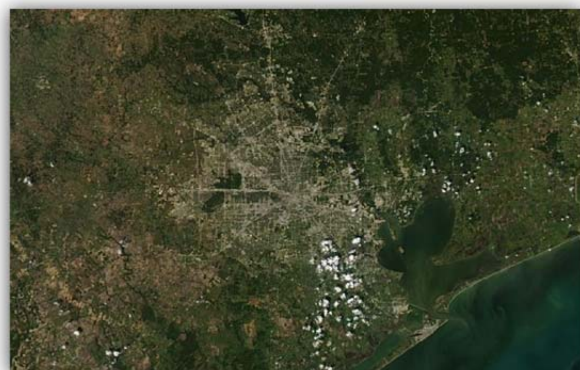
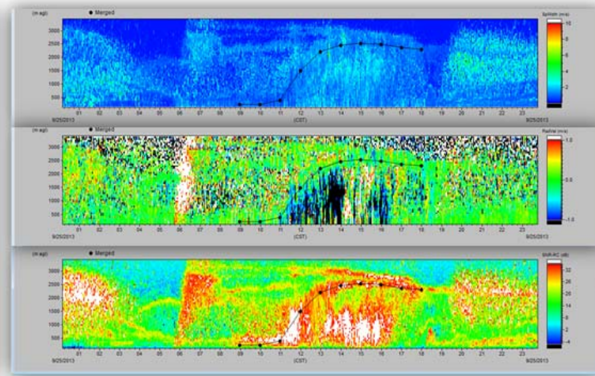
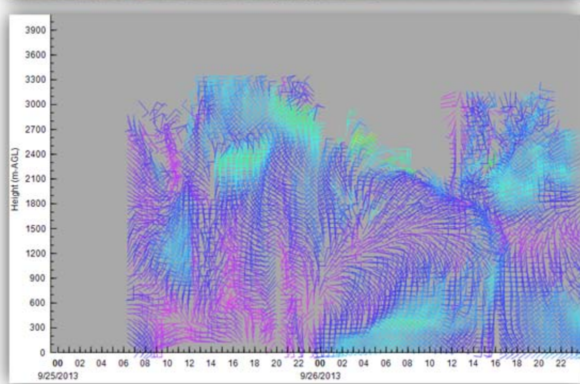
Characterization of Boundary Layer Meteorology During DISCOVER-AQ, Houston, 2013







Final Report 2 Prepared for

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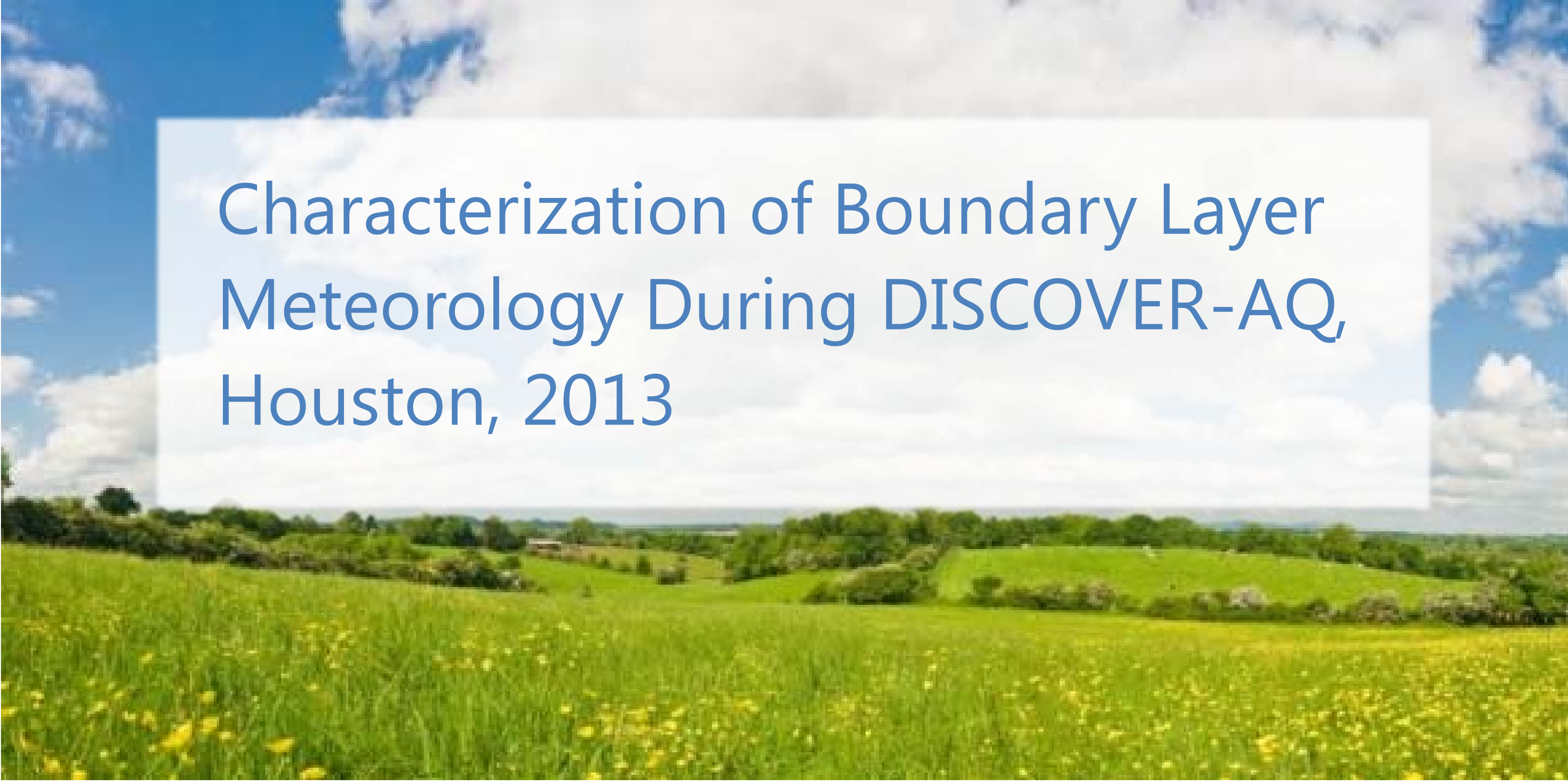

Characterization of Boundary Layer Meteorology During DISCOVER-AQ, Houston, 2013

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Final Report 2

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QA Requirements: Audits of Data Quality: 10% Required.
All data analyzed for this project have been quality controlled and audited.

June 30, 2015

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1. Characterizing the Atmospheric Boundary Layer During DISCOVER-AQ

Executive Summary

DISCOVER-AQ (Deriving Information on Surface Conditions from Column and Vertically Resolved Observations Relevant to Air Quality) is a National Aeronautics and Space Administration (NASA) Earth Venture program-funded mission that consists of field studies in several locations across the United States, with an overall objective to improve the use of satellites to monitor near-surface air quality, and in turn, to help scientists make better air quality forecasts, more accurately determine pollution sources, and develop successful strategies to reduce pollution and improve public health. The DISCOVER-AQ Houston field study took place in September 2013. During this study, detailed meteorological and air quality observations were taken throughout the Houston area by instruments on the ground, on aircraft, on payloads of balloons (both tethered and free-released), and in Earth orbit. Instrumentation operated during the field campaign included seven radar wind profilers (RWPs) and three ozonesonde sites in and around Houston, Texas. Measurements were taken to provide data to characterize the atmospheric boundary layer conditions during DISCOVER-AQ to support the analysis of chemical data and future air quality modeling by the Texas Commission on Environmental Quality (TCEQ).

This report provides a basis for understanding key meteorological processes that were observed during the 2013 DISCOVER-AQ campaign in the Houston area. Meteorological and air quality data from standard surface monitors, RWPs, ozonesondes, weather satellites and radar, and air parcel trajectory models were analyzed by meteorologists at Sonoma Technology, Inc. (STI) and Gary Morris, PhD (St. Edwards University) to characterize atmospheric boundary layer conditions and relate those findings to observed air quality during the DISCOVER-AQ campaign, as well as on some days with high ozone levels that occurred following the campaign. This analysis stands alone but can also assist other researchers with the interpretation of measurements collected during DISCOVER-AQ and provide context for the results derived from data collected during DISCOVER-AQ. A summary of key findings from this analysis is provided below.

- Two general meteorological regimes were identified during the DISCOVER-AQ period: (1) deep onshore flow with lower ozone concentrations, and (2) weak large-scale flow and complex local flows with higher ozone concentrations.
- In agreement with previous analyses, the highest ozone concentrations occurred during periods of weak large-scale flow, typically following the passage of a surface cold front. Two days with such events were identified during the time period analyzed in this report: September 25 and October 8, 2013.
- On high-ozone days, mixing heights were typically low (at or below 500 m) at coastal and inland locations during the early- to mid-morning hours, before increasing rapidly to near

2000 m inland during the late-morning and early-afternoon hours while remaining steady at the coast. In contrast, mixing heights on low-ozone days showed less diurnal and spatial variation.

- Surface ozone concentrations were more spatially and diurnally variable on high-ozone days compared to low-ozone days, due to the presence of complex, local flow patterns.
- During both meteorological regimes identified (deep onshore flow with long transport distances or weak offshore/shore-parallel flow with short transport distances), ozone concentrations were typically highest on the downwind side of Houston, illustrating the important impact of local pollution emissions on regional air quality.

Section 1.1 contains a description of the data sets, instrumentation, and methods used for this analysis. Section 1.2 contains a detailed description of the atmospheric boundary layer on DISCOVER-AQ flight days and days with high ozone levels in the Houston, Texas, area between August 28 and October 9, 2013. Figures accompanying the daily boundary layer analyses are in Section 1.3. The comparison of boundary layer conditions during DISCOVER-AQ to those observed during the TexAQS-II study is found in Section 2.1, and a comparison of general meteorological conditions and ozone profiles observed in DISCOVER-AQ to the September 10-yr averages is found in Section 2.2.

1.1 Data Sets, Instrumentation, and Methods

Several data sets were used to assess large-scale aloft and large-scale surface weather patterns, local meteorological conditions, transport and surface winds, mixing, cloud cover, and surface ozone patterns. The data sets and their uses are described in Table 1.

Table 1. Data sets and their uses for boundary layer characterization analysis.

Data Set	Data Usage
Surface and 500 mb weather maps	Characterizing large-scale meteorological patterns and identifying areas of general rising and sinking motion
Satellite and radar imagery	Assessing impacts of cloud cover and precipitation on ozone formation
Surface meteorological data	Analyzing local-scale meteorological patterns and development and motion of diurnal land/sea breezes
Radar wind profiler data	Assessing spatial and temporal structure of boundary layer winds and mixing heights
Air parcel trajectories	Identifying pollution source regions and transport distances
Surface ozone data	Characterizing regional ozone patterns in relation to local winds and transport

1.1.1 RWPs and Ozonesondes

The RWP data were crucial for assessing the structure of complex boundary layer winds and the spatial and temporal variability of mixing heights. Table 2 contains the RWP sites, locations, and elevations, and Figure 1 shows the RWP sites and ozonesonde launch locations. STI and National Oceanic and Atmospheric Administration (NOAA) operated and processed data from four of the seven RWPs (College Station, Round Top, Wharton, and Smith Point) during DISCOVER-AQ. The remaining three RWPs are in permanent operation.

Table 2. Location metadata for the seven RWP sites.

Site Name	Latitude (°N)	Longitude (°W)	Elevation (m)	Site Operator	Geographic Description
College Station	30.53	96.43	68	STI/NOAA	Inland
Round Top	29.96	96.75	129	STI/NOAA	Inland
Wharton	29.26	96.15	52	STI/NOAA	Inland
Beaumont	30.10	94.10	5	TCEQ	Near-coastal
LaPorte	29.67	95.06	23	TCEQ	Near-coastal
University of Houston Coastal Center	29.39	95.04	5	University of Houston	Coastal
Smith Point	29.55	94.78	2	STI/NOAA	Coastal

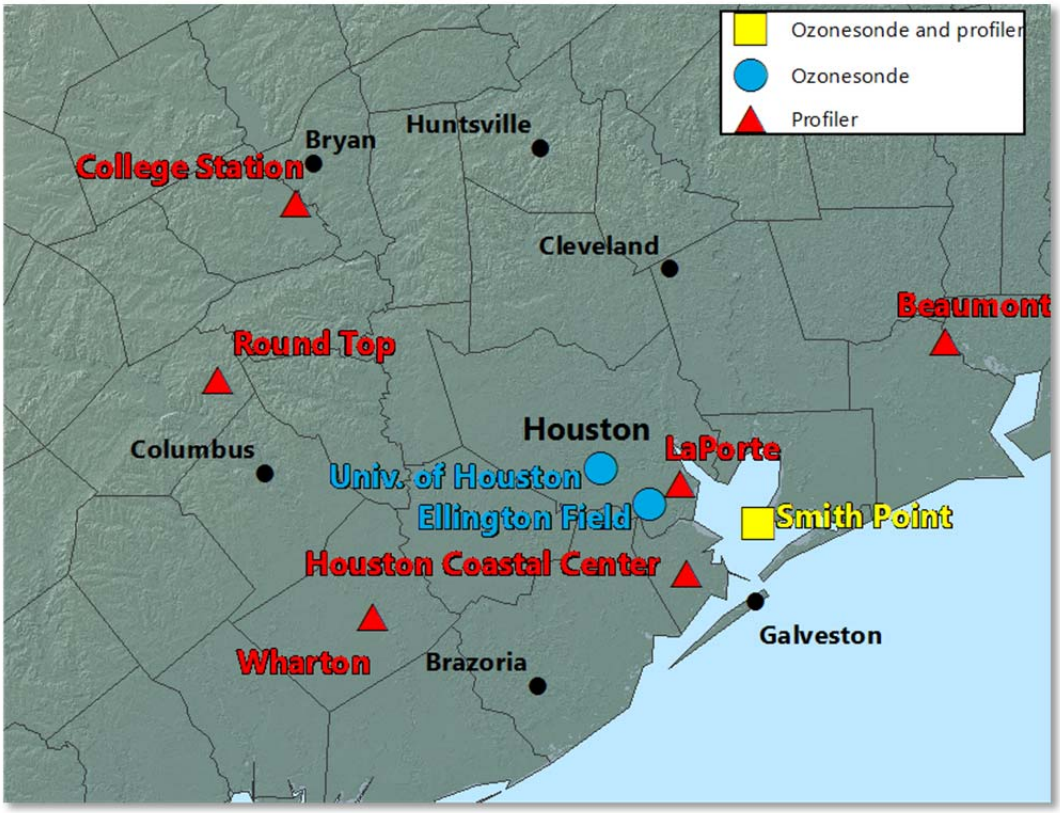


Figure 1. Locations of RWP and ozonesonde sites used to characterize atmospheric boundary layer processes.

The 915 MHz RWPs collected continuous (hourly) vertical profiles of boundary layer winds from about 100 m to about 3,500 m above ground level (agl). The RWP backscatter data can be used to estimate continuous (hourly or sub-hourly) daytime boundary layer heights up to 3,500 m agl. The balloon soundings provide a snapshot of the vertical profile of winds, temperature, relative humidity, and ozone from the surface to at least 20,000 m agl. Data are available from all seven RWPs from August 22, 2013, through October 22, 2013. Balloon sounding data are available for most days during DISCOVER-AQ at one or more of the sites.

The RWPs used in this study consisted of a single phased-array antenna. A radar beam was electronically pulsed 23° from the vertical, in any of four orthogonal directions. The RWP transmitted an electromagnetic pulse along each of the beam directions, one at a time. These signals were then scattered by small-scale turbulent fluctuations in the atmosphere. A receiver measured the fraction of the transmitted energy that was scattered back toward the RWP (referred to as “backscattering”). These backscattered signals were received at a slightly different frequency than the transmitted signals. This difference is called the Doppler frequency shift and it is directly related to the velocity of the air moving toward or away from the RWP along the direction the beam is pointing (radial velocity). Using appropriate trigonometry, the three-dimensional meteorological velocity components (u, v, w), wind speed, and wind direction were calculated from the radial velocities.

The mixing height is defined as the vertical extent to which pollutants, emitted at the surface, mix. For this study, mixing heights were estimated by using RWP backscatter data. Backscatter is strongly influenced by the refractive index of the atmosphere. Turbulence produces variations in atmospheric temperature, humidity, and pressure, which in turn cause variations in the radar refractive index. In the planetary boundary layer (PBL), humidity fluctuations contribute most to the variations in the radar refractive index. The greatest humidity variations tend to occur at the top of the convective or marine boundary layers. For example, Wyngaard and LeMone (1980) showed that the radar refractive index peaked at the inversion at the top of the convective boundary layer (CBL) because of the entrainment of warm, dry, aloft air into cooler, moister air below the inversion.

A RWP, like all radar, is sensitive to reflections from other targets and to electromagnetic radiation from sources other than the atmosphere. For instance, aircraft, birds, or insects may generate spurious radar echoes that can be mistaken for an atmospheric return. Migrating birds are a well-documented source of wind measurement errors, especially in Texas. For DISCOVER-AQ, the RWPs produced data with good height and time coverage (Knoderer and MacDonald, 2013); thus, those data were very useful for characterizing wind patterns within the atmospheric boundary layer (ABL). During data quality control performed under a separate contract, STI staff removed spurious data values due to bird interference, which primarily occurred at night. At the Wharton Airport RWP site, a nearby rotating radar caused interference of the RWP at night; under these circumstances, these data values were removed from the data set.

The balloon sounding system consisted of the electrochemical concentration cell (ECC) type En-Sci 2Z ozonesonde instruments (Komhyr, 1969) with 0.5% buffered KI cathode solutions (solutions prepared by B. Johnson, NOAA Climate Monitoring and Diagnostics Laboratory), as recommended by the Jülich Ozone Sonde Intercomparison Experiment (JOSIE) (Smit et al., 2007). Meteorological measurements are provided by the InterMet radiosonde system. An integrated, on-board global positioning system (GPS) provided latitude, longitude, altitude, wind speed, and wind direction data. The effective vertical resolution of the ozone profile data is about 125 m. All data were processed with Holger Voemel's STRATO software or NOAA's SkySonde software, and data for all nominal flights were posted to the project website (physics.valpo.edu/ozone).

The Tropospheric Ozone Pollution Project began in Houston in July 2004. To date, the database includes more than 500 ozone profiles for areas in southeast Texas, mostly from the Rice University and University of Houston campuses. The project has been continuously funded since its inception with grants from the Shell Center for Sustainability at Rice University (2004-2005), the Texas Commission on Environmental Quality (2005-present), the AQRP administered by the University of Texas (2013), and NASA's Division of Earth Science (2004 and 2006). Additional support has been provided by Valparaiso University.

1.1.2 Late-Summer Houston Climate Summary

The major factors that influence local meteorology in the Houston area during late-summer are the position of the semi-permanent surface high-pressure system near the East Coast of the United

States (e.g., the Bermuda High), the diurnal land/sea breeze cycle, and the passage of mid-latitude cold fronts. In September, average daytime highs are near 90°F, nighttime lows are near 70°F, and rainfall occurs on about 8 days. Rainfall is typically generated by passing mid-latitude cold fronts, afternoon convection (often associated with the sea-breeze), and occasionally from land-falling tropical storms.

The diurnal land/breeze pattern is typically stronger and better defined when the large-scale surface pressure gradient is weak, allowing local flows to dominate. The large-scale pressure gradient weakens when the Bermuda High builds westward across the southeastern United States. Under such conditions, afternoon onshore winds often begin as easterly winds off Galveston Bay (the Bay breeze), followed by a switch to southeasterly winds off the Gulf of Mexico (the Gulf breeze). When the Bermuda High shifts eastward (or a mid-latitude low-pressure system approaches from the northwest), a stronger large-scale onshore pressure gradient develops, resulting in a less-defined diurnal sea breeze with onshore winds extending well inland. In contrast, a strong offshore pressure gradient can limit the sea breeze to immediate coastal areas or prevent it from forming entirely. Depth of the low-level onshore winds is modulated by the strength of the large-scale pressure gradient and the presence of subsidence aloft.

1.1.3 Audits of Data Quality

All ozonesonde and RWP data used in this project underwent complete quality control and assessment as part of previous projects. As documented in an STI data report (Knoderer and MacDonald, 2013), STI staff reviewed time-height cross-sections of the RWP data to identify and remove spurious data values due to bird interference, ground clutter, and/or electronic interference. At the Wharton Airport RWP site, a nearby rotating radar caused interference of the RWP at night, therefore these data values were removed from the data set. STI also compared each RWP site's data to data from other RWP sites and to maps of large-scale weather patterns to confirm that the data are consistent. The ozonesonde data were collected by Valparaiso University and the University of Houston under AQRP project number 13-016. Quality control measures performed on the ozonesonde data are described in that project's QAPP.[1] The Smith Point and Ellington Field data were collected by Pennsylvania State University and NASA/USRA, respectively, and the same quality control protocols were applied to these data as to data collected at the AQRP-funded sites.

As an additional check of data quality, during this project analysts reviewed the profiler and ozone data used in the analysis for outliers or other abnormalities by viewing time-height cross-sections of the data; no data quality issues were found. In addition, time standards, units, and measurement locations were verified. As part of this project, a primary STI analyst created boundary layer heights. A secondary analyst then reviewed all boundary layer height data for meteorological reasonableness including comparing the mixing height data to vertical profiles of wind. This latter step helped STI determine the boundary layer type (convective, marine, or nocturnal) and that the mixing heights were consistent with the layer types. The data quality control procedures, data analysis methods, and

[1] http://aqrp.ceer.utexas.edu/projectinfoFY12_13%5C13-016%5C13-016%20QAPP.pdf

analysis results as reported in this final report were reviewed by an STI senior scientist who was not directly involved in the data analysis.

1.1.4 Methods

Boundary layer meteorological conditions were characterized for all DISCOVER-AQ flight days and surrounding days when ozone levels were high in the Houston area (Table 3). Days with high ozone levels are defined as days when one or more surface monitors recorded an 8-hr average ozone concentration above 75 ppb (the current federal ozone standard). The surface ozone monitoring network in the Houston area is shown in Figure 2.

Table 3. Days between late August and mid-October 2013 for which boundary layer processes are characterized and the associated Houston-area maximum 8-hr ozone concentrations and NASA DISCOVER-AQ flight days.

Date	Metro-Houston Maximum 8-hr Ozone (ppb)	DISCOVER-AQ Flight Day
8/28/2013	83	
8/29/2013	78	
8/30/2013	78	
8/31/2013	84	
9/4/2013	62	✓
9/6/2013	45	✓
9/11/2013	51	✓
9/12/2013	66	✓
9/13/2013	66	✓
9/14/2013	64	✓
9/24/2013	51	✓
9/25/2013	124	✓
9/26/2013	89	✓
9/27/2013	63	
10/8/2013	85	
10/9/2013	99	

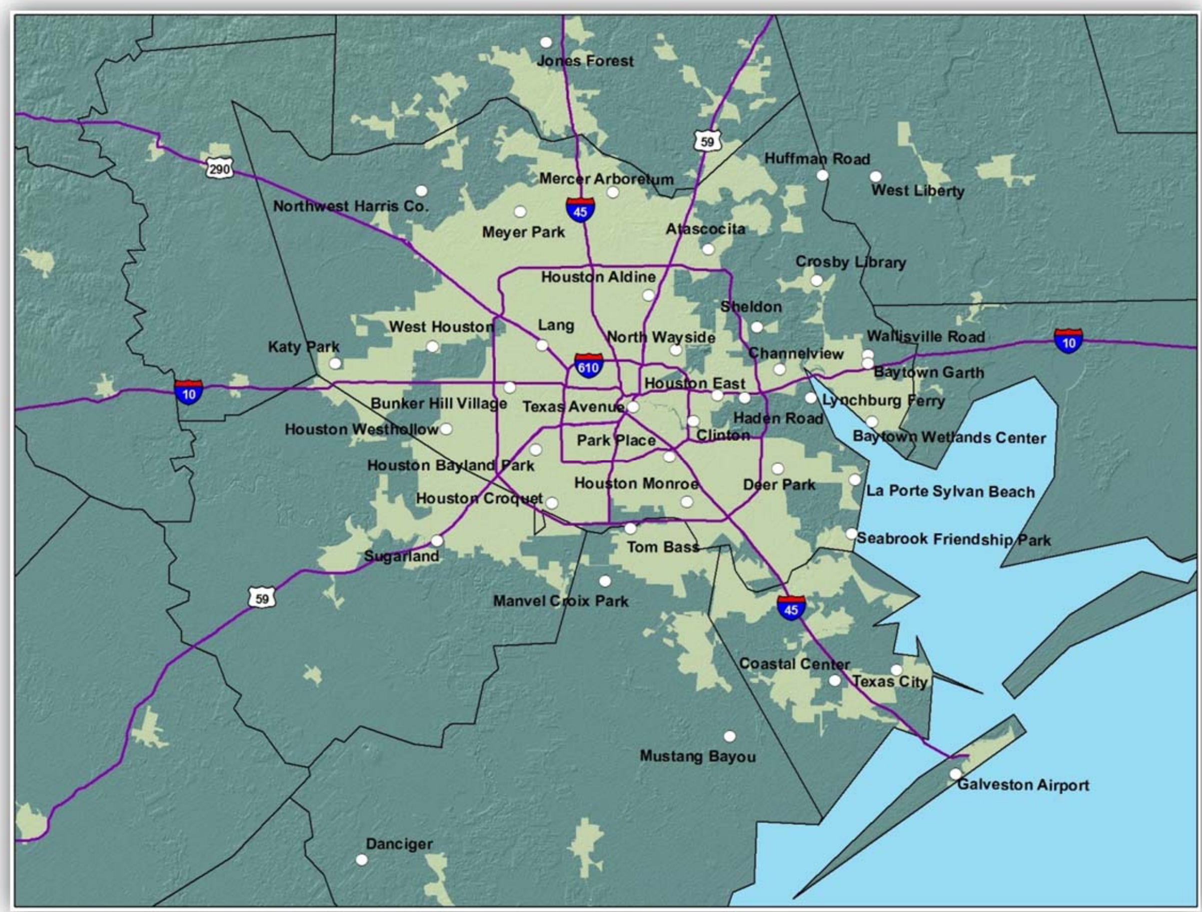


Figure 2. Surface ozone monitors (white dots) in the Houston area.

The RWP data were examined using STI's LAPMom software. LAPMom reads RWP moment data and allows users to view time sequences of signal-to-noise ratio, spectral width, and radial velocity. LAPMom also uses algorithms to automatically calculate mixing heights. Hourly daytime mixing heights were calculated for all seven RWPs when data were available during the DISCOVER-AQ period. The automated mixing height calculations were visually inspected and edited by meteorologists at STI.

The mixing layer depths can be identified in the ozonesonde data at the locations of sharp vertical gradients in relative humidity, ozone, and potential temperature. A software analysis provides the initial estimate, which is reviewed and edited by independent visual inspection of each profile by multiple individuals. Estimated mixing heights from the University of Houston and Smith Point launch sites are shown in Table 4 and Table 5, respectively.

Table 4. Estimated mixing heights from ozonesonde launches at the University of Houston.

Date	Time (CST)	Estimated Mixing Height (km)
8/29/2013	1:09 p.m.	1.9
8/30/2013	1:15 p.m.	2.9
8/31/2013	1:03 p.m.	1.7
9/3/2013	1:07 p.m.	1.75
9/4/2013	12:34 p.m.	2.1
9/5/2013	12:47 p.m.	1.7
9/6/2013	11:18 a.m.	1.7
9/9/2013	12:35 p.m.	2.3
9/10/2013	12:31 p.m.	1.7
9/11/2013	12:18 p.m.	1.3
9/12/2013	11:52 a.m.	1.3
9/13/2013	11:41 a.m.	1.8
9/14/2013	1:22 p.m.	1.6
9/15/2013	12:12 p.m.	1
9/17/2013	12:55 p.m.	2
9/18/2013	12:57 p.m.	2.3
9/21/2013	1:13 p.m.	1.8
9/22/2013	12:05 p.m.	0.8
9/23/2013	12:32 p.m.	0.9
9/24/2013	1:13 p.m.	1.1
9/25/2013	2:32 p.m.	2.2
9/26/2013	6:11 a.m.	0.1
9/26/2013	2:20 p.m.	1.6
9/27/2013	12:13 p.m.	2.9
10/08/2013	2:01 p.m.	1.4
10/09/2013	1:34 p.m.	1.6

Table 5. Estimated mixing heights from ozonesonde launches at Smith Point.

Date	Time (CST)	Estimated Mixing Height (km)
9/1/2013	9:00 p.m.	0.75
9/3/2013	1:00 p.m.	0.9
9/4/2013	8:21 a.m.	1.5
9/7/2013	12:00 p.m.	1.6
9/8/2013	12:00 p.m.	1.2
9/9/2013	1:00 p.m.	0.8
9/11/2013	8:15 a.m.	0.2
9/11/2013	11:57 a.m.	0.7
9/12/2013	8:17 a.m.	0.2
9/12/2013	11:37 a.m.	1.6
9/13/2013	8:09 a.m.	0.5
9/13/2013	11:10 a.m.	0.9
9/14/2013	12:44 p.m.	1.8
9/15/2013	1:00 p.m.	2.3
9/16/2013	1:00 p.m.	0.5
9/17/2013	11:00 a.m.	2.1
9/18/2013	8:00 a.m.	0.2
9/18/2013	10:00 a.m.	2
9/19/2013	1:00 p.m.	1.6
9/22/2013	12:00 p.m.	1
9/23/2013	12:00 p.m.	1.2
9/24/2013	8:07 a.m.	0.2
9/24/2013	1:36 p.m.	2.3
9/25/2013	8:07 a.m.	0.1
9/25/2013	1:09 p.m.	0.1
9/26/2013	8:16 a.m.	0.3
9/26/2013	10:53 a.m.	0.6
9/26/2013	1:54 p.m.	0.6
9/27/2013	8:28 a.m.	1.1
9/27/2013	1:00 p.m.	0.7

The following figures were used to assist in analyzing boundary layer meteorological conditions and are provided for each day discussed in Section 1.2:

- A 500 mb weather map from 6:00 a.m. CST (1200 UTC) to identify locations of upper-level synoptic features.
- A surface weather map from 6:00 a.m. CST (1200 UTC) to identify locations of surface pressure systems and pressure gradients.
- A map summarizing daily maximum 8-hr ozone concentrations and surface wind speeds at Houston metropolitan area monitors.
- A map showing regional daily maximum 8-hr ozone concentrations and 24-hr backward trajectories ending at three receptor locations in the Houston area at 6:00 p.m. CST. The trajectories were produced by NOAA's Earth System Research Laboratory (ESRL) trajectory tool,[2] using a combination of National Center for Environmental Prediction (NCEP) reanalysis data and observed upper-air data from the RWPs in operation during the DISCOVER-AQ project. The three receptor locations used were the LaPorte monitor (southeast Houston), the Texas Avenue monitor (downtown Houston), and the Northwest Harris County monitor (northwest Houston). The trajectories were run at end-altitudes of 200 m, 500 m, 1000 m, and 2000 m. Points located along the trajectories are placed at 6-hr intervals.
- A graph of estimated hourly mixing heights from the seven RWPs. Vertical heights used throughout this report are expressed as heights above ground level (agl).
- Images of wind data from the RWPs to highlight the development and progression of low-level meteorological features, such as land/sea breezes and nocturnal low-level jets (LLJs). The daily wind data from the seven profilers are shown on one plot, with inland sites along the top and coastal sites along the bottom.
- Ozonesonde data to illustrate and diagnose the vertical structure of ozone, temperature, winds, and relative humidity. Ozonesonde data were available for all days listed in Table 3 except August 28.
- A visible satellite image from the Moderate Resolution Imaging Spectroradiometer (MODIS) instrument to assess cloud cover.
- A regional radar composite image to assess precipitation and possible convective outflows.

[2] NOAA's ESRL trajectory tool: http://www.esrl.noaa.gov/psd/programs/2013/texaqs/traj/.

1.2 Findings from Analysis of Atmospheric Boundary Layer Conditions

The meteorological conditions observed during the DISCOVER-AQ period can be grouped into one of two general weather regimes: (1) onshore flow, driven synoptically and/or locally by a moderate to strong sea breeze with lower ozone levels (Figure 3), and (2) light large-scale flow and a weak sea breeze with higher ozone levels (Figure 4). Table 6 describes meteorological and ozone conditions that are typical of each weather regime. Specific conditions and ozone levels on days within each group may vary, due to factors such as cloud cover, precipitation, and pollutant transport and recirculation,

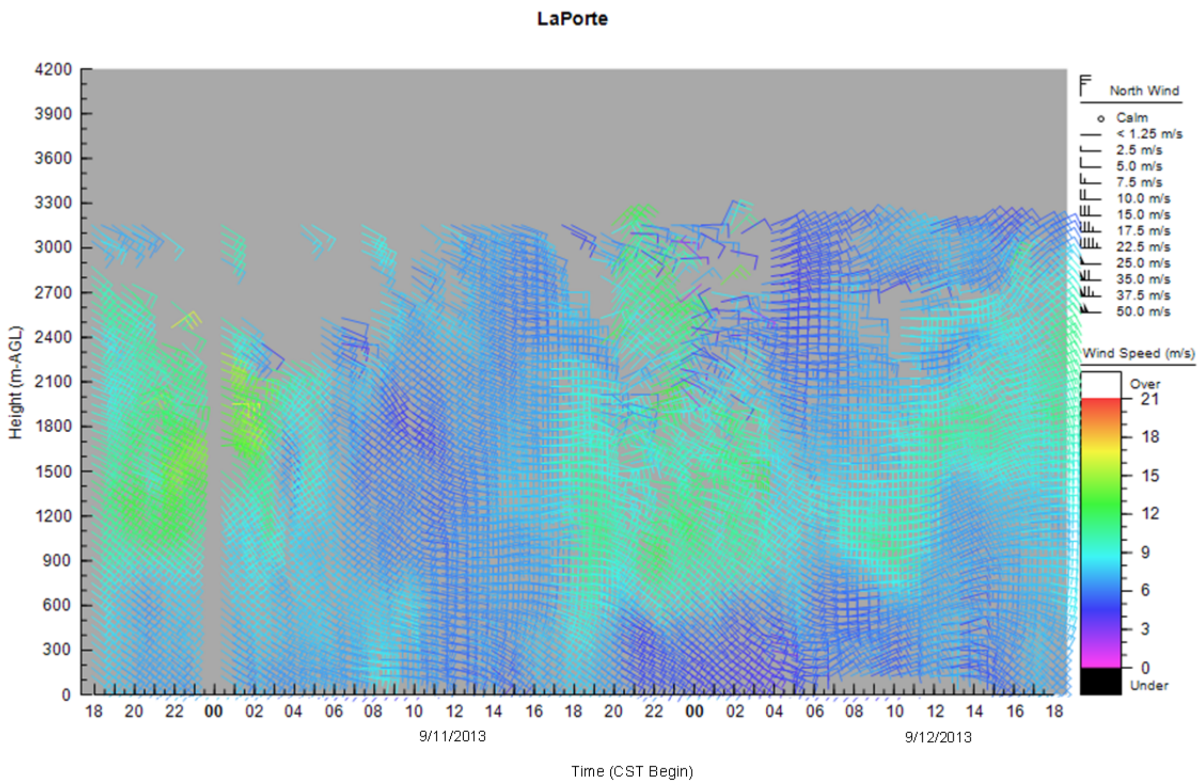


Figure 3. Deep onshore (east and southeasterly) flow as evidenced by wind data from the LaPorte radar wind profiler on September 11-12, 2013. Deep onshore flow disperses pollutants and transports cleaner maritime air into southeastern Texas, typically resulting in lower ozone concentrations in the Houston area.

