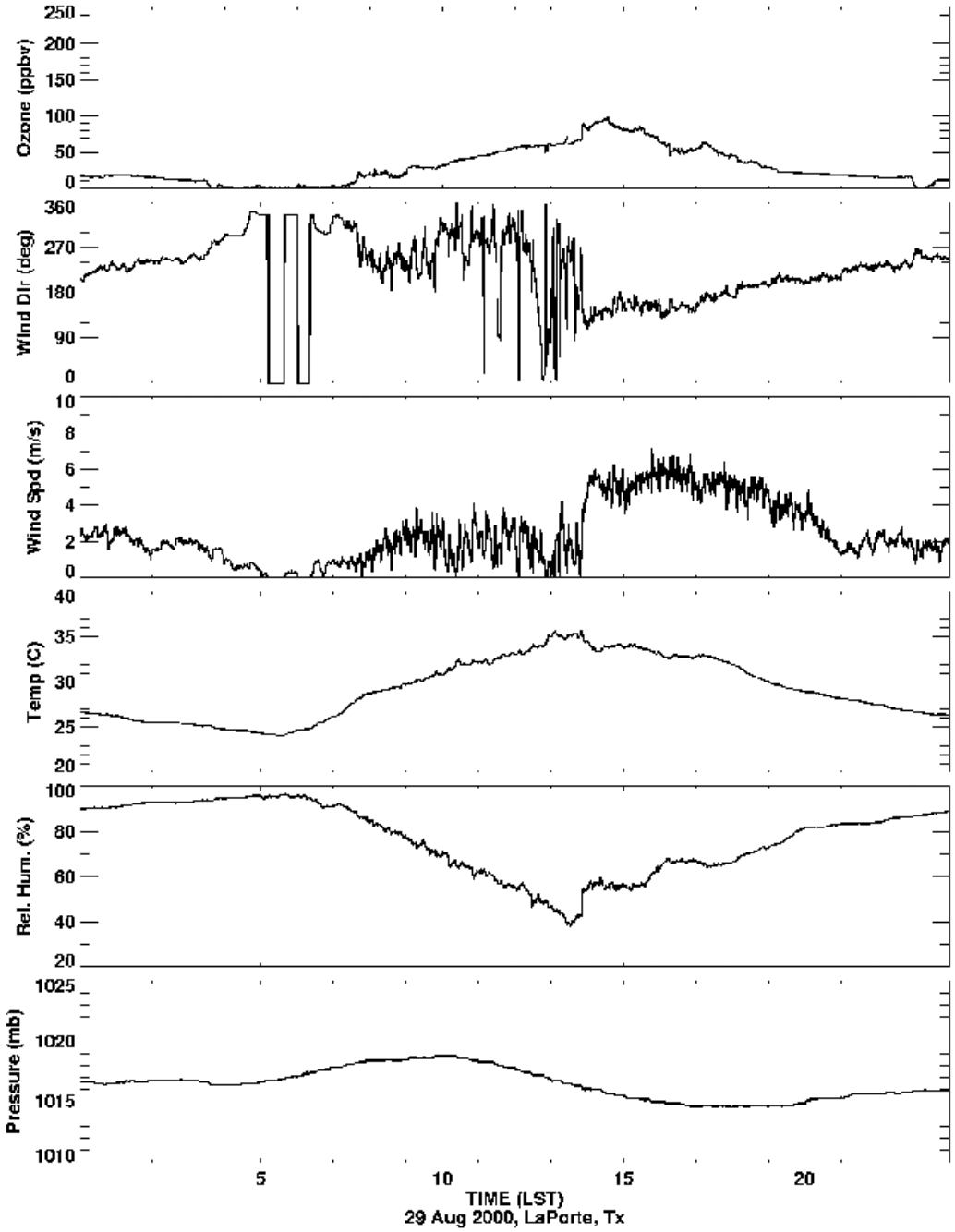


Figure 9: As in Figure 5, except for 29 August 2000.

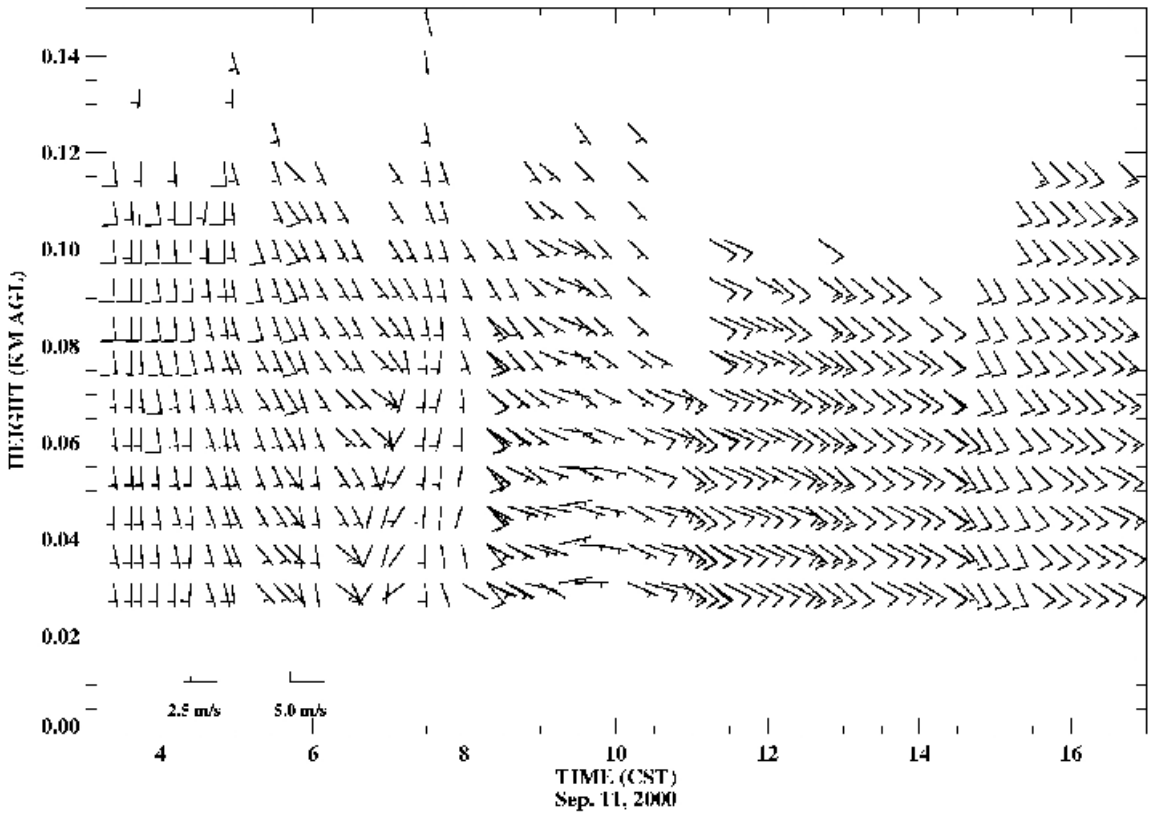


Figure 10: As in Figure 2, except for 11 September 2000, and scans from 1E to 2E elevation were used.

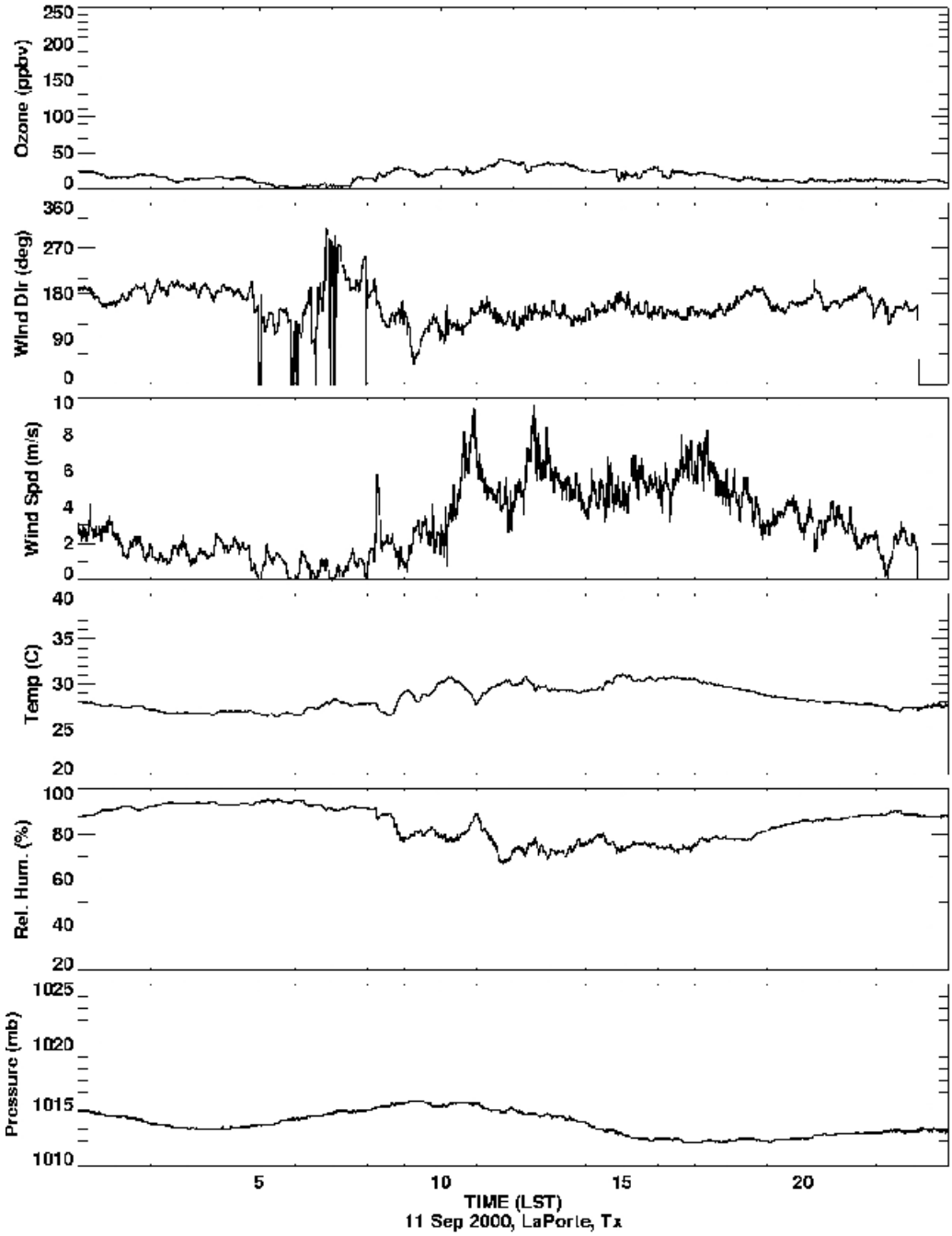


Figure 11: As in Figure 5, except for 11 September 2000.