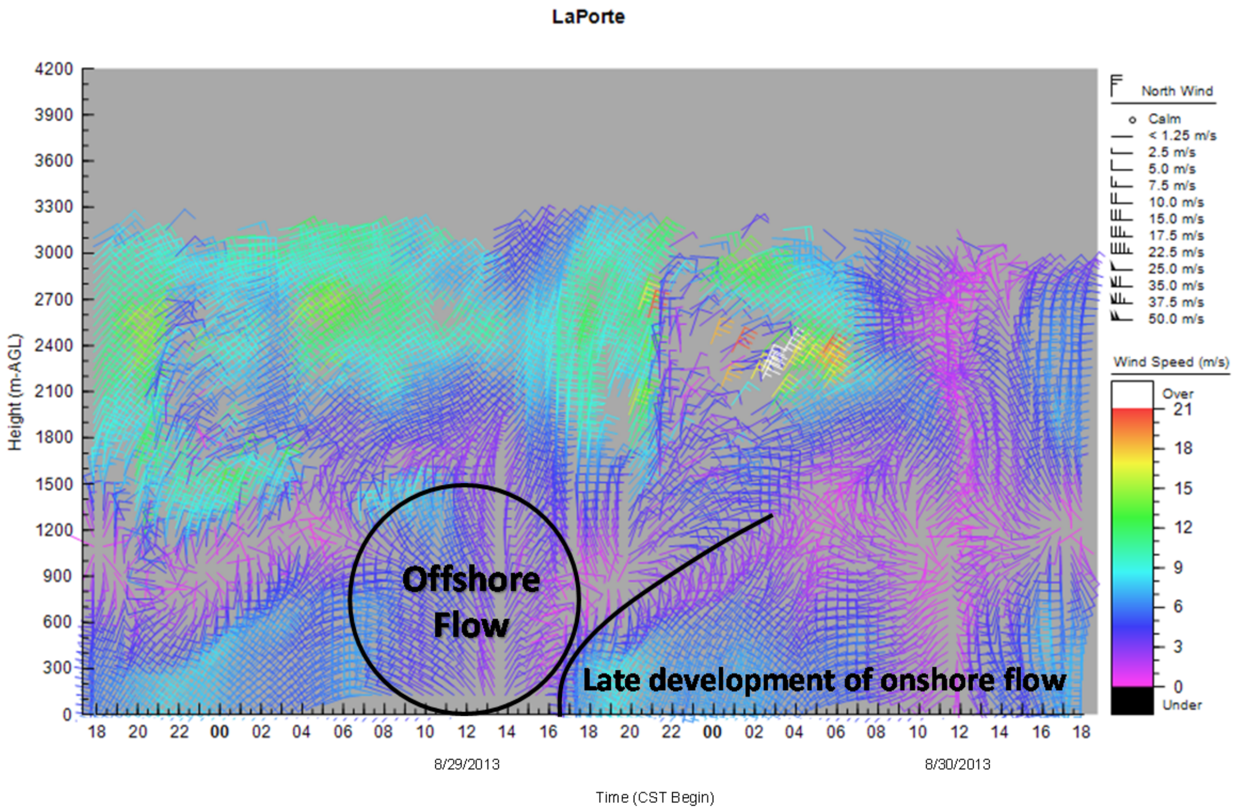


Figure 4. Offshore flow followed by late development of onshore flow as evidenced by wind data from the LaPorte radar wind profiler on August 29, 2013. Light winds in general limit pollutant dispersion, and light offshore winds can transport polluted continental air into the Houston area. Furthermore, a switch to shallow onshore flow can result in recirculation of pollutants. These conditions typically result in higher ozone concentrations in the Houston area.

Table 6. Meteorological conditions typical of the two weather regimes identified during the DISCOVER-AQ campaign in Houston.

Parameter	Onshore Flow	Light Large-Scale Flow
Surface weather pattern	Surface high pressure over the eastern United States.	Surface high pressure over the Gulf Coast region
Surface winds	Moderate easterly to southeasterly, sometimes shifting to southerly if a strong Gulf breeze develops. Weak offshore flow may occur overnight in coastal areas due to land breezes.	Light offshore during the overnight/morning hours, followed by a weak afternoon sea breeze limited to coastal areas
Aloft winds	Moderate northeasterly to southeasterly (Figure 3)	Complex vertical structure; typically northeasterly above 500 m, light onshore or light/variable with recirculation below 500 m (Figure 4)
24-hr boundary layer trajectories	Over 250 km in length, originating over the Gulf of Mexico	Under 250 km in length, typically originating north or northeast of Houston above 500 m and near or just south of Houston below 500 m
Mixing heights	Coastal: Steady ~500-700 m Houston: Increase gradually from ~500 m at sunrise to ~1200 m by noon Inland: Increase gradually from ~500 m at sunrise to ~1500 m by noon and ~2000 m by late afternoon	Coastal: Steady ~500-700 m Houston: Increase rapidly from ~500 m at sunrise to ~1500 m by noon Inland: Increase rapidly from ~500 m at sunrise to ~2000 m by noon
Ozone	Generally low regionwide, but slightly higher on the downwind side of Houston	Strong spatial gradients, but generally higher in all areas compared to deep onshore flow regime; very high ozone levels in calm/light wind areas just ahead of sea breeze, much lower ozone levels following passage of sea breeze

Of the sixteen days analyzed for this project, eight had moderate to strong onshore flow, and seven had weak large-scale flow with a light-to-moderate afternoon Gulf and/or Bay breeze. Particular attention was given to this second group of days due to their complex aloft wind patterns and higher surface ozone levels. One day (September 24) fit in neither category due to a frontal passage with strong offshore winds and cloud cover. Ozone concentrations were low on all of the onshore wind regime days, with the exception of September 26, when recirculation and carryover of pollutants from the previous day resulted in continued high ozone levels. In addition, one of the weak large-scale flow days, September 4, had low ozone levels due to cloud cover and rain. Each day's peak ozone and ozone pattern, surface and aloft wind pattern, mixing heights, and overall flow regime are summarized in Table 7. Detailed summaries of meteorological boundary layer conditions for each day follow Table 7.

Table 7. Summary of daily meteorological boundary layer conditions. Regime 1 indicates moderate/deep onshore flow; Regime 2 indicates weak large-scale flow and complex local flows. Mixing heights refer to afternoon conditions as determined by the RWP data.

Date	Peak 8-hr Ozone (ppb)	Surface Winds	Aloft Winds	Mixing Heights	Regime
8/28/2013	83 NW side	Light offshore winds inland, light Gulf breeze at the coast	Weak onshore at the coast below 500 m; weak offshore above	Steady 500-1000 m at the coast; rapid increase to 1500-2000 m inland	2
8/29/2013	78 E side along Galveston Bay	Light offshore winds except at immediate coast	Weak southwesterly shifting to onshore below 500 m; offshore above	Steady 500-1000 m at the coast; rapid increase to near 1500 m inland	2
8/30/2013	78 E side north of Galveston Bay	Calm winds during the morning, light Gulf breeze along coast in afternoon	Light to moderate onshore below 500 m; offshore above	Steady 500-1000 m at immediate coast; rapid increase to 1000-1500 m inland.	2
8/31/2013	84 N side	Slightly stronger onshore compared to previous days. Calm to light winds during the morning, light to moderate onshore during the afternoon	Light to moderate onshore below 500 m; light easterly above	Steady 750-1000 m at immediate coast, increase to 1500 m just inland from coast, and 2000+ m well inland	1
9/4/2013	62 NW side	Offshore during the morning due to a land breeze, then a weak Bay and Gulf breeze	Light offshore during the morning, then light to moderate onshore below 500 m; light north easterly above	Steady 500-1000 m at the coast; gradual increase to 1000-1500 m inland, highest furthest inland	2
9/6/2013	45 W side	Light offshore early, then moderate to strong onshore	Light offshore early below 1000 m, then moderate onshore. Moderate easterly to northeasterly above 1000 m.	Steady 500-1000 m at coast and near-coast; increase to 1500-2000 m well inland	1

Date	Peak 8-hr Ozone (ppb)	Surface Winds	Aloft Winds	Mixing Heights	Regime
9/11/2013	51 W side	Moderate easterly, shifting to southeasterly late	Moderate onshore at all levels	Steady 500-1000 m inland; gradual increase to 1000-1500 m near-coast and 1500-2000 m well inland	1
9/12/2013	66 SW side	Moderate easterly, shifting to southeasterly late	Moderate easterly at the surface, moderate east-northeasterly aloft	Below 1000 m at immediate coast; increase to near 1500 m near-coast and inland	1
9/13/2013	66 SW side	Moderate easterly, shifting to southeasterly late	Moderate easterly at the surface, moderate east-northeasterly aloft	Gradual increase to 1000-1500 m at the coast and near-coast; 2000-2500 m well inland	1
9/14/2013	64 SW side	Moderate easterly, shifting to southeasterly late	Moderate east-southeasterly at the surface, moderate east-northeasterly aloft	Rapid drop from near 1000 m to 500 m at the coast with onshore winds; increase to near 1500 m near-coast and well inland	1
9/24/2013	51 Uniform gradient	Moderate to strong offshore	Moderate offshore at all levels	Gradual increase to 1000-1500 m at the coast; up to 1500-2000 m inland	--
9/25/2013	124 E side	Light offshore inland and at the coast; then very light Bay and Gulf breeze at immediate coast	Light onshore with recirculation below 200 m; offshore above 200 m	Steady near 500 m at the coast; rapid increase to 1500-2500 m near-coast and inland	2
9/26/2013	89 N side	Calm inland and light onshore at the coast; onshore flow increasing through the day	Light onshore at all levels	Steady near 500 m at the coast; rapid increase to 1000-1500 m near-coast and 1500+ m well inland	1

Date	Peak 8-hr Ozone (ppb)	Surface Winds	Aloft Winds	Mixing Heights	Regime
9/27/2013	63 NW side	Moderate onshore	Moderate onshore at all levels	Steady between 800-1200 m at the coast and inland	1
10/8/2013	85 SW side	Light offshore inland and at the coast; then very light Bay and Gulf breeze at immediate coast	Light easterly to southeasterly below 200 m; northeasterly to northerly above 200 m	Below 500 m at all areas initially; rapid increase to near 1000 m near the coast and to near 1500 m inland	2
10/9/2013	99	Light offshore inland and light onshore at the coast; then increasing onshore flow through the day	Light onshore below 1000 m; light offshore above	Initially near 1000 m at the coast, then falling to near 600 m; rapid increase from near 500 m to 1500 m well inland	2

August 28, 2013

Eight-hour average ozone concentrations above 75 ppb were reported at several surface monitors in the Houston area on this date, with the highest concentrations reported on the northwest side of Houston. The combination of a surface high-pressure system centered over Mississippi and the development of a Gulf breeze during the afternoon hours produced moderate southeasterly (onshore) winds in coastal areas and lighter onshore winds further inland. These winds transported ozone precursors and ozone to the northwest side of Houston.

- **Large-Scale Aloft:** A strong upper-level high-pressure system centered over Missouri covered much of the central United States, including Texas, increasing the likelihood of subsidence and reduced atmospheric mixing in the Houston area (Figure 5).
- **Large-Scale Surface:** Surface pressure gradients over southeastern Texas were weak due to a broad surface high-pressure system centered over Mississippi. The weak pressure gradients allowed local flows to dominate (Figure 6).
- **Local Meteorology:**
  - Surface Winds: Calm or light northeasterly during the overnight and early-morning hours before increasing and shifting to southeasterly starting after 12:00 p.m. CST at the coast with the development of a Gulf breeze (Figure 7).

- Transport: 24-hr backward trajectories ending at 6:00 p.m. CST showed weak northeasterly (offshore) winds at 2000 m at coastal and inland locations, but showed light onshore winds at 200 m, 500 m, and 1000 m, illustrating the development of a Gulf breeze and transport of pollutants in the boundary layer northwestward across the Houston area (Figure 8).
- Profiler Data: Weak offshore winds were noted at the coastal profilers during the early morning hours. Development of a shallow but deepening marine layer was then evident at the coastal profilers, beginning around 10:00 a.m. CST with a Bay breeze at the LaPorte profiler (Figure 9), followed by a Gulf breeze at all coastal locations after 12:00 p.m. CST. Inland, low-level winds were light southerly to southeasterly for most of the day. A low-level jet (LLJ) was evident below 300 m at Round Top and College Station after 8:00 p.m. CST.
- Mixing: Mixing heights at the inland regional RWPs (College Station, Wharton, and Round Top) rose to between 1500 and 2000 m during the afternoon hours. Mixing heights were generally less than 1000 m at the coastal profilers (La Porte, Smith Point, and the University of Houston Coastal Center), consistent with the observed onshore flow and marine layer (Figure 10).

- **Cloud Cover and Precipitation:** Scattered fair-weather cumulus clouds developed over inland areas during the late-morning and early-afternoon hours. Coastal areas had much less cloud cover due to passage of the Gulf breeze (Figure 11). Scattered showers developed along the Gulf breeze front near Corpus Christi, but no precipitation was observed in the Houston area (Figure 12).

- **Ozone Patterns:** Hourly ozone concentrations increased rapidly in central Houston and on the southeast side of Houston between 9:00 and 11:00 a.m. CST. As onshore winds increased, the highest ozone concentrations shifted to the northwest side of Houston after 12:00 p.m. CST. The regional peak 1-hr ozone concentration was 108 ppb at the West Houston ozone monitor. Ozone levels remained elevated on the far western and northwestern sides of Houston through 6:00 p.m. CST.

August 29, 2013

Eight-hour average ozone concentrations above 75 ppb were reported only at the surface ozone monitor in Seabrook Friendship Park, located along Galveston Bay southeast of Houston. Light west-southwesterly winds during the overnight and morning hours transported ozone precursors and ozone from Houston toward Galveston Bay, with some potential for recirculation of pollutants from the previous day. A weak Bay and Gulf breeze developed during the afternoon hours, which gradually transported pollutants northwestward from Galveston Bay. The onshore winds were weaker compared to those observed the previous day (August 28); as a result, the southeast side of Houston was impacted by high ozone levels for a longer duration than were other parts of the Houston area.

- **Large-Scale Aloft:** A strong upper-level high-pressure system persisted over the central United States, including Texas, increasing the likelihood of subsidence in the Houston area (**Figure 13**).
- **Large-Scale Surface:** Surface pressure gradients over southeastern Texas were weak due to a surface high-pressure system centered over Mississippi and Louisiana. The weak pressure gradients allowed local flows to dominate (**Figure 14**).
- **Local Meteorology:**
  - Surface Winds: Light west-southwesterly during the overnight and early-morning hours. Winds gradually shifted to southeasterly during the afternoon and evening hours with the development of a weak Bay and Gulf breeze (**Figure 15**). Compared to conditions observed on August 28 (the previous day), weaker large-scale gradients on August 29 resulted in very slow inland progression of the Bay and Gulf breeze.
  - Transport: 24-hr backward trajectories ending at 6:00 p.m. CST depicted offshore winds at 1000 m and 2000 m. At 200 m and 500 m, winds were light southwesterly initially before shifting to light southerly late in the afternoon with the development of weak onshore flow (**Figure 16**).
  - Profiler Data: Pronounced offshore winds were evident during the morning hours at the coastal profilers. The onset of the afternoon onshore flow was slightly later and its initial depth was shallower on August 29 than August 28, consistent with stronger large-scale offshore flow and a strengthening high-pressure system aloft (**Figure 17**). The onset of the onshore flow was well defined at all four coastal profilers. Inland, a LLJ below 600 m was again observed after 8:00 p.m. CST.
  - Mixing: Late-morning mixing heights were below 1000 m regionwide, indicating reduced mixing consistent with the strong upper-level high-pressure system. Afternoon mixing heights rose to at least 1500 m inland but remained between 500 and 1000 m at coastal locations, indicating the continued presence of a shallow marine layer (**Figure 18**).
  - Ozonesonde: An inversion was present near 1800 m with sharp drop-offs in moisture and ozone concentrations above it. Layers with higher ozone levels were detected aloft around 4000 m and again above 10000 m. Ozone mixing ratios in the surface mixed layer were between 60 and 70 ppbv (**Figure 19**).
- **Cloud Cover and Precipitation:** Scattered fair-weather cumulus clouds developed over inland areas during the late-morning/early-afternoon hours. The clouds were not widespread enough to have significant impacts on ozone formation (**Figure 20**). Regional radar showed no precipitation in the immediate Houston area (**Figure 21**).
- **Ozone Patterns:** Hourly ozone concentrations increased rapidly on the east and southeast sides of Houston between 9:00 and 11:00 a.m. CST. Ozone concentrations remained highest in these areas due to light winds through the early afternoon hours. As the afternoon Bay and Gulf breeze moved inland, higher ozone concentrations gradually shifted northwestward toward central Houston. The regional peak 1-hr ozone concentration was 103 ppb at the Seabrook Friendship Park ozone monitor (located on Galveston Bay); this peak occurred at 3 p.m. CST, just before the Gulf breeze moved through that area

August 30, 2013

Eight-hour average ozone concentrations above 75 ppb were reported at the Wallisville Road surface ozone monitor, located inland of Galveston Bay on the east side of Houston. Light winds during the overnight and morning hours reduced pollutant dispersion. A light-to-moderate Gulf breeze developed during the late morning, which gradually brought pollutants inland from Galveston Bay to the east side of Houston.

- **Large-Scale Aloft:** A strong upper-level high-pressure system centered over Colorado covered much of the central and southwestern United States, including Texas, increasing the likelihood of subsidence in the Houston area (Figure 22).
- **Large-Scale Surface:** Surface pressure gradients over southeastern Texas were weak due to a surface high-pressure system centered near New Orleans, allowing local flows to dominate. However, the southeast-northwest pressure gradient was slightly stronger than in previous days, which resulted in a slightly stronger Gulf breeze with an earlier onset (Figure 23).
- **Local Meteorology:**
  - Surface Winds: Light and variable or light southwesterly during the overnight and early-morning hours before shifting to southerly during the late morning and afternoon hours with the development of a Gulf breeze (Figure 24).
  - Transport: 24-hr backward trajectories ending at 6:00 p.m. CST depicted northeasterly (offshore) winds at 1000 m and 2000 m. At 200 m and 500 m, winds were light southerly due to a weak onshore pressure gradient and the development of an afternoon Gulf breeze (Figure 25). The low-level trajectories on August 30 were longer compared to those on previous days, illustrating slightly stronger but still relatively shallow onshore flow.
  - Profiler Data: Onshore flow was stronger on August 30 compared to previous days, with no indication of surface offshore winds at any time at the coastal profilers (Figure 26). A Gulf breeze developed between 10:00 a.m. and 12:00 p.m. at the coast, and the onshore flow gradually deepened to near 1200 m (compared to ~900 m in previous days). Onshore winds also developed well-inland during the afternoon hours, and a LLJ developed below 900 m after 8:00 p.m. CST.
  - Mixing: Late-morning mixing heights were near 1000 m, indicating reduced mixing consistent with the strong upper-level high-pressure system and light low-level winds. Afternoon mixing heights were slightly higher at near-coastal locations (LaPorte and University of Houston Coastal Center) compared to the previous day, suggesting slightly weaker onshore flow (Figure 27).
  - Ozonesonde: An inversion was noted near 1200 m, with a second inversion near 3000 m. A layer of higher ozone was located near 6000 m. Ozone mixing ratios in the surface mixed layer were near 60 ppbv (Figure 28).
- **Cloud Cover and Precipitation:** Scattered fair-weather cumulus clouds developed over inland areas during the late-morning/early-afternoon hours. The clouds were not widespread

enough to have significant impacts on ozone formation, and the clouds dissipated in most areas by 4:00 p.m. CST. Coastal areas had little cloud cover due to passage of the Gulf breeze (Figure 29). No precipitation was observed in the immediate Houston area (Figure 30).

- **Ozone Patterns:** Hourly ozone concentrations increased rapidly on the far eastern side of Houston between 9:00 and 11:00 a.m. CST. This area was directly downwind of central Houston due to very light southwesterly winds during the overnight hours. As the Gulf breeze developed and moved inland, higher ozone concentrations shifted northward and spread over most of the Houston area. The regional peak 1-hr ozone concentration was 98 ppb at the Wallisville Road and Atascocita Road monitors, located on the east and northeast sides of Houston, respectively. Ozone concentrations fell rapidly from south to north between 4:00 and 6:00 p.m. CST following passage of the Gulf breeze.

August 31, 2013

Eight-hour average ozone concentrations above 75 ppb were reported at five monitors located on the north side of Houston. Light south-southwesterly winds during the overnight and morning hours transported ozone precursors and ozone from central/south Houston to the north and east sides of Houston. A moderate Gulf breeze developed during the late morning, which continued to transport pollutants northward toward the north side of Houston.

- **Large-Scale Aloft:** A strong upper-level high-pressure system centered over New Mexico covered much of the central and southwestern United States, including Texas, increasing the likelihood of subsidence in the Houston area (Figure 31).

- **Large-Scale Surface:** A light southeast to northwest surface pressure gradient was in place over southeastern Texas due to a surface high-pressure system located over the eastern Gulf of Mexico. This pressure gradient, combined with the development of a Gulf breeze, resulted in persistent light-to-moderate onshore winds in the Houston area (Figure 32).

- **Local Meteorology:**
  - Surface Winds: Light south-southwesterly winds during the overnight and early-morning hours. Winds shifted to southerly and southeasterly during the late morning and afternoon with the development of a Gulf breeze (Figure 33).
  - Transport: 24-hr backward trajectories ending at 6:00 p.m. CST illustrated east-northeasterly (offshore) winds at 2000 m and light east-southeasterly winds at 1000 m. Trajectories at 500 m and 200 m showed persistent southerly (onshore) winds, consistent with a weak large-scale onshore pressure gradient and an afternoon Gulf breeze (Figure 34). This air flow pattern resulted in pollutant transport from to the north side of Houston.
  - Profiler Data: Surface offshore winds were not indicated at coastal profilers, with a strengthening of onshore winds noted beginning around 10:00 a.m. CST (Figure 35). Similar to conditions observed the previous day, onshore winds continued to strengthen

through the afternoon and deepened to around 1200 m. Inland, light southerly winds were observed from the surface up to 1200 m through much of the day, with strong nocturnal LLJs evident before sunrise and after sunset.

- Mixing: Late-morning mixing heights were near or below 1000 m, indicating reduced vertical mixing consistent with the upper-level ridge overhead and moderate onshore flow at the surface. Afternoon mixing heights were highly variable, with mixing heights at Smith Point and the University of Houston Coastal Center less than 1000 m, while mixing heights at College Station exceeded 3000 m (Figure 36).
- Ozonesonde: The 1:15 p.m. CST launch from the University of Houston found an inversion near 2700 m with a rapid drop in moisture above it. A deep layer of higher ozone mixing ratios was located aloft from 5000 to 9000 m. Ozone mixing ratios in the surface mixed layer (below 1900 m) were near 70-80 ppbv (Figure 37).

- **Cloud Cover and Precipitation:** Scattered fair-weather cumulus clouds developed over inland areas during the late-morning/early-afternoon hours. The clouds were not widespread enough to have significant impacts on ozone formation, and they dissipated in most areas by 3:00 p.m. CST. Coastal areas had little cloud cover (Figure 38). No precipitation was observed in the Houston area (Figure 39).

- **Ozone Patterns:** Hourly ozone concentrations increased rapidly in central Houston and on the north side of Houston between 10:00 and 11:00 a.m. CST. As the Gulf breeze developed and moved inland, higher ozone concentrations shifted northward and spread over most of the Houston area. The regional peak 1-hr ozone concentration was 98 ppb at the Wallisville Road and Atascocita Road monitors, located on the east and northeast sides of Houston, respectively. Ozone concentrations fell rapidly from south to north between 4:00 and 6:00 p.m. CST following passage of the Gulf breeze.

September 4, 2013

This was a DISCOVER-AQ flight day. Ozone concentrations were low on this day due to cloud cover and scattered thunderstorms. The regional maximum 8-hr average ozone concentration of 62 ppb was reported at one monitor on the far northwest side of the Houston area. Light to moderate southeasterly winds ahead of an approaching cold front transported pollutants from central Houston to the northwest side of the Houston area. The pressure gradient associated with this approaching front and outflow boundaries from nearby thunderstorms disrupted the typical diurnal Bay/Gulf breeze pattern.

- **Large-Scale Aloft:** A strong upper-level high-pressure system centered over Colorado covered much of the central and southwestern United States, including Texas, increasing the likelihood of subsidence in the Houston area (Figure 40).

- **Large-Scale Surface:** A cold front was located north of Houston, stretching from central Texas eastward to Georgia. Widespread cloud cover and thunderstorms occurred for much of the day along and south of the front. Winds over southeastern Texas were light to moderate southeasterly ahead of the front (Figure 41).

- **Local Meteorology:**
  - Surface Winds: Light northwesterly during the overnight and early morning hours, consistent with a typical land-breeze pattern. Thunderstorms developed just offshore of southeast Texas and over Galveston Bay during the late-morning hours. Outflow from these thunderstorms combined with the approach of the cold front from the north produced southeasterly winds across coastal and inland areas during the late morning and afternoon (Figure 42).
  - Transport: 24-hr backward trajectories ending at 6:00 p.m. CST showed that winds aloft were from the northeast, consistent with the strong upper-level high-pressure system located northwest of Texas. Lower-level trajectories illustrated light to moderate onshore winds (Figure 43). Trajectories ending on the northwest side of Houston resided over the urban Houston area, unlike trajectories ending nearer the coast; thus, the northwest side received more transport of urban pollutants. Coastal areas likely experienced the least pollutant transport due to proximity to thunderstorms and an earlier shift to southeasterly winds.
  - Profiler Data: Low-level offshore winds were observed at coastal profilers before 10:00 a.m. CST consistent with a land breeze. A Bay breeze then developed at LaPorte around 10:00 a.m., followed by gradual development of a Gulf breeze (Figure 44). The onshore winds gradually deepened to near 900 m. Inland, some low-level recirculation was noted as winds shifted from light westerly in the morning to light easterly in the afternoon. LLJs were noted before sunrise and after sunset.
  - Mixing: Afternoon mixing heights reached 1200 to 1800 m at inland locations and remained below 1000 m at coastal locations, consistent with light to moderate onshore flow. Mixing heights were highly temporally variable during the day at some monitors, likely due to convection (Figure 45).
  - Ozonesonde: An inversion was located near 1800 m with a sharp drop in moisture above it. Ozone mixing ratios were relatively consistent (near 70 ppbv) through the troposphere (Figure 46). The temperature profile for the University of Houston ozonesonde, launched at 12:34 p.m. CST (not shown), did not indicate an inversion in the lowest 5 km. Humidity shows a strong decrease with altitude beginning at around 2100 m (Figure 46), where the temperature profile shows a strong decrease and the ozone gradient changes. Potential temperature is constant from near the surface up to ~1400 m. Ozone mixing ratios increased from 60–75 ppb in the lowest 500 m, then were roughly constant between 75–80 ppb up to 1400 m. Lower concentrations at the immediate surface (near 60 ppbv) may have been due to increasing low-level onshore winds. The morning ozonesonde launched at Smith Point at 8:21 a.m. CST (not shown) revealed a temperature inversion near 2300 m, where relative humidity also showed a sharp decrease and potential temperature began increasing more rapidly. Ozone increased from ~20 ppbv in the lowest 800 m to ~60 ppbv at 2700 m.
- **Cloud Cover and Precipitation:** Skies were partly to mostly cloudy for most of the day. These clouds and the associated thunderstorms limited ozone formation in the Houston area (Figure 47). While no precipitation was officially recorded in Houston, radar imagery showed

a cluster of showers and thunderstorms south and east of Houston during the morning hours on September 4 (Figure 48).

- **Ozone Patterns:** Hourly ozone concentrations increased only gradually during the morning and early afternoon hours due to widespread cloud cover. As winds shifted to southeasterly and increased in speed, higher ozone concentrations were reported on the northwest side of Houston. The regional peak 1-hr ozone concentration was 87 ppb at the Northwest Harris County monitor.

September 6, 2013

This was a DISCOVER-AQ flight day. Ozone concentrations in the Houston area were low on this date due to cloud cover and scattered thunderstorms. The regional maximum 8-hr average ozone concentration was 45 ppb with limited regional variation in ozone concentrations. Winds were light northeasterly during the overnight and morning hours before shifting to southeasterly and increasing during the afternoon hours. This wind shift was due to a combination of the typical diurnal Bay and Gulf breeze pattern and outflow from thunderstorms.

- **Large-Scale Aloft:** A strong upper-level high-pressure system centered over Colorado covered much of the central and southwestern United States, including Texas, increasing the likelihood of subsidence in the Houston area (Figure 49). Despite the upper-level subsidence, the afternoon sea breeze front initiated scattered thunderstorms in parts of southeastern Texas.
- **Large-Scale Surface:** Surface pressure gradients over southeastern Texas were generally weak, which allowed local flows to dominate (Figure 50).
- **Local Meteorology:**
  - Surface Winds: Light northeasterly winds during the overnight and early morning hours were consistent with a typical land-breeze pattern. Thunderstorms developed just offshore during the late morning and moved inland through the Houston area during the afternoon hours. The thunderstorms were likely initiated in part by the Gulf breeze, with thunderstorms developing along a large section of the Texas and Louisiana coasts. Winds shifted to southeasterly during the afternoon hours and were locally gusty during thunderstorms (Figure 51).
  - Transport: 24-hr backward trajectories ending at 6:00 p.m. CST showed that winds at 1000 m and 2000 m were moderate east-northeasterly, and winds at 200 m and 500 m were light to moderate east-southeasterly (onshore) (Figure 52). The low-level onshore winds likely transported cleaner, maritime air into the Houston area.
  - Profiler Data: The gradual progression from a land breeze to deep easterly and southeasterly winds was evident at the coastal profilers, without a well-defined passage of the Gulf breeze (Figure 53). Similar conditions were noted well inland, with the addition of LLJs before sunrise and after sunset.

- Mixing: Afternoon mixing heights exceeded 1000 m at inland locations and remained below 1000 m at coastal locations, consistent with the development of light to moderate onshore flow. Mixing heights at College Station briefly exceeded 2500 m, since this site is far inland (removed from maritime influence) and experienced less cloud cover on this date (Figure 54).
- Ozonesonde: Ozonesondes launched at the University of Houston (11:18 a.m. CST) and Smith Point (12:40 p.m. CST) revealed temperature profiles with clear inversions below 5 km. The University of Houston sounding (Figure 55) suggests a mixed layer depth of ~1700 m, with nearly constant ozone mixing ratios below that level of 35–40 ppbv, and steadily increasing ratios above that altitude. Relative humidity is roughly constant through the lower free troposphere as well, not showing a sharp decrease until >4.5 km. The afternoon Smith Point sounding (not shown) has similar characteristics. An inversion was present near 1200 m, but was not well defined. Near-surface ozone mixing ratios were low at both sites due to strong onshore winds.

- **Cloud Cover and Precipitation:** Skies were mostly cloudy for most of the day. These clouds and the associated thunderstorms limited ozone formation in the Houston area (Figure 56). Radar imagery showed scattered showers and thunderstorms throughout the Houston area (Figure 57).
- **Ozone Patterns:** Hourly ozone concentrations were below 60 ppb at all Houston-area monitors. Ozone concentrations were slightly higher on the southwest side of Houston during the morning hours and on the northwest side of Houston during the afternoon hours, consistent with the gradual veering of winds from east-northeasterly to southeasterly during the day.

September 11, 2013

This was a DISCOVER-AQ flight day. Ozone concentrations in the Houston area were low on this day due to moderate onshore winds and areas of cloud cover. The regional maximum 8-hr average ozone concentration was 51 ppb. Winds were light northeasterly during the overnight and morning hours before shifting to southeasterly during the afternoon hours.

- **Large-Scale Aloft:** A broad upper-level high-pressure system covered much of the central and southeastern United States, including Texas, increasing the likelihood of subsidence in the Houston area (Figure 58).
- **Large-Scale Surface:** A northeast to southwest surface pressure gradient was located over southeastern Texas due to a surface high-pressure system centered over Tennessee. This pressure gradient produced northeasterly to easterly winds in the Houston area (Figure 59).
- **Local Meteorology:**
  - Surface Winds: Light northeasterly during the overnight and early-morning hours, consistent with the large-scale surface pressure pattern. Winds gradually increased and

shifted to east-southeasterly during the afternoon hours as the large-scale surface pattern was augmented by the diurnal Gulf breeze pattern (Figure 60).

- Transport: 24-hr backward trajectories ending at 6:00 p.m. CST depicted deep east-southeasterly (onshore) flow winds (Figure 61). These winds transported cleaner, maritime air into the Houston area.
- Profiler Data: Deep easterly to southeasterly winds were observed at coastal and inland profilers, extending from the surface to above 4000 m (Figure 62). A gradual shift from easterly winds in the morning to southeasterly winds in the afternoon was also evident near the surface in response to an increasingly onshore gradient.
- Mixing: Afternoon mixing heights exceeded 1200 m at inland locations and remained below 1000 m at coastal locations, consistent with light to moderate onshore flow (Figure 63).
- Ozonesonde: Humidity and temperature were unavailable from the University of Houston ozonesonde launch (12:18 p.m. CST). Near-surface ozone mixing ratios were near 50 ppbv with strong onshore winds occurring (Figure 64). The Smith Point morning ozonesonde (8:15 a.m. CST) suggests a shallow marine boundary layer (<200 m) with ozone near 30 ppbv, increasing rapidly to 40 ppbv by 350 m. The morning data from Smith Point show no other clear dynamical boundaries below 5 km. The afternoon sounding (1:57 p.m. CST) shows a weak temperature inversion and negative relative humidity gradient at ~700 m. Ozone, however, is roughly constant at 50–55 ppbv from the surface to 1700 m.

- **Cloud Cover and Precipitation:** Skies were partly cloudy for most of the day. Scattered cumulus clouds developed during the morning hours throughout southeastern Texas. Mid- and high-level debris clouds from regional thunderstorms also moved over parts of the Houston area during the afternoon hours. These clouds likely caused some reduction in ozone formation (Figure 65). Numerous thunderstorms were located southwest of Houston throughout the day, but no precipitation was officially recorded in Houston (Figure 66).
- **Ozone Patterns:** Hourly ozone concentrations were below 60 ppb at most Houston-area monitors. Ozone concentrations were slightly higher on the west side of Houston, consistent with the persistent easterly wind.

September 12, 2013

This was a DISCOVER-AQ flight day. The regional maximum 8-hr average ozone concentration was 66 ppb, occurring at the Sugarland ozone monitor on the southwest side of the Houston area. Winds were light northeasterly during the overnight and morning hours before shifting to southeasterly during the afternoon hours.

- **Large-Scale Aloft:** An upper-level high-pressure system covered much of the central and southeastern United States, including Texas, increasing the likelihood of subsidence in the Houston area (Figure 67).

- **Large-Scale Surface:** A weak east-northeast to west-southwest surface pressure gradient was located over southeastern Texas due to a broad surface high-pressure system over the southeastern United States (**Figure 68**). This pressure gradient typically produces northeasterly to easterly winds in the Houston area. The pressure gradient was similar to but weaker than the pressure gradient present on September 11, 2013.
- **Local Meteorology:**
  - Surface Winds: Light northeasterly during the overnight and early-morning hours, consistent with the large-scale surface pressure pattern and a weak land breeze. Winds gradually increased and shifted to east-southeasterly during the afternoon hours as the large-scale surface pattern was enhanced by the diurnal Bay and Gulf breeze (**Figure 69**).
  - Transport: 24-hr backward trajectories ending at 6:00 p.m. CST showed that winds were east-northeasterly at 1000 m and 2000 m, and easterly to east-southeasterly at 200 m and 500 m (**Figure 70**).
  - Profiler Data: The aloft wind structure on September 12 was similar to that on September 11, with deep easterly winds in place. Below 900 m, winds shifted to northeasterly during the morning hours in coastal and inland locations, consistent with a land breeze. Low-level winds gradually shifted to easterly and then southeasterly in response to the diurnal strengthening of the onshore gradient (**Figure 71**).
  - Mixing: Afternoon mixing heights exceeded 1000 m at inland locations and remained below 1000 m at coastal locations. Mixing heights fell at coastal locations during the early afternoon hours as onshore flow developed (**Figure 72**).
  - Ozonesonde: The afternoon (12:52 p.m. CST) ozonesonde profile from the University of Houston indicated an inversion was located near 1300 m with a sharp drop in moisture above it. Ozone mixing ratios in the surface mixed layer were from 50–60 ppbv. Residual ozone layers aloft were identified near 5000-6000 m and 7000-8000 m (**Figure 73**). The morning (8:17 a.m. CST) ozonesonde profile from Smith Point indicates a shallow marine boundary layer (<200 m) with ozone ~22 ppbv, increasing to ~45 ppbv above that layer by 400 m. The afternoon (1:57 p.m. CST) ozonesonde profile from Smith Point shows a strong temperature inversion at 1600 m, with near-constant ozone concentrations of 35–40 ppbv below that level and increasing ozone concentrations above it.
- **Cloud Cover and Precipitation:** Skies were mostly sunny on this day. A few cumulus clouds developed inland during the late morning, but these clouds were not widespread enough to have significant impacts on ozone formation (**Figure 74**). Widely scattered showers developed across southeastern Texas, but did not affect the immediate Houston area (**Figure 75**).
- **Ozone Patterns:** Hourly ozone concentrations were highest on the west and southwest sides of Houston, consistent with the east-northeasterly winds that were present during the overnight and morning hours. The regional peak 1-hr ozone concentration of 79 ppb occurred at the Sugarland ozone monitor on the southwest side of Houston.

September 13, 2013

This was a DISCOVER-AQ flight day. The regional maximum 8-hr average ozone concentration was 66 ppb, occurring at the Houston Bayland Park ozone monitor on the southwest side of Houston. Winds were light northeasterly during the overnight and morning hours, and east-southeasterly during the afternoon hours as a Bay/Gulf breeze developed. Meteorological conditions on September 13 were very similar to those observed on September 12.

- **Large-Scale Aloft:** An upper-level high-pressure system centered over Oklahoma covered much of the south-central United States, including Texas, increasing the likelihood of subsidence in the Houston area (Figure 76).
- **Large-Scale Surface:** A weak cold front was located north of Houston, stretching from northern Texas eastward to Georgia. There was little pressure gradient associated with this front; therefore, local flows were able to dominate (Figure 77).
- **Local Meteorology:**
  - Surface Winds: Light northeasterly during the overnight and early morning hours, consistent with a land breeze. Winds gradually increased and shifted to east-southeasterly as a Bay/Gulf breeze developed (Figure 78). The onshore winds may have been enhanced during the afternoon hours by the approaching cold front.
  - Transport: 24-hr backward trajectories ending at 6:00 p.m. CST showed that winds were east-northeasterly at 1000 m and 2000 m, and easterly to east-southeasterly at 200 m and 500 m (Figure 79); this trajectory pattern is very similar to that observed on September 12, except that low-level trajectories were slightly shorter on September 13, indicating lighter near-surface winds.
  - Profiler Data: The aloft wind structure on September 13 was similar to that on September 11 and 12, with deep easterly winds in place. Below 900 m, winds again shifted to northeasterly during the morning hours in coastal and inland locations, consistent with a land breeze. Low-level winds gradually shifted to easterly and then southeasterly in response to the diurnal strengthening of the onshore gradient. The switch to onshore winds was slightly more defined at LaPorte and Smith Point compared to the previous two days (Figure 80).
  - Mixing: Mostly sunny skies allowed for a rapid increase in mixing heights at all locations during the late-morning hours. Mixing heights fell from near 1500 m to less near 500 m at Smith Point, La Porte, and Round Top during the afternoon hours as onshore flow developed (Figure 81).
  - Ozonesonde: The midday (11:41 a.m. CST) University of Houston ozonesonde launch indicated a weak inversion near 1800 m with a sharp drop-off in moisture and ozone mixing ratios above it, and a much stronger inversion near 3000 m with humidity dropping to very low values (< 5%). Below the first weak inversion, ozone in the mixed layer was 65–75 ppbv, while in the layer between the two inversions, ozone decreased to 50–60 ppbv. The ozone mixing ratios in the surface mixed layer were generally higher than values observed at surface monitors. A deep layer of higher ozone mixing ratios was

also located between 5000 and 9000 m (**Figure 82**). Two ozonesondes were launched from Smith Point. The morning sounding (8:15 a.m. CST) showed a shallow marine boundary layer (<200 m) with ozone concentrations of 30–35 ppbv. A sharp vertical gradient in ozone just above that layer resulted in a near constant ozone mixing ratio from ~250–2000 m of 45–50 ppbv. A temperature inversion appears near 500 m with a stronger one near 3000 m, with relative humidity dropping sharply at both altitudes and increasing between them from ~750 m to 3000 m. The afternoon sounding (1:10 p.m. CST) shows a weak inversion at 900 m with a much stronger inversion at 2800 m. Ozone is roughly constant near 60 ppbv from the surface to the higher inversion level, with relative humidity showing a small drop near 900 m and a sharp drop (to values <5%) at 2800 m.

- **Cloud Cover and Precipitation:** Skies were mostly sunny on this day. A few cumulus clouds developed inland between 2:00 and 5:00 p.m. CST, but these clouds were not widespread enough to have significant impacts on ozone formation (**Figure 83**). No precipitation was observed throughout the Houston area (**Figure 84**).
- **Ozone Patterns:** Hourly ozone concentrations were highest on the southwest side of Houston, consistent with the northeasterly winds that were present during the overnight and early-morning hours. The regional peak 1-hr ozone concentration of 76 ppb occurred at the Houston Bayland Park ozone monitor on the southwest side of Houston. Hourly ozone concentrations briefly increased on the northwest side of Houston late in the day as winds shifted to southeasterly. Ozone levels were slightly higher on this day compared to ozone levels on September 12, despite similar large-scale meteorological conditions. This difference is possibly partly attributable to slightly weaker surface winds on September 13.

September 14, 2013

This was a DISCOVER-AQ flight day. The regional maximum 8-hr average ozone concentration was 64 ppb, which occurred at the Houston Westhollow ozone monitor on the west side of Houston. Winds were light east-northeasterly during the overnight and morning hours, and moderate southeasterly during the afternoon hours as a Bay and Gulf breeze developed.

- **Large-Scale Aloft:** An upper-level ridge of high pressure was located over the south-central United States, including Texas, increasing the likelihood of subsidence in the Houston area (**Figure 85**).
- **Large-Scale Surface:** A weak cold front moved through southeastern Texas late on September 13 and was located south of Houston on September 14 (**Figure 86**). This front, in combination with surface high pressure over the Midwest, produced a weak northeast-to-southwest surface pressure gradient in the Houston area. The weak pressure gradient allowed local flows to dominate.

- **Local Meteorology:**
  - Surface Winds: Surface winds were light east-northeasterly during the overnight and early-morning hours, consistent with the large-scale pressure pattern and a weak land breeze. Winds gradually increased and shifted to southeasterly during the afternoon hours as a Bay and Gulf breeze developed (**Figure 87**).
  - Transport: 24-hr backward trajectories ending at 6:00 p.m. CST showed that winds were east-northeasterly at 1000 m and 2000 m, and east-southeasterly at 200 m and 500 m (**Figure 88**); this trajectory pattern is similar to that observed on September 12 and 13.
  - Profiler Data: The overall aloft wind structure on September 14 was similar to that on September 11, 12, and 13, with deep easterly winds in place. Below 900 m, winds shifted to east-northeasterly during the morning hours in coastal and inland locations, consistent with a land breeze. Low-level winds gradually shifted to easterly and then southeasterly in all areas in response to the diurnal strengthening of the onshore gradient (**Figure 89**).
  - Mixing: Partly to mostly sunny skies allowed for a rapid increase in mixing heights at most locations during the late-morning hours. Mixing heights then fell rapidly at coastal locations around noon CST with the development of onshore winds, but exceeded 1200 m at inland locations (**Figure 90**).
  - Ozonesonde: The afternoon (1:22 p.m. CST) ozonesonde launch from the University of Houston indicated a weak inversion near 1600 m with a deep, moist layer above it to near 5000 m. A second, much stronger inversion was located near 5000 m. Ozone mixing ratios in the surface mixed layer ranged between 60 near the surface to a nearly constant 70 ppbv from 250–1600 m. A very dry layer with higher ozone mixing ratios was located between 5000 and 7000 m (**Figure 91**). The profile from Smith Point (12:44 p.m. CST) similarly showed a weak inversion near 1700 m and stronger ones near 3000 m and 4700 m, with ozone rising from 45–50 ppbv in the lowest 250 m to 60 ppbv at 1000 m to 65–70 ppbv at 4700 m. Relative humidity shows sharp drops at all three altitudes of the inversions, with the strongest drop at 4700 m.
- **Cloud Cover and Precipitation:** Skies were partly sunny on this day. A scattered to broken deck of cumulus clouds and associated showers developed inland between 11:00 a.m. and 7:00 p.m. CST, which likely reduced ozone formation in the Houston area (**Figure 92**). Regional radar imagery detected several small showers moving through the Houston area around 2:00 p.m. CST (**Figure 93**).
- **Ozone Patterns:** Houston often experiences its highest ozone levels following cold frontal passages during the spring and fall. However, ozone levels were generally low on this day despite a prior frontal passage, likely due to residual cloud cover. Hourly ozone concentrations were highest on the west and southwest sides of Houston, consistent with the east-northeasterly winds that were present during the overnight and early-morning hours. The regional peak 1-hr ozone concentration of 78 ppb occurred at the Houston Bayland Park ozone monitor on the southwest side of Houston. Hourly ozone concentrations briefly increased on the northwest side of Houston late in the day as winds shifted to southeasterly.

September 24, 2013

This was a DISCOVER-AQ flight day. Ozone concentrations in the Houston area were low on this date due to cloud cover and moderate northerly winds associated with a low-pressure system southeast of Houston. The regional maximum 8-hr average ozone concentration was 51 ppb.

- **Large-Scale Aloft:** An upper-level trough of low pressure was located over the central United States, and extended southward into Texas; this pattern enhanced atmospheric mixing in the Houston area (**Figure 94**).
- **Large-Scale Surface:** A surface low-pressure system was located over the northwestern Gulf of Mexico (**Figure 95**); as a result, winds were northerly to north-northeasterly for the entire day across the Houston area. The low-pressure system disrupted the typical diurnal Bay/Gulf breeze pattern.
- **Local Meteorology:**
  - Surface Winds: The typical Bay and Gulf breeze pattern was disrupted on this date due to a surface low-pressure system located just southeast of Houston. This system produced moderate northerly (offshore) winds throughout the region (**Figure 96**).
  - Transport: 24-hr backward trajectories ending at 6:00 p.m. CST showed low-level northeasterly winds and north-northwesterly winds aloft (**Figure 97**).
  - Profiler Data: Winds were backing with height (turning counterclockwise) (**Figure 98**), consistent with cold air advection behind a low-pressure system and an approaching upper-level trough. The strong offshore flow prevented the development of an afternoon sea breeze, even at coastal locations.
  - Mixing: Mixing heights exceeded 1500 m during the afternoon hours; mixing was likely enhanced by an upper-level trough of low pressure moving through the region and less cloud cover observed inland. Mixing heights at coastal locations rose from near 500 m during the morning hours to near 1000 m in the afternoon (**Figure 99**).
  - Ozonesonde: The afternoon (1:13 p.m. CST) ozonesonde profile from the University of Houston showed inversions at multiple levels, with a weak inversion at the top of the mixed layer near 1100 m, a stronger one near 2000 m, at which point relative humidity dropped off sharply, and the strongest of the three at 3100 m, again with a sharp drop in relative humidity. Ozone mixing ratios increased from ~40–45 near the surface to ~50 ppbv by 300 m, then remained 45-50 ppbv up to 3000 m (**Figure 100**). The morning ozonesonde at Smith Point (8:07 a.m. CST) showed a shallow marine boundary layer (<200 m) with ozone of 20–25 ppbv, increasing to 35–40 ppbv by 350 m. Several inversions appear in the profile, accompanied by strong drops in relative humidity near 1250 m, 1700 m, 3000 m, and 3750 m. By the afternoon at Smith Point, the ozonesonde profile showed a strong temperature inversion at 2300 m associated with a sharp drop in relative humidity and an increase in ozone from ~38 ppbv to ~47 ppbv.
- **Cloud Cover and Precipitation:** Skies were mostly cloudy during the morning hours and partly sunny during the afternoon hours as the low-pressure system offshore moved away

from the Houston area (**Figure 101**). These clouds likely significantly reduced ozone formation in the Houston area. Light precipitation was also detected in parts of the Houston area throughout the day (**Figure 102**).

- **Ozone Patterns:** Hourly ozone concentrations were at or below 60 ppb at all Houston-area monitors on this date. Ozone concentrations were slightly higher on the south side of Houston, consistent with the northerly winds that were observed.

September 25, 2013

This was a DISCOVER-AQ flight day. Ozone concentrations were very high in the Houston area on this date; the regional maximum 8-hr average ozone concentration was 124 ppb and occurred at the LaPorte Sylvan Beach ozone monitor located near Galveston Bay east of Houston. Numerous other monitors reported 8-hr average ozone concentrations above 75 ppb. Surface winds were calm or light northerly during the overnight and early-morning hours, before shifting to light southeasterly at the coast during the afternoon hours and then inland during the evening hours. Sunny skies and light winds during the morning hours allowed for ozone concentrations to increase rapidly in the Houston area, and the late arrival of the Bay breeze allowed ozone concentrations to remain high for several hours. The highest ozone concentrations occurred on the east side of Houston, near the interface of continental air and maritime air in association with the Bay breeze.

- **Large-Scale Aloft:** An upper-level ridge of high pressure was located over Texas; this pattern increased the likelihood of subsidence in the Houston area (**Figure 103**).
- **Large-Scale Surface:** A surface high-pressure system was located over central Texas with a very weak north-to-south pressure gradient over southeastern Texas (**Figure 104**). This pressure gradient was weak enough to allow local flows to dominate, but also likely delayed the development and inland progression of the Bay breeze in Houston.
- **Local Meteorology:**
  - Surface Winds: Winds were calm inland and light northerly (offshore) along the coast during the overnight and early-morning hours, consistent with the large-scale pressure gradient and a weak land breeze. A weak Bay breeze developed over the eastern side of Houston and a weak Gulf breeze developed along the immediate coast after 12:00 p.m. CST. Winds remained calm or light northerly until the evening over inland areas due to very slow inland progression of the Bay and Gulf breezes (**Figure 105**).
  - Transport: 24-hr backward trajectories ending at 6:00 p.m. CST depicted northerly (offshore) winds at and above 500 m; these winds transported polluted continental air into the Houston area. Trajectories at 200 m depicted very light southeasterly to southerly (onshore) winds, illustrating the development of a very shallow marine layer (**Figure 106**). The low-level wind shift from offshore to onshore indicates potential for recirculation of pollutants and cross-city pollutant transport (**Figure 107**).
  - Profiler Data: Low-level offshore winds continued at inland and coastal areas during the morning hours following the previous day's cold frontal passage (**Figure 108**). The

offshore gradient delayed the onset and deepening of the sea breeze, as winds did not shift to onshore until around or after 2:00 p.m. CST at the coast. Offshore winds persisted until 6:00 p.m. CST at Beaumont/Port Arthur. Inland, winds were generally light and variable for most of the day, with a gradual increase in onshore winds occurring after 6:00 p.m. CST at Round Top and College Station. A strong nocturnal LLJ also developed inland after 8:00 p.m. CST.

- Mixing: Mixing heights were 500-1000 m during the late-morning hours and increased rapidly to 1500-2500 m during the afternoon hours (**Figure 109**). The suppressed mixing heights at most sites during the morning hours are attributable to the strong upper-level high-pressure system over the area. In addition, clear skies and a dry air mass allowed for cool overnight temperatures and a strong morning temperature inversion. Mixing heights rapidly increased after 11 a.m., consistent with the continental, dry air mass in place. The mixing heights observed during the morning hours on this date were far lower than mixing heights averaged over the study period. The low mixing heights helped confine ozone precursors emitted during the morning hours near the surface, and under sunny skies, allowed photochemical reactions to rapidly form ozone.
- Ozonesonde: The afternoon (2:32 p.m. CST) ozonesonde profile from the University of Houston showed a strong inversion near 2200 m. Ozone was well-mixed beneath this inversion with mixing ratios generally between 95 and 100 ppbv, dropping to 90 ppbv in the lowest 200 m. The air mass above the ~2200 m inversion was very dry, consistent with the continental air mass in place. With ozone mixing ratios of 60–75 ppbv from 2200–5000 m (**Figure 110**). The morning (8:07 a.m. CST) ozonesonde profile from Smith Point showed a shallow layer with increasing temperature from the surface to ~300 m in which ozone increased from 15–65 ppbv by 500 m. The afternoon (1:09 p.m. CST) ozonesonde profile at Smith Point showed a very shallow surface layer (<200 m) with ozone > 120 ppbv, dropping to 75–80 ppbv by 500 m. A sharp inversion near 1900 m separated the surface mixed layer from the lower free troposphere, with a sharp gradient in relative humidity but little change in ozone above and below the boundary (65–75 ppbv).

- **Cloud Cover and Precipitation:** Skies were sunny for the entire day in the Houston area (**Figure 111**). No precipitation was observed throughout southeastern Texas (**Figure 112**).
- **Ozone Patterns:** Hourly ozone concentrations across the Houston area increased rapidly after 8:00 a.m. CST and were as high as 110 ppb at 10:00 a.m. CST east of Houston along Galveston Bay. The regional maximum 1-hr ozone concentration was 151 ppb at the LaPorte Sylvan Beach ozone monitor. Ozone concentrations were highest near the Bay/Gulf breeze boundary, which was nearly stationary for much of the day on the southeast side of Houston. Winds gradually shifted to southeasterly across most of the Houston area as the Bay/Gulf breeze moved northward between 4:00 and 6:00 p.m. CST, after which ozone concentrations decreased rapidly.

September 26, 2013

This was the final DISCOVER-AQ flight day. After very high ozone concentrations in the Houston area on September 25, several monitors again recorded 8-hr ozone averages above 75 ppb on September 26. The regional maximum 8-hr average ozone concentration was 89 ppb, occurring at the Jones Forest monitor north of Houston. Winds were calm or light southerly during the overnight and early-morning hours, and were light to moderate south-southeasterly during the late morning and afternoon hours. The persistent light south-southeasterly winds transported pollutants to the north side of Houston.

- **Large-Scale Aloft:** An upper-level ridge of high pressure was located over southeast Texas and Louisiana (Figure 113); this pattern increases the likelihood of subsidence in the Houston area.
- **Large-Scale Surface:** A surface high-pressure system was located over southern Louisiana with a weak southeast to northwest pressure gradient over southeastern Texas (Figure 114). This pressure gradient supported light but persistent south-southeasterly winds in the Houston area. The pressure gradient was weak enough to allow for development of a Gulf breeze.
- **Local Meteorology:**
  - Surface Winds: Winds were calm or very light southerly (offshore) both inland and along the coast during the overnight and early-morning hours. Light southerly winds developed more uniformly across the Houston area around 8:00 a.m. CST. Winds gradually increased through the late morning and afternoon and backed slightly to south-southeasterly (Figure 115). The stronger south-southeasterly winds observed on this day compared to the previous day are attributable to the Gulf breeze being supported (instead of opposed) by the large-scale pressure gradient.
  - Transport: 24-hr backward trajectories ending at 6:00 p.m. CST illustrated that winds were light to moderate southerly (onshore) at 200 m, 500 m, and 1000 m, and were light to moderate southwesterly at 2000 m (Figure 116). These trajectories are consistent with surface wind observations and illustrate transport of pollutants to the north side of the Houston area.
  - Profiler Data: With the weakening of the large-scale offshore pressure gradient, onshore winds were much more pronounced on September 26 compared to the previous day at coastal and inland locations, both at the surface and aloft (Figure 117). Weak low-level offshore winds occurred briefly at Beaumont/Port Arthur and Smith Point before onshore winds developed and rapidly deepened. Inland, strong LLJs were evident before sunrise and after sunset.
  - Mixing: A strong temperature inversion again resulted in low mixing heights into the late-morning hours at most profilers, but to a lesser extent than observed the previous day (Figure 118). Mostly sunny skies and surface heating resulted in a rapid increase in mixing heights at inland areas. However, gradually increasing onshore winds kept mixing heights near 500 m all day at Smith Point and the University of Houston Coastal Center,

and resulted in much lower afternoon mixing heights at LaPorte compared to the previous day.

- Ozonesonde: Two ozonesondes were launched at the University of Houston. The morning sounding (6:11 a.m. CST) showed a shallow surface layer topped by an inversion near 300 m, with ozone increasing from ~5 ppbv at the surface to 70 ppbv by 500 m. A strong inversion at 1800 m was associated with a strong drop in relative humidity, but showed little change in ozone across the boundary. The afternoon sounding (2:20 p.m. CST) indicated a mixed layer height of ~1600 m with ozone of ~85 ppbv in that layer down to ~300 m, dropping to 80–85 ppbv at the surface. From 1600 m to 2200 m, ozone decreased steadily to a local minimum of 45–50 ppbv at ~2400 m, near a strong inversion and sharp decrease in relative humidity. Like on September 25, the air mass was very dry above 2400 m, but was slightly moister below (**Figure 119**). Three ozonesondes were launched at Smith Point. The morning (8:16 a.m. CST) sounding showed a shallow marine boundary layer marked by an inversion near 350 m accompanied by a sharp drop in relative humidity and a sharp increase in ozone from 50–55 ppbv to 75–80 ppbv by 600 m. A second strong inversion located near 1900 m was also accompanied by a sharp drop in relative humidity, but little change in ozone across the boundary (~70 ppbv). The mid-morning sounding (10:53 a.m. CST) showed a mixed layer of ~700 m with ozone increasing from 70 ppbv at the surface to 80 ppbv by 1200 m, just above the mixed layer. A strong inversion near 2200 m was associated with a strong drop in relative humidity and an increase in ozone, from 65 ppbv to ~85 ppbv by 3500 m. The sounding suggested dry air throughout the troposphere. The afternoon sounding (1:54 p.m. CST) indicated a mixed layer depth of ~600 m, with a sharp drop in relative humidity at that level and with ozone of 70–75 ppbv. Ozone decreased in the next layer up, dropping from 75 ppbv to ~40 ppbv by the next inversion near 2300 m. Relative humidity increased from 1500 m to 1700 m before dropping sharply above the inversion at 2300 m.

- **Cloud Cover and Precipitation:** Scattered clouds developed southwest of Houston, but skies in the immediate Houston area were mostly sunny (**Figure 120**). No precipitation was observed throughout the Houston area (**Figure 121**).
- **Ozone Patterns:** Hourly ozone concentrations across the Houston area increased steadily after 7:00 a.m. CST and exceeded 90 ppb at noon CST on the north side of Houston. The regional maximum 1-hr ozone concentration was 101 ppb at the Jones Forest ozone monitor. Ozone concentrations on the north side of Houston remained at or above 80 ppb through 5:00 p.m. CST. In the central and southern sections of the Houston area, ozone concentrations peaked between 70 and 80 ppb around noon CST before gradually decreasing as south-southeasterly winds increased and transported cleaner maritime air inland.

September 27, 2013

The regional maximum 8-hr average ozone concentration was 63 ppb. Persistent light to moderate southeasterly winds occurred throughout the region during the overnight, morning, and afternoon hours, helping to reduce ozone concentrations compared to those observed on September 25 and 26. In addition, extensive cloud cover reduced ozone formation. The diurnal ozone peak occurred on the northwest side of Houston, consistent with moderate onshore flow that was occurring. However, ozone also increased after sunset on the east side of Houston.

- **Large-Scale Aloft:** An upper-level ridge of high pressure covered the Gulf Coast region, including eastern Texas (Figure 122); this pattern increases the likelihood of subsidence in the Houston area.
- **Large-Scale Surface:** A broad surface high-pressure system was stretched from eastern Canada south-southwestward to the Gulf of Mexico, and a surface low-pressure system was located over eastern Colorado (Figure 123). These systems produced a weak to moderate east-to-west pressure gradient over southeastern Texas, which enhanced onshore flow in the Houston area.
- **Local Meteorology:**
  - Surface Winds: Winds were light east-southeasterly both inland and along the coast during the overnight and early morning hours and were light to moderate southeasterly along the coast and inland during the late morning and afternoon hours. Wind speeds gradually increased during the day due to the combination of a Gulf breeze and a large-scale pressure gradient (Figure 124).
  - Transport: 24-hr backward trajectories ending at 6:00 p.m. CST illustrated that winds were light to moderate southerly to southeasterly at 200 m, 500 m, and 1000 m, and were southwesterly at 2000 m (Figure 125). The trajectories originated over the central Gulf of Mexico, depicting transport of cleaner, maritime air into the Houston area.
  - Profiler Data: Deep onshore winds were evident in radar wind profiler data at coastal and inland locations (Figure 126). There was no evidence of a defined sea breeze, as winds only very gradually shifted from southerly to southeasterly through the day.
  - Mixing: Mixing heights were more uniform throughout the region on this date, with mixing heights at all sites being generally between 800 and 1300 m for most of the day (Figure 127). The little variation in mixing heights is attributable to cloud cover, which reduced surface heating and subsequent boundary layer growth.
  - Ozonesonde: The afternoon ozonesonde profile from the University of Houston indicates a mixed layer depth of ~800 m, with ozone near 55 ppbv a the surface and 60–65 ppbv from ~300–800 m. A strong inversion appeared near 2900 m where relative humidity drops sharply. Ozone between 800 m and 1500 m dropped from 65 ppbv to 45 ppbv, where it remained up to the inversion, above which it increased sharply to 60 ppbv. Ozone mixing ratios were lower compared to the previous two days. The layer between 1000 and 3000 m was relatively moist, likely due to increasingly deep onshore winds (Figure 128). The morning (8:28 a.m. CST) sounding from Smith Point shows a weak

inversion of 1100 m, with a weak gradient of relative humidity. Ozone was well mixed below 600 m of 65–70 ppbv, then decreasing steadily to ~30 ppbv by 1600 m. Stronger inversions were found at 2100 m and 2700 m, with sharp drops in relative humidity at both heights and increasing ozone at both levels, from 30–40 ppbv at the lower inversion to 50–60 ppbv at the upper inversion. The afternoon (1:00 p.m. CST) showed a weak inversion near 700 m, with nearly constant ozone of 65–70 ppbv below that level and a sharp drop to 30 ppbv by 1750 m above it. A second, much stronger inversion near 2600 m was accompanied by a strong drop in relative humidity. Ozone increased only slightly at that level, with a much stronger increase beginning near 3200 m, where ozone increased from 40 ppbv to 55–60 ppbv by 3500 m.

- **Cloud Cover and Precipitation:** Skies were partly to mostly cloudy for the entire day in the Houston area, which likely caused significant reductions in ozone formation (**Figure 129**). A few light showers were also detected in the Houston area (**Figure 130**).
- **Ozone Patterns:** Hourly ozone concentrations across the Houston area were generally between 40 and 60 ppb at most monitors during the daytime hours. Slightly higher ozone concentrations were reported on the northwest side of Houston, likely due to pollutant transport by the persistent southeasterly winds. The regional maximum 1-hr ozone concentration was 71 ppb, reported at the Meyer Park monitor on the northwest side of Houston.

October 8, 2013

Maximum 8-hr average ozone concentrations above 75 ppb occurred at four monitors on the west side of Houston. Winds were calm or light northerly during the overnight and early-morning hours, and gradually shifted to southeasterly during the afternoon hours. Low wind speeds overall throughout the day reduced pollutant dispersion, and sunny skies enhanced ozone formation.

- **Large-Scale Aloft:** An upper-level ridge of high pressure was located over Texas; this pattern increased the likelihood of subsidence in the Houston area (**Figure 131**).
- **Large-Scale Surface:** A broad surface high-pressure system was located from the Great Lakes southwestward to Texas (**Figure 132**). A weak northeast-to-southwest pressure gradient was located over southeastern Texas, which supported light northeasterly winds in the Houston area but still allowed some influence from local flows.
- **Local Meteorology:**
  - Surface Winds: Winds were calm inland and light northerly along the coast during the overnight hours, consistent with a weak land breeze. Winds were light northeasterly or easterly during the morning hours, consistent with the large-scale pressure pattern. During the early-afternoon hours, a very light Bay breeze developed along the coast, but winds in inland areas were calm or light northeasterly for much of the afternoon (**Figure 133**). Southeasterly winds associated with the Bay and Gulf breeze developed in all areas after 6:00 p.m. CST.

- Transport: 24-hr backward trajectories ending at 6:00 p.m. CST showed that winds in the boundary layer were light to moderate northerly at 1000 m and 2000 m and were light easterly to northeasterly at 200 m and 500 m (**Figure 134**). These winds were favorable for transport of more-polluted, continental air into the Houston area, including smoke from fires in far southeastern Texas and southwestern Louisiana.
- Profiler Data: The weak large-scale pressure gradient in place resulted in complex low-level wind structures on this day, In most coastal locations, low-level winds were light east-northeasterly to northeasterly (offshore) during the morning hours, with the exception of LaPorte, where low-level winds were light east-southeasterly (onshore). During the afternoon, a weak, very shallow onshore flow developed, with a depth of only 300 m per the Smith Point profiler. Winds remained directed offshore throughout the day at Beaumont/Port Arthur. Inland, winds were generally light, with a gradual increase in onshore winds after 4:00 p.m. CST and development of a LLJ after 8:00 p.m. CST (**Figure 135**).
- Mixing: Mixing heights were near or below 1000 m during the late-morning hours and near 1500 m during the afternoon hours (**Figure 136**). Morning suppression of the surface mixed layer is attributable to a strong nocturnal temperature inversion. Mixing heights fell after 1:00 p.m. CST at Smith Point and the University of Houston Coastal Center, consistent with a weak afternoon sea breeze.
- Ozonesonde: The afternoon (2:01 p.m. CST) ozonesonde launch at the University of Houston showed a strong inversion was located near 1400 m, with a sharp drop in ozone and moisture above it. Ozone was well mixed beneath 1400 m with mixing ratios of 90–95 ppbv, decreasing in the lowest 200 m to 85 ppbv at the surface. The air mass above the 1400 m inversion was very dry, consistent with the continental air mass in place (**Figure 137**).

- **Cloud Cover and Precipitation:** Skies were sunny the entire day in the Houston area (**Figure 138**). No precipitation was observed throughout the Houston area (**Figure 139**).

- **Ozone Patterns:** Hourly ozone concentrations across the Houston area increased rapidly on the west side of the Houston area after 8:00 a.m. CST and peaked at 115 ppb at the Bunker Hill Village monitor at 4:00 p.m. CST. Ozone concentrations were highest downwind of central Houston and north the Bay/Gulf breeze boundary, which was nearly stationary for much of the day on the south side of Houston. Winds gradually shifted to southeasterly across most of the Houston area as the Bay/Gulf breeze moved northward between 5:00 and 6:00 p.m. CST, after which ozone concentrations decreased rapidly. Hourly ozone concentrations were generally below 60 ppb over the far northern and eastern sections of the Houston area.

October 9, 2013

High ozone concentrations occurred on the north side of the Houston area, with a regional maximum 8-hr average ozone concentration of 99 ppb reported at the Meyer Park monitor. Winds were calm or light northeasterly during the overnight and early-morning hours and gradually shifted to southeasterly during the late morning and afternoon hours. The southeasterly winds resulted in downwind transport of ozone to the north side of Houston.

- **Large-Scale Aloft:** An upper-level ridge of high pressure was located over the southeastern United States, including eastern Texas (**Figure 140**).
- **Large-Scale Surface:** A broad surface high-pressure system was located from New England southward to the Gulf Coast (**Figure 141**). A weak east-to-west pressure gradient was located over southeastern Texas, which supported light easterly winds in the Houston area.
- **Local Meteorology:**
  - Surface Winds: Winds were calm or light easterly over inland and coastal areas during the overnight and early-morning hours, consistent with the larger-scale pressure gradient. Winds shifted to southeasterly over the coastal areas and south side of Houston starting around 10:00 a.m. CST as a weak Bay breeze developed. Light southeasterly winds were reported in most areas by 1:00 p.m. CST, except for the far north side of Houston, where winds were still calm or light/variable until the Bay/Gulf breeze arrived after 3:00 p.m. CST (**Figure 142**).
  - Transport: 24-hr backward trajectories ending at 6:00 p.m. CST illustrated air flow from the southeast (onshore) at 200 m, 500 m, and 1000 m, consistent with the development of a weak Bay and Gulf breeze. Trajectories at 2000 m showed light northerly (offshore) winds (**Figure 143**). The northwest side of Houston was more affected by pollutant transport, as trajectories ending there passed through and resided longer over the urban Houston area.
  - Profiler Data: Onshore winds were more pronounced (but still relatively light) on October 9 compared to the previous day, in response to a stronger onshore pressure gradient. Low-level winds were briefly offshore from about 8:00 to 10:00 a.m. at the University of Houston Coastal Center and Smith Point before winds switched to onshore. The onshore winds were relatively light but deepened to at least 600 m along the coast. Inland, winds were generally light southerly to southeasterly during the day, with LLJs again evident before sunrise and after sunset (**Figure 144**).
  - Mixing: Mixing heights were near or below 1000 m during the late-morning hours and near 1500 m the afternoon hours (**Figure 145**). Morning suppression of the surface mixed layer is again attributable to a strong nocturnal temperature inversion. Mixing heights fell during the afternoon hours at most profilers as onshore winds developed, initially at coastal locations between noon and 2:00 p.m. CST, and then at inland locations between 4:00 and 6:00 p.m. CST.
  - Ozonesonde: The afternoon (1:34 p.m. CST) ozonesonde profile from the University of Houston shows a strong inversion was again present but was slightly higher than on the previous day (near 1600 m vs. 1400 m). Moisture and ozone dropped off rapidly above the inversion. Ozone mixing ratios in the surface mixed layer were 75–80 ppbv, dropping below 200 m to 65 ppbv at the surface. Moisture also increased in the surface mixed layer compared to the previous day, consistent with increasing onshore flow, but showed a sharp decrease to very low values above the inversion (**Figure 146**).

- **Cloud Cover and Precipitation:** Skies were mostly sunny the entire day in the Houston area (**Figure 147**). No precipitation was observed throughout the Houston area (**Figure 148**).
- **Ozone Patterns:** A sharp gradient in ozone concentrations was observed across the Houston area. Hourly ozone concentrations increased rapidly over the north half of the Houston area after 10:00 a.m. CST and peaked at 131 ppb at the Meyer Park monitor at 4:00 p.m. CST. Ozone concentrations were highest on the northwest side of Houston, downwind of the urban core of the Houston area. Hourly ozone concentrations fell rapidly after 4:00 p.m. CST in the northern areas as southeasterly winds developed. Hourly ozone concentrations were generally below 60 ppb in southern sections of the Houston area throughout the day due to onshore winds transporting in cleaner maritime air.

1.3 Figures

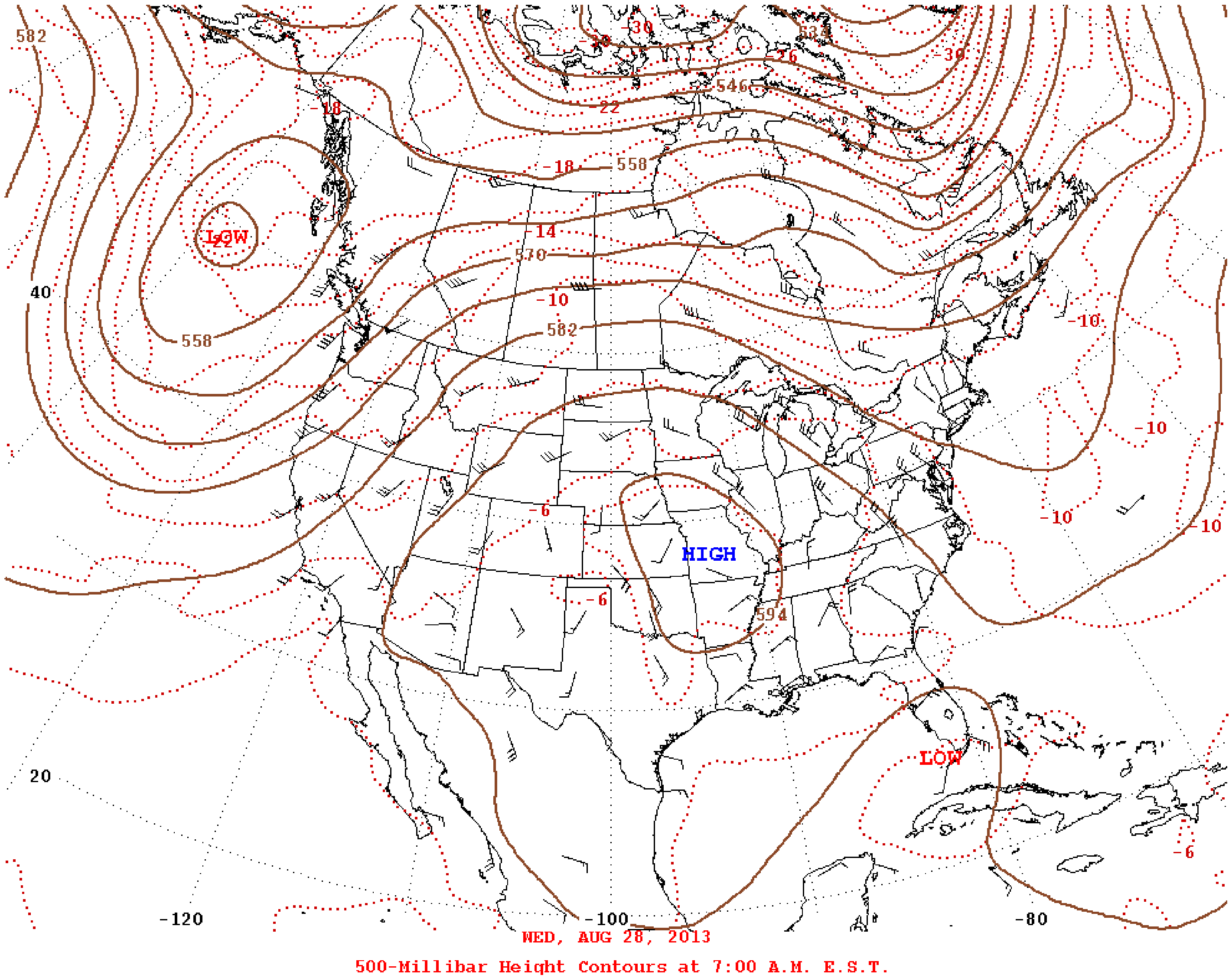
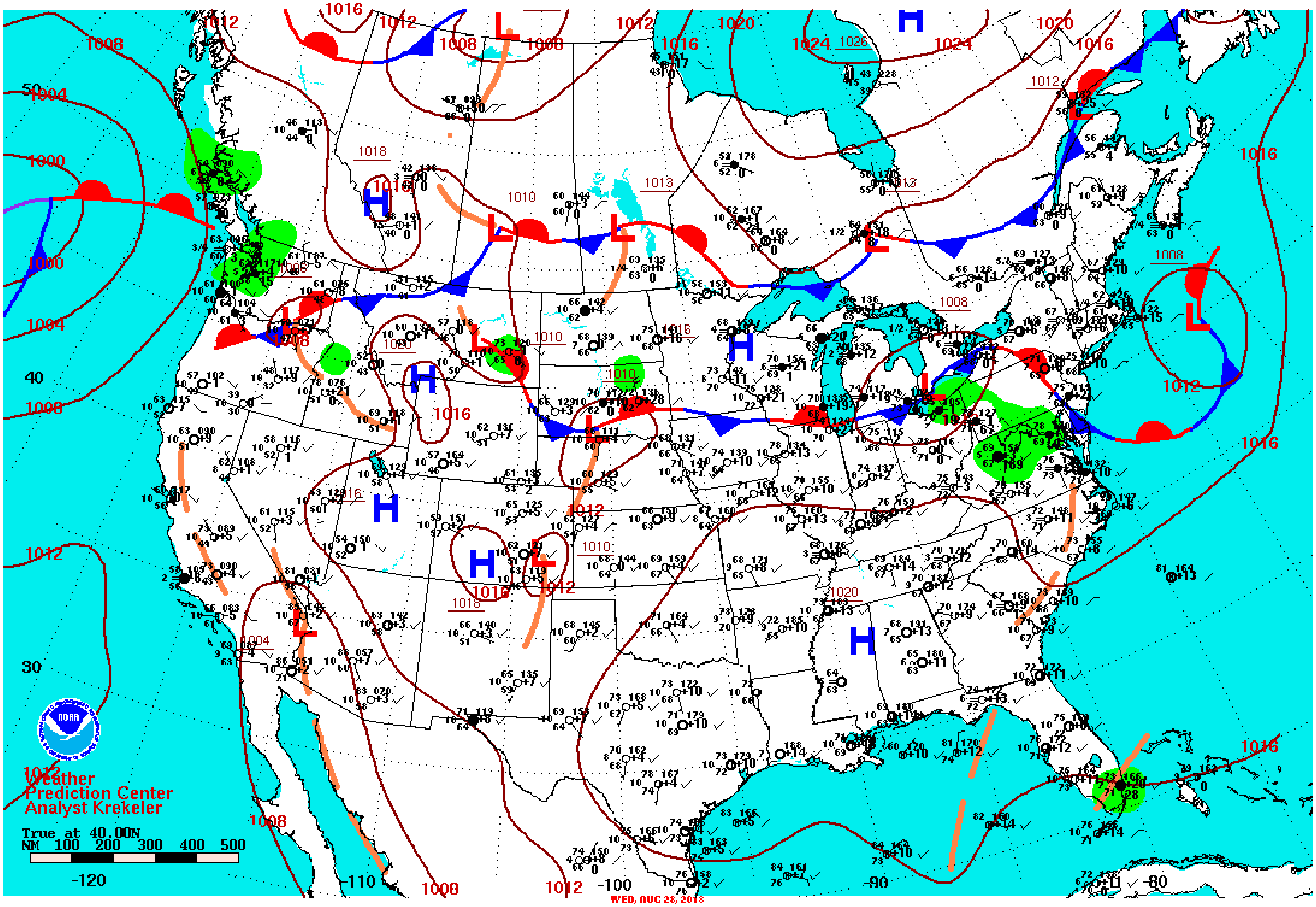


Figure 5. A map showing the height of the 500 mb pressure surface at 6:00 a.m. CST on August 28, 2013. An upper-level high-pressure system was located over the central Plains.