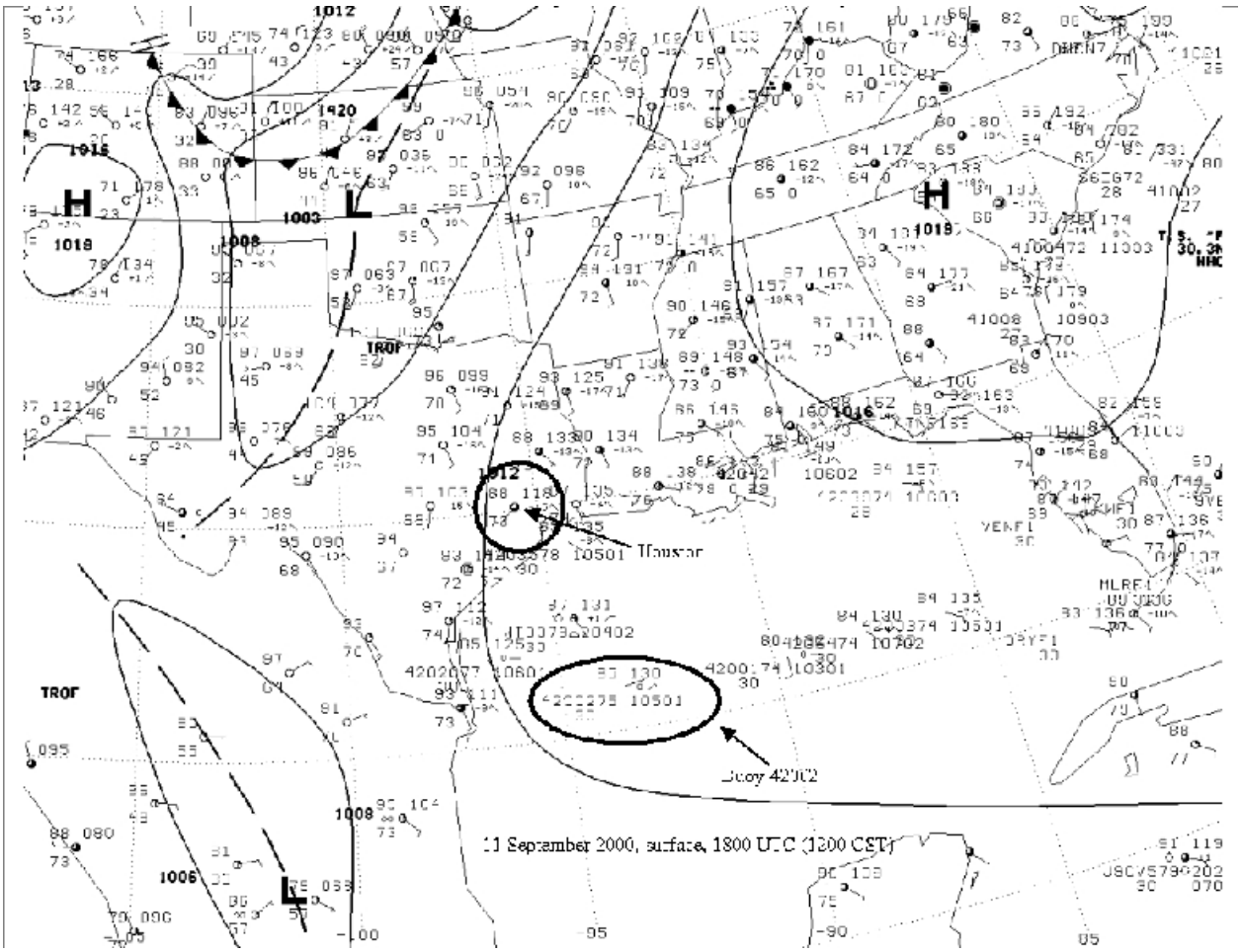
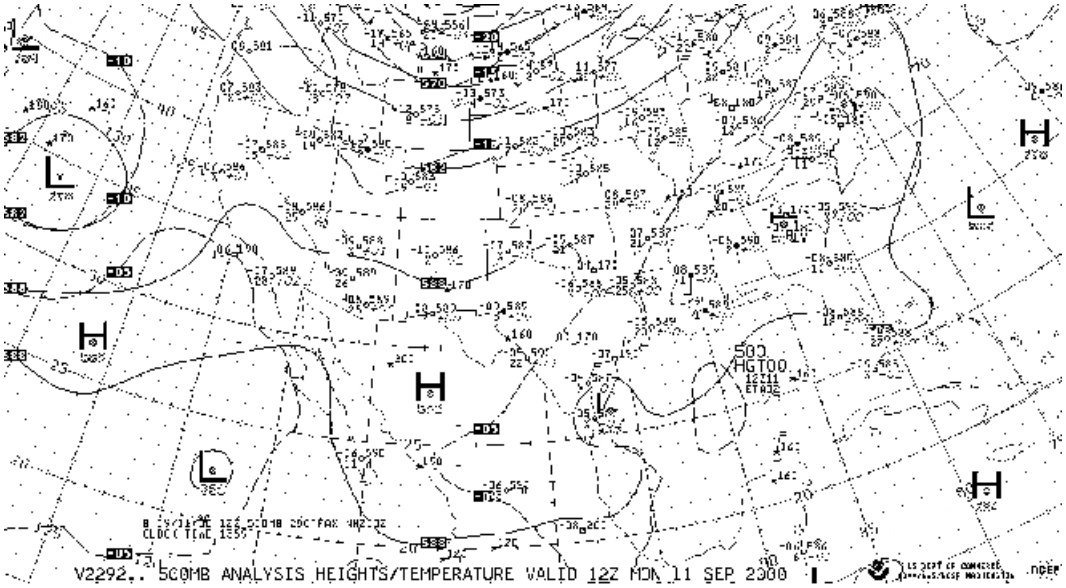


Figure 12: As in Figure 6, except for 11 September 2000.

a)



b)

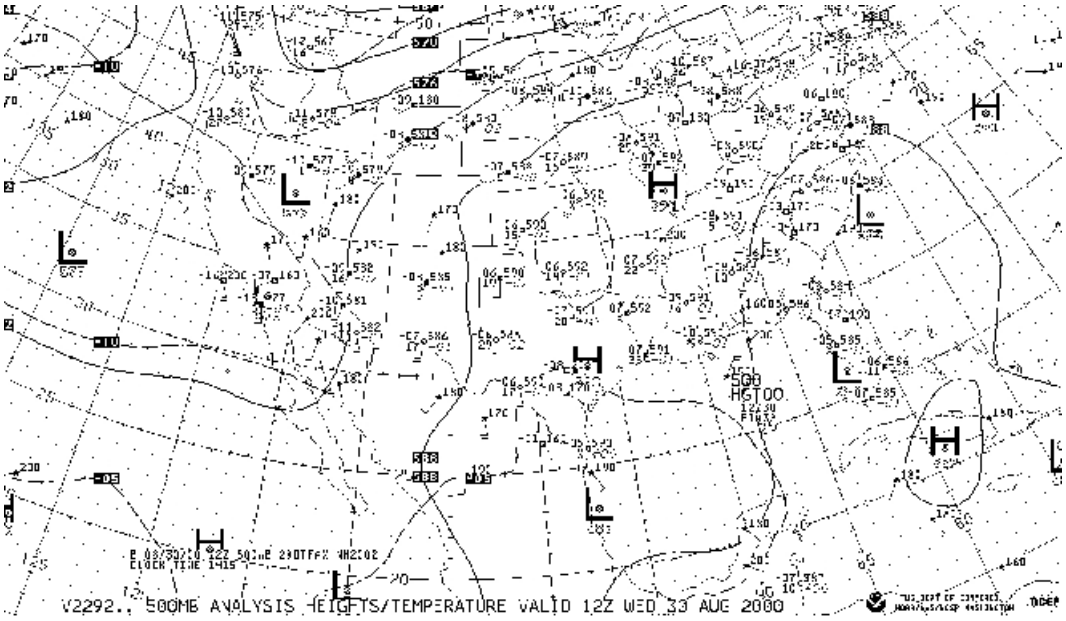


Figure 13: (a) 500 mb analysis acquired from the NOAA/National Climatic Data Center for 1200 UTC (0600 CST), 11 September 2000. (b) As in (a), except for 30 August 2000.

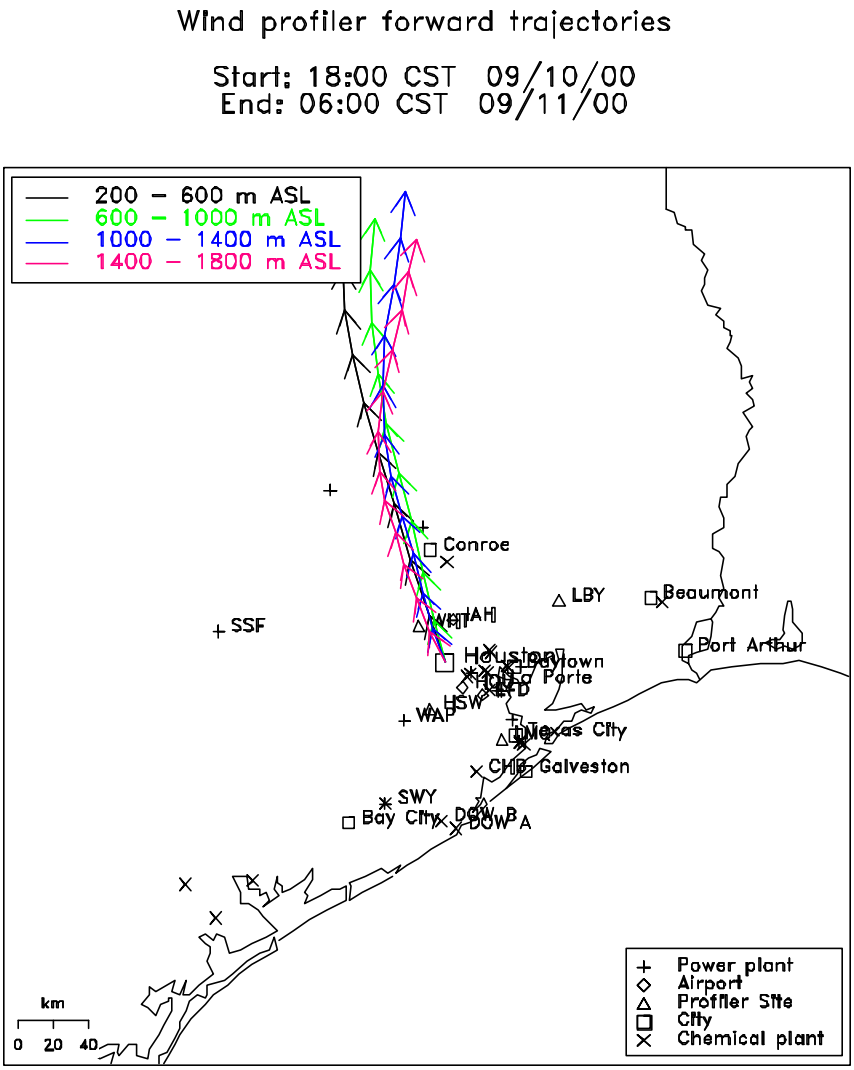


Figure 14: Forward trajectories from 1800 CST, 10 September to 0600 CST, 11 September 2000. Trajectories were calculated from the profiler network deployed for TexAQS 2000.

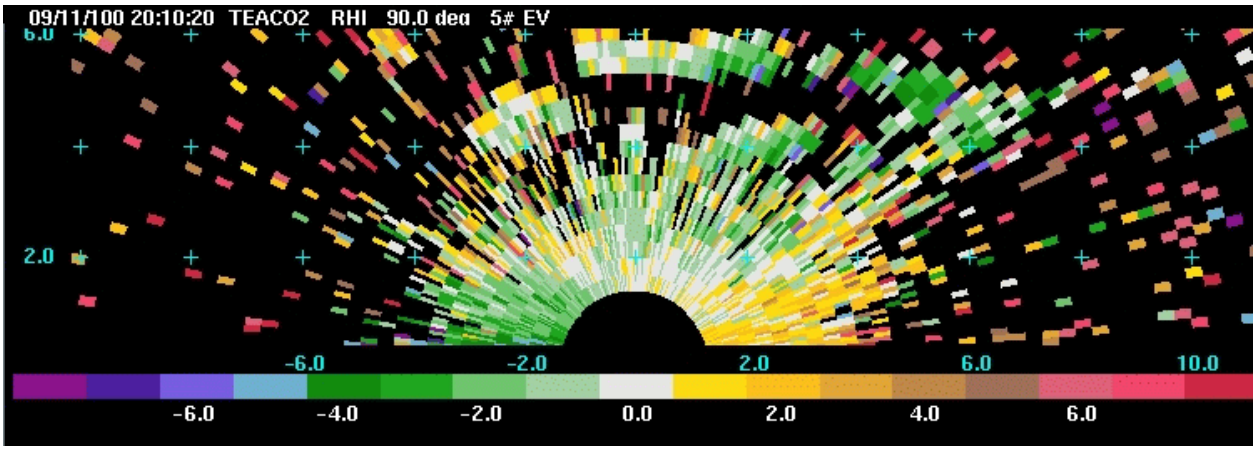


Figure 15: As in Figure 7, except for 2010:20 UTC (1410:20 CST), 11 September 2000.

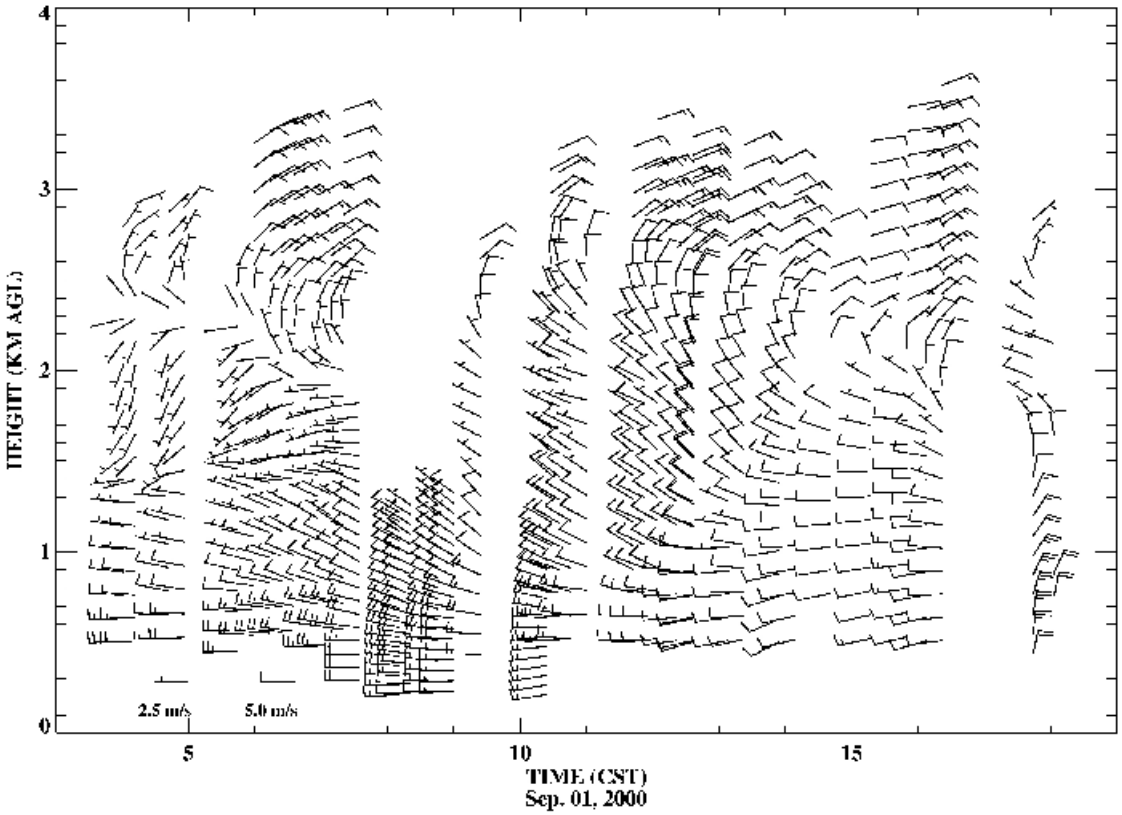


Figure 16: As in Figure 4, except for 01 September 2000, and the profiles were derived from 10E to 30E scans.