Surface Weather Map and Station Weather at 7:00 A.M. E.S.T.

Figure 6. Surface pressure map at 6:00 a.m. CST on August 28, 2013. A broad surface high-pressure system was located over the southeastern United States, resulting in a weak large-scale pressure gradient in the Houston area.

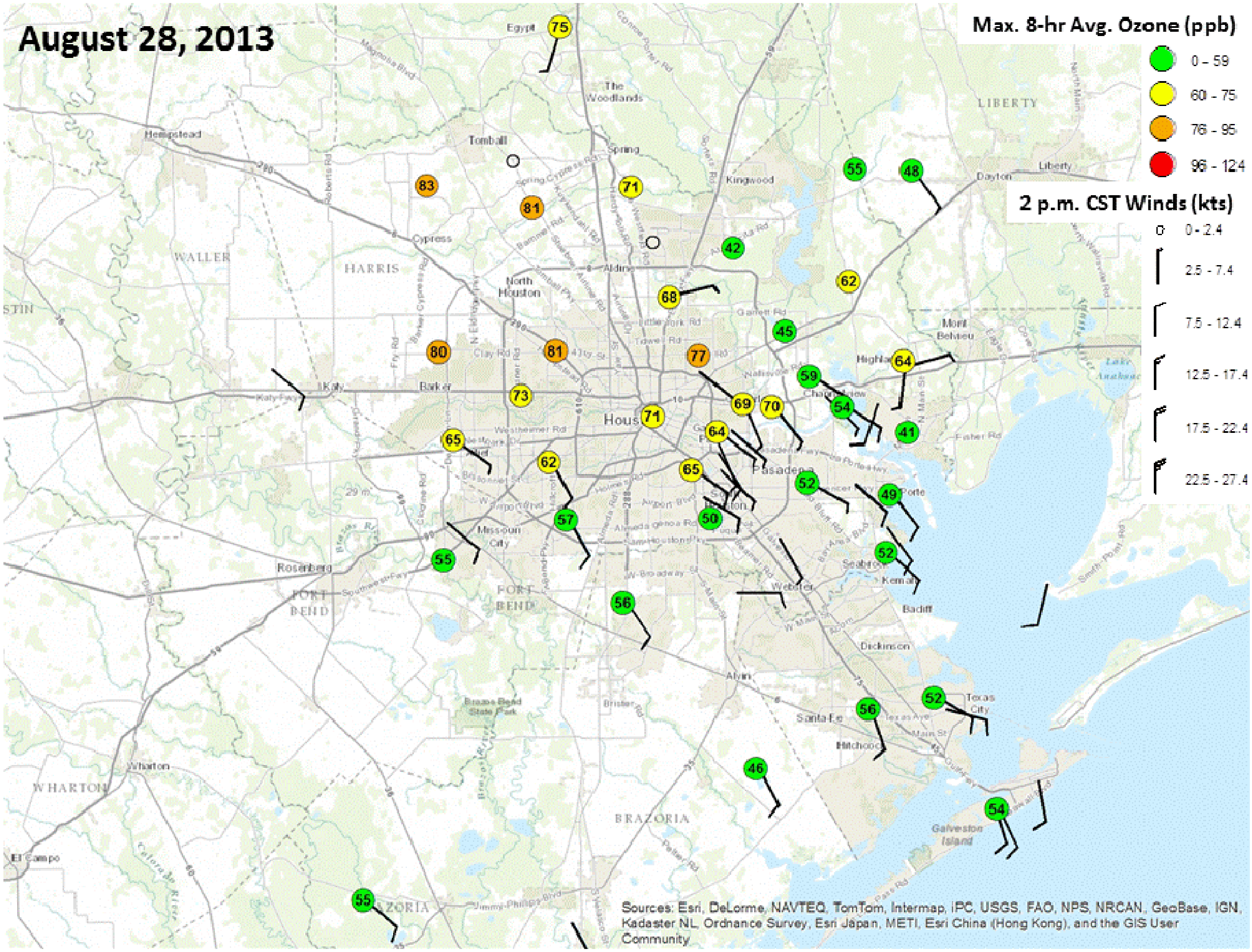


Figure 7. Daily maximum 8-hr average ozone concentrations and surface wind observations from Houston-area monitors on August 28, 2013. Light to moderate southeasterly (onshore) winds developed during the afternoon hours. These winds transported pollutants northwestward across the Houston area. As a result, 8-hr ozone concentrations were highest on the northwest side of Houston.

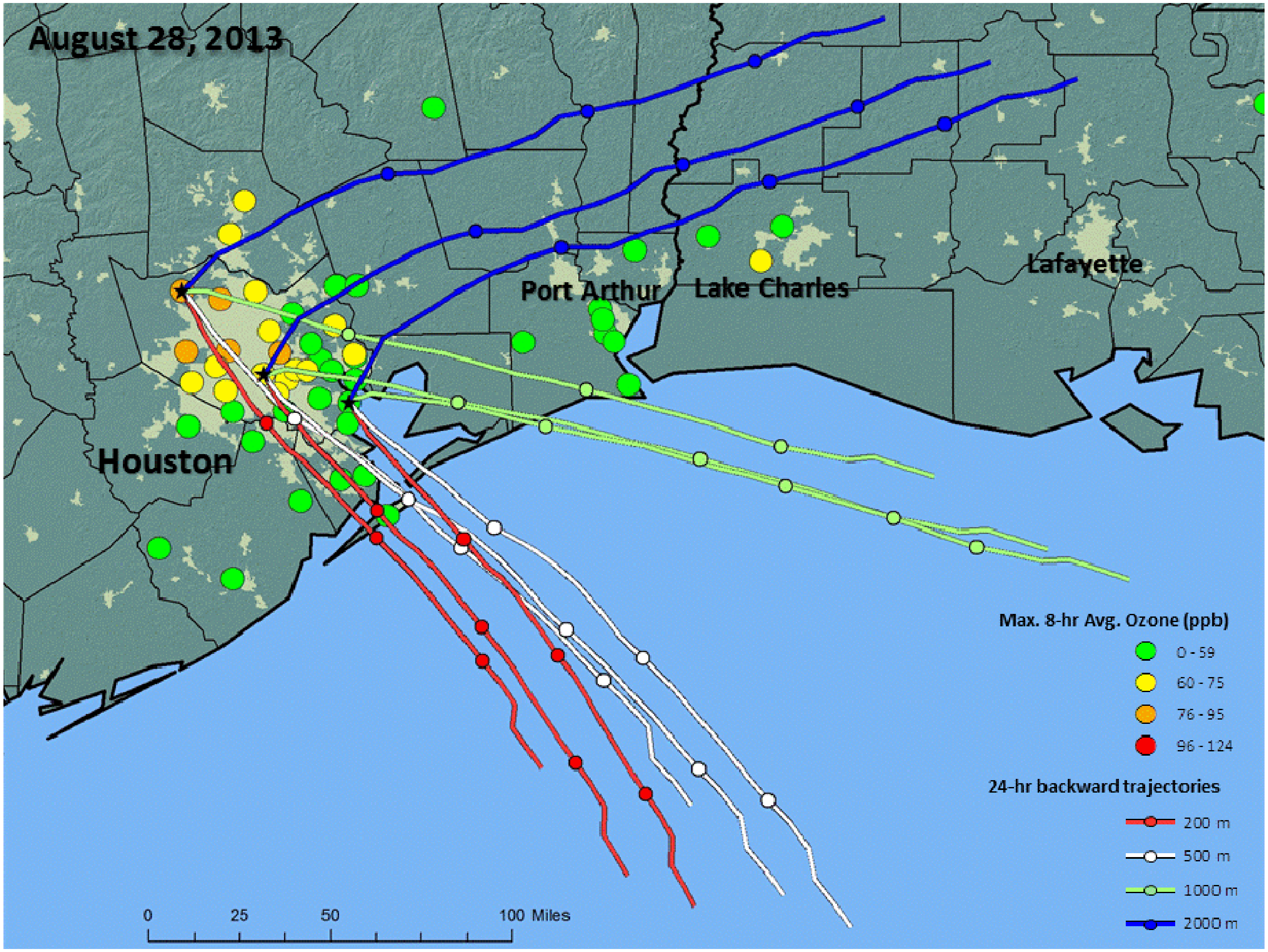


Figure 8. Daily maximum 8-hr average ozone concentrations and 24-hr backward trajectories ending at 6:00 p.m. CST on August 28, 2013. Light to moderate southeasterly (onshore) winds below 1000 m transported pollutants northwestward across the Houston area. As a result, 8-hr ozone concentrations were highest on the northwest side of Houston. Dots along the trajectories are at 6-hr intervals.

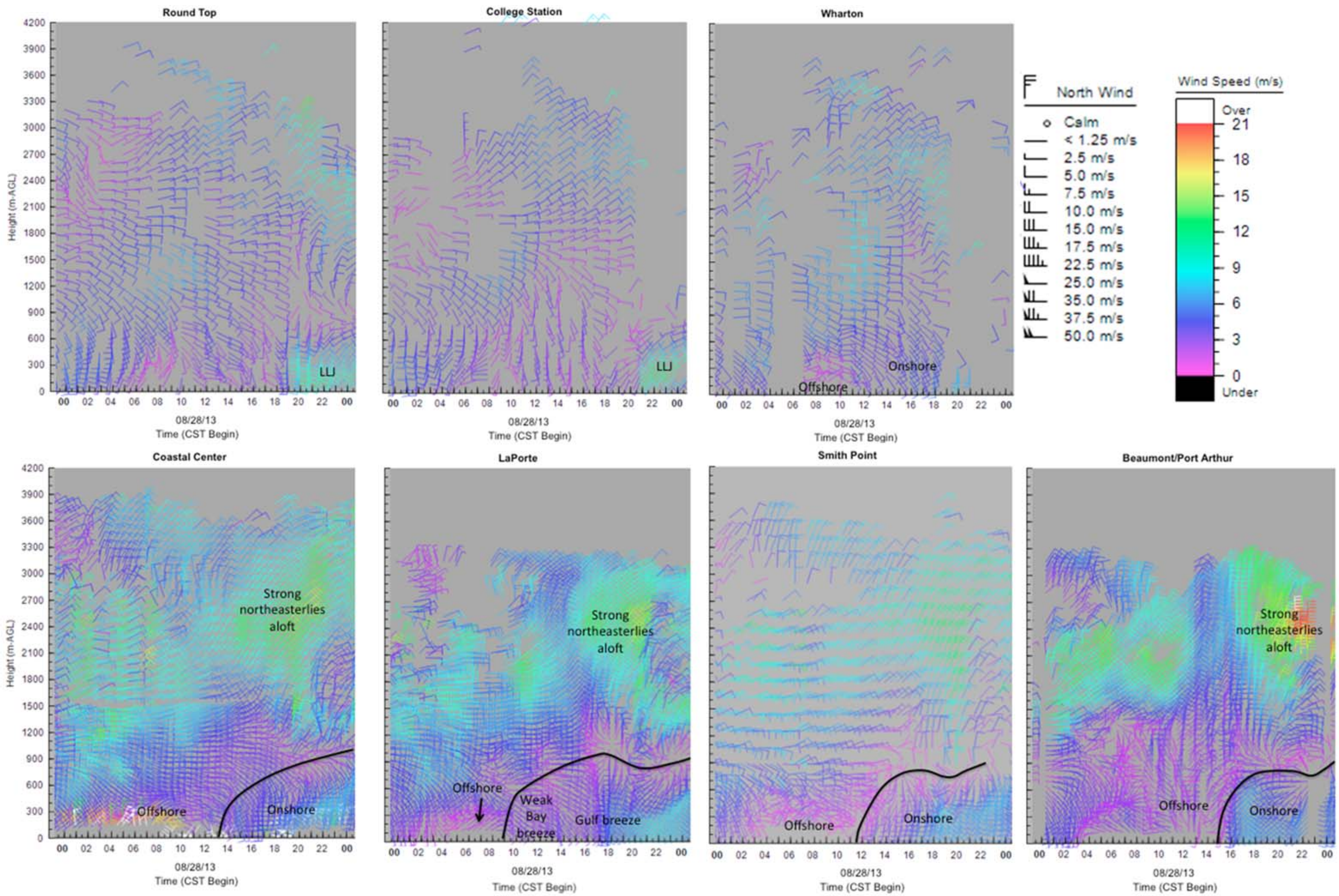


Figure 9. Wind profiler data on August 28, 2013. A weak Gulf breeze developed around noon on August 28 and spread slowly inland.

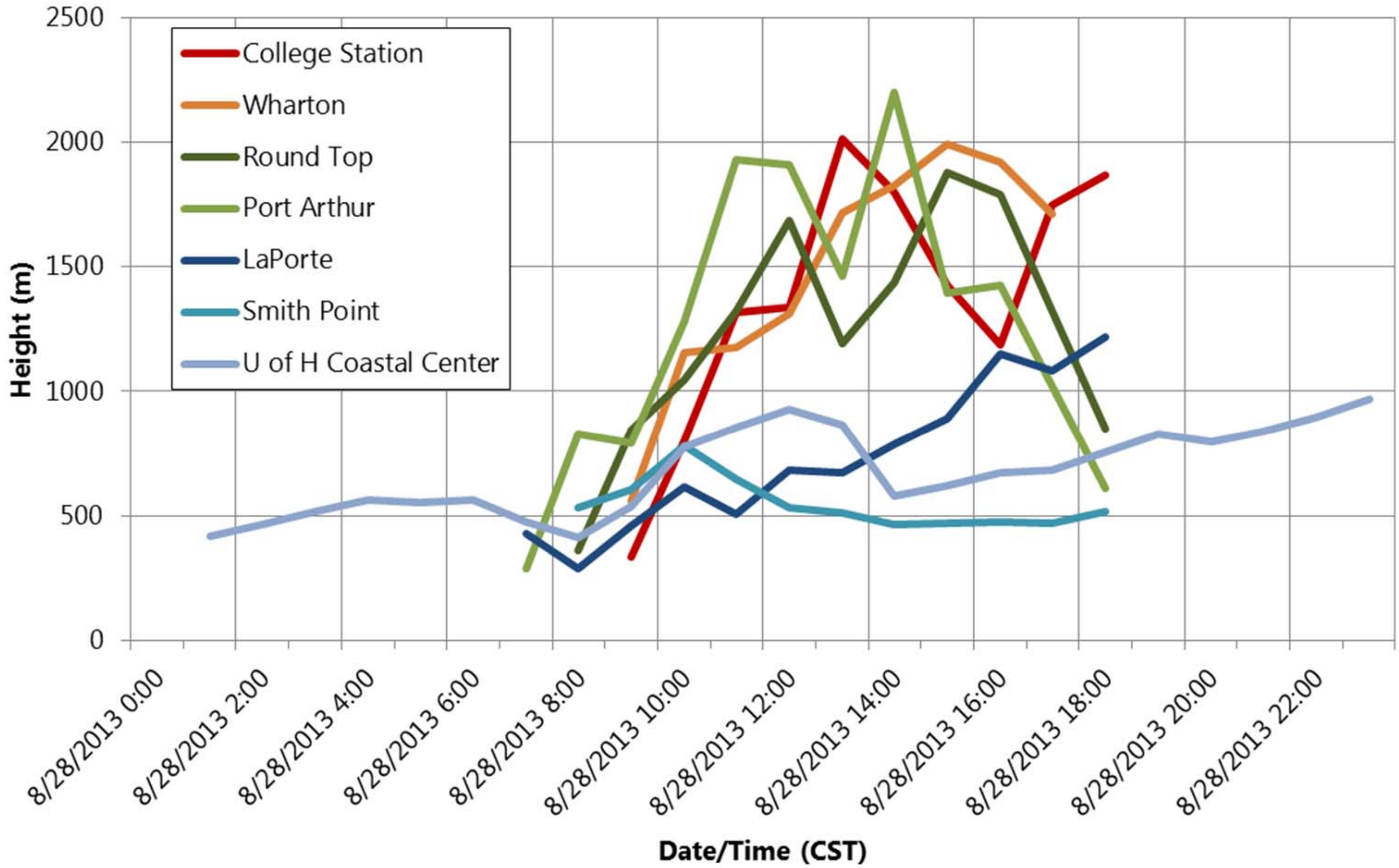


Figure 10. Hourly mixing heights on August 28, 2013.

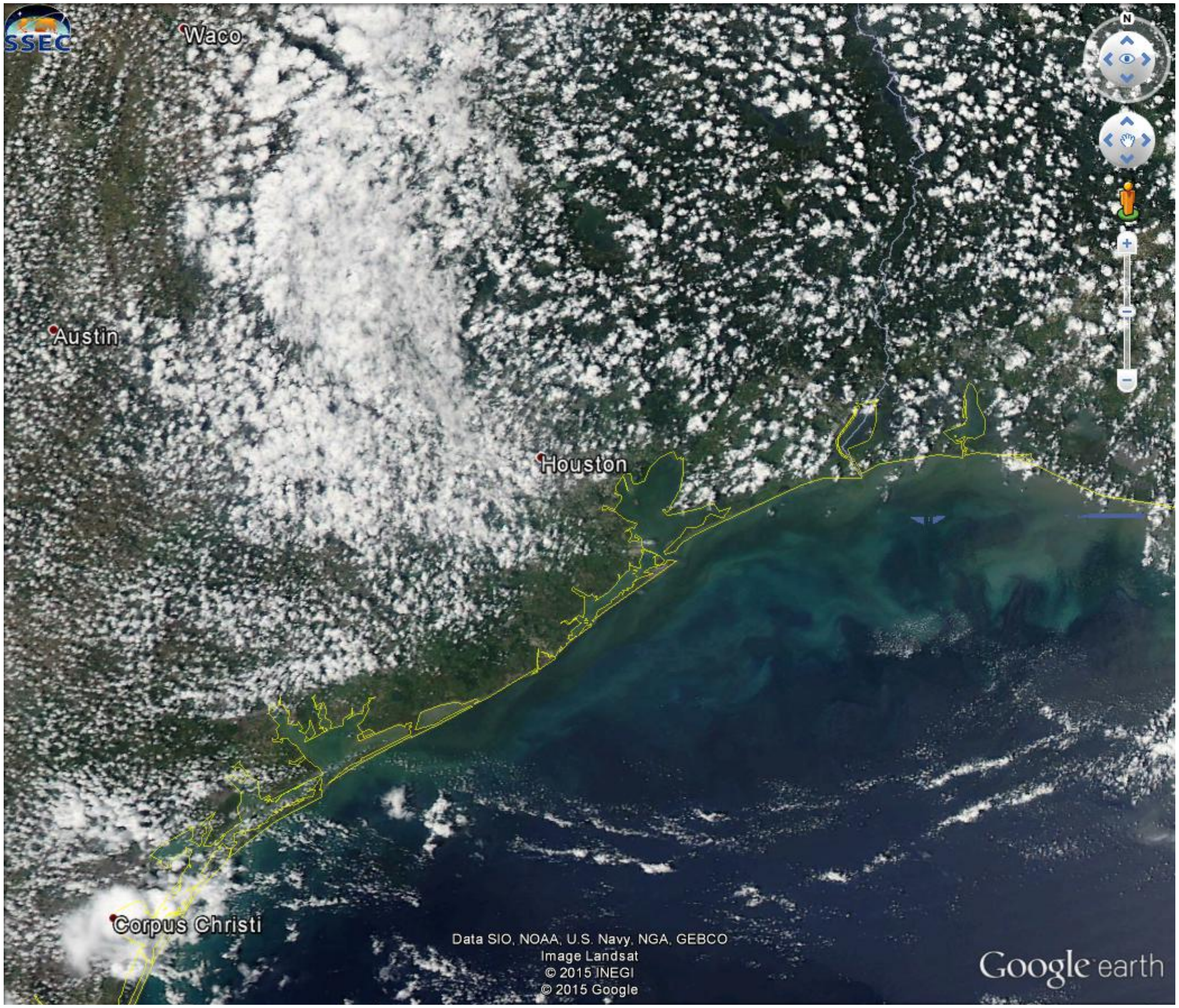


Figure 11. MODIS-AQUA image from August 28, 2013. Scattered fair weather cumulus clouds developed inland while coastal areas were clear following passage of the Gulf breeze.

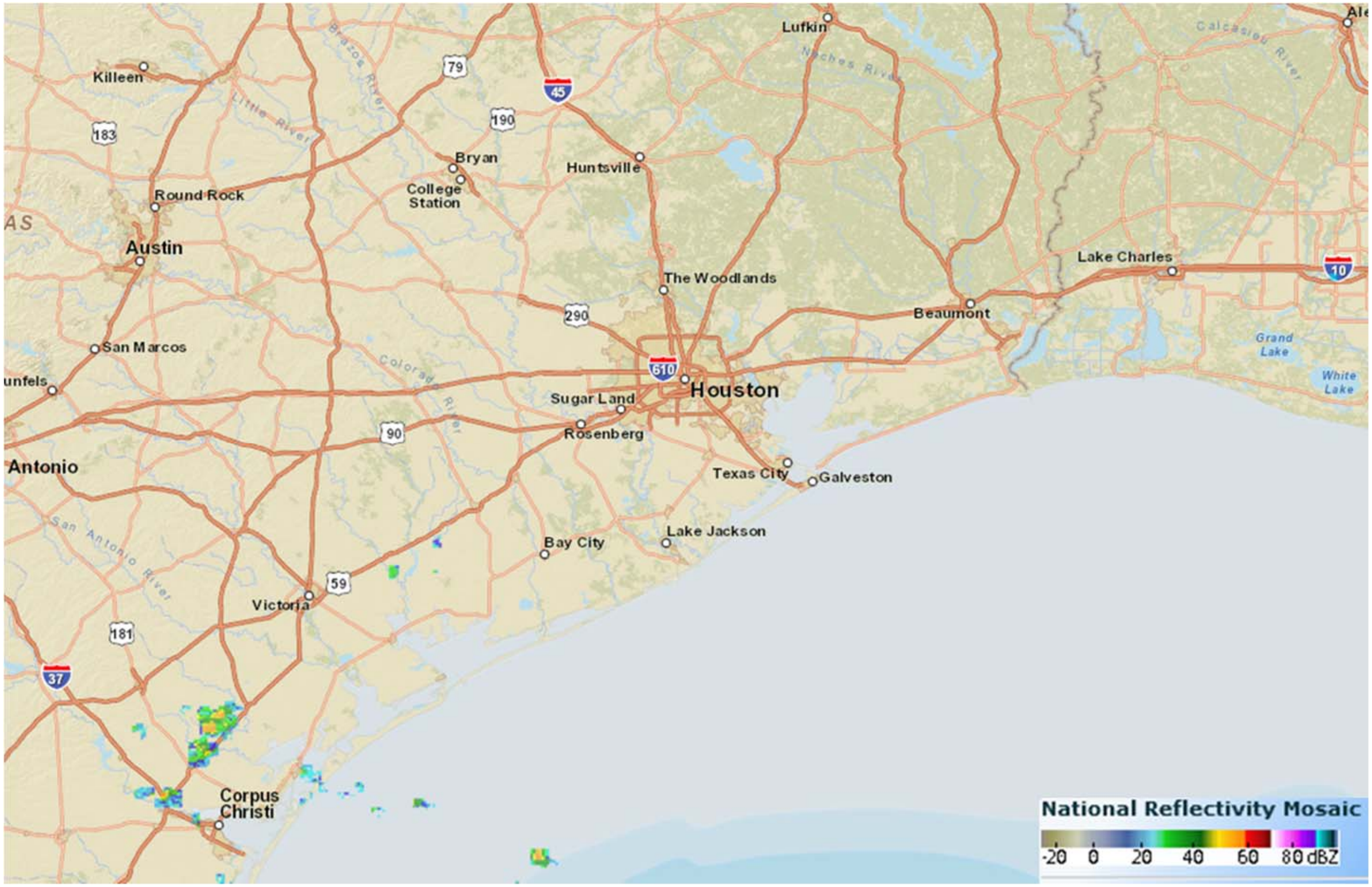


Figure 12. Regional radar image from 2:00 p.m. CST on August 28, 2013. No precipitation was observed in the Houston area.

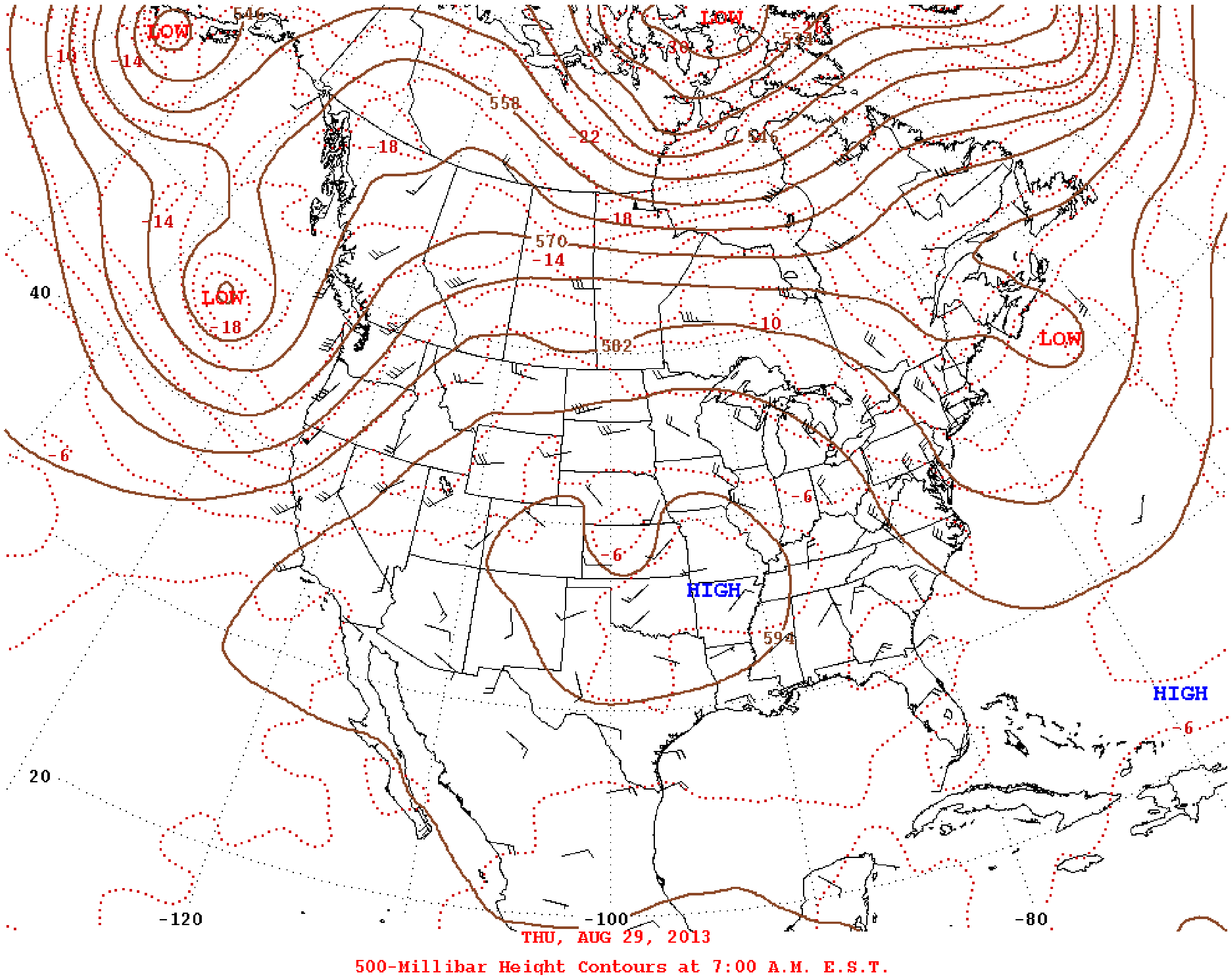
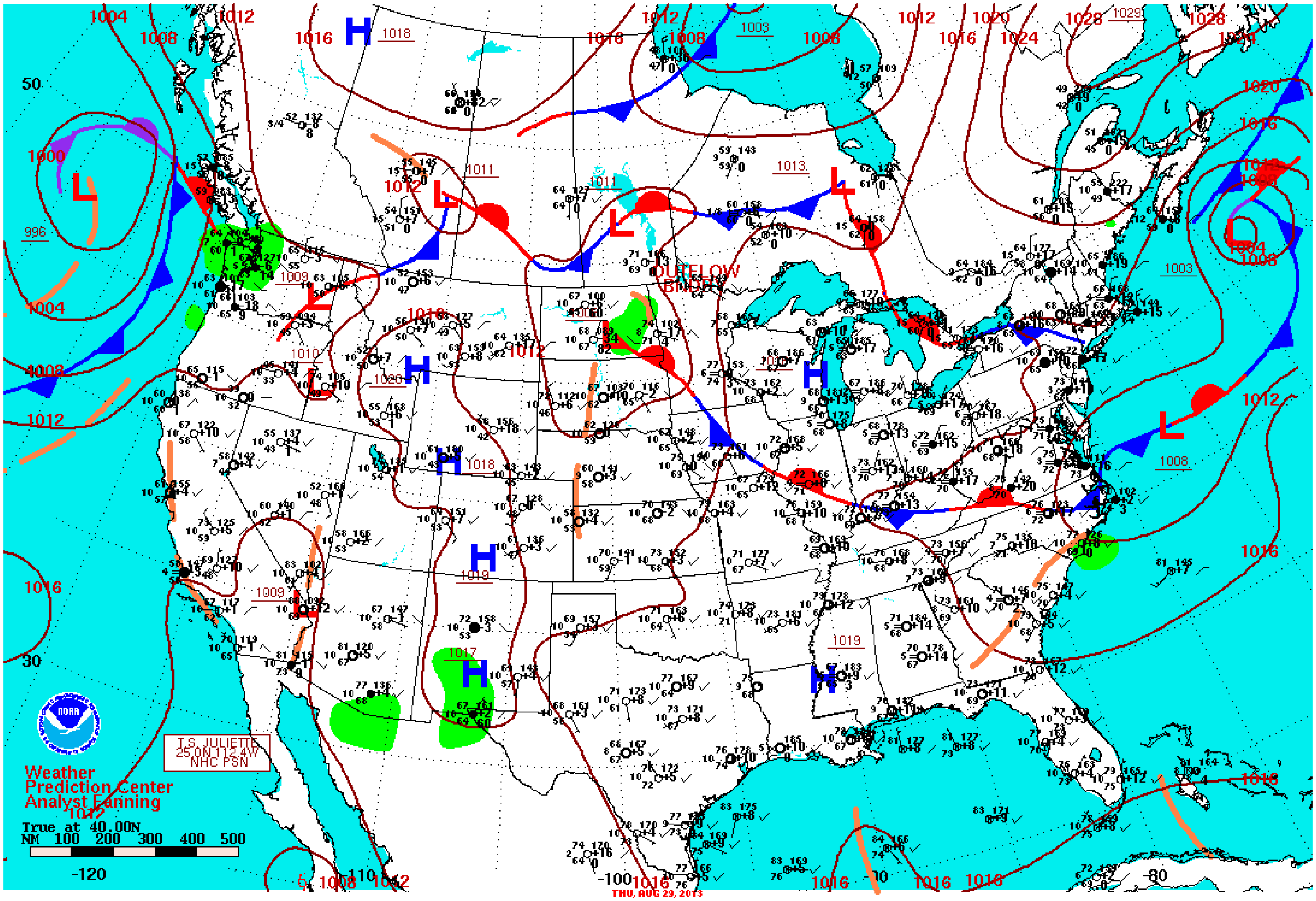


Figure 13. A map showing the height of the 500 mb pressure surface at 6:00 a.m. CST on August 29, 2013. An upper-level high-pressure system was located over the central Plains.



Surface Weather Map and Station Weather at 7:00 A.M. E.S.T.

Figure 14. Surface pressure map at 6:00 a.m. CST on August 29, 2013. A broad surface high-pressure system was located over the southeastern United States, resulting in a weak large-scale pressure gradient in the Houston area.