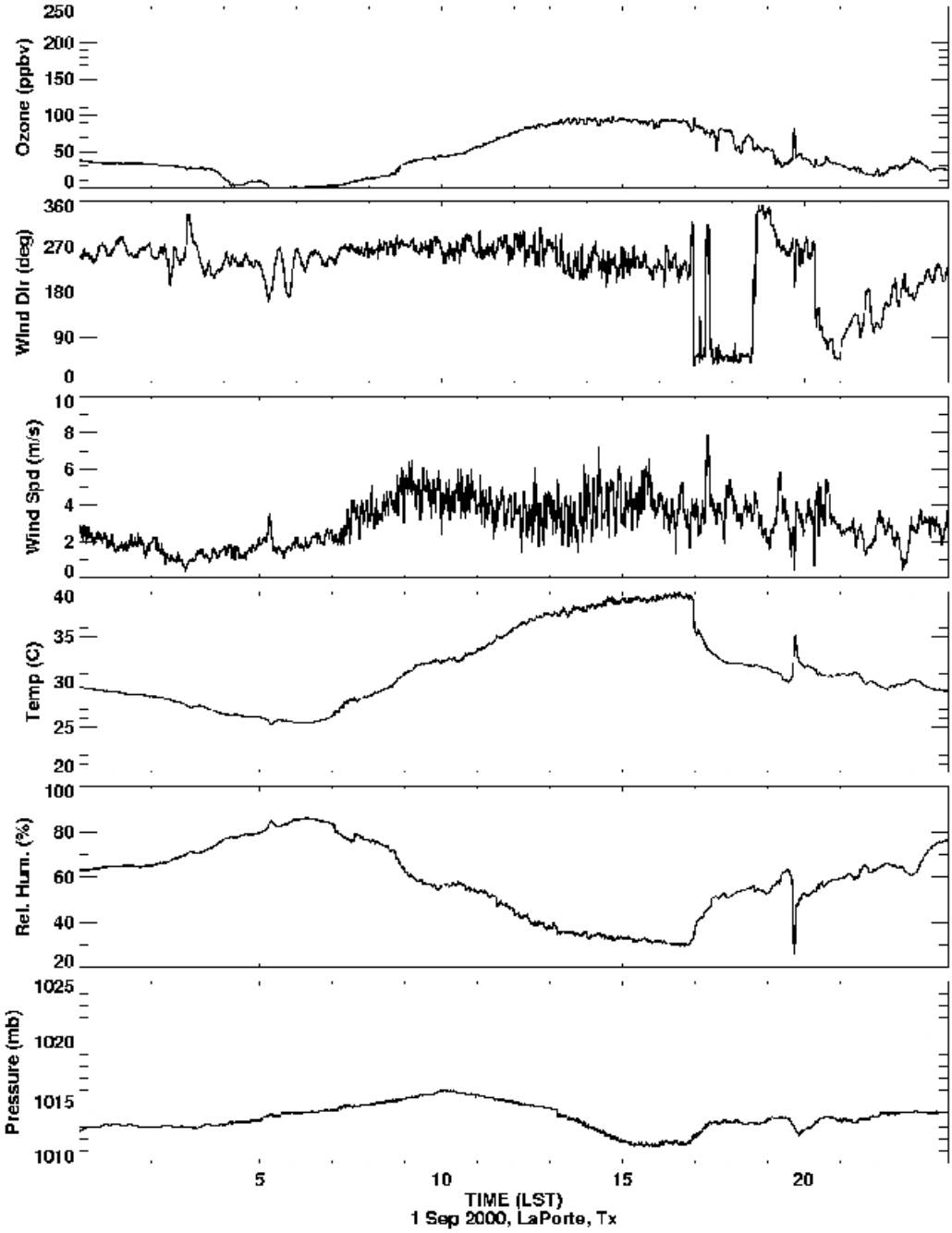


Figure 17: As in Figure 5, except for 01 September 2000.

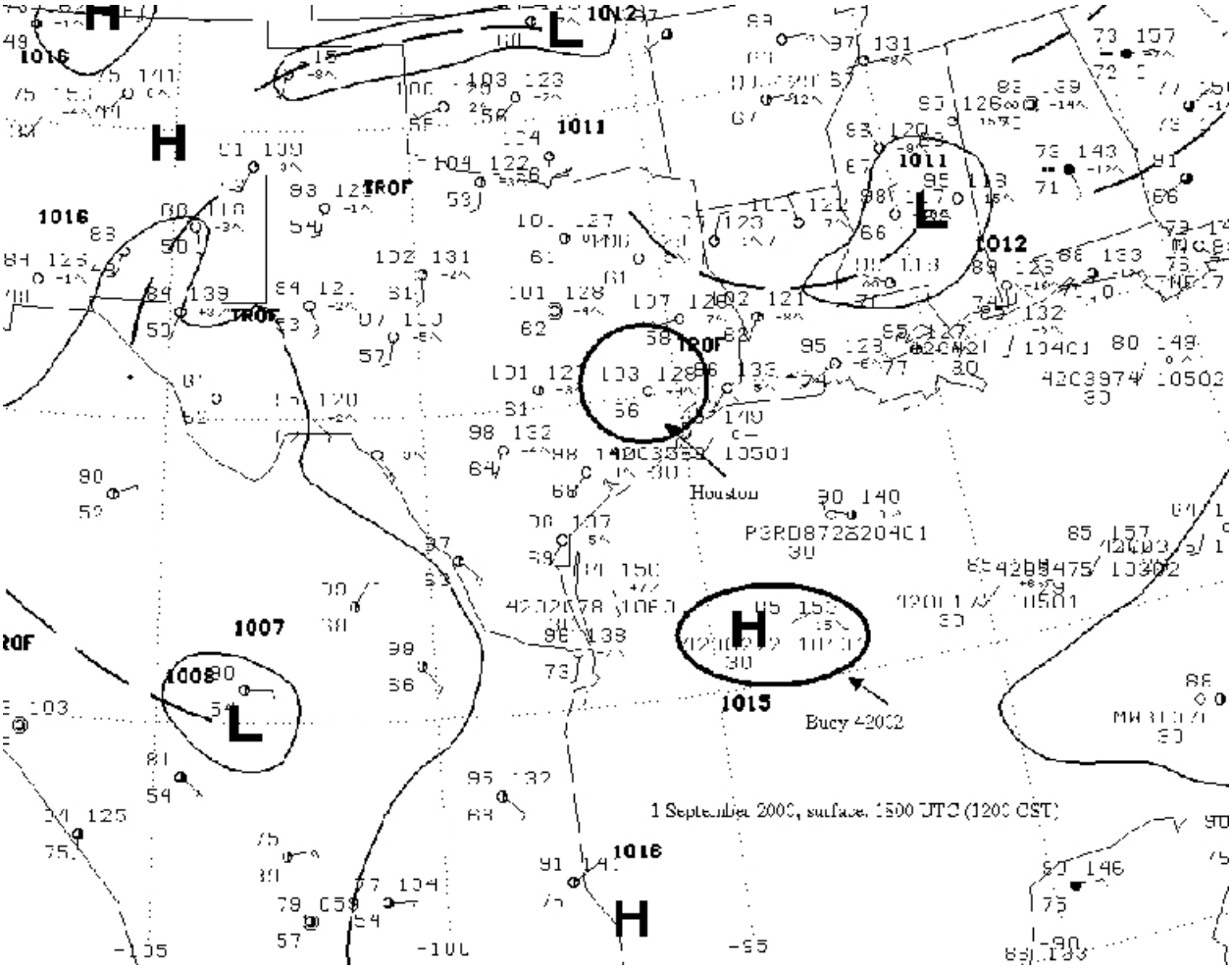


Figure 18: As in Figure 6, except for 01 September 2000.

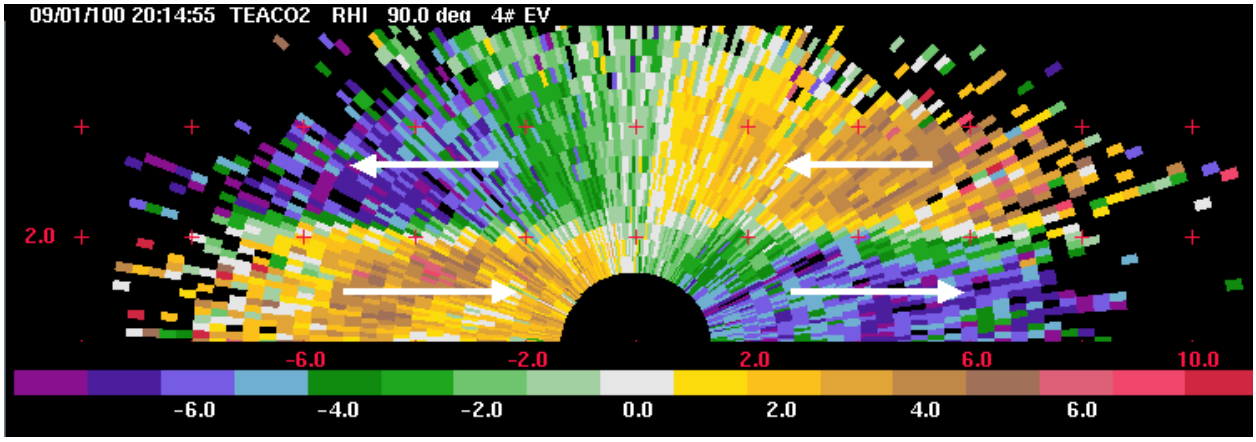
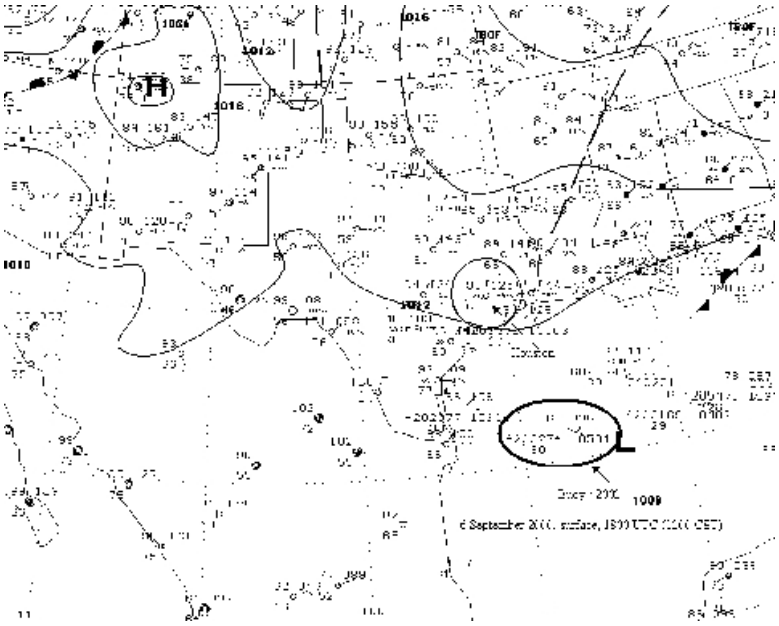


Figure 19: As in Figure 7, except for 01 September 2000.

a)



b)

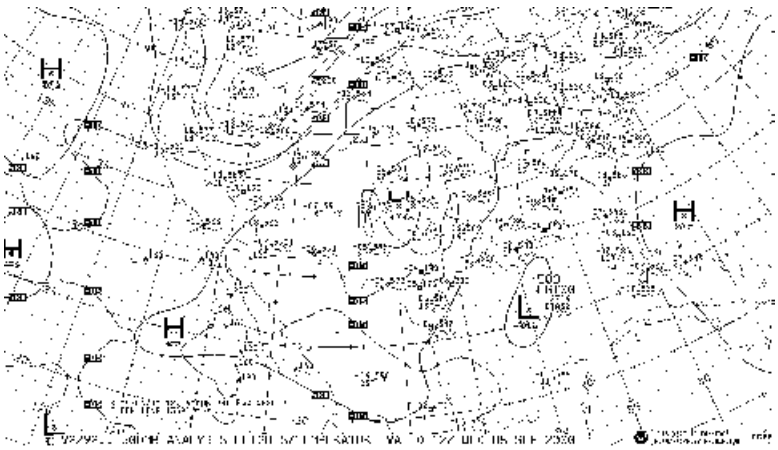


Figure 20: (a) As in Figure 6, except for 06 September 2000. (b) As in Figure 13, except for 06 September 2000.