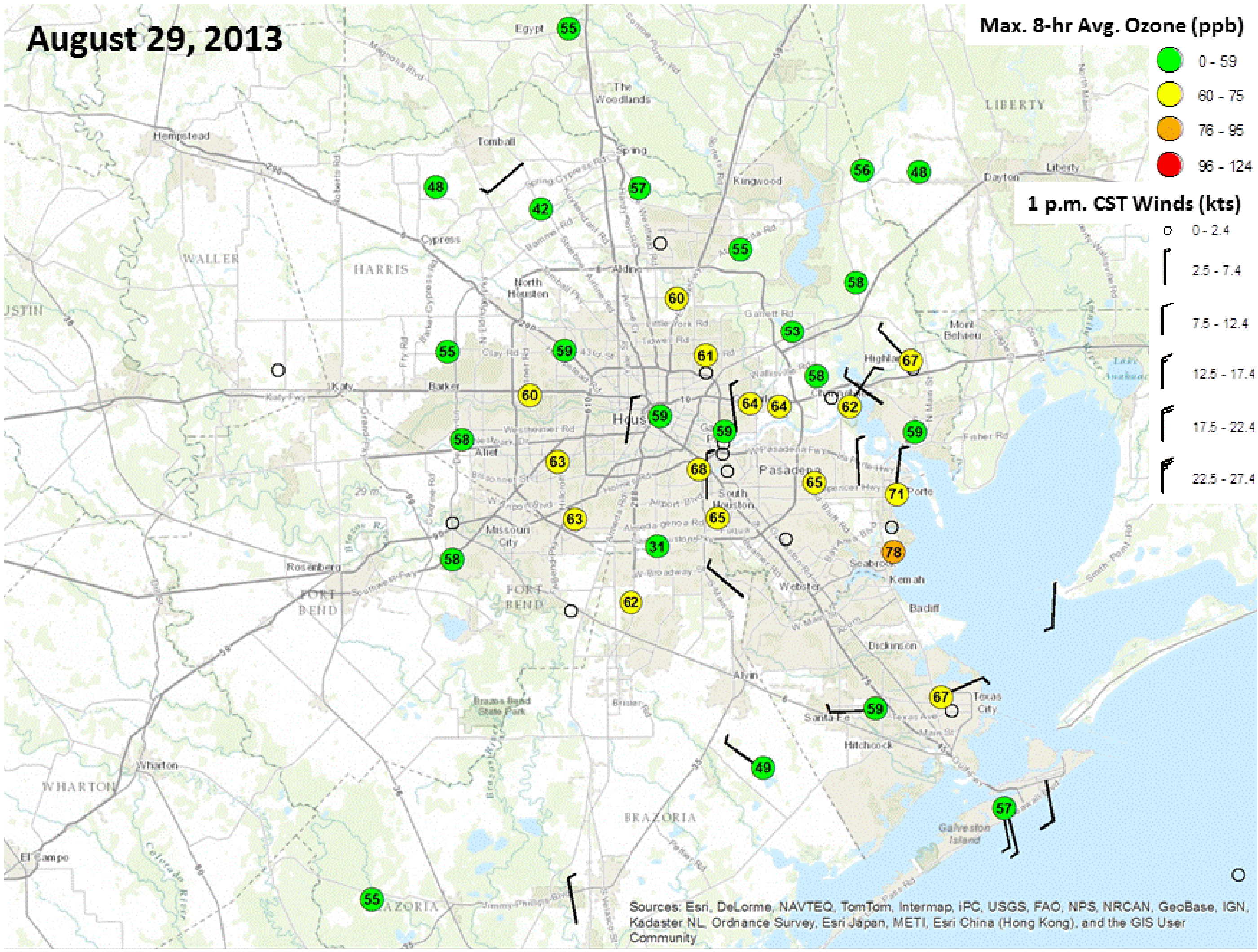


Figure 15. Daily maximum 8-hr average ozone concentrations and surface wind observations from Houston-area monitors on August 29, 2013. Winds were calm or light northerly (offshore) over inland areas and light southerly (onshore) at the coast due to the development of a weak Bay and Gulf breeze. Eight-hour ozone concentrations were highest near the interface of the low-level continental and maritime air masses along the west side of Galveston Bay.

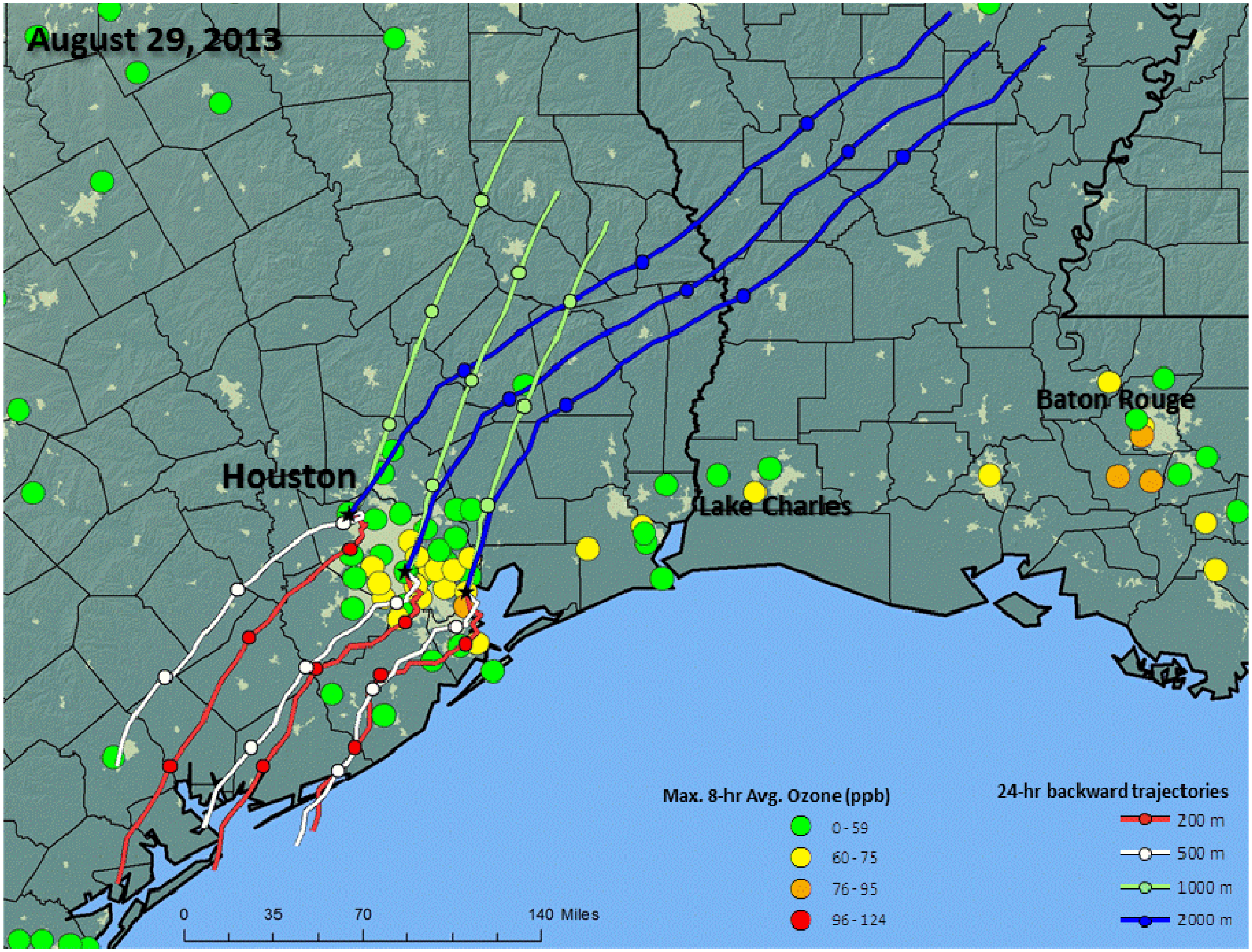


Figure 16. Daily maximum 8-hr average ozone concentrations and 24-hr backward trajectories ending at 6:00 p.m. CST on August 29, 2013. Stronger offshore flow aloft and a weaker low-level afternoon sea breeze compared to the previous day confined higher ozone levels to the southeast side of Houston near Galveston Bay. Dots along the trajectories are at 6-hr intervals.

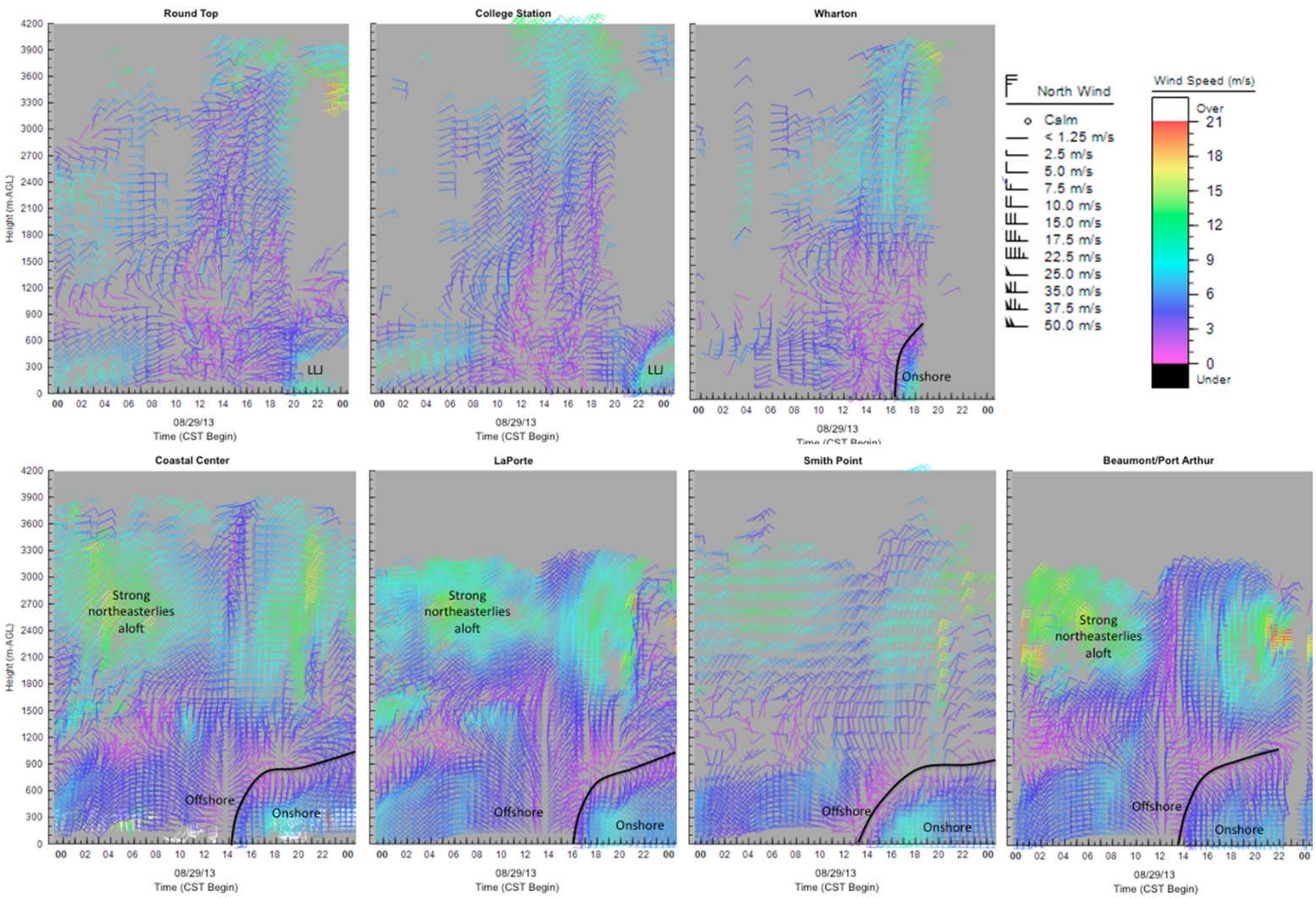


Figure 17. Wind profiler data on August 29, 2013. A weak Gulf breeze developed during the early afternoon hours on August 29 and spread very slowly inland.

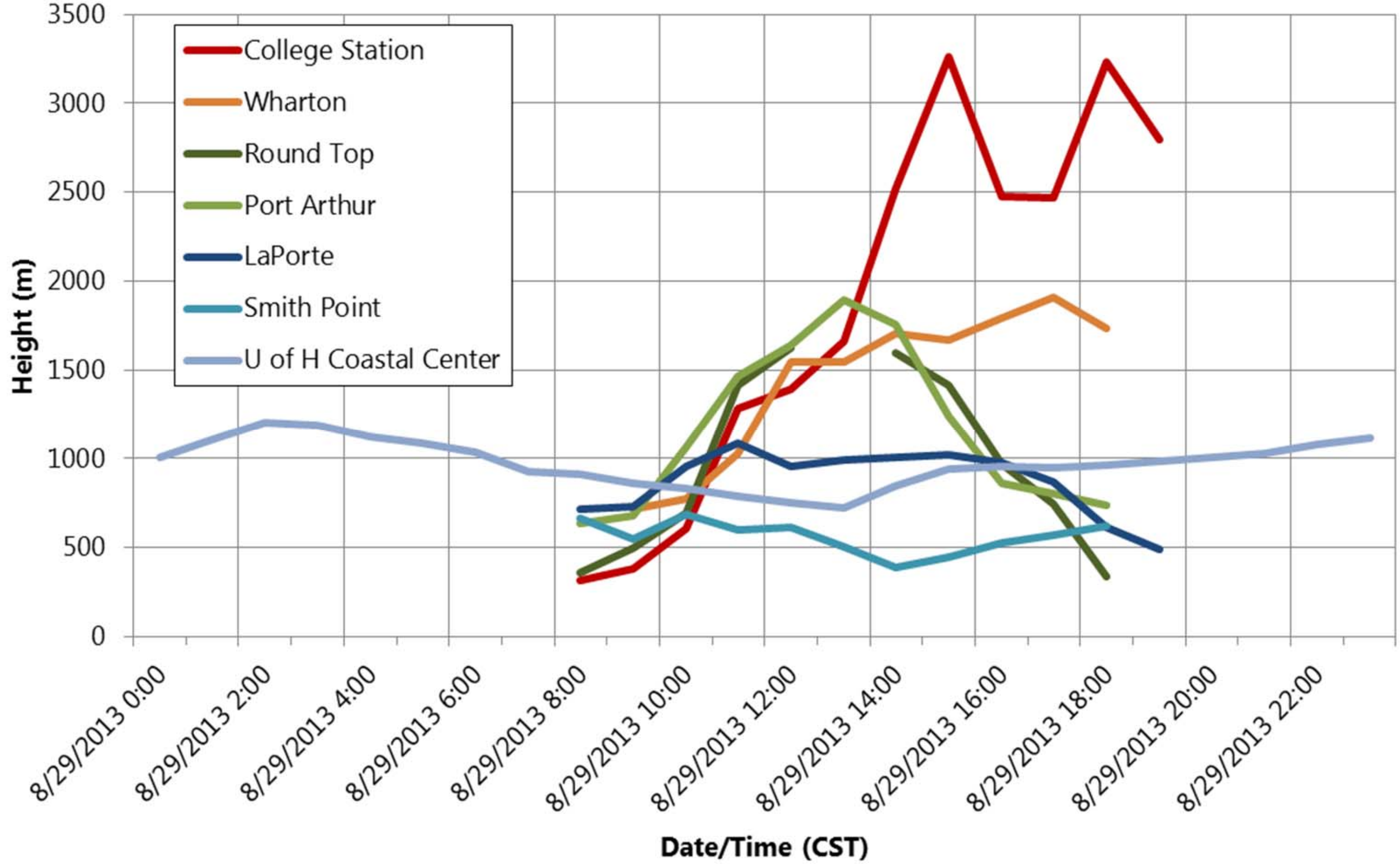


Figure 18. Hourly mixing heights on August 29, 2013.

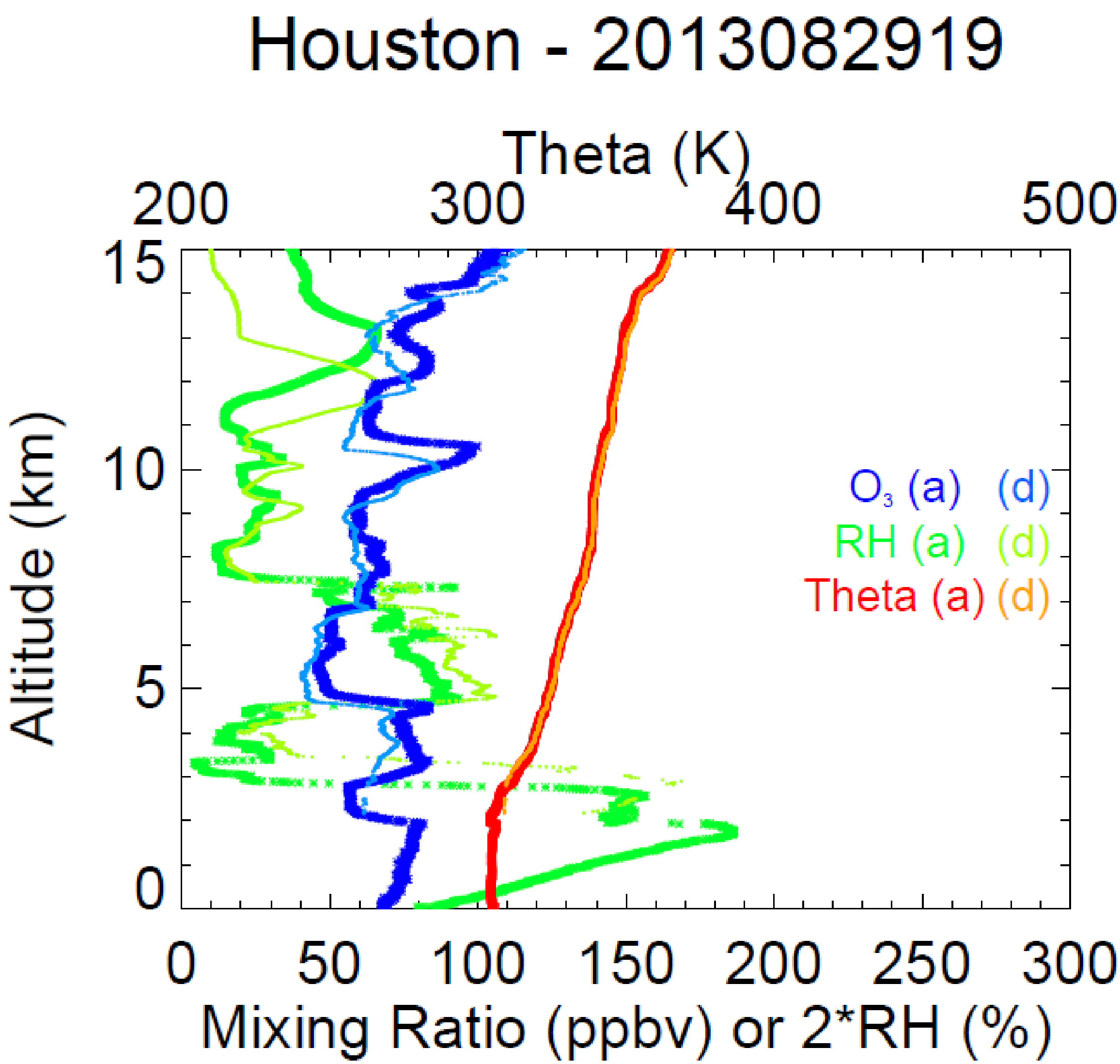


Figure 19. Ozonesonde data on August 29, 2013, launched from the University of Houston at 1:09 p.m. CST.

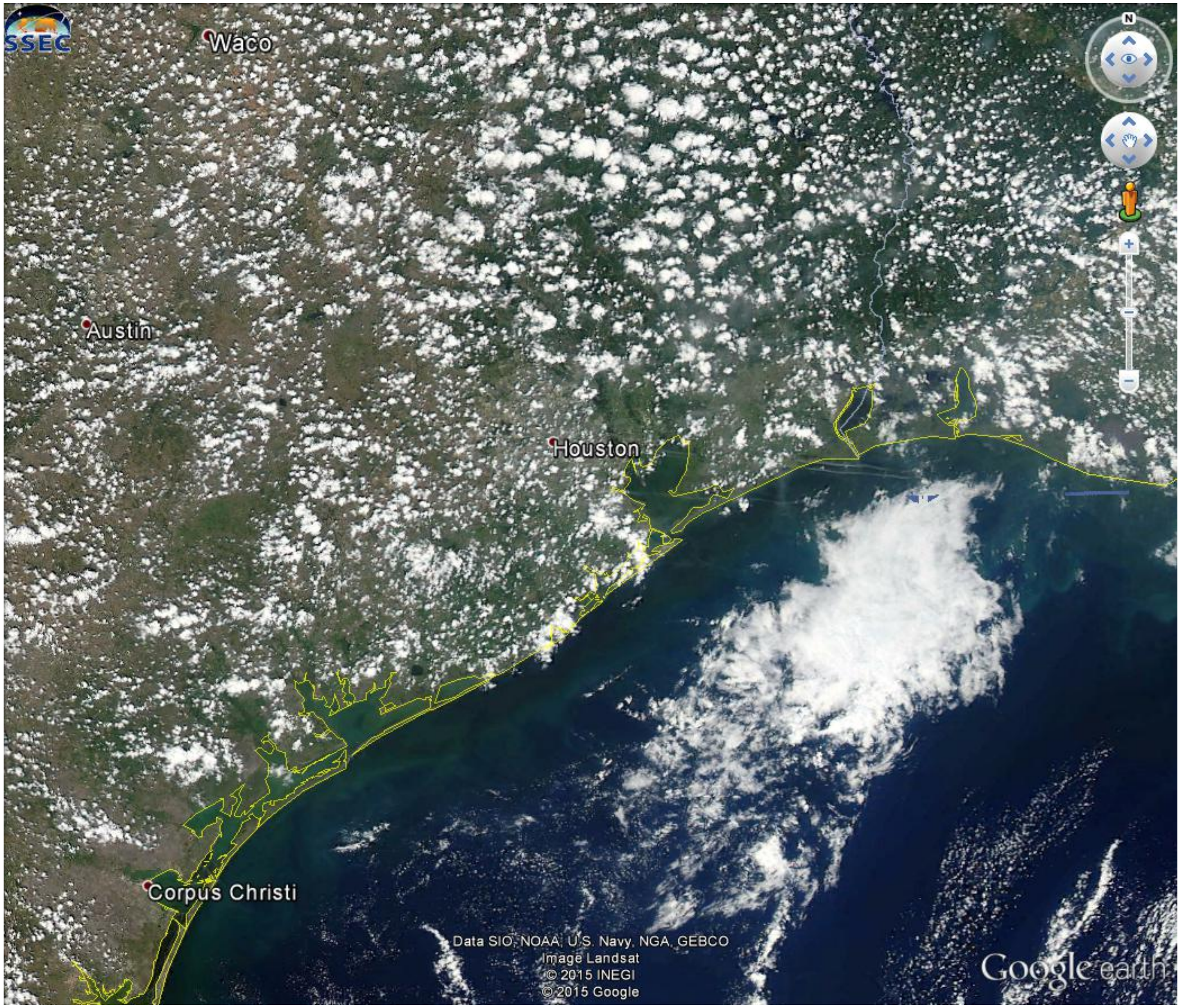


Figure 20. MODIS-AQUA image from August 29, 2013. Scattered fair weather cumulus clouds developed throughout the Houston area, but skies remained partly to mostly sunny.

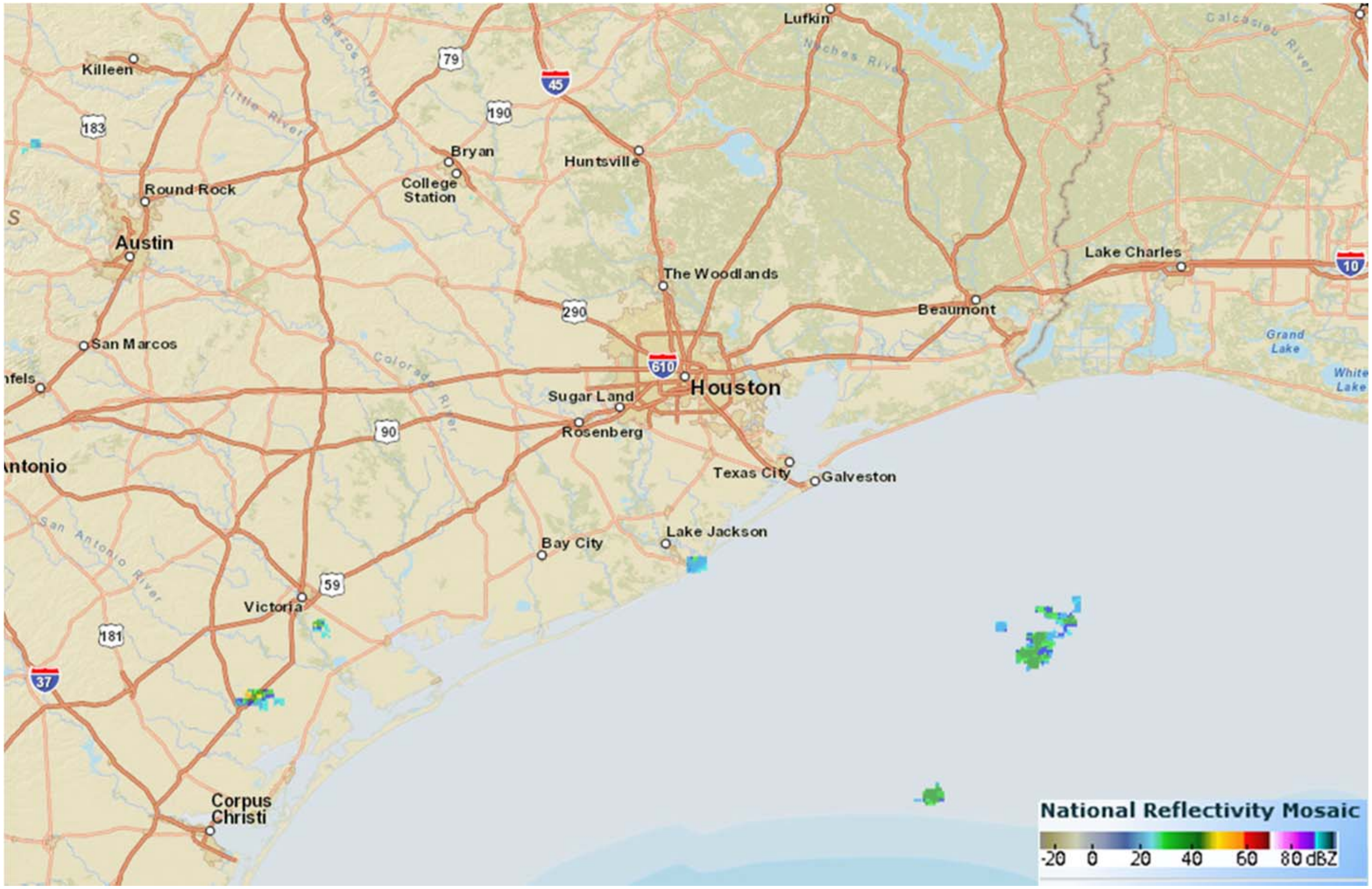


Figure 21. Regional radar image from 2:00 p.m. CST on August 29, 2013. No precipitation was observed in the immediate Houston area.

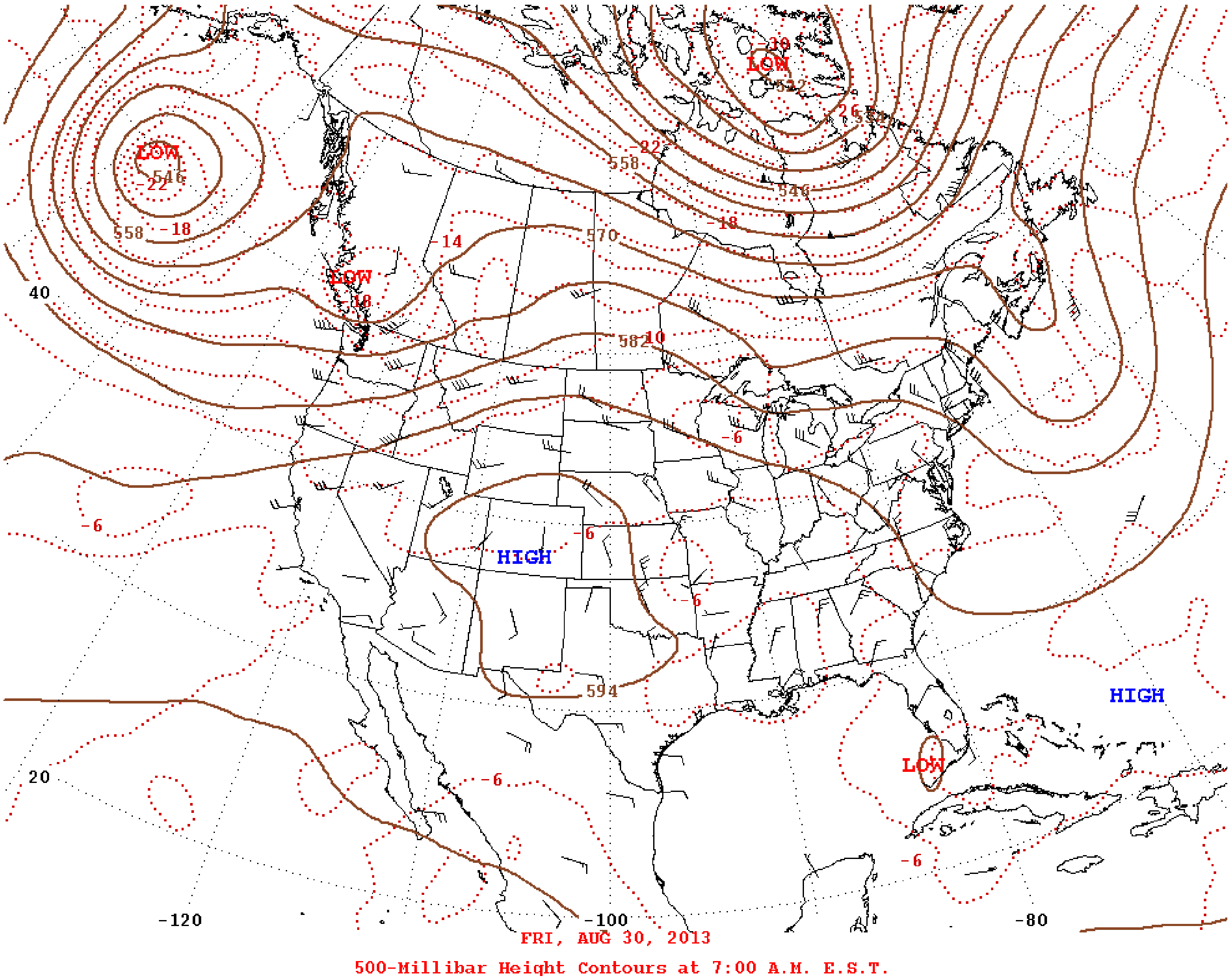
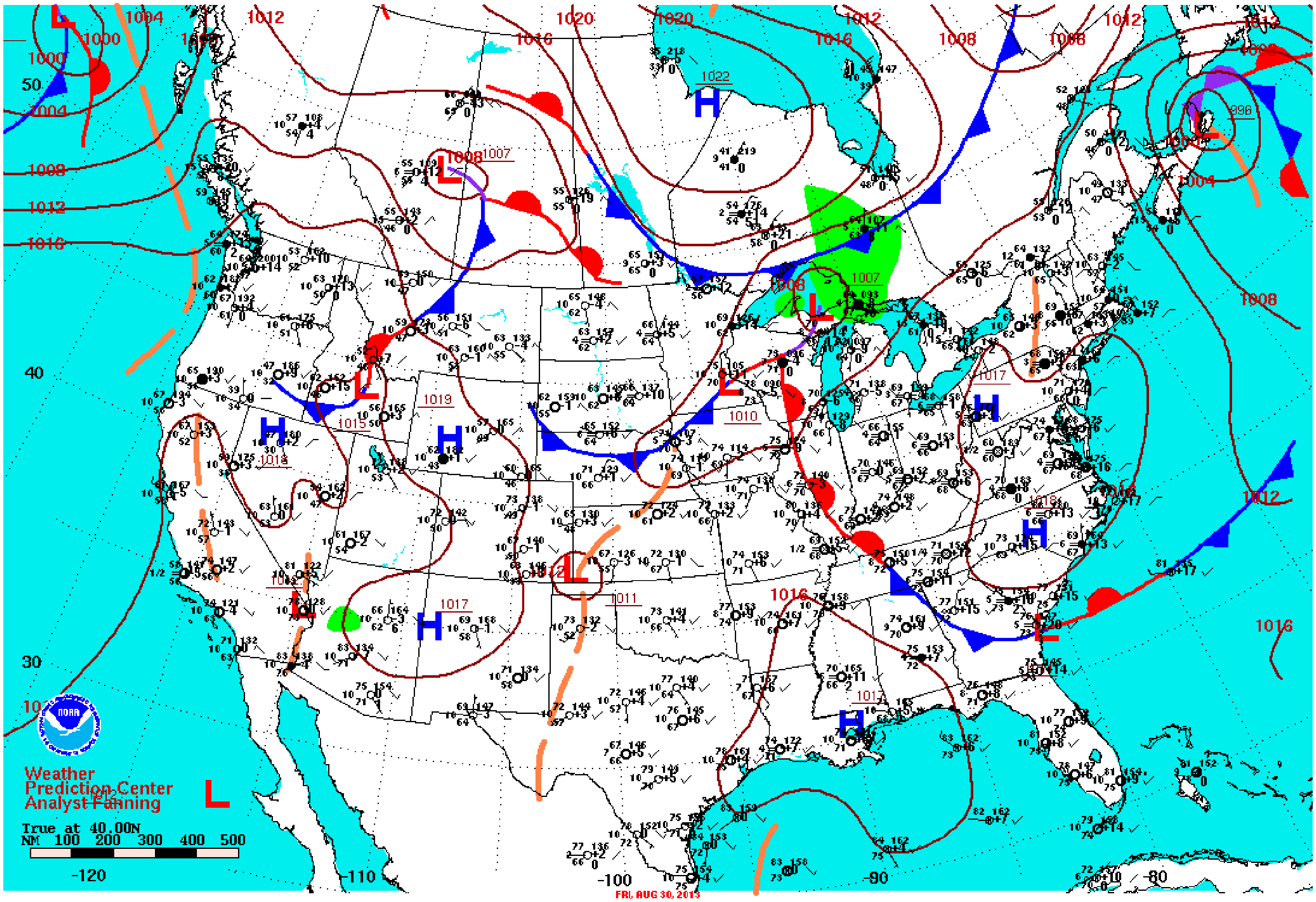


Figure 22. A map showing the height of the 500 mb pressure surface at 6:00 a.m. CST on August 30, 2013. An upper-level high-pressure system was located over the Rocky Mountains and central Plains.



Surface Weather Map and Station Weather at 7:00 A.M. E.S.T.

Figure 23. Surface pressure map at 6:00 a.m. CST on August 30, 2013. A surface high-pressure system was located over Louisiana, resulting in a weak onshore pressure gradient in the Houston area.

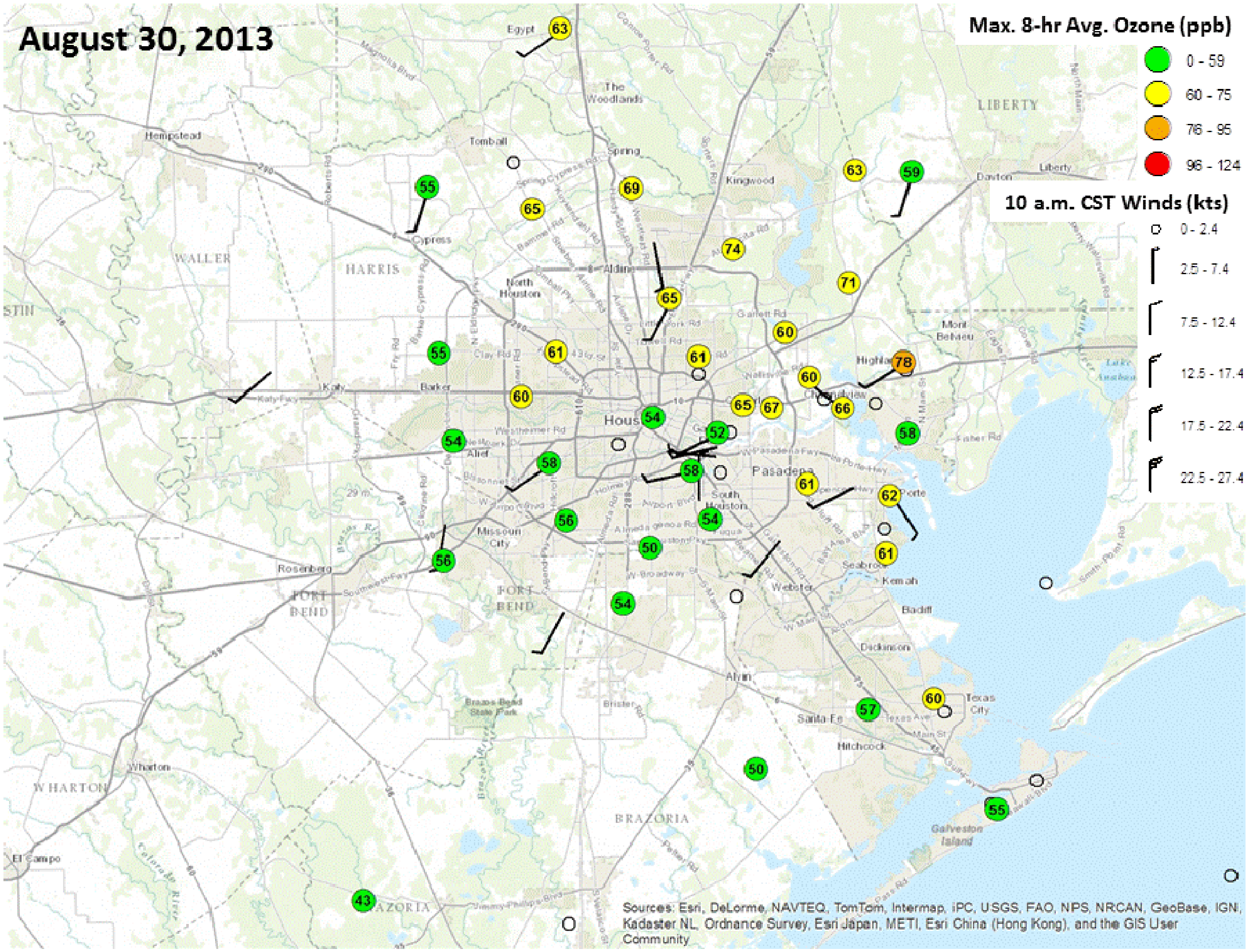


Figure 24. Daily maximum 8-hr average ozone concentrations and surface wind observations from Houston area monitors on August 30, 2013. A very weak Bay breeze developed along the north side of Galveston Bay, while calm to light southwesterly winds were reported inland. Eight-hour ozone concentrations were highest downwind of Houston on the north side of Galveston Bay.

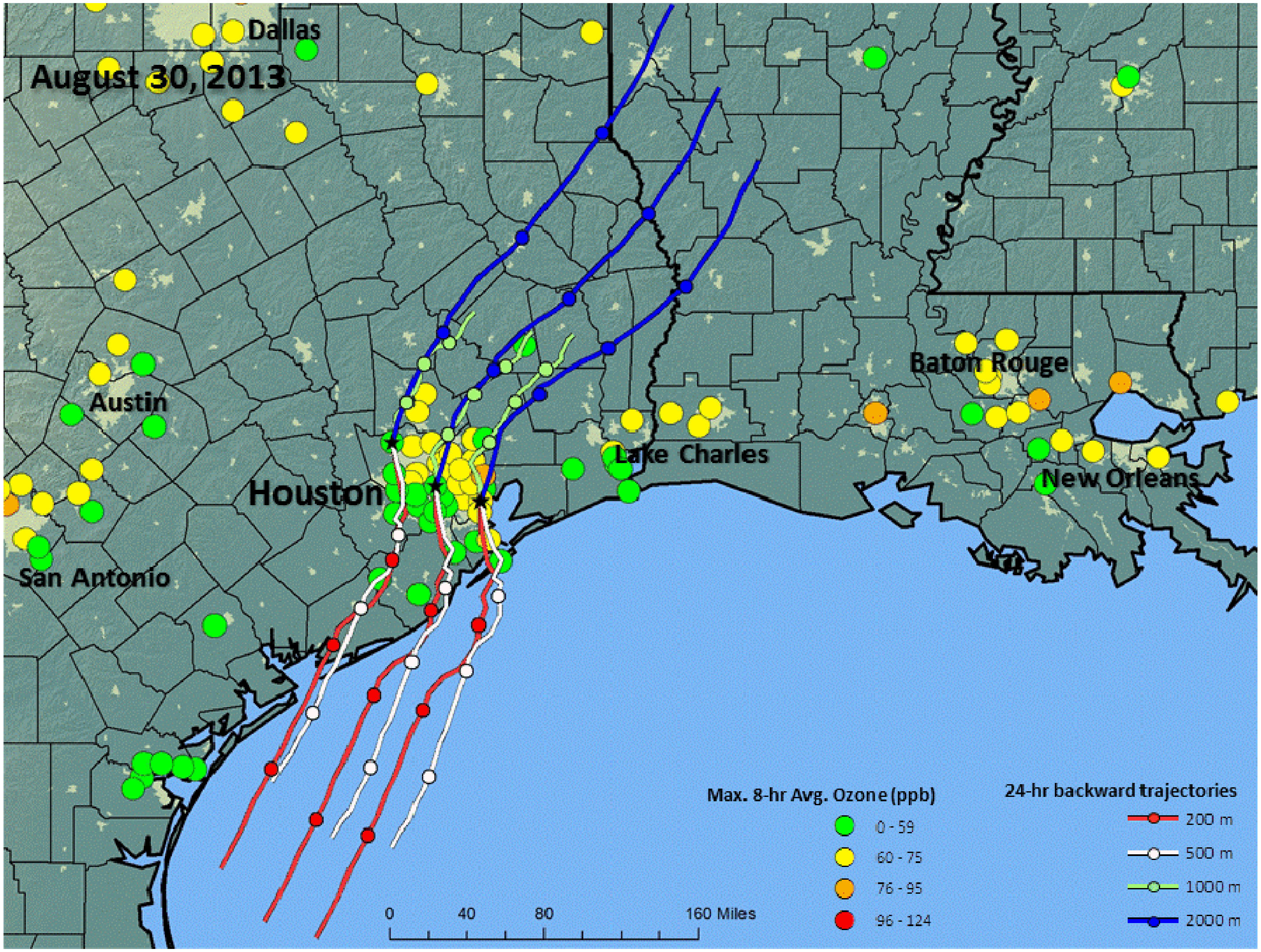


Figure 25. Daily maximum 8-hr average ozone concentrations and 24-hr backward trajectories ending at 6:00 p.m. CST on August 30, 2013. Stronger low-level afternoon onshore winds (compared to the previous day) transported pollutants northward, resulting in higher ozone concentrations north of Galveston Bay. Dots along the trajectories are at 6-hr intervals.

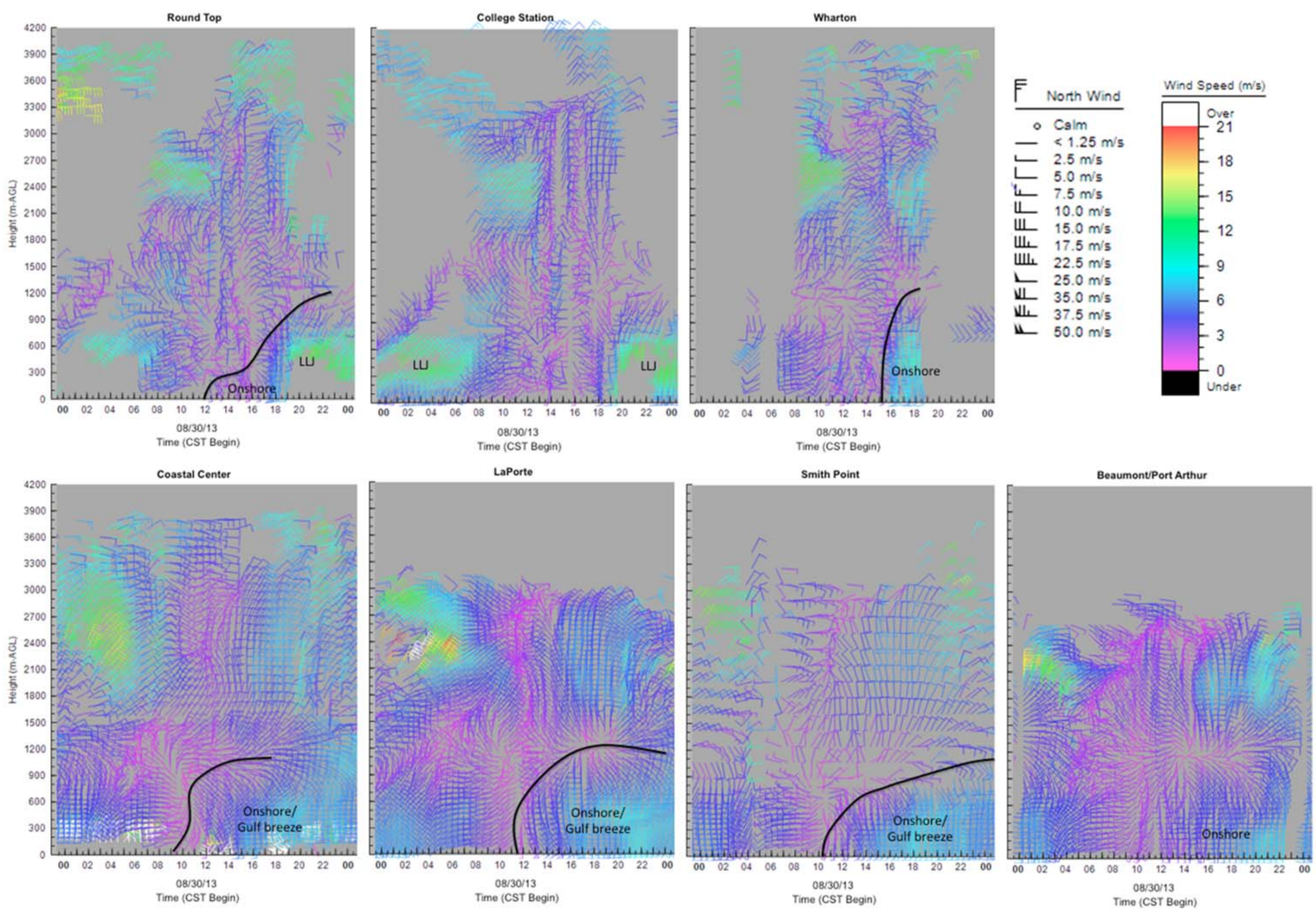


Figure 26. Wind profiler data on August 30, 2013. Light southwesterly winds during the morning hours shifted to southerly during the afternoon hours as a weak Bay breeze developed.

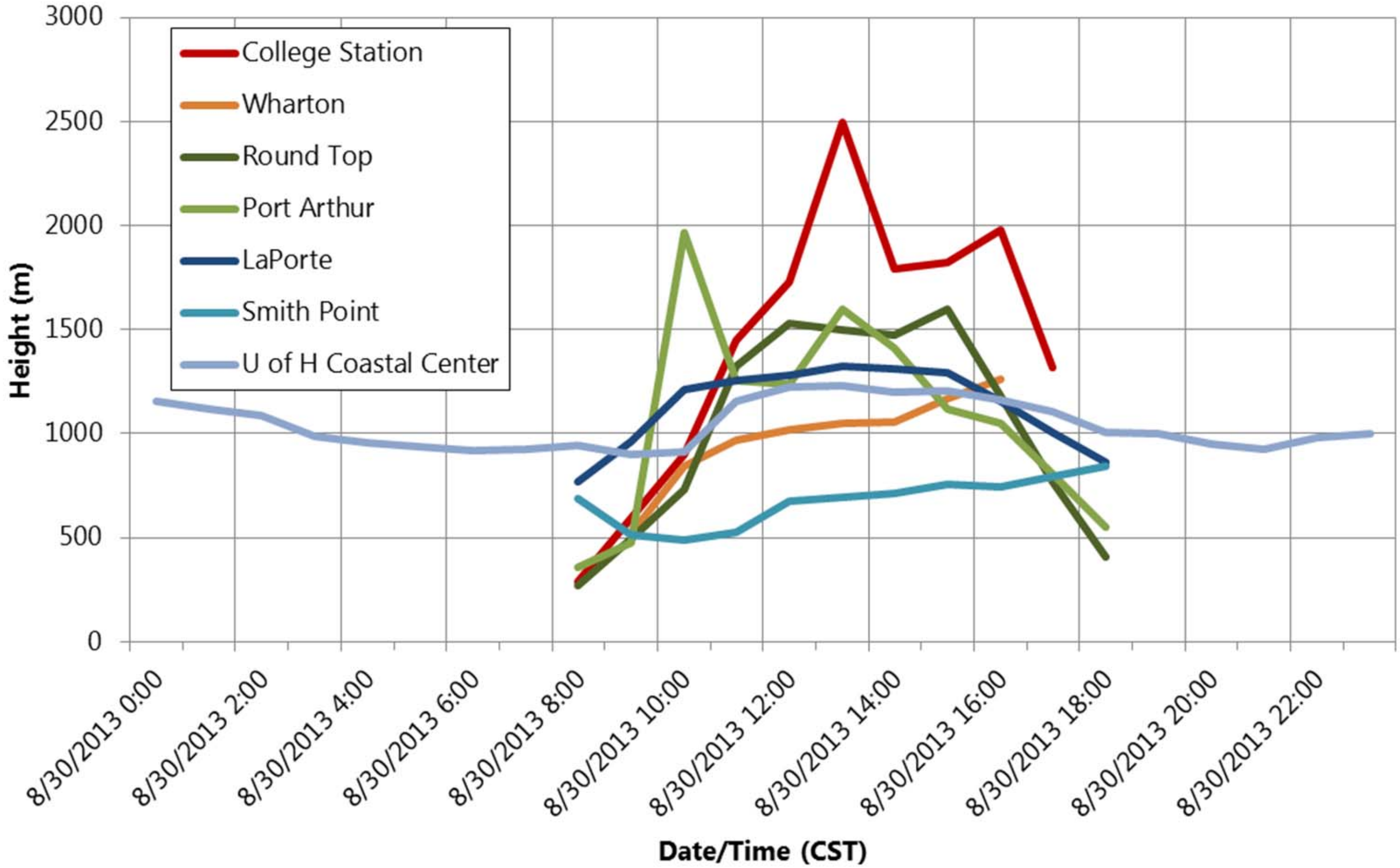


Figure 27. Hourly mixing heights on August 30, 2013.

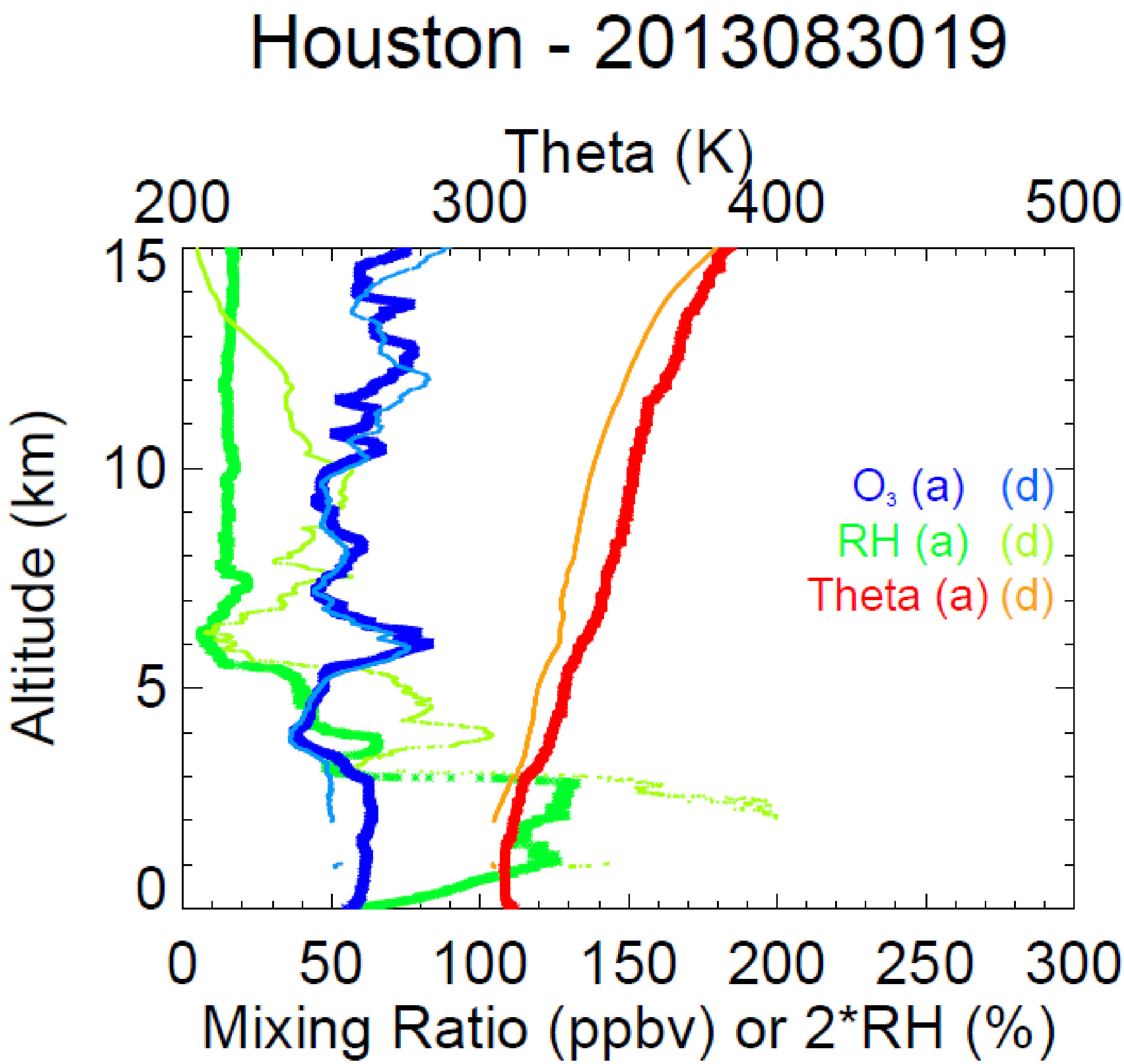


Figure 28. Ozonesonde data on August 30, 2013, launched from the University of Houston at 1:15 p.m. CST.

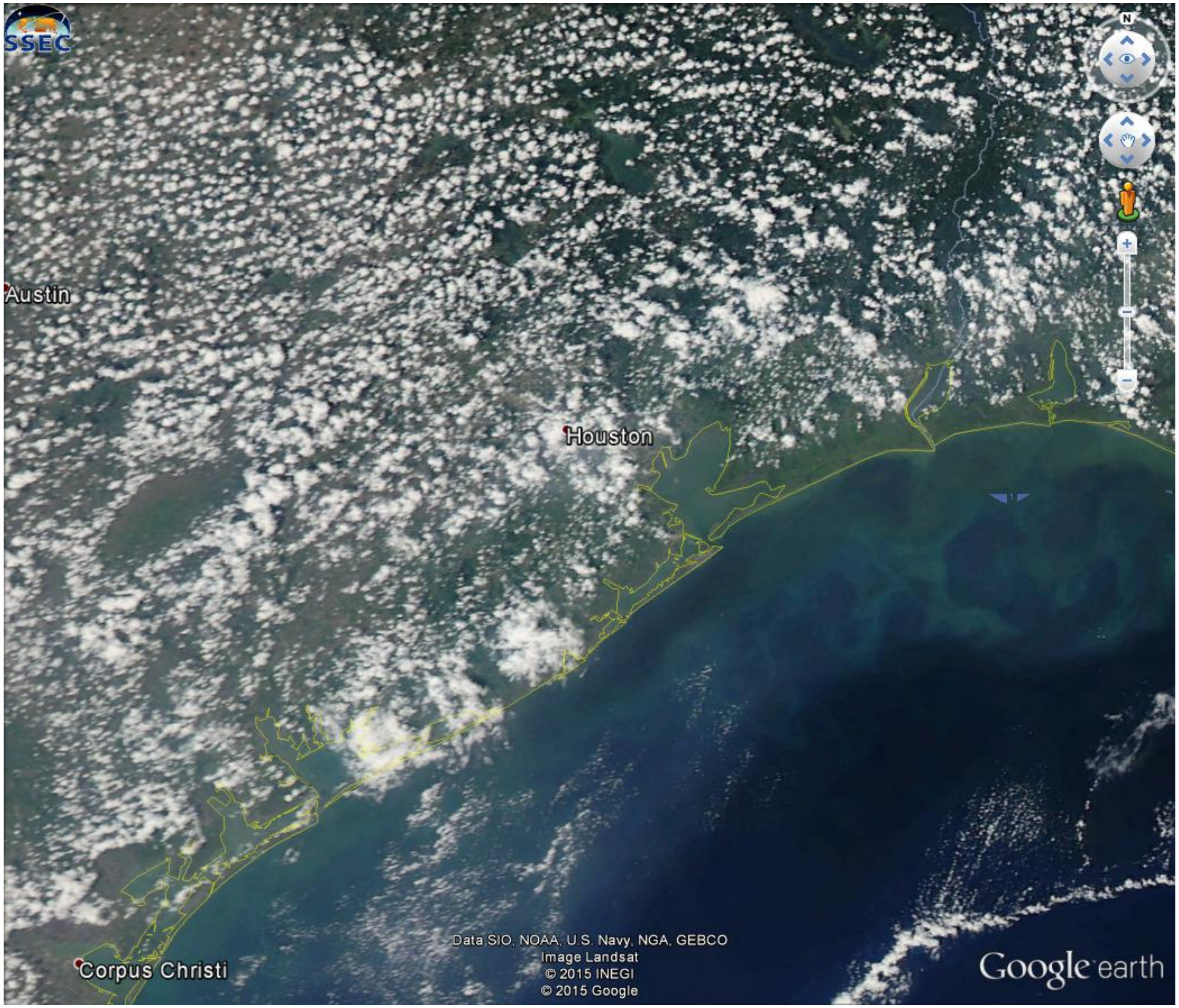


Figure 29. MODIS-AQUA image from August 30, 2013. Scattered fair weather cumulus clouds developed over inland areas, with less cloud cover at the coast due to passage of the Gulf breeze.

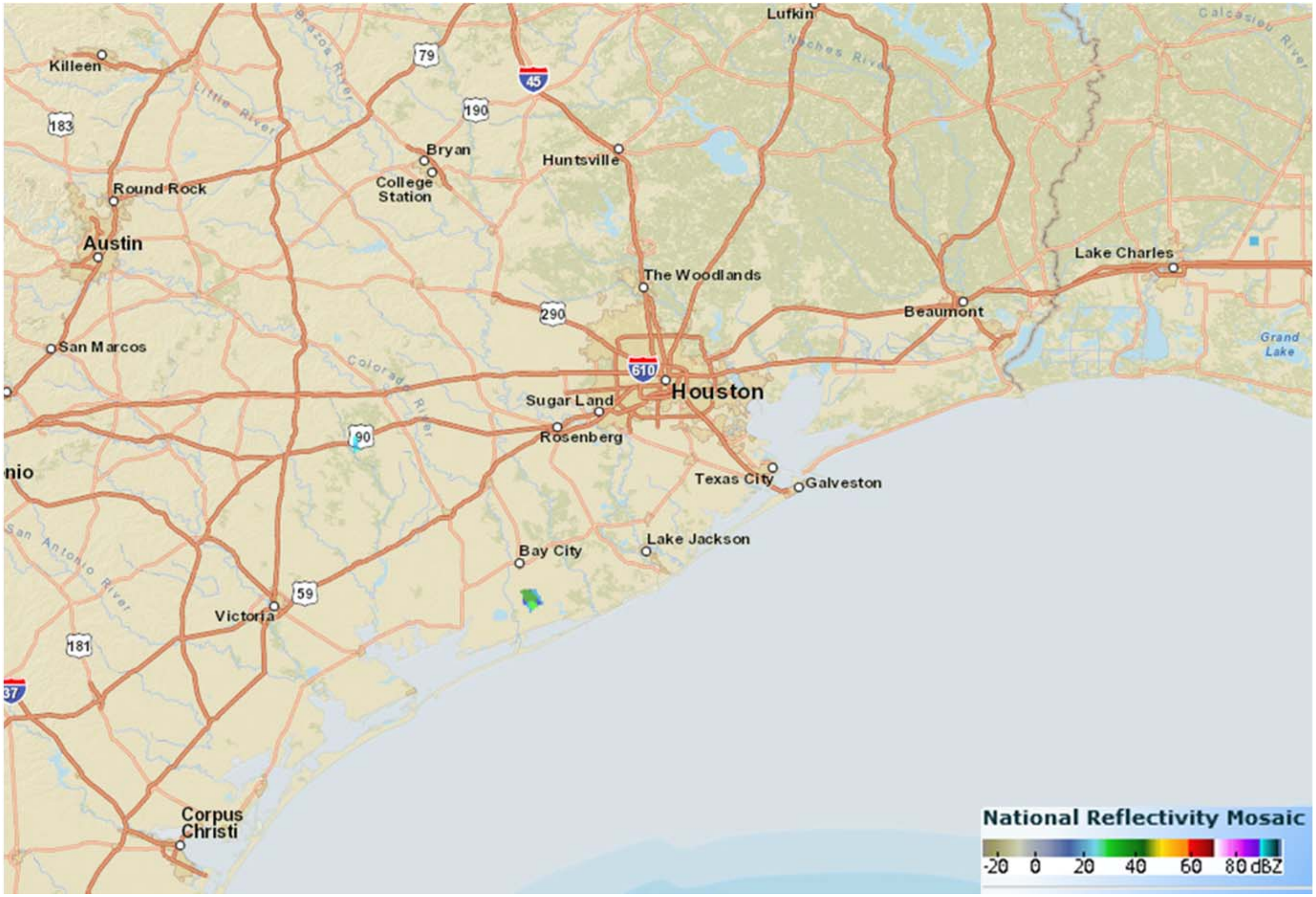


Figure 30. Regional radar image from 2 p.m. CST on August 30, 2013. No precipitation was observed in the immediate Houston area.

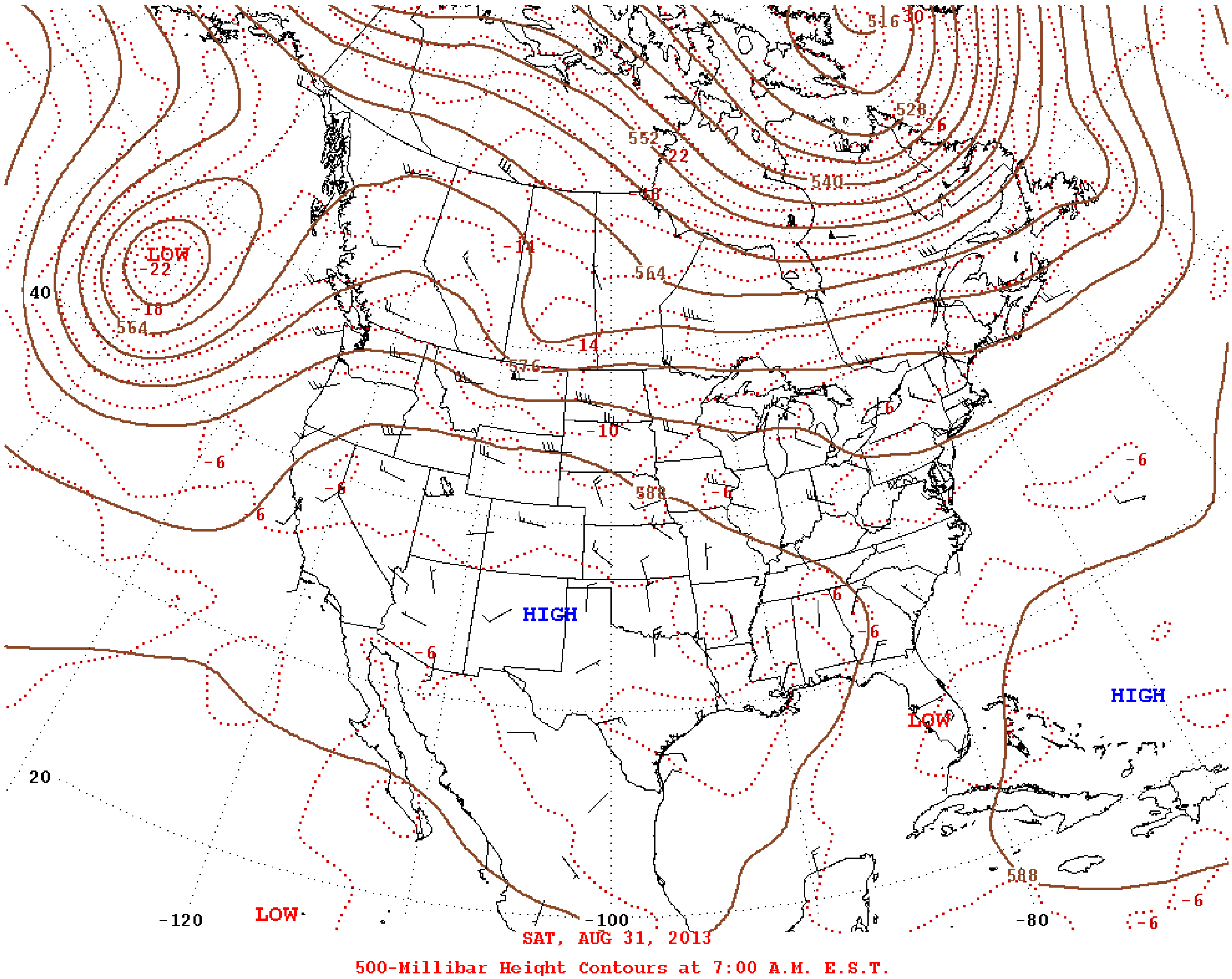
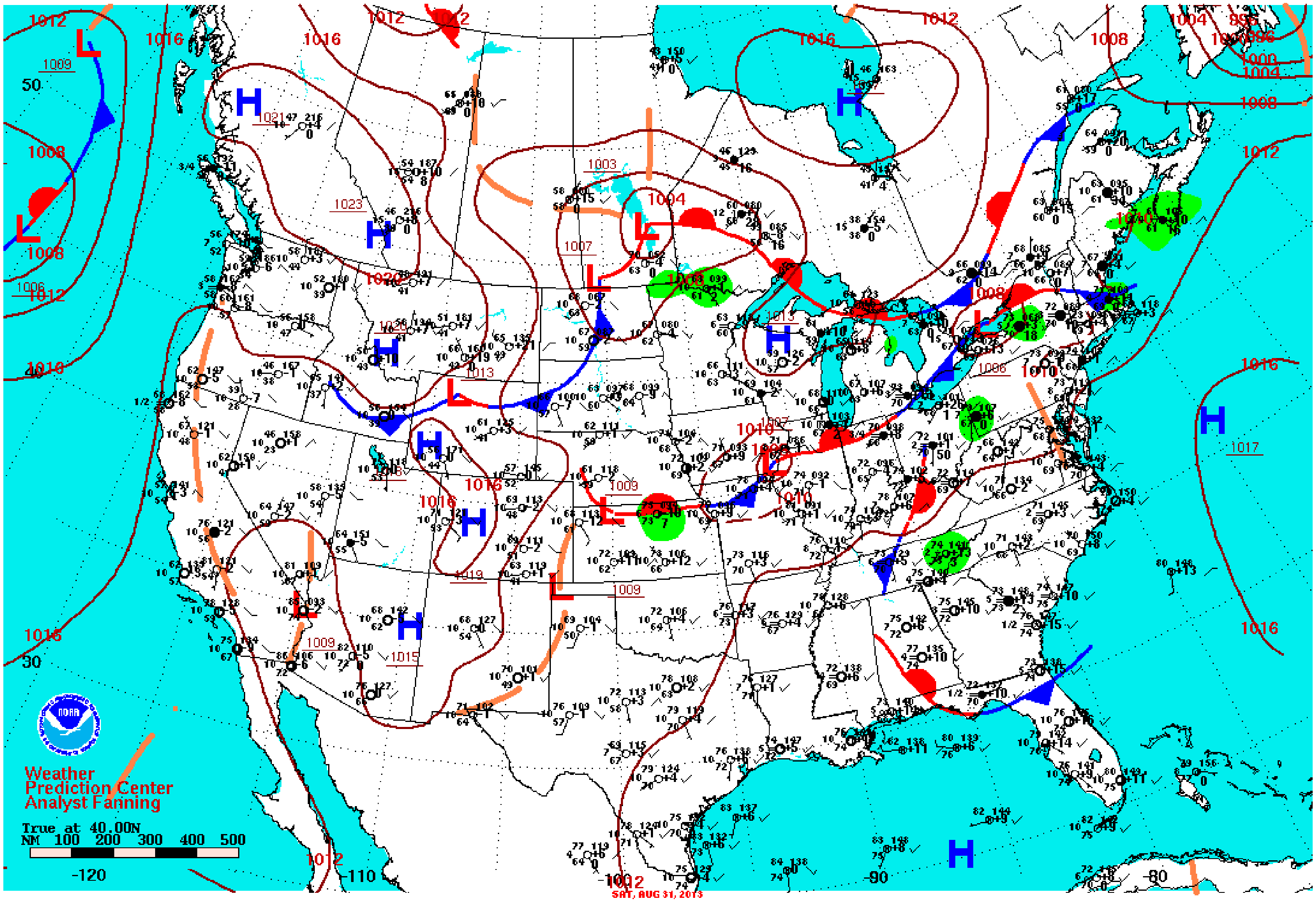


Figure 31. A map showing the height of the 500 mb pressure surface at 6:00 a.m. CST on August 31, 2013. An upper-level high-pressure system was located over the Rocky Mountains and central Plains.



Surface Weather Map and Station Weather at 7:00 A.M. E.S.T.

Figure 32. Surface pressure map at 6:00 a.m. CST on August 31, 2013. A surface high-pressure system was located over the eastern Gulf of Mexico, resulting in a weak onshore pressure gradient in the Houston area.

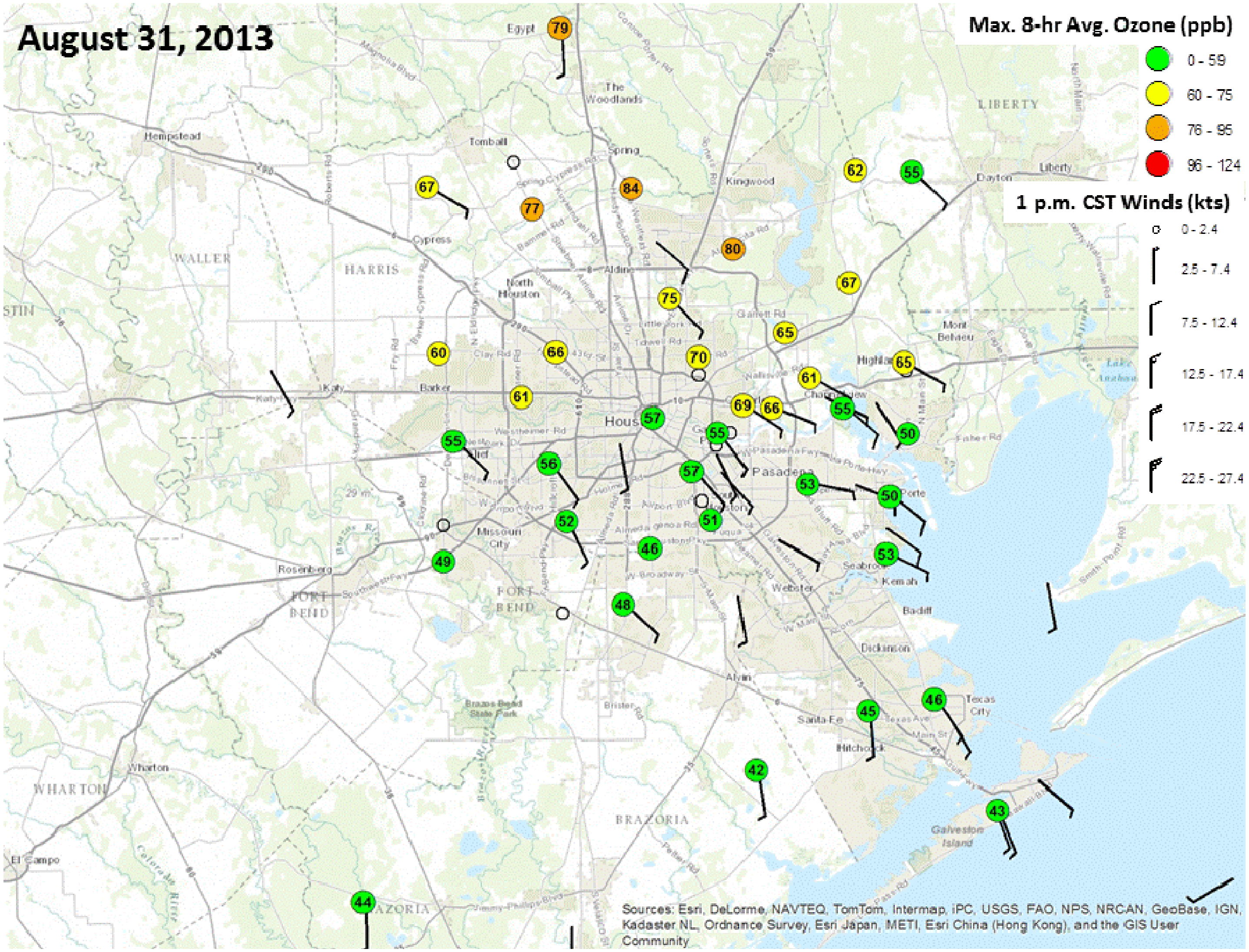


Figure 33. Daily maximum 8-hr average ozone concentrations and surface wind observations from Houston area monitors on August 31, 2013. Light to moderate southeasterly (onshore) winds developed during the afternoon hours. These winds transported pollutants northwestward across the Houston area. As a result, 8-hr ozone concentrations were highest on the north side of Houston.