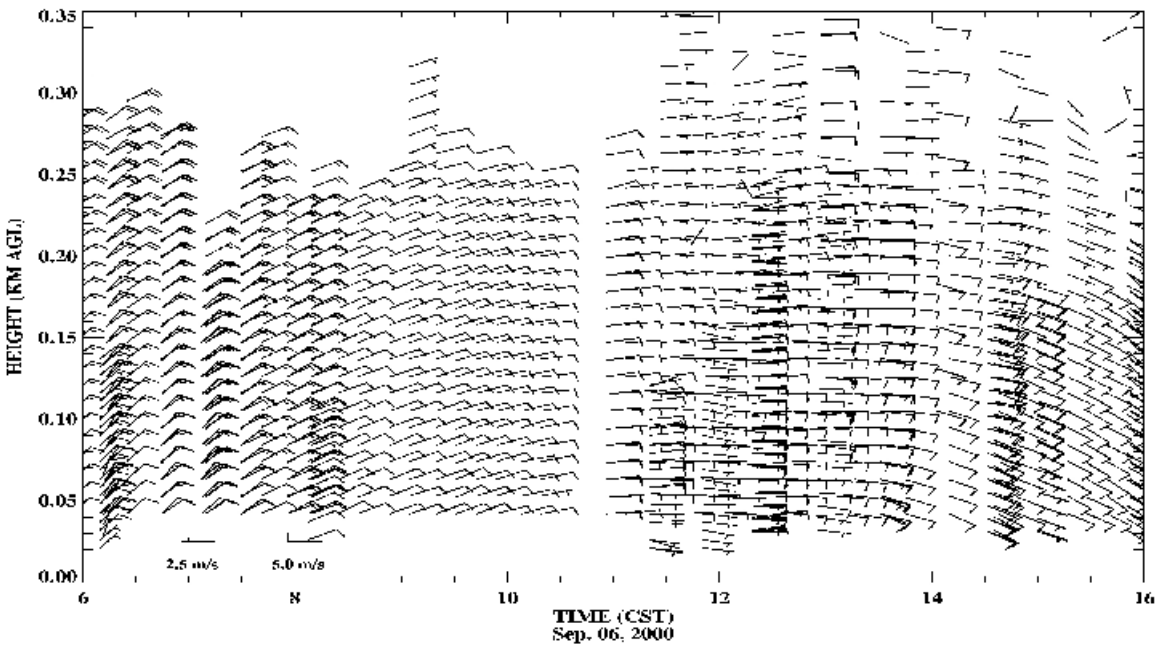


Figure 21: As in Figure 2, except for 06 September 2000. Elevation angles of 1E - 6E were used to calculate the profiles.

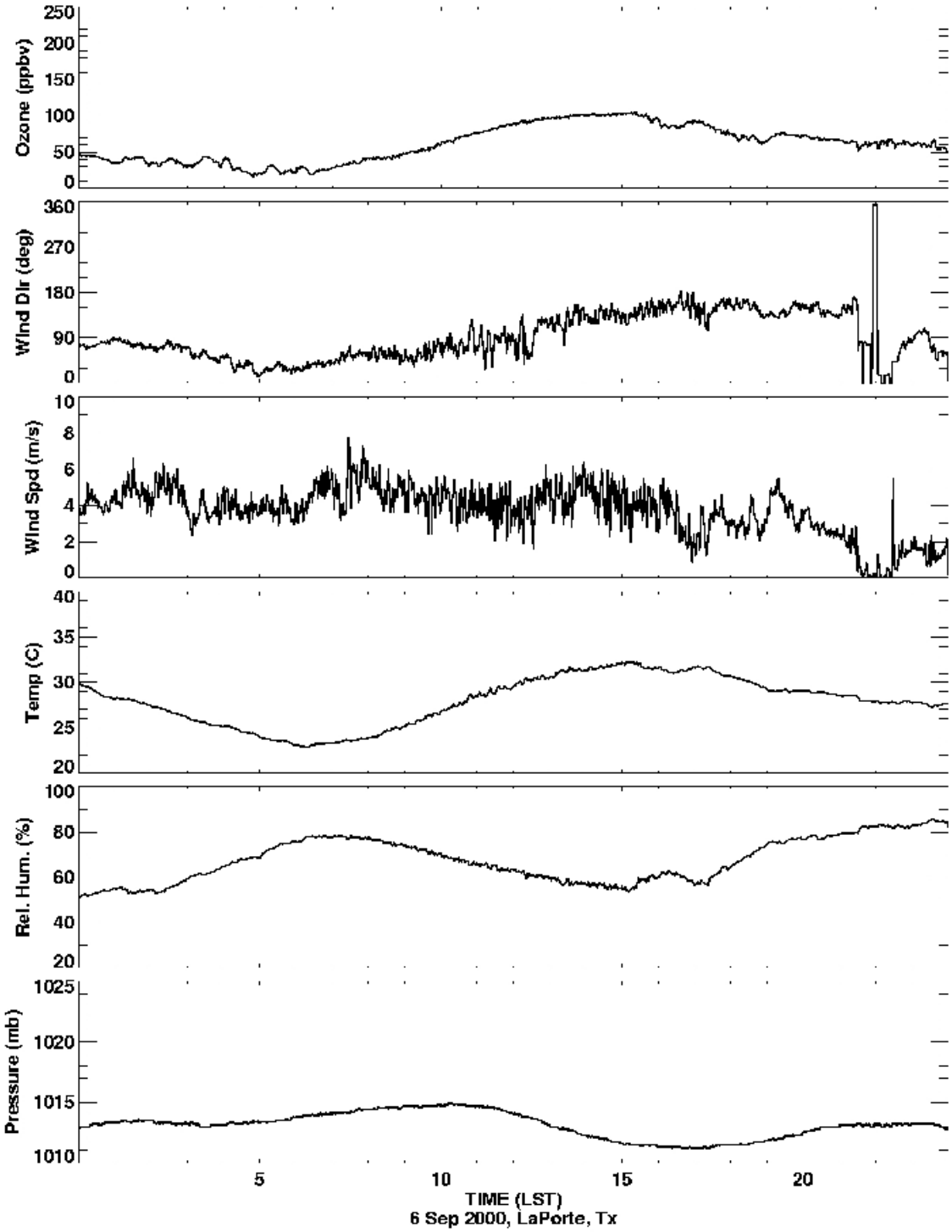


Figure 22: As in Figure 5, except for 06 September 2000.

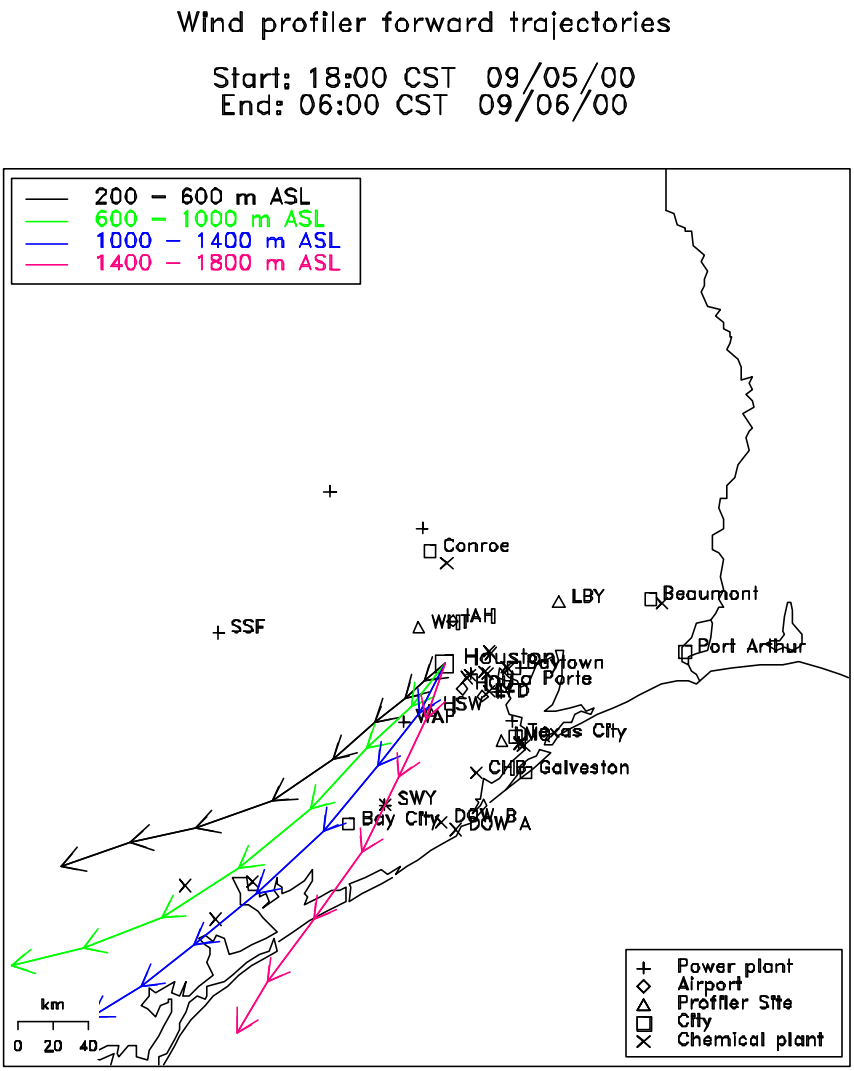


Figure 23: As in Figure 14, except for 05/06 September 2000.

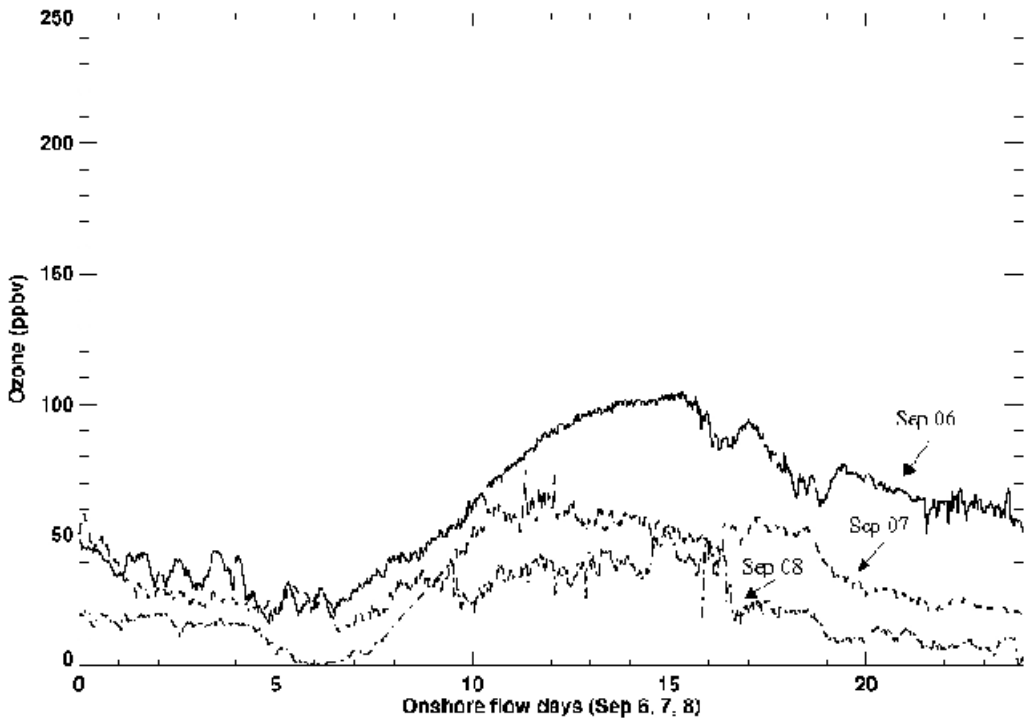


Figure 24: Time series of surface ozone concentrations from LaPorte on 6, 7, and 8 September 2000.