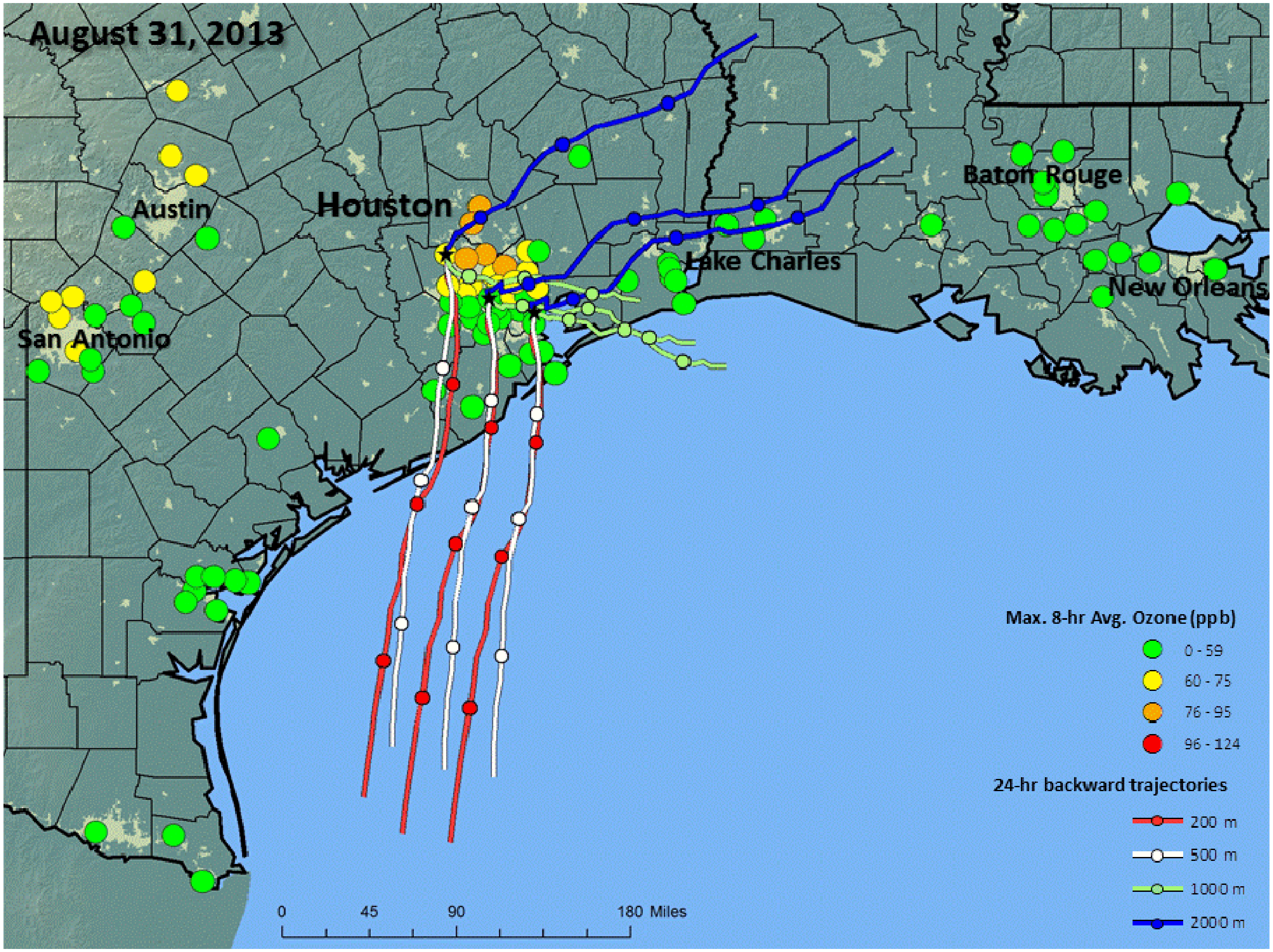


Figure 34. Daily maximum 8-hr average ozone concentrations and 24-hr backward trajectories ending at 6:00 p.m. CST on August 31, 2013. Moderate onshore winds below 1000 m transported pollutants northward, resulting in higher ozone concentrations north of Houston. Dots along the trajectories are at 6-hr intervals.

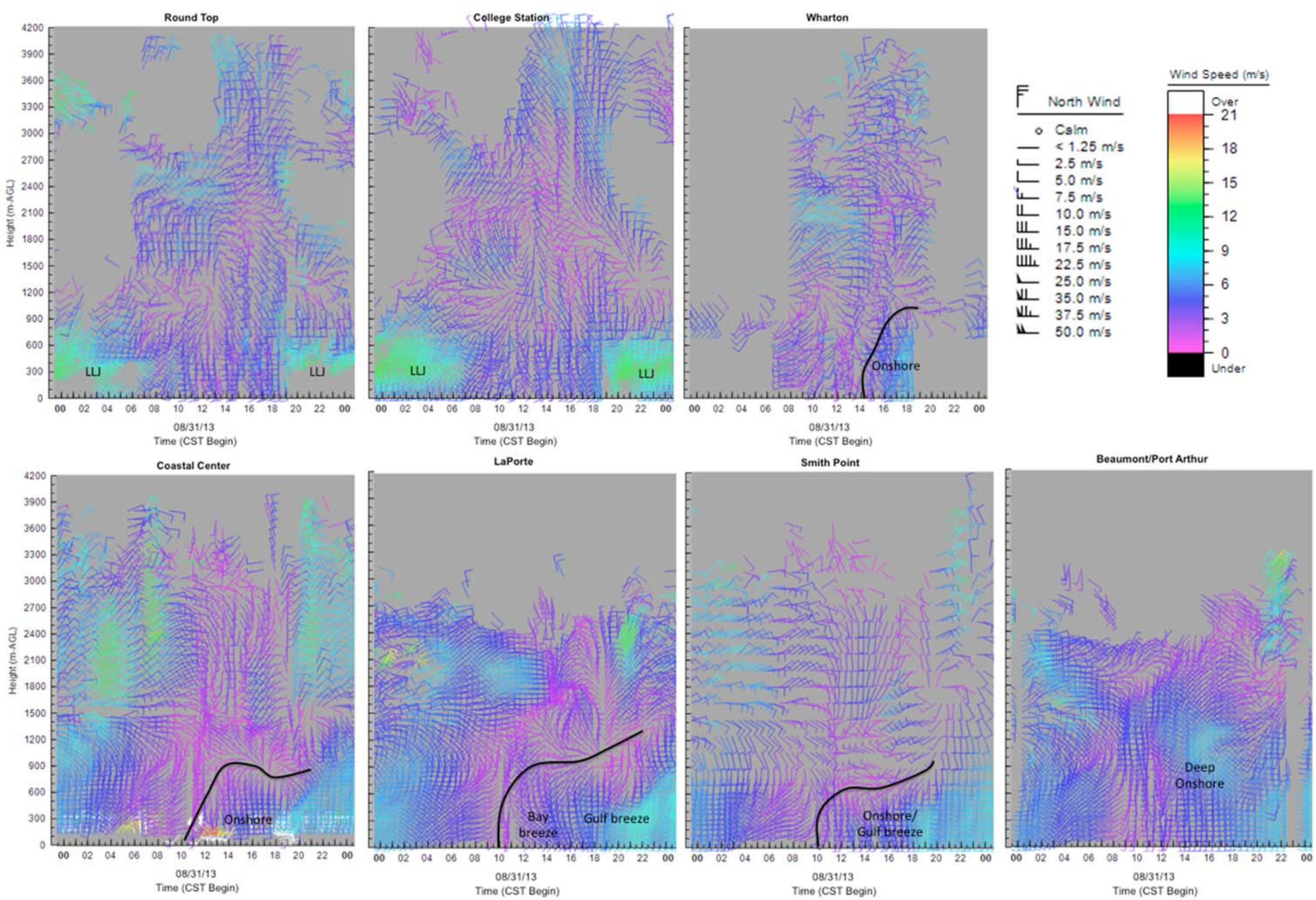


Figure 35. Wind profiler data on August 31, 2013. A weak Bay/Gulf breeze developed during the late-morning hours, aided by a stronger large-scale onshore pressure gradient than in previous days. As a result, higher ozone concentrations were transported to the north side of Houston.

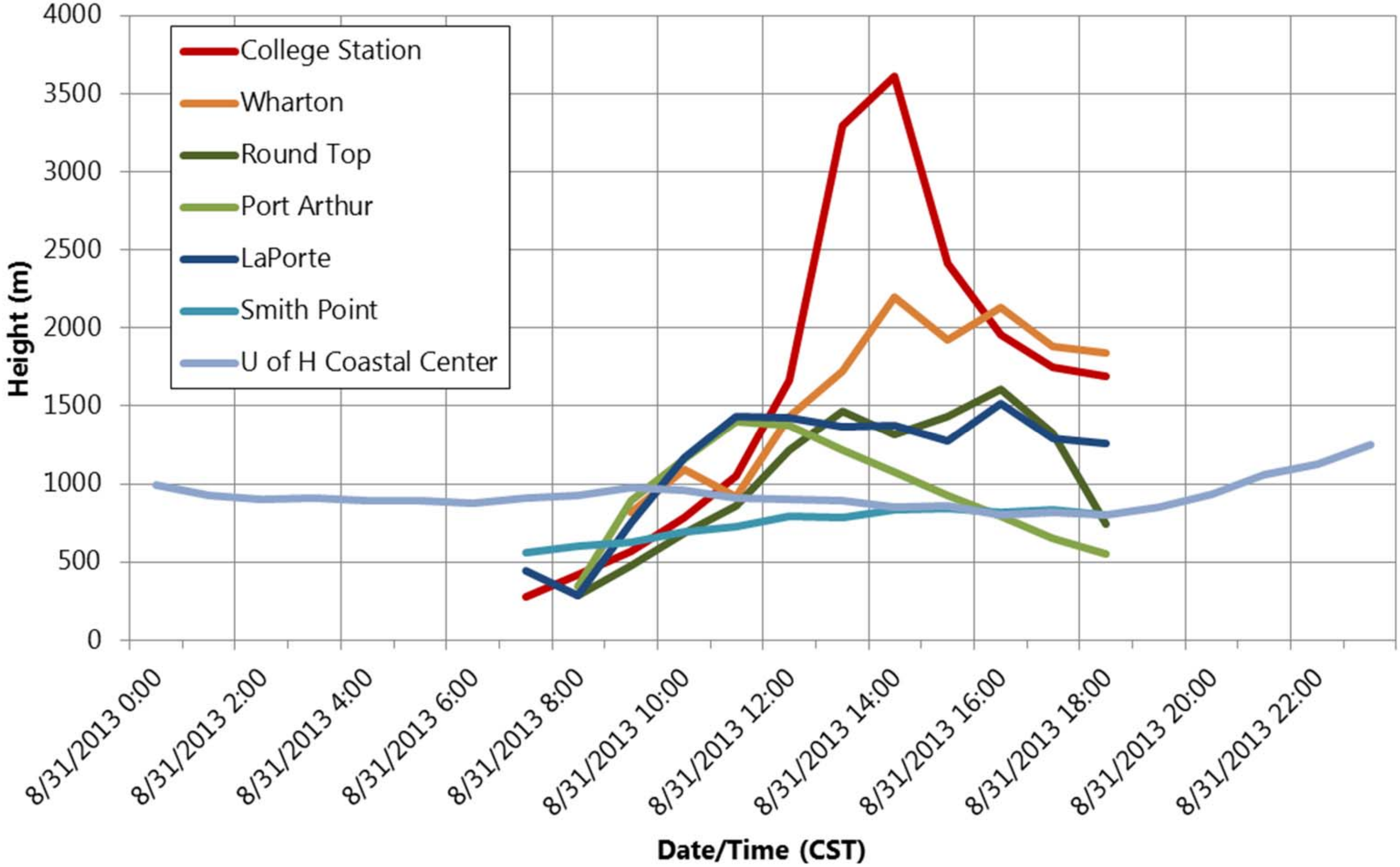


Figure 36. Hourly mixing heights on August 31, 2013.

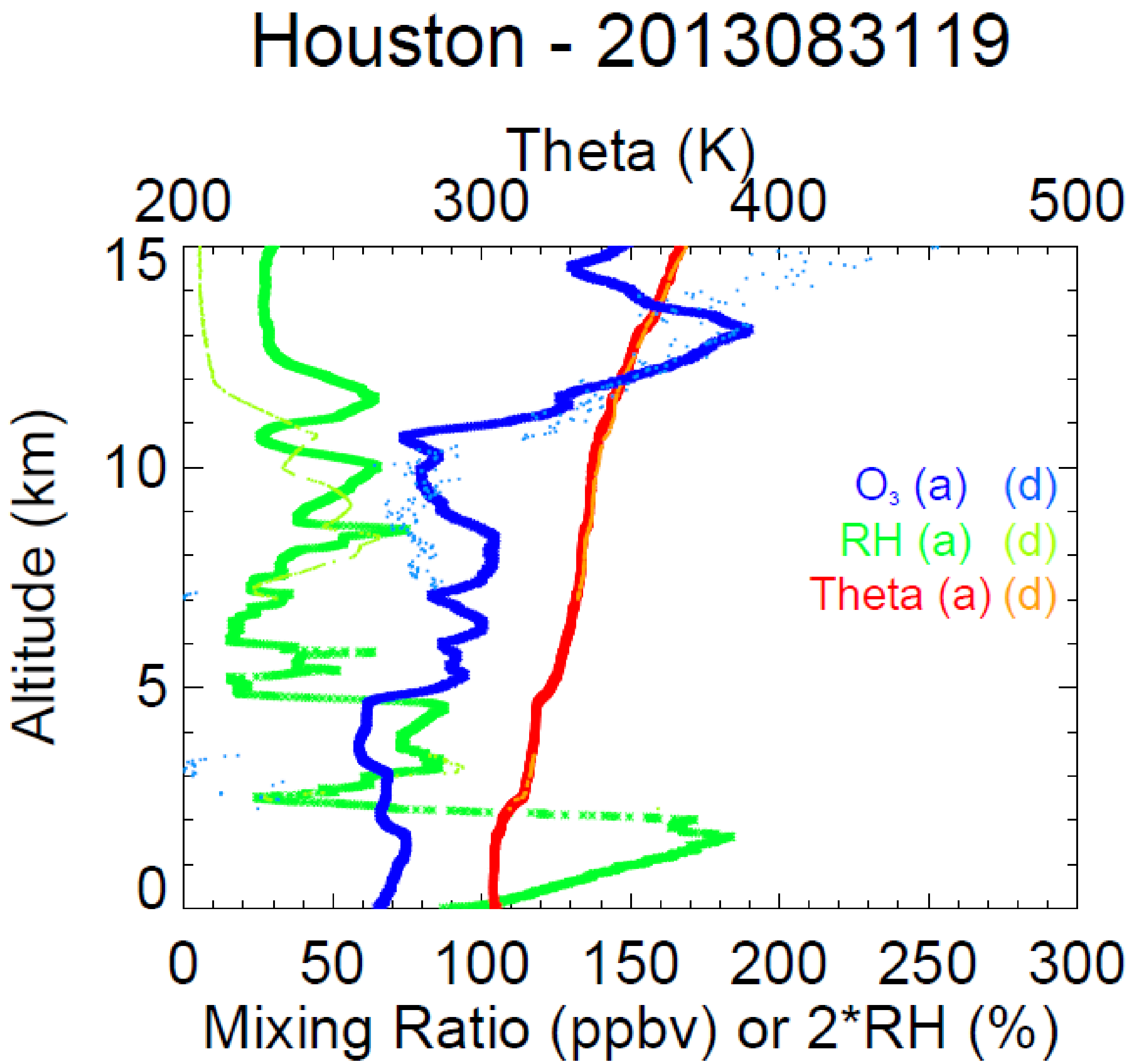


Figure 37. Ozonesonde data on August 31, 2013, launched from the University of Houston at 1:03 p.m. CST.

Figure 38. MODIS-AQUA image from August 31, 2013. Scattered fair weather cumulus clouds developed over inland areas, with less cloud cover at the coast due to passage of the Gulf breeze.

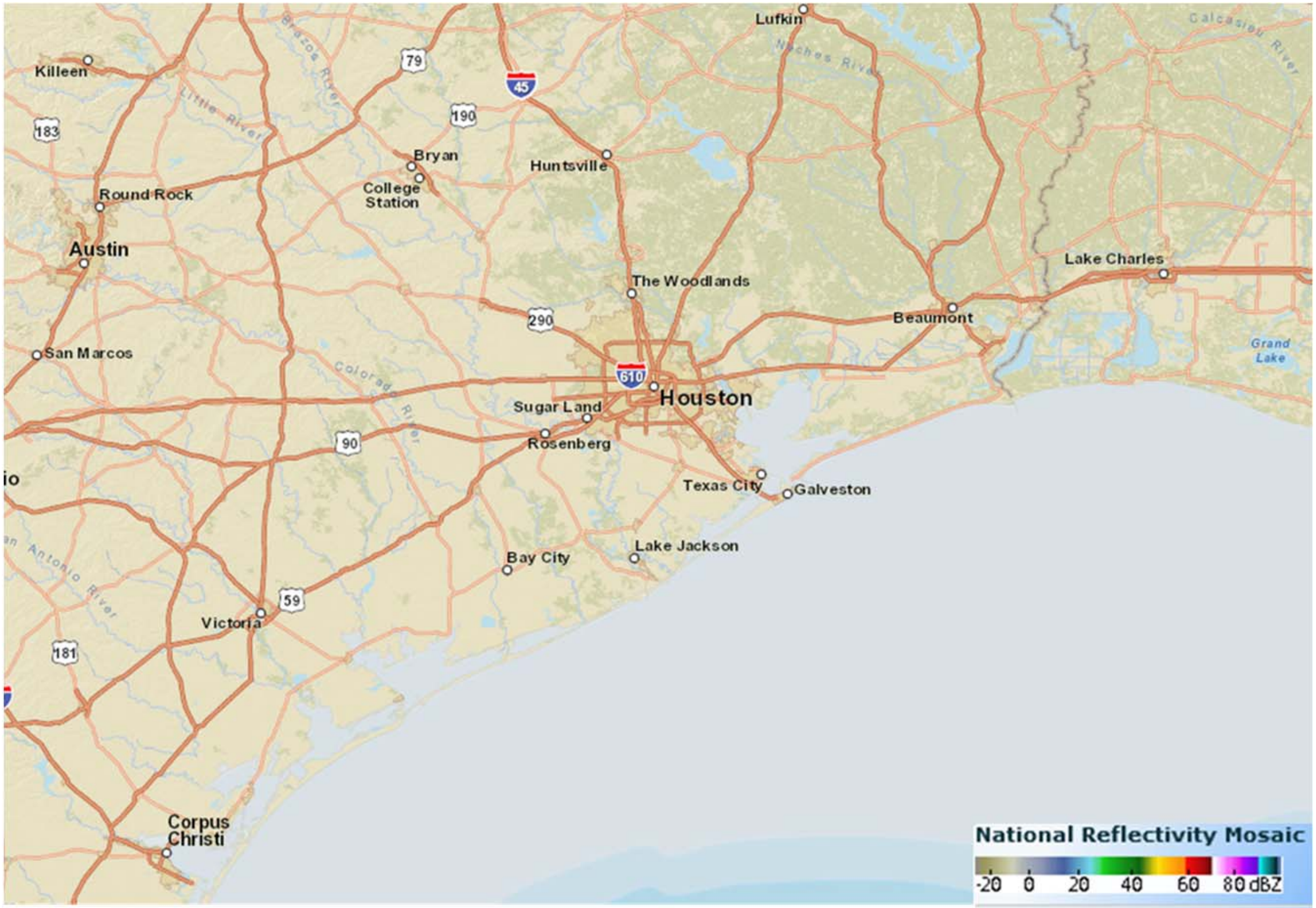


Figure 39. Regional radar image from 2:00 p.m. CST on August 31, 2013. No precipitation was observed in the Houston area.

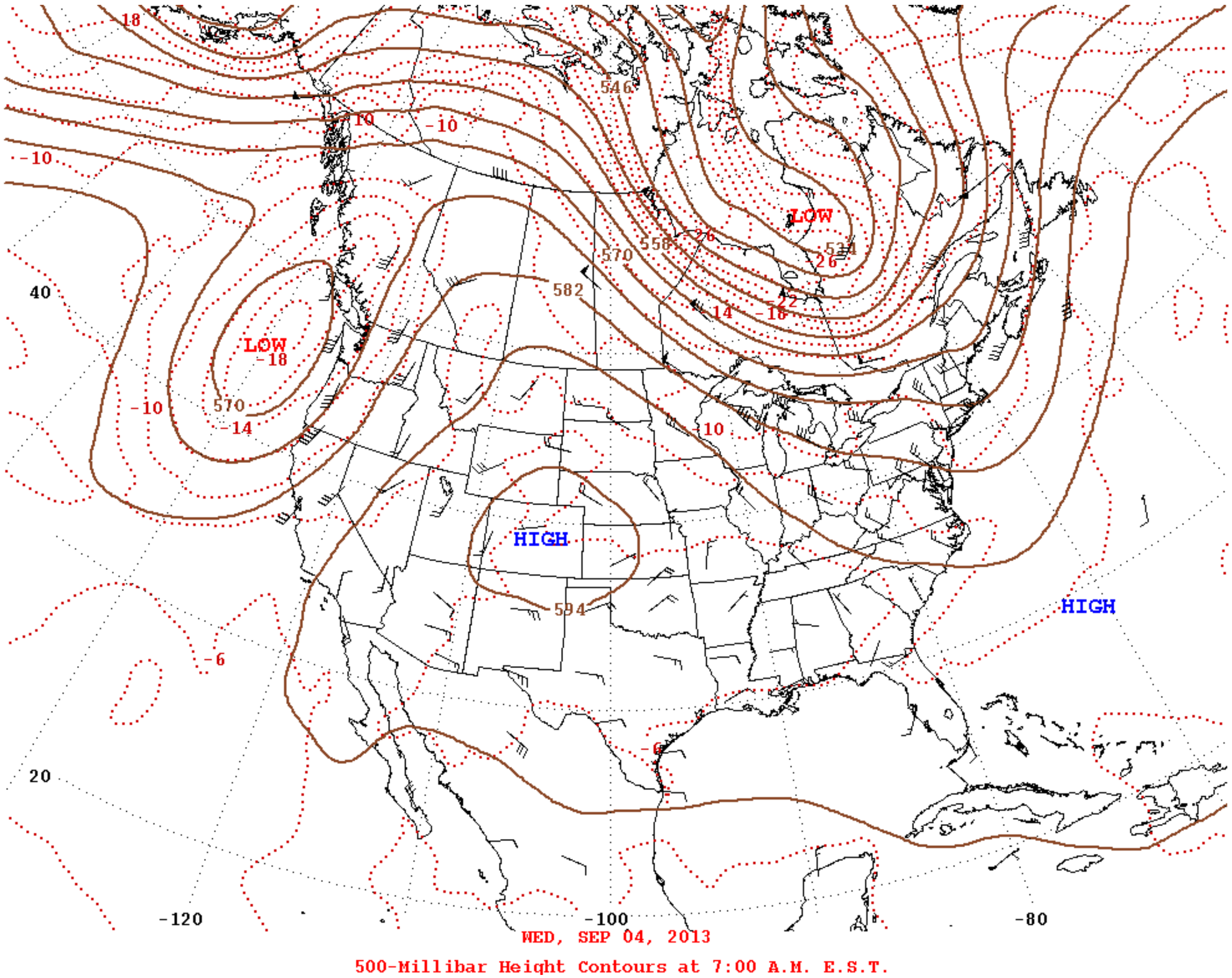


Figure 40. A map showing the height of the 500 mb pressure surface at 6:00 a.m. CST on September 4, 2013. An upper-level high-pressure system was located over the Rocky Mountains and central Plains.

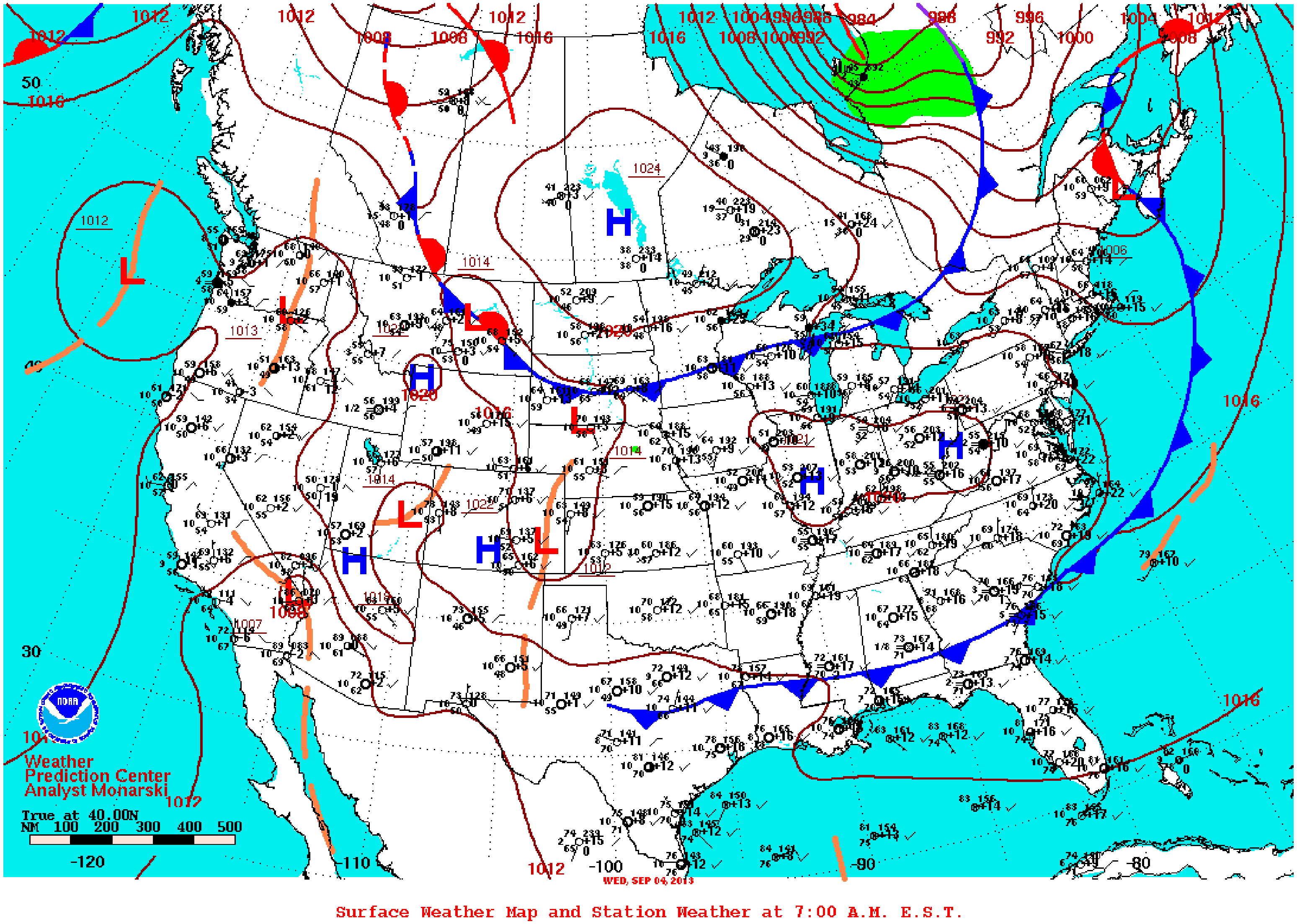


Figure 41. Surface pressure map at 6:00 a.m. CST on September 4, 2013. A cold front was located north of Houston, producing an onshore pressure gradient in the Houston area.

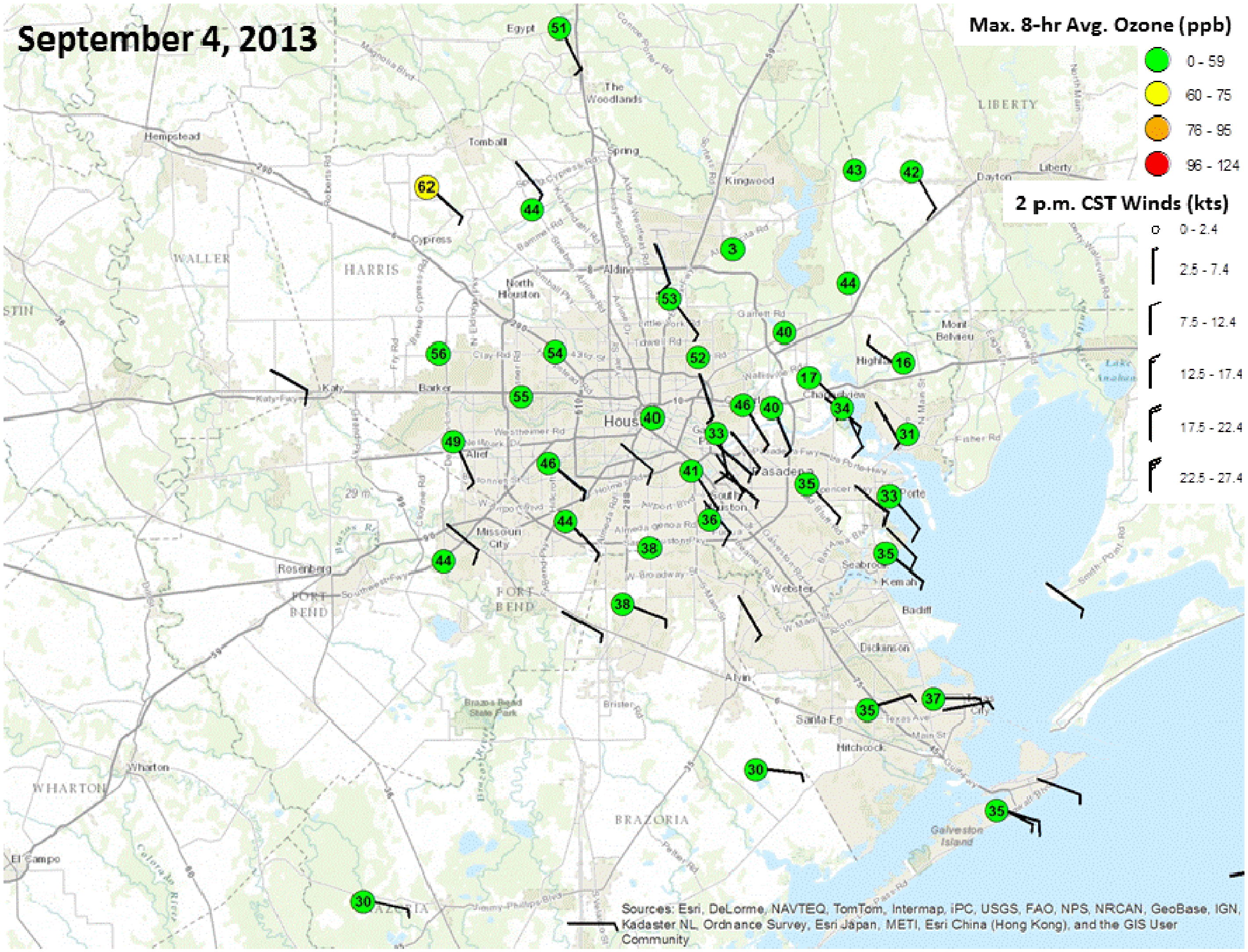


Figure 42. Daily maximum 8-hr average ozone concentrations and surface wind observations from Houston-area monitors on September 4, 2013. Moderate southeasterly (onshore) winds transported pollutants northwestward across the Houston area. As a result, 8-hr ozone concentrations were highest on the northwest side of Houston. These winds also transported cleaner, maritime air into the Houston area.

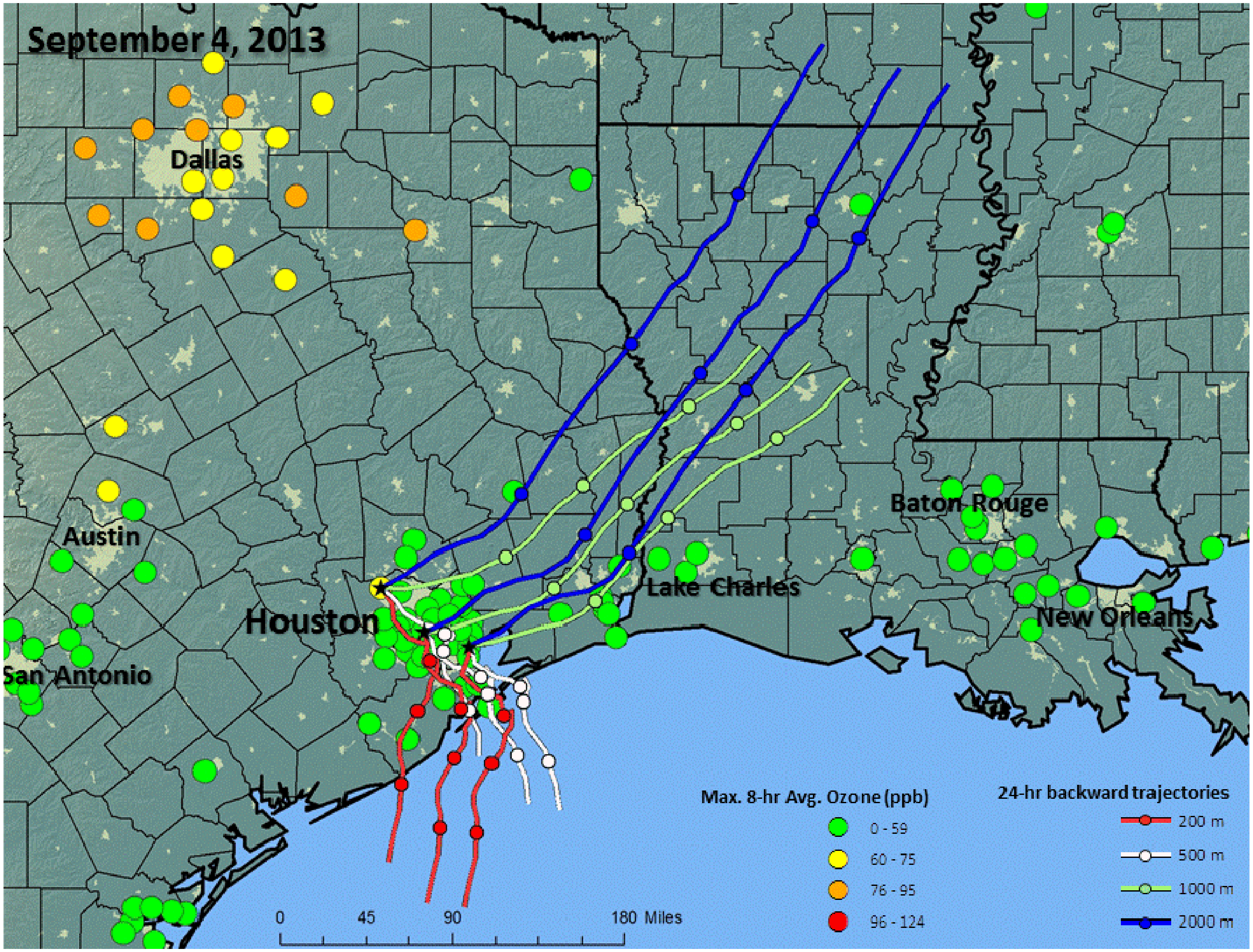


Figure 43. Daily maximum 8-hr average ozone concentrations and 24-hr backward trajectories ending at 6:00 p.m. CST on September 4, 2013. Light to moderate onshore winds transported cleaner maritime air into the Houston area. Extensive cloud cover on this day limited ozone formation in the Houston area. Dots along the trajectories are at 6-hr intervals.

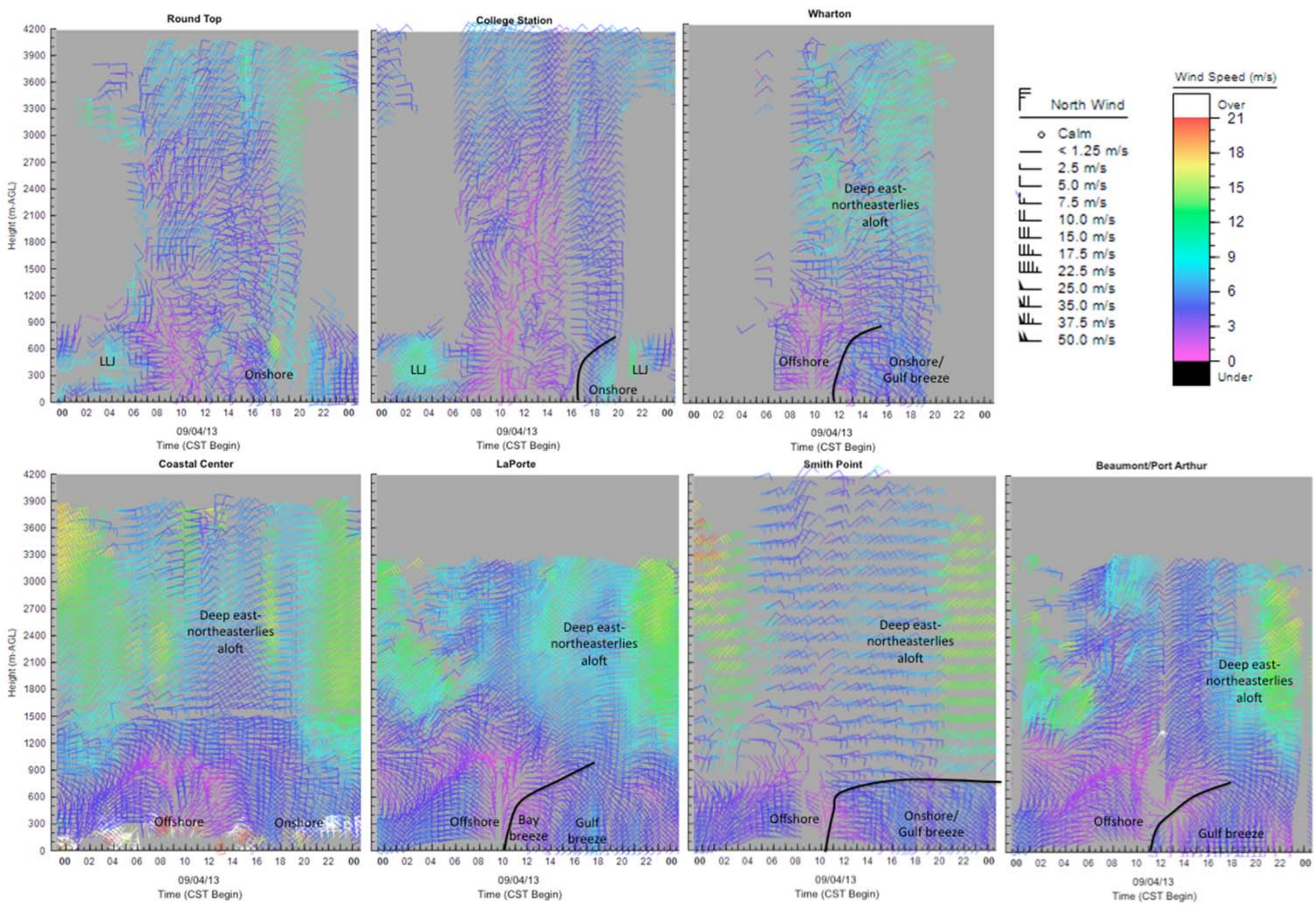


Figure 44. Wind profiler data on September 4, 2013. Weak offshore flow transitioned to onshore flow during the late-morning hours as a Bay/Gulf breeze developed, aided by a strengthening large-scale onshore pressure gradient.