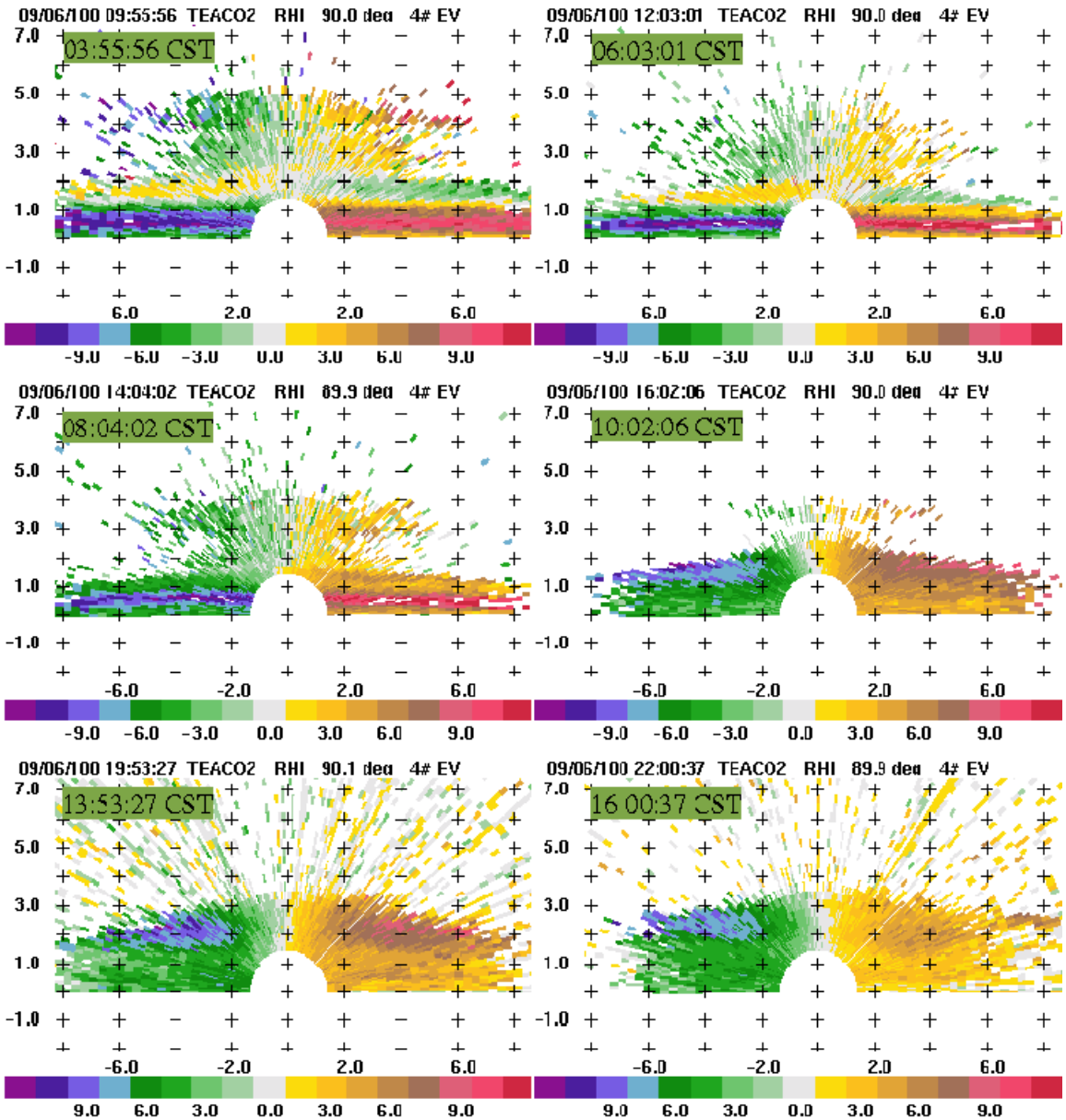


Figure 25: As in Figure 7, except for 06 September 2000, and there is a series of 6 scans depicting the east-west radial velocities throughout the day.

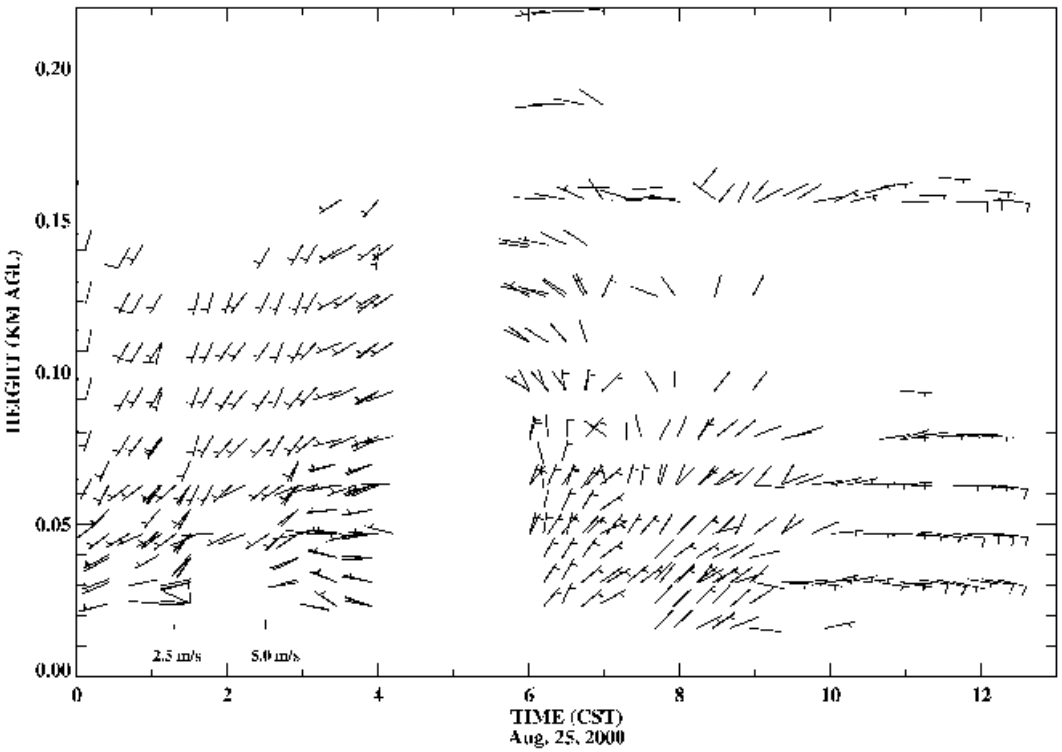


Figure 26: As in Figure 2, except for 25 August 2000.

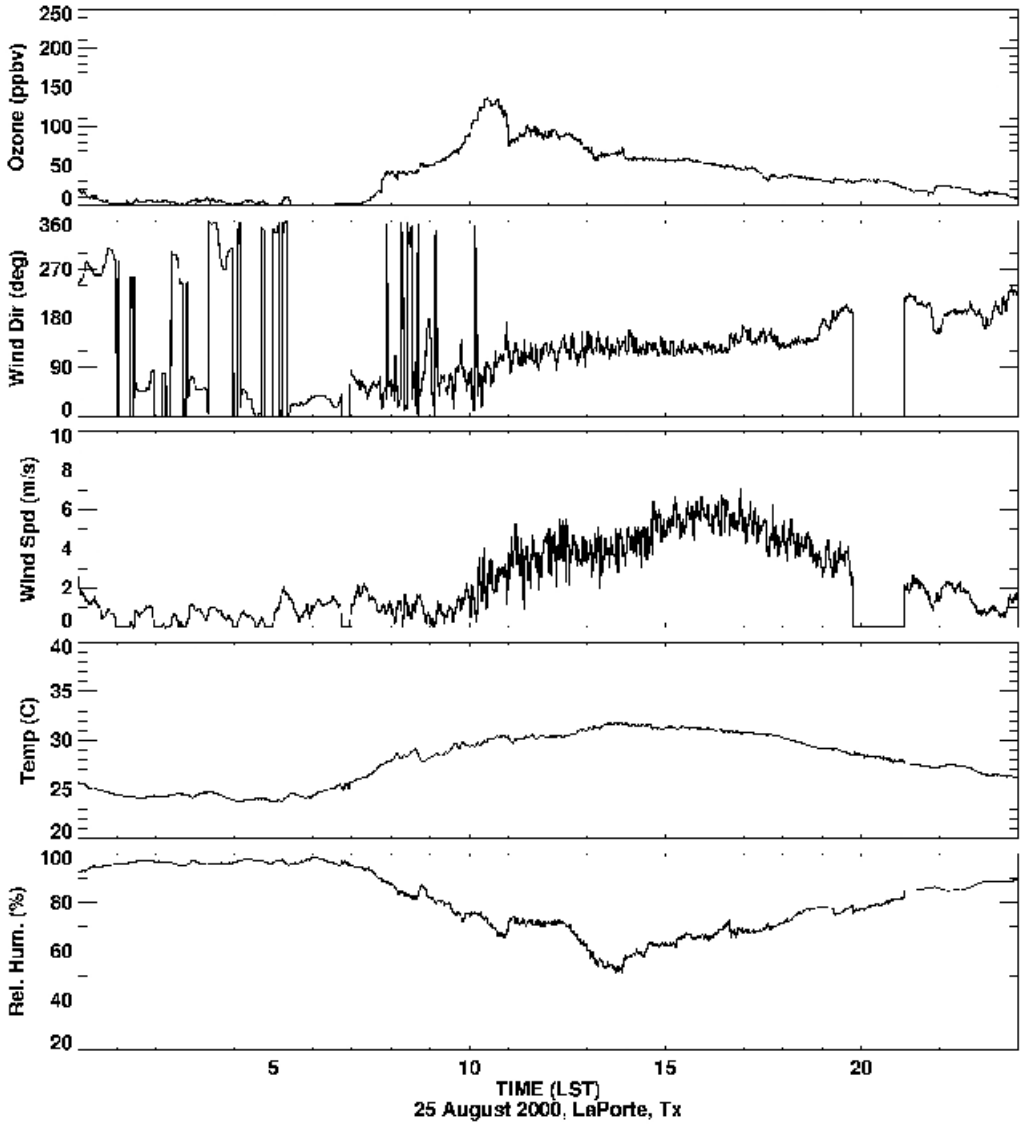


Figure 27: As in Figure 5, except for 25 August 2000.

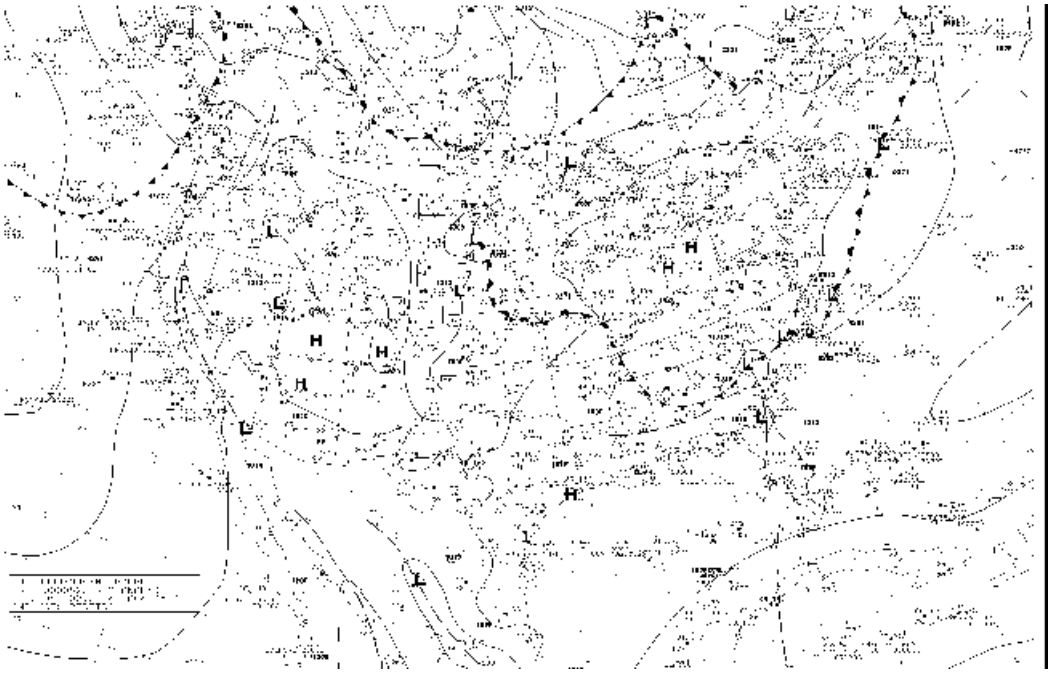


Figure 28: As in Figure 6, except for 25 August 2000.

a)

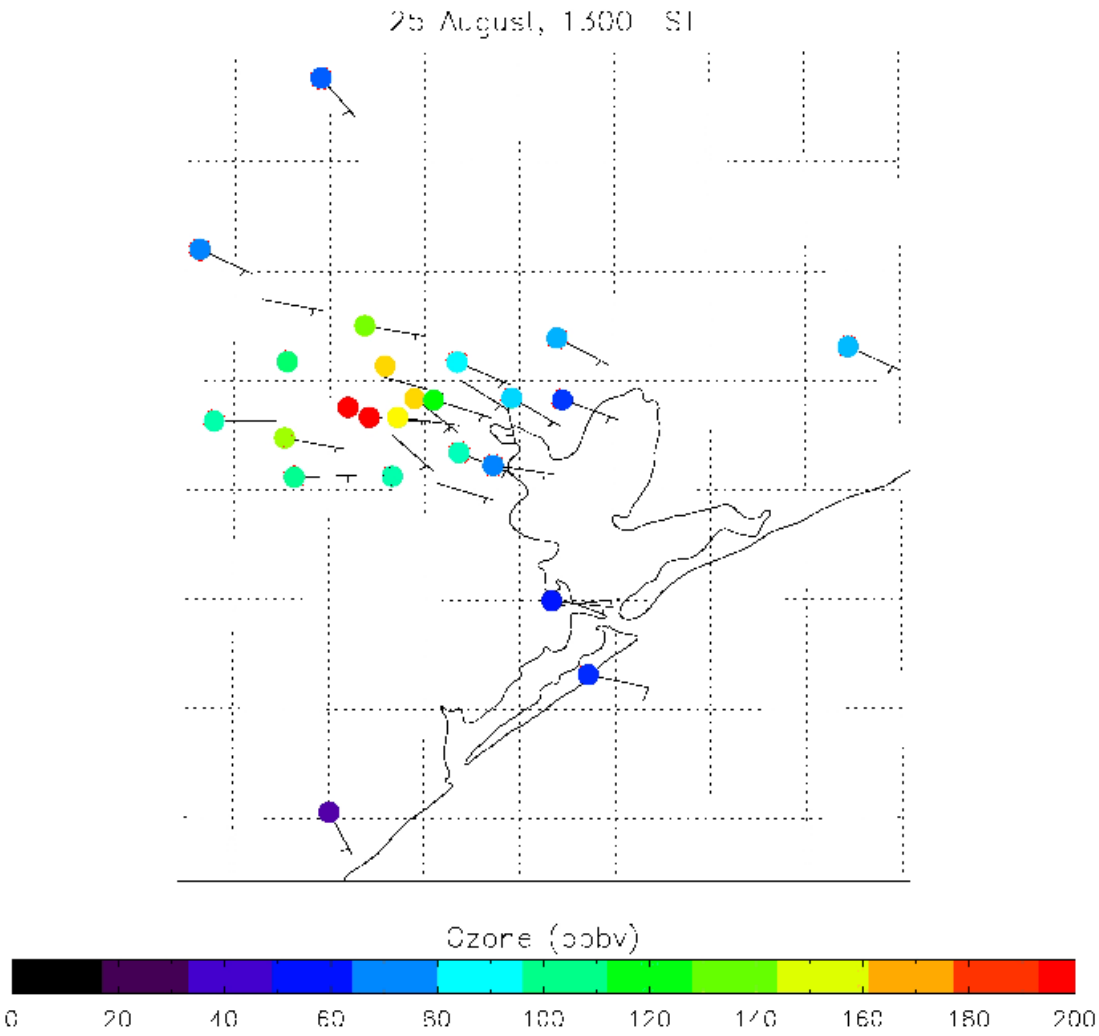


Figure 29: TNRCC surface network data for Houston, Galveston, and Brazoria. The station circle represents the hourly averaged ozone. The wind barb points into the wind. A half-barb represents 2.5 m s^{-1} and a full barb represents 5 m s^{-1}. a) 1300 CST, 25 August 2000; b) 1500 CST, 25 August 2000.

b)

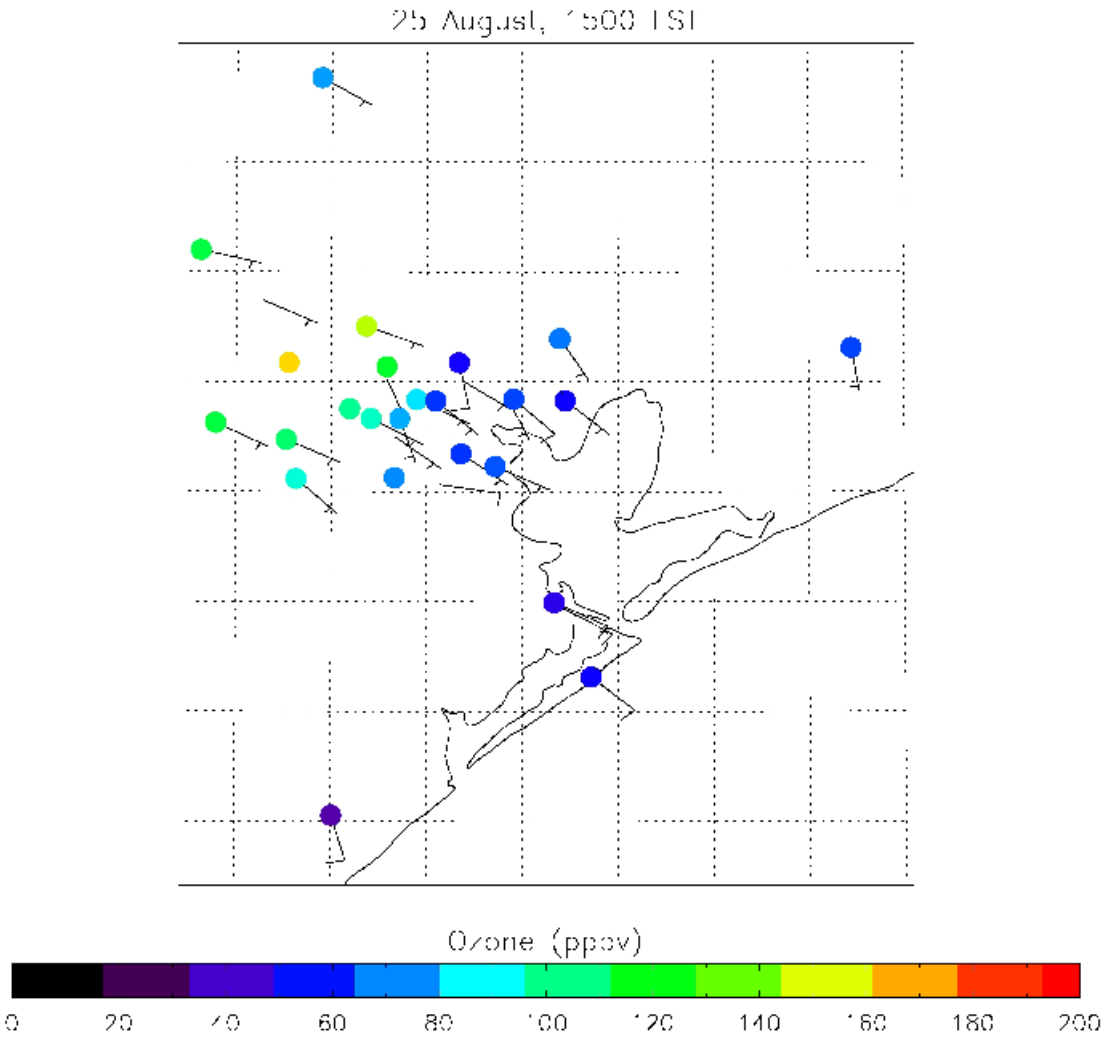


Figure 29: TNRCC surface network data for Houston, Galveston, and Brazoria. The station circle represents the hourly averaged ozone. The wind barb points into the wind. A half-barb represents 2.5 m s^{-1} and a full barb represents 5 m s^{-1}. a) 1300 CST, 25 August 2000; b) 1500 CST, 25 August 2000.

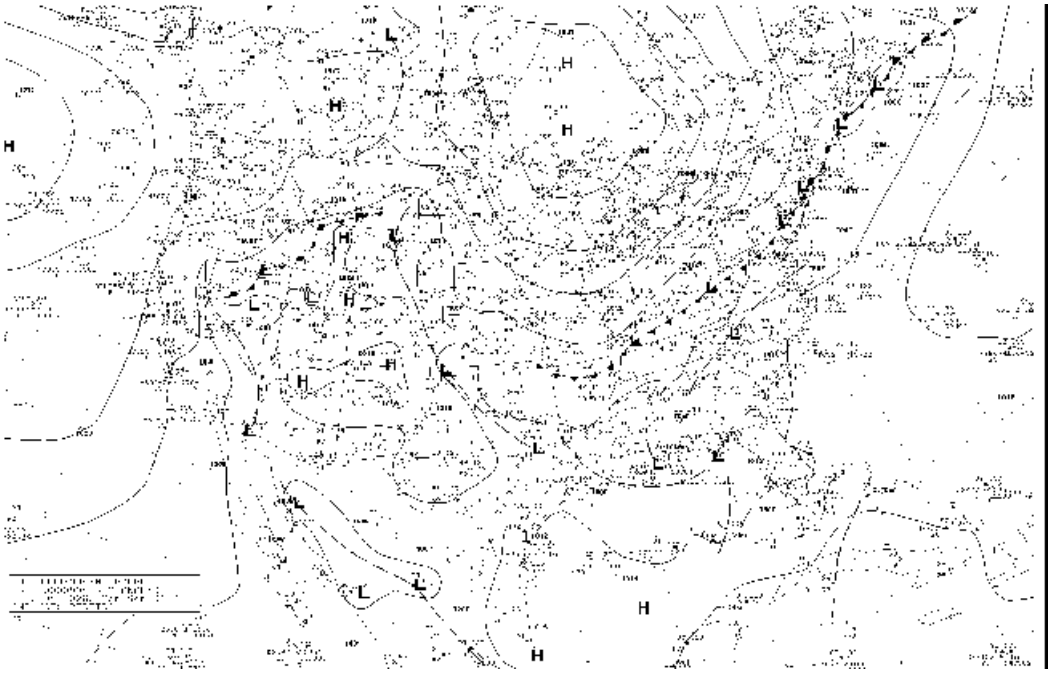


Figure 30: As in Figure 6, except for 4 September 2000.

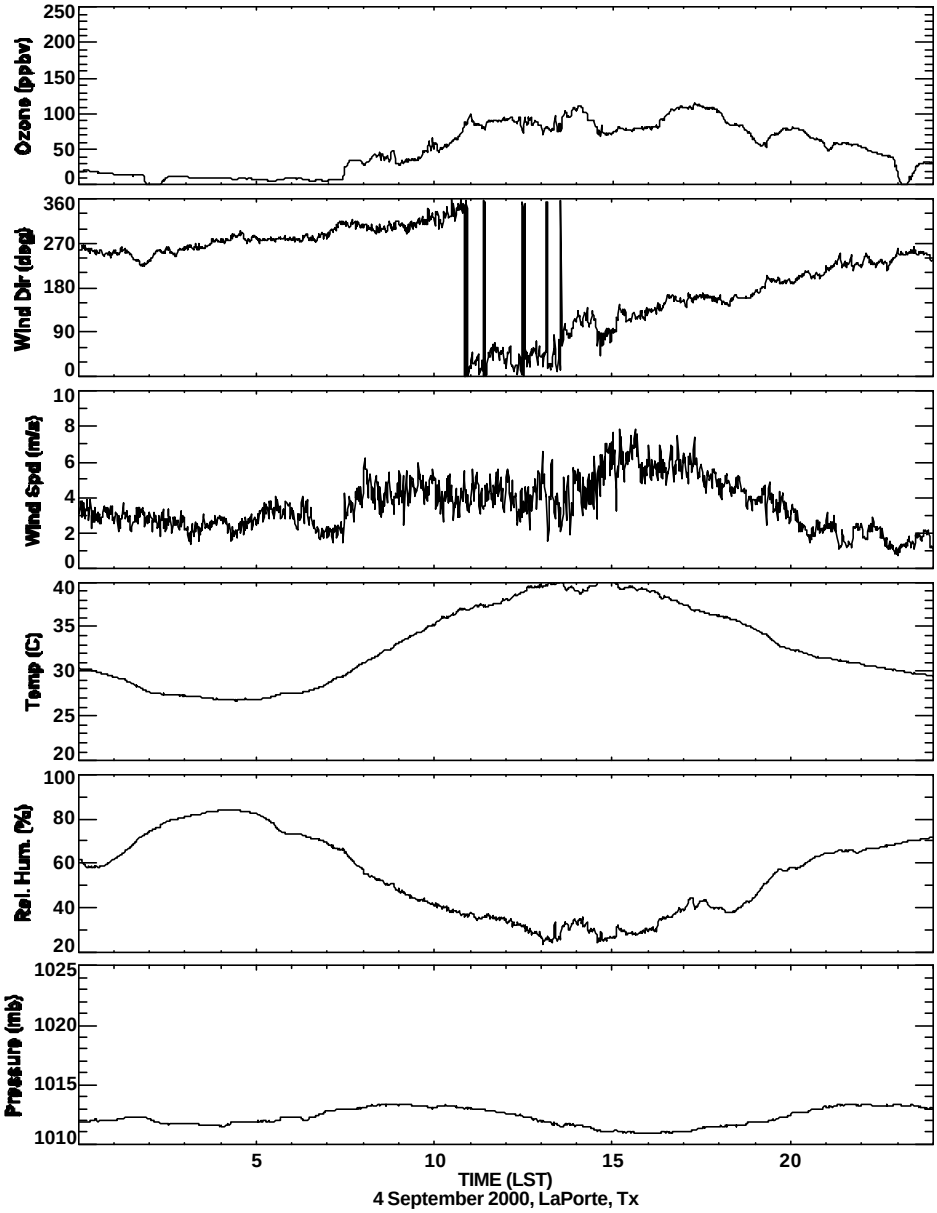


Figure 31: As in Figure 5, except for 4 September 2000.

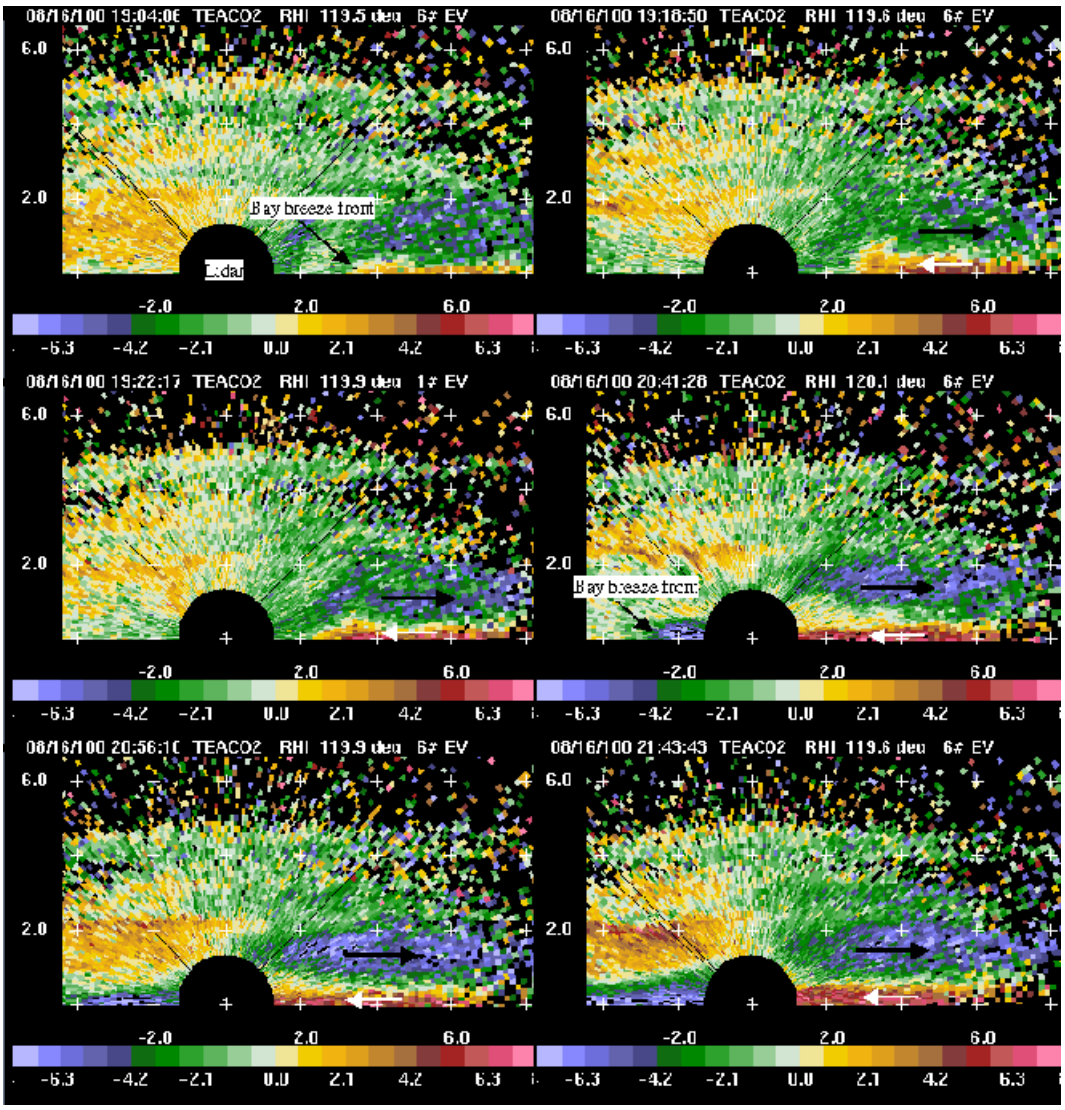


Figure 32: Doppler lidar range-height scans from 16 August 2000. The location of the lidar is noted in 3.1a. Warm colors indicate flow toward the lidar, cool colors indicate flow away from the lidar. The color scale at the bottom of the plot represents wind speed in m s^{-1}. Horizontal and vertical tick marks are in 2 km increments. Arrows serve as reminders as to whether the flow was toward or away from the lidar. Times are UTC; the right side of the scan points toward 120E azimuth, the left side points to 300E azimuth.

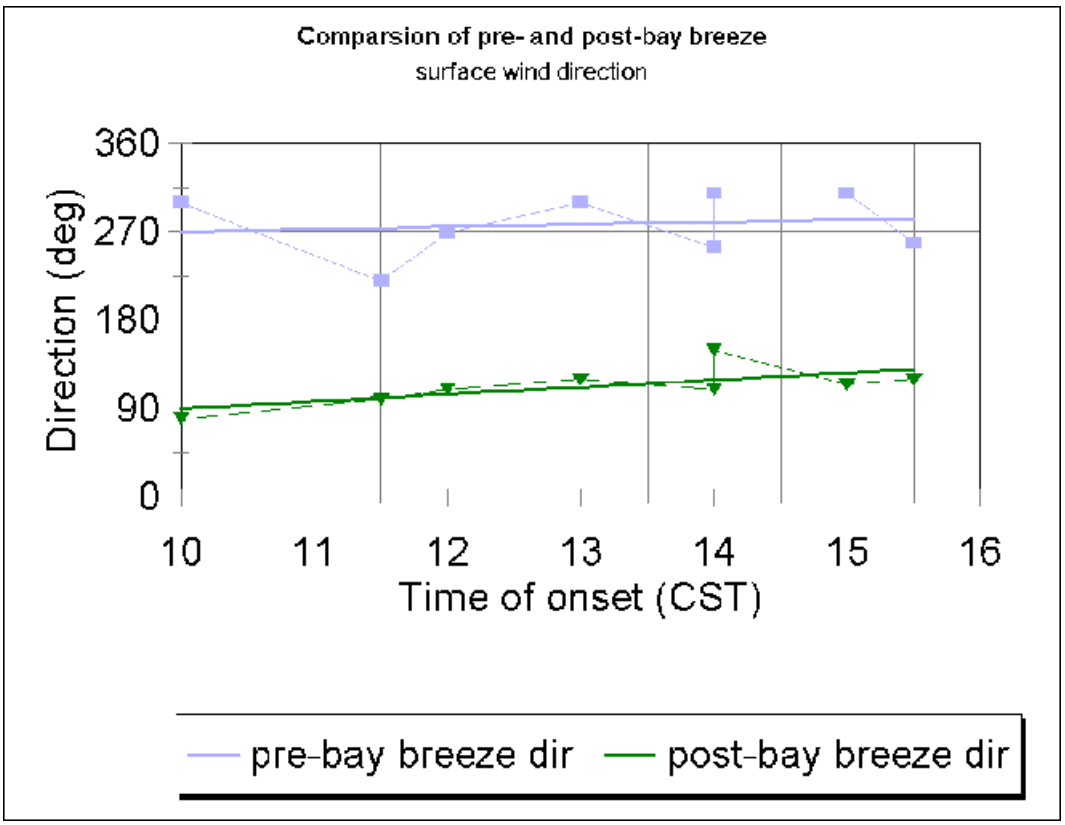


Figure 33: Surface wind direction pre- and post-bay breeze (taken from Table 3.1) are plotted against time of bay breeze onset. Blue line represents morning offshore flow, green line represents bay breeze flow direction.

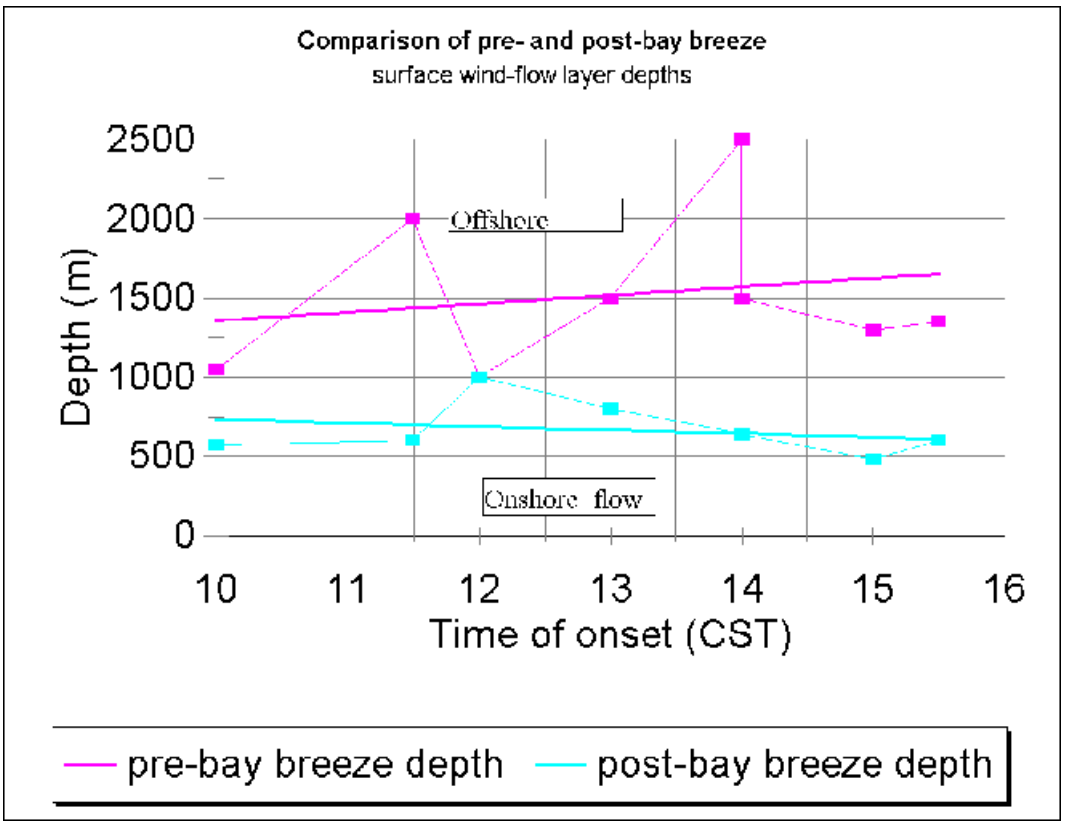


Figure 34: Depth of offshore flow (pink line) and onshore flow (blue line), taken from lidar range-height scans and cross-checked with lidar wind profiles, plotted against time of bay breeze onset. Values also taken from Table 3.1.

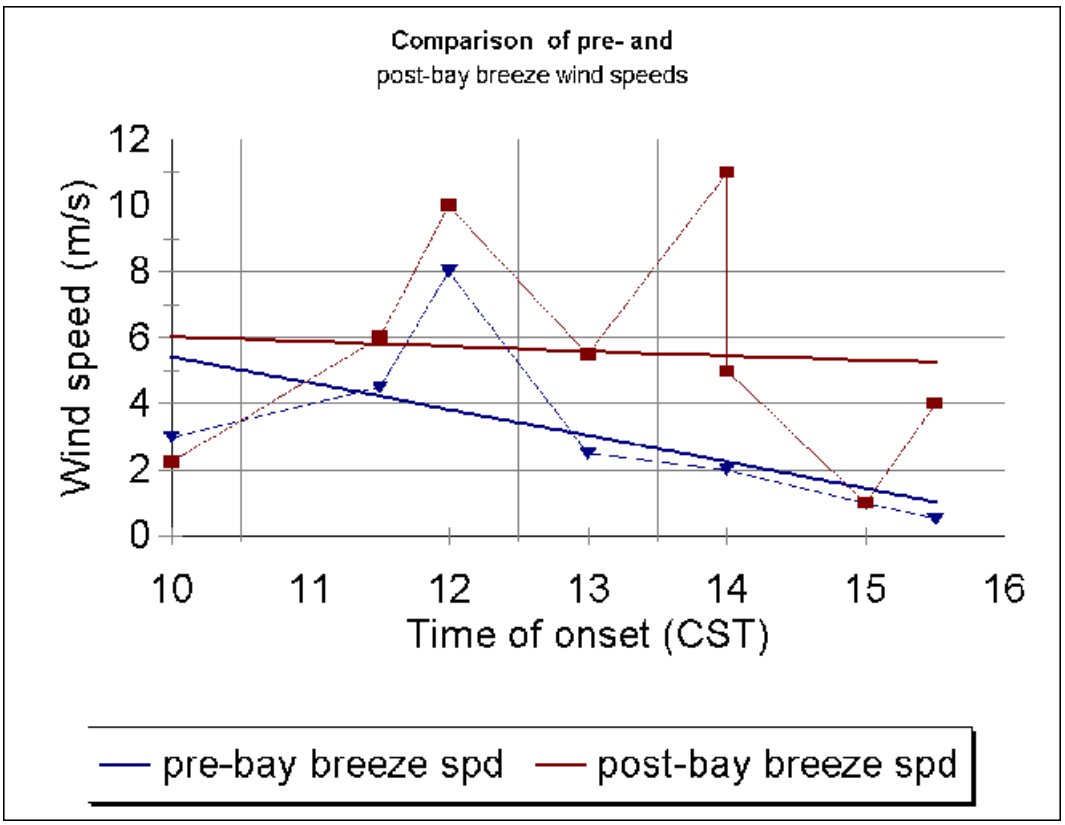


Figure 35: Surface wind speed (m s^{-1}) before (blue line) and after (red line) bay breeze onset, plotted against time of bay breeze onset. Values also taken from Table 3.1.

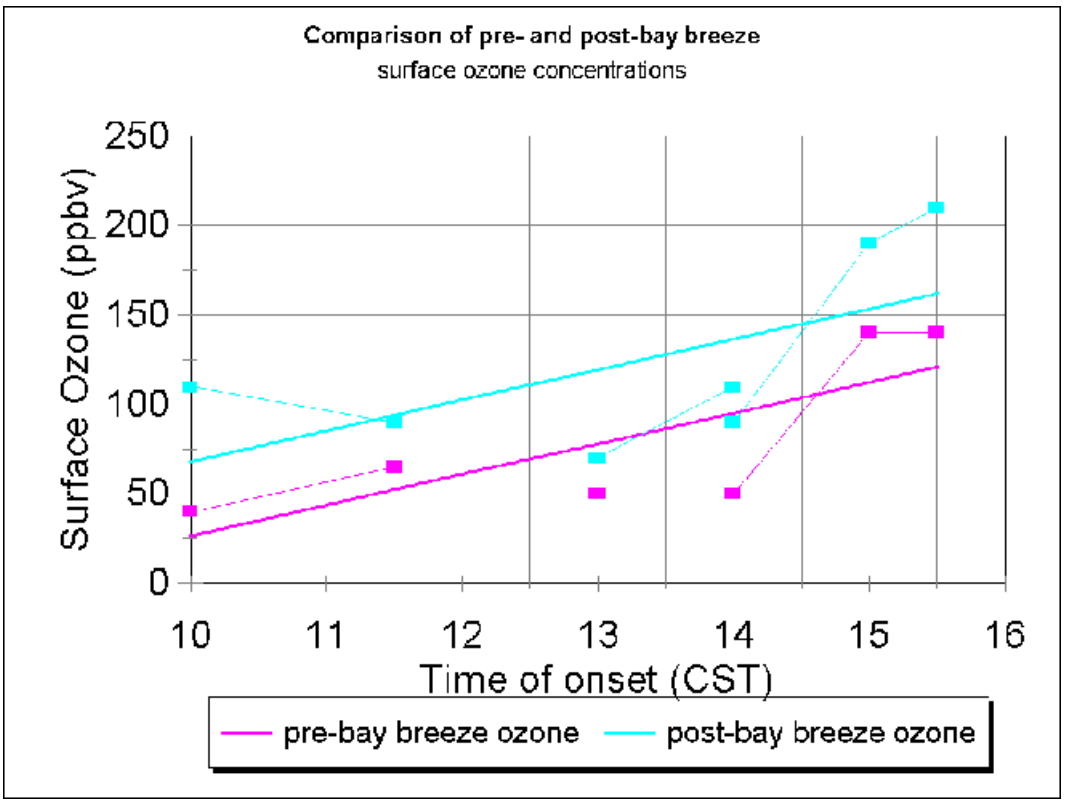


Figure 36: Surface ozone concentrations before (pink line) and after (blue line) bay breeze onset, plotted against time of bay breeze onset. Values also taken from Table 3.1

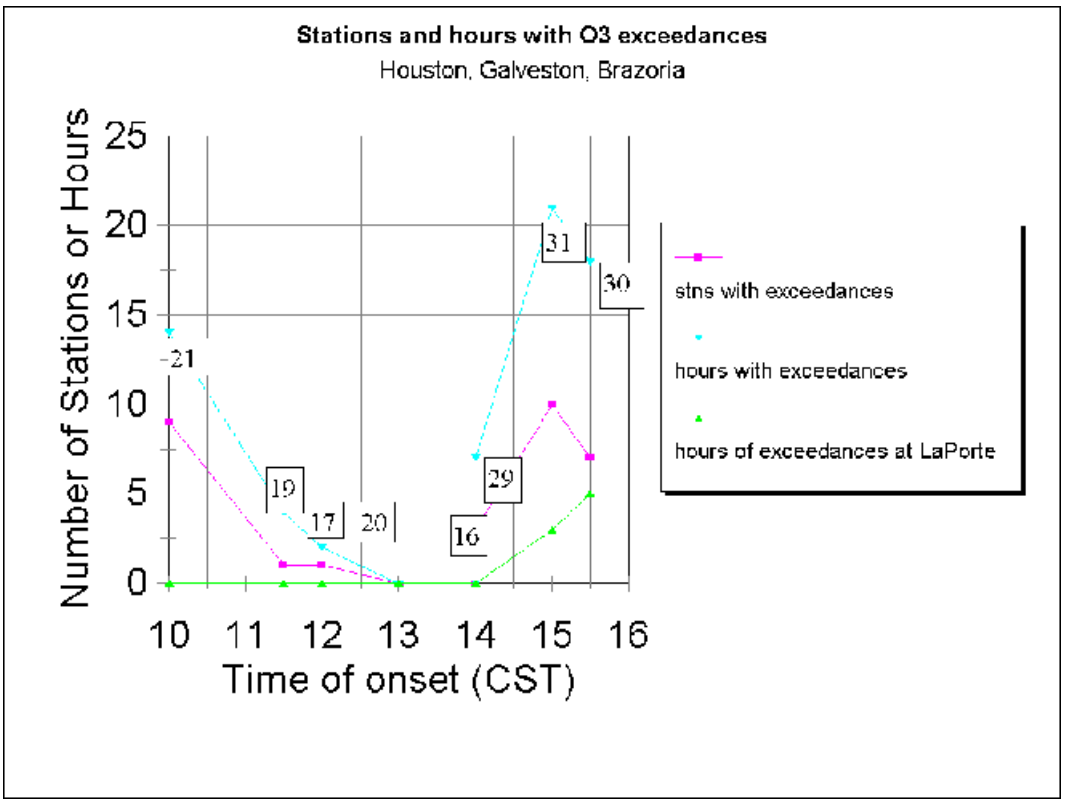


Figure 37: Number of stations in the Houston, Galveston, Brazoria network with an hourly average of ozone exceeding 125 ppbv (pink line), total number of hours with hourly averages exceeding 125 ppbv (blue line) across the Houston, Galveston, Brazoria network, and number of hours exceeding 125 ppbv at LaPorte only, plotted against onset time of the bay breeze. (Data taken from TNRCC web site: http://www.tnrcc.state.tx.us/cgi-bin/monops/daily_average).

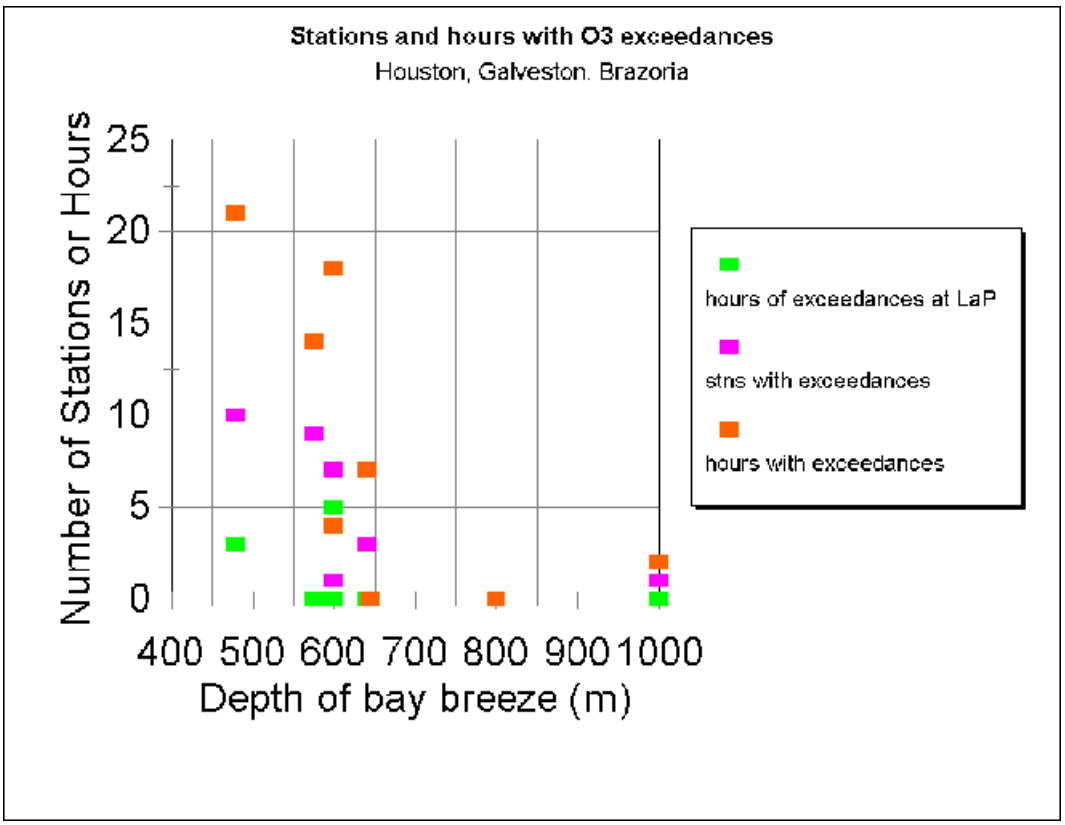


Figure 38: As in Figure 37, except exceedance information is plotted against depth of the bay breeze one hour after onset.

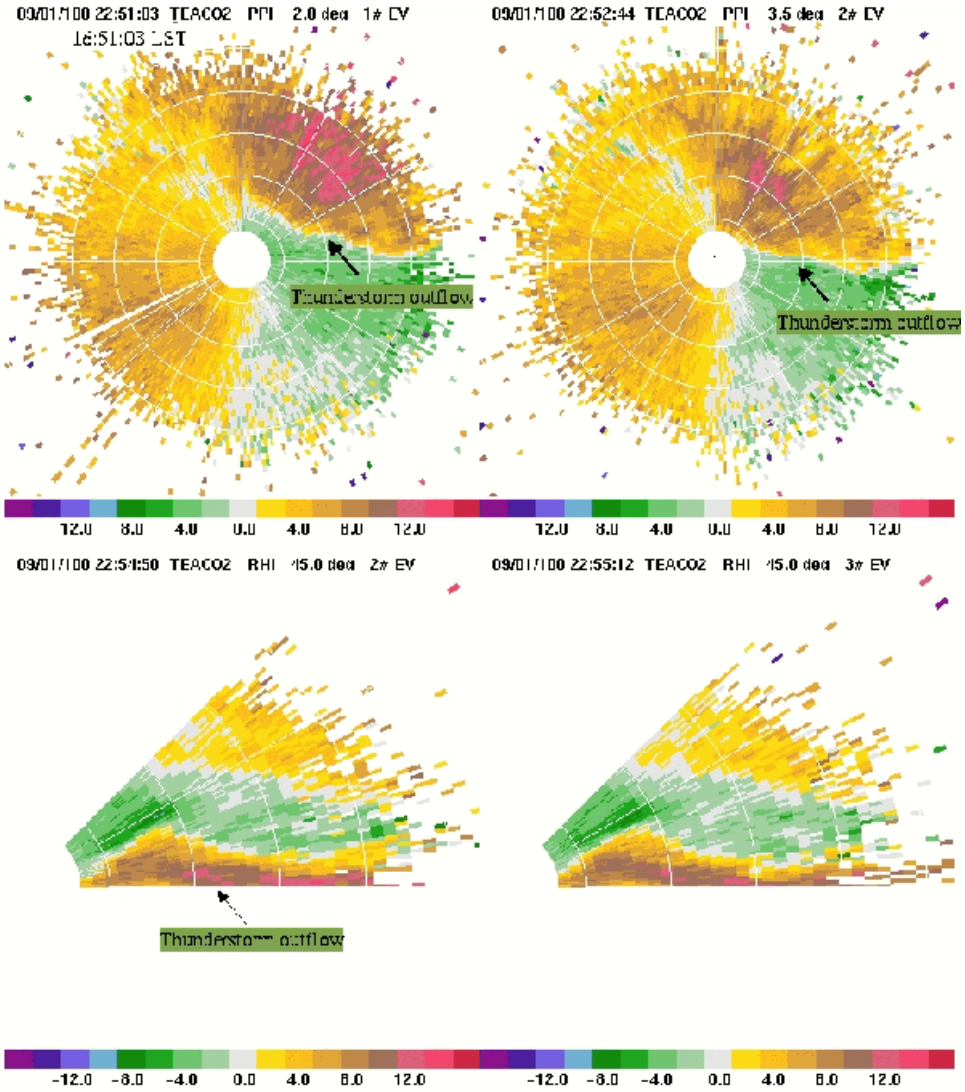


Figure 39: The bottom two panels are similar to the scans shown in Figure 7, except the azimuth angle was 45E, the times were ~2300 UTC (1700 CST), and the date was 01 September 2000. The thunderstorm outflow was seen at the surface with a layer of opposing flow above it. The top two scans were constant-elevation-angle scans at 2E and 3.5E. The lidar is in the center of each scan; north is to the top. Before the thunderstorm outflow passage the winds were westerly, indicated by the yellow on the left side of the scan and the green on the right side of the scans (also seen in the profiles in Fig. 15). The thunderstorm outflow boundary is indicated on the figure.

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