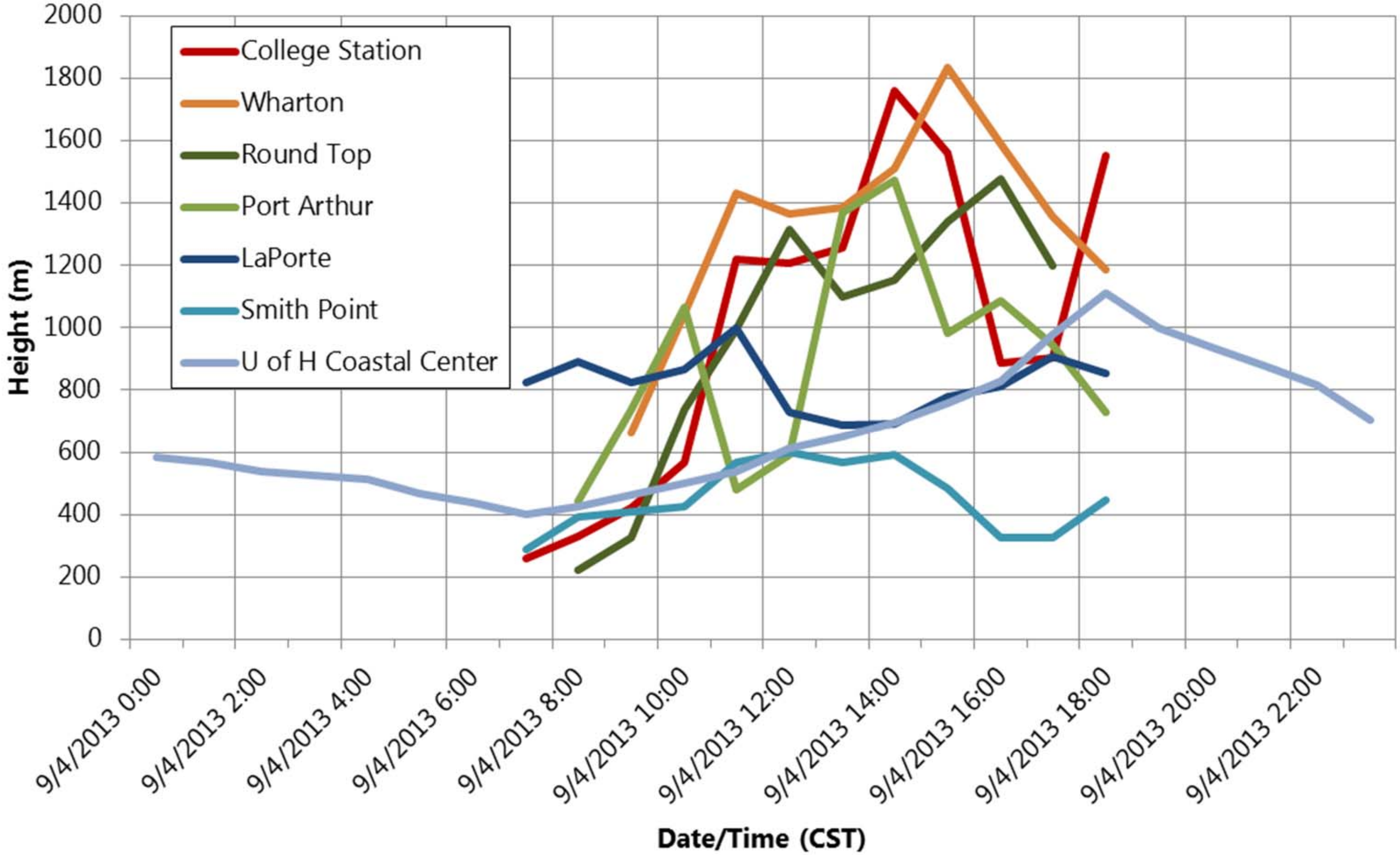


Figure 45. Hourly mixing heights on September 4, 2013.

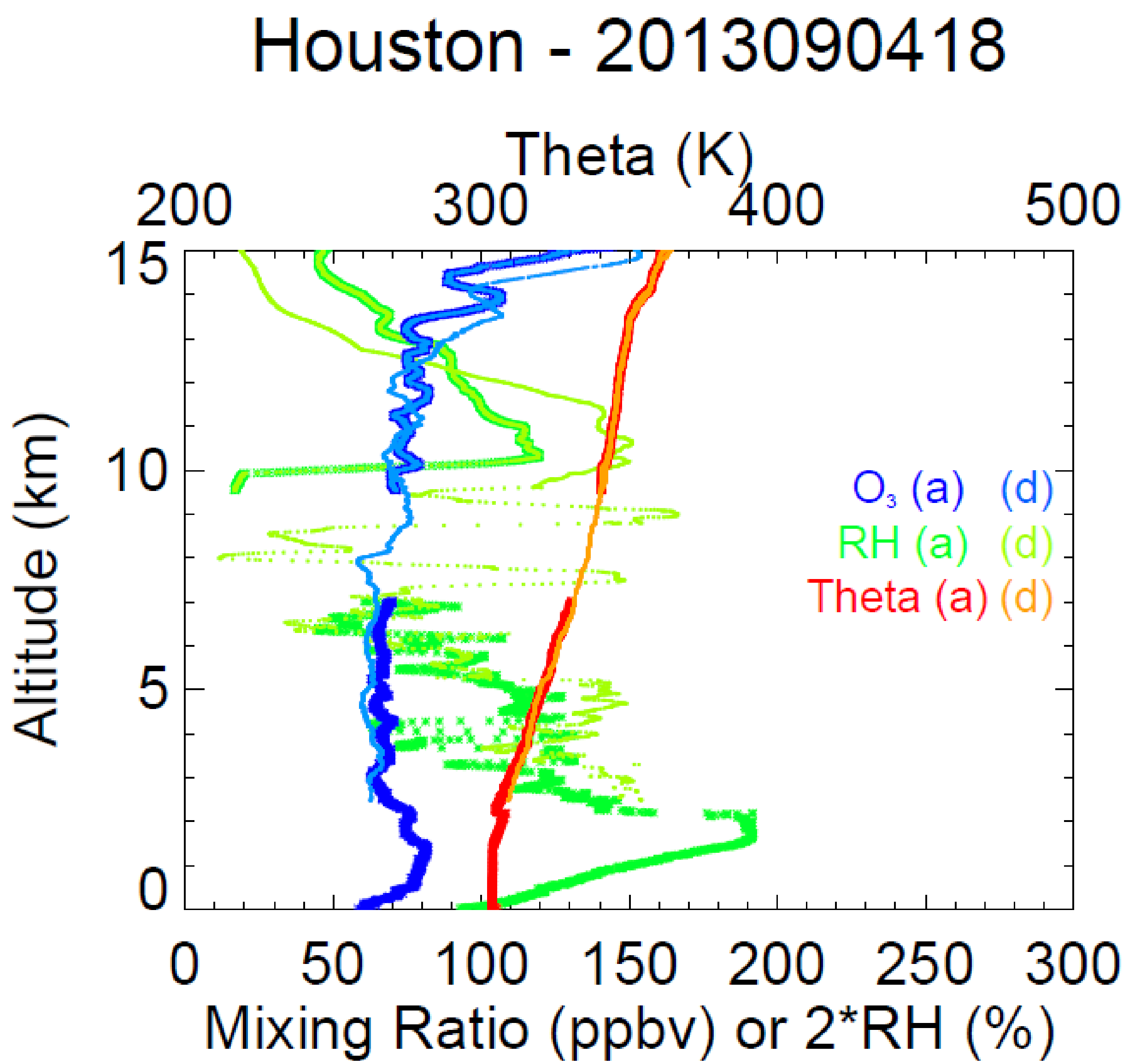


Figure 46. Ozonesonde data on September 4, 2013, launched from the University of Houston at 12:00 p.m. CST.

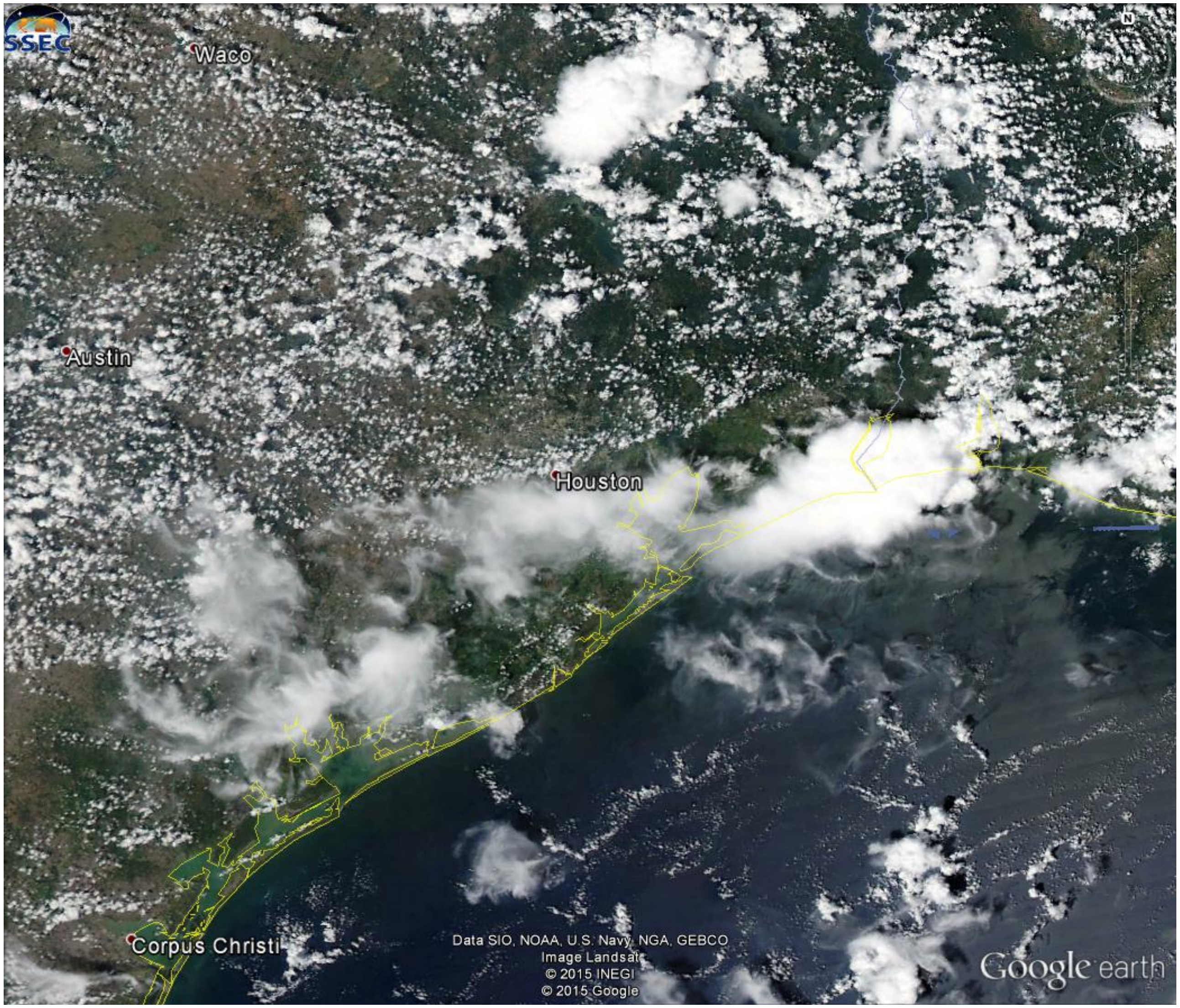


Figure 47. MODIS-AQUA image from September 4, 2013. Scattered convective clouds developed along the Texas coastline and inland, resulting in partly to mostly cloudy skies in the Houston area.

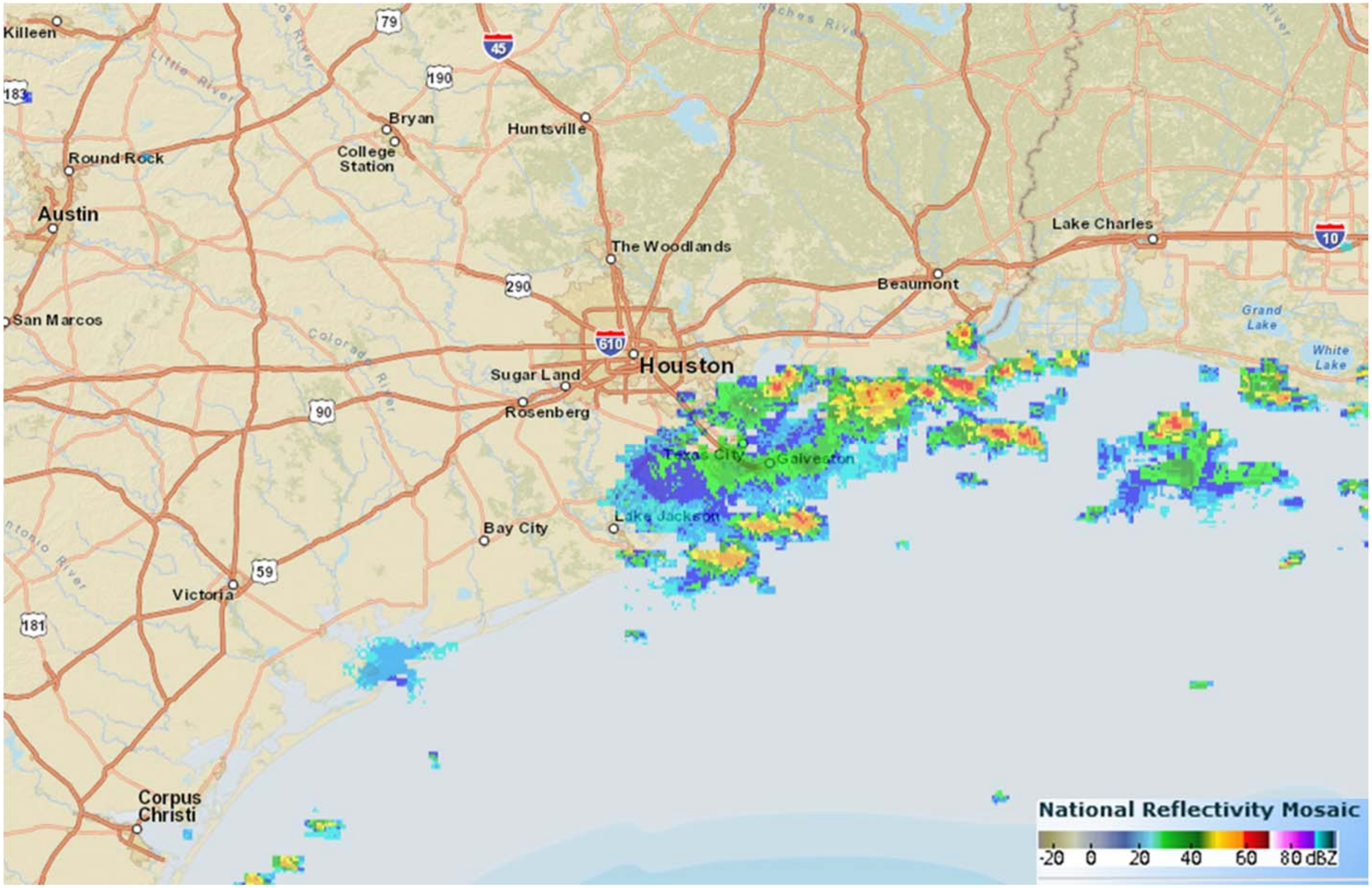


Figure 48. Regional radar image from 10:00 a.m. CST on September 4, 2013. Showers and thunderstorms were detected south and east of Houston. These showers weakened during the afternoon before redeveloping north of Houston.

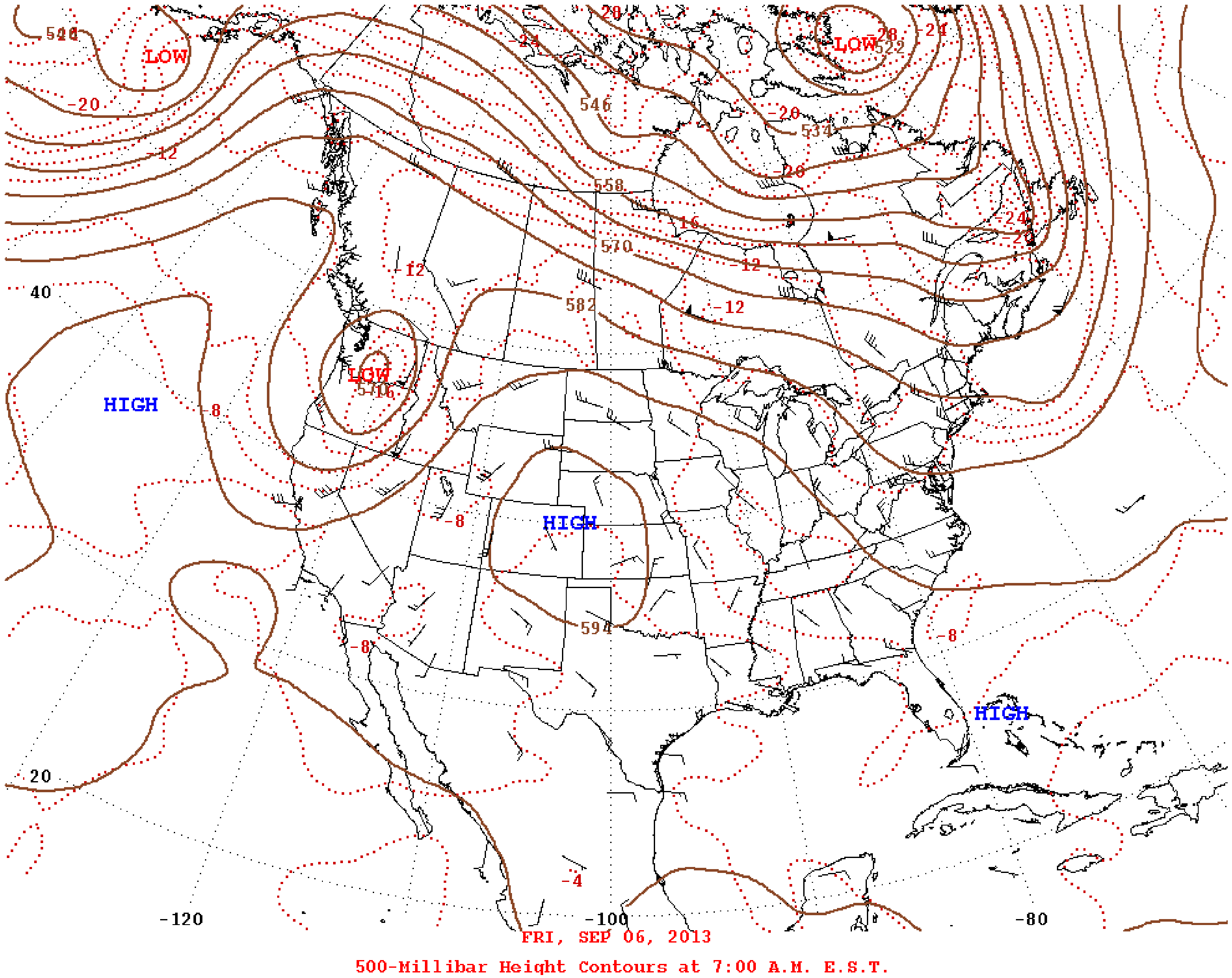
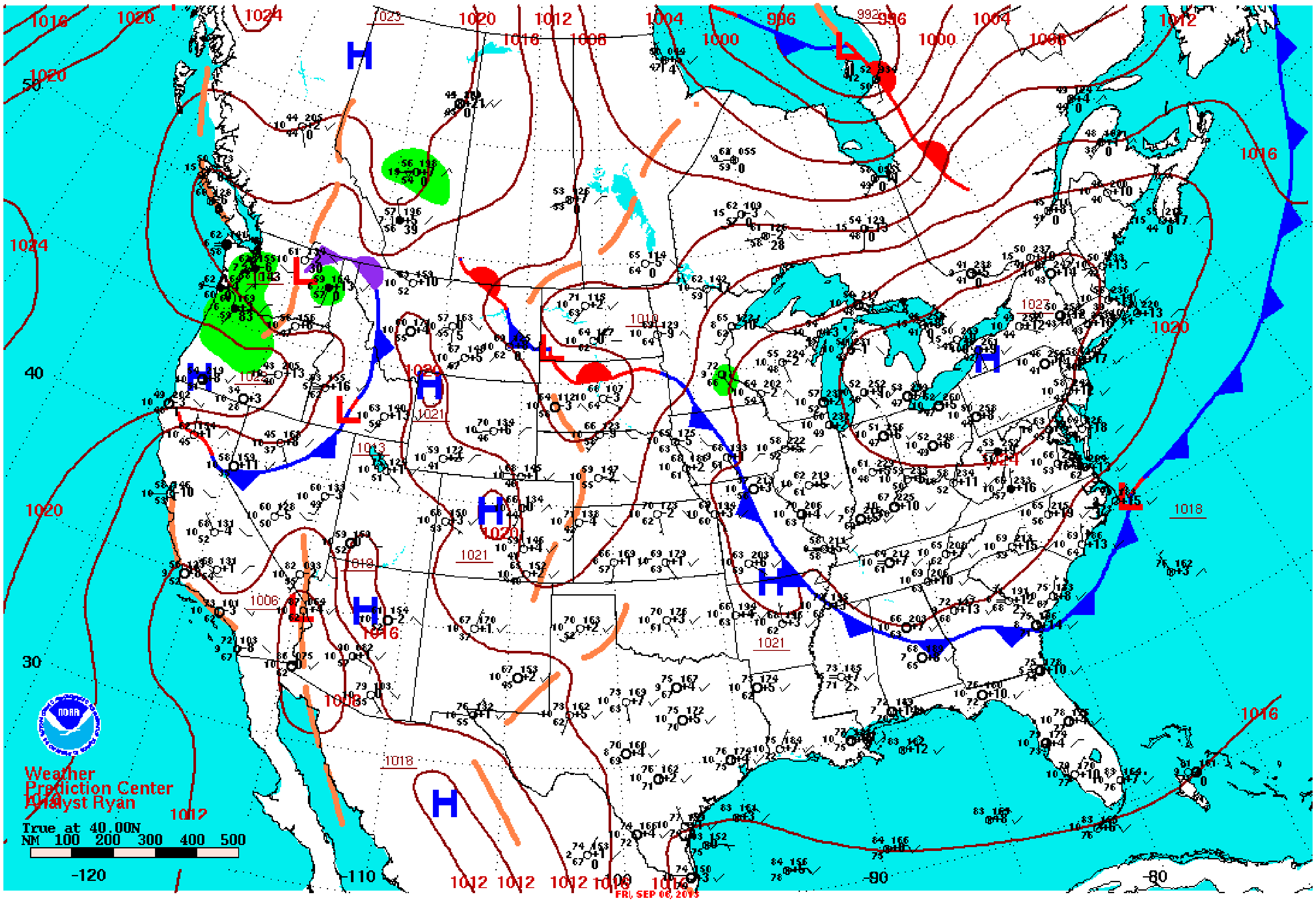


Figure 49. A map showing the height of the 500 mb pressure surface at 6:00 a.m. CST on September 6, 2013. An upper-level high-pressure system was located over the Rocky Mountains and central Plains.



Surface Weather Map and Station Weather at 7:00 A.M. E.S.T.

Figure 50. Surface pressure map at 6:00 a.m. CST on September 6, 2013. A broad surface high-pressure system over the southern Plains resulted in a weak large-scale pressure gradient in the Houston area.

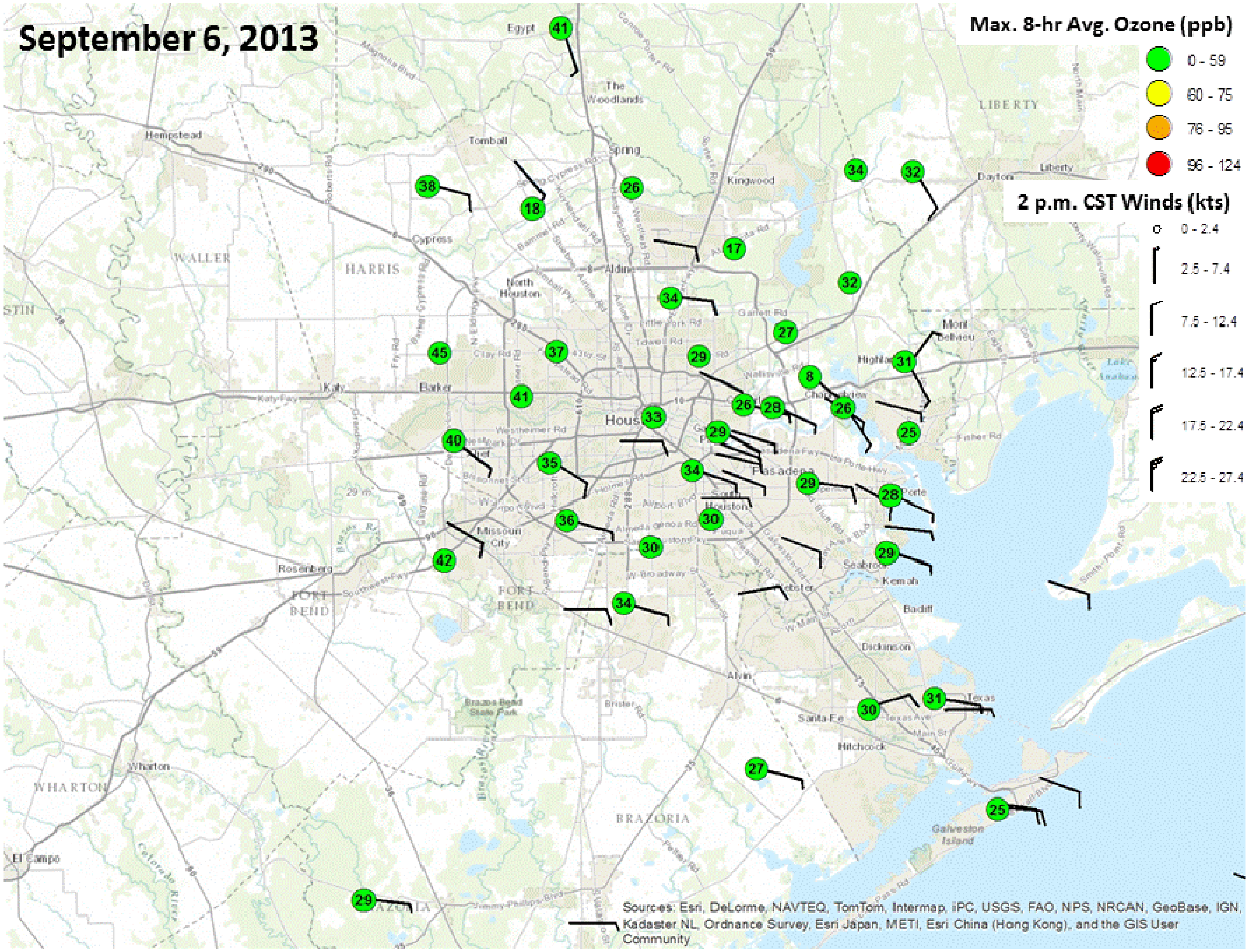


Figure 51. Daily maximum 8-hr average ozone concentrations and surface wind observations from Houston-area monitors on September 6, 2013. Moderate east-southeasterly winds transported pollutants west-northwestward across the Houston area. As a result, 8-hr ozone concentrations were highest on the west side of Houston. Cloud cover kept ozone levels low regionwide, however.

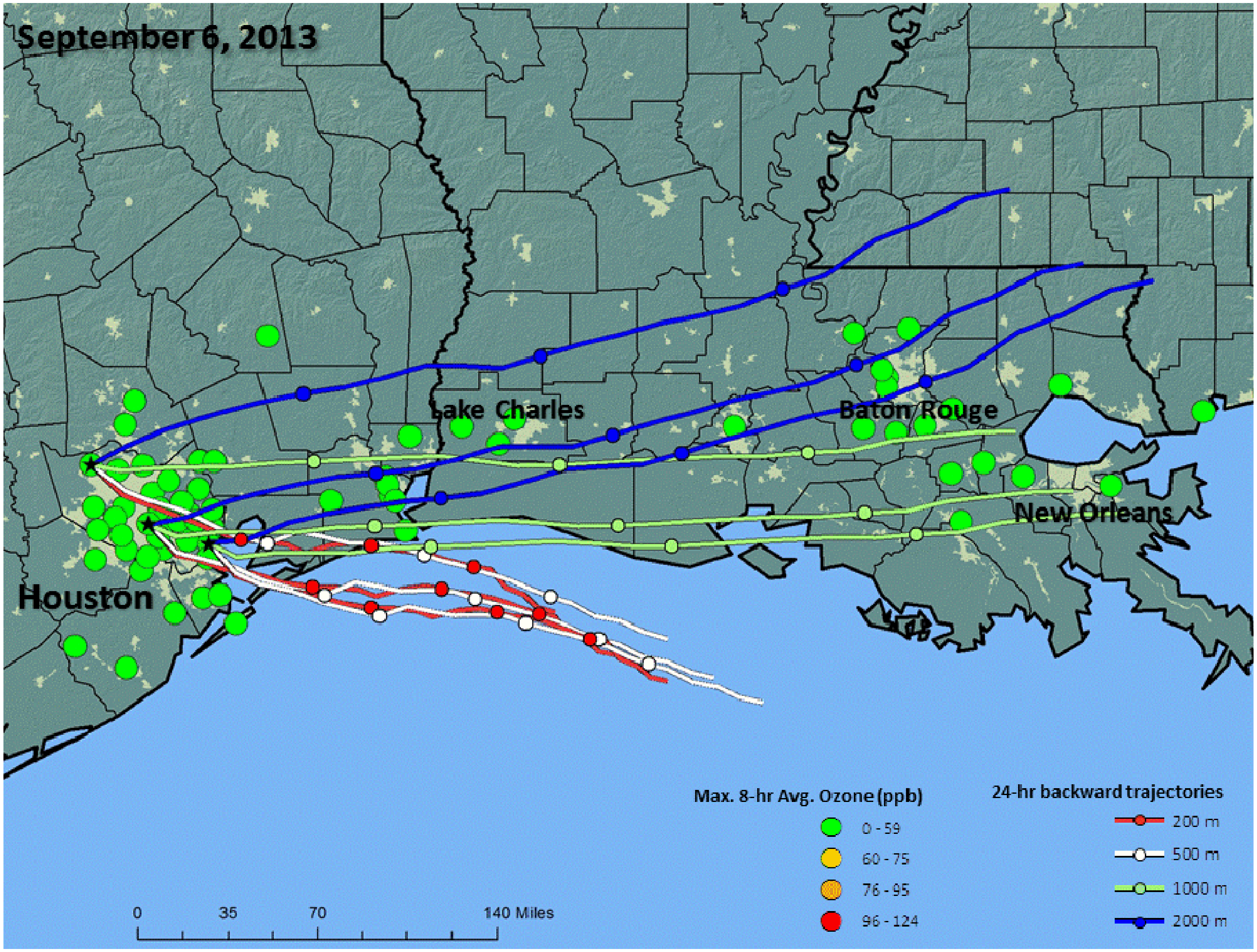


Figure 52. Daily maximum 8-hr average ozone concentrations and 24-hr backward trajectories ending at 6:00 p.m. CST on September 6, 2013. Deep easterly winds transported relatively cleaner air into the Houston area, and cloud cover limited ozone formation. Dots along the trajectories are at 6-hr intervals.

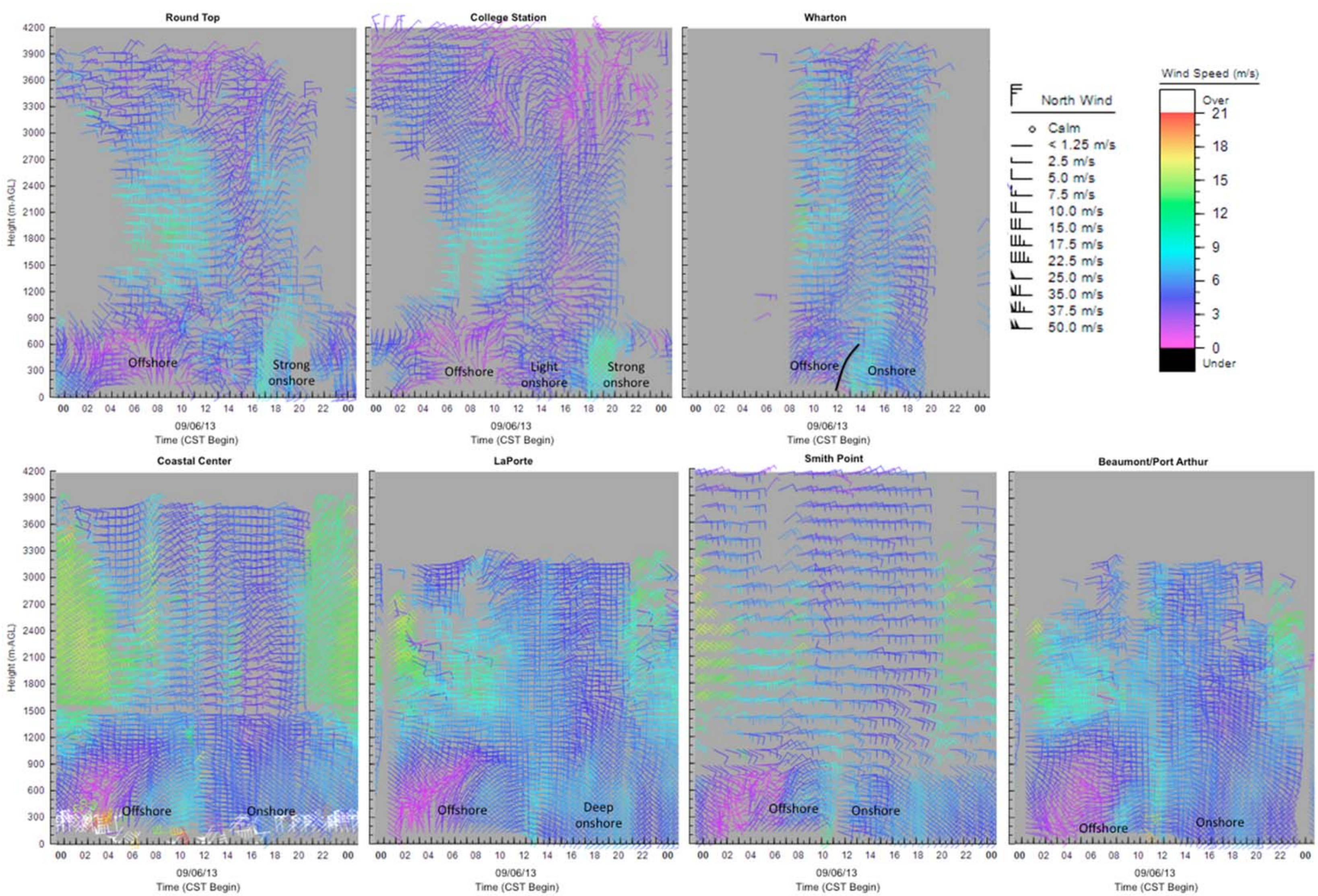


Figure 53. Wind profiler data on September 6, 2013. Weak low-level offshore flow associated with an overnight land breeze transitioned to easterly and southeasterly flow during the afternoon hours as onshore pressure gradients increased and easterly momentum aloft mixed downward.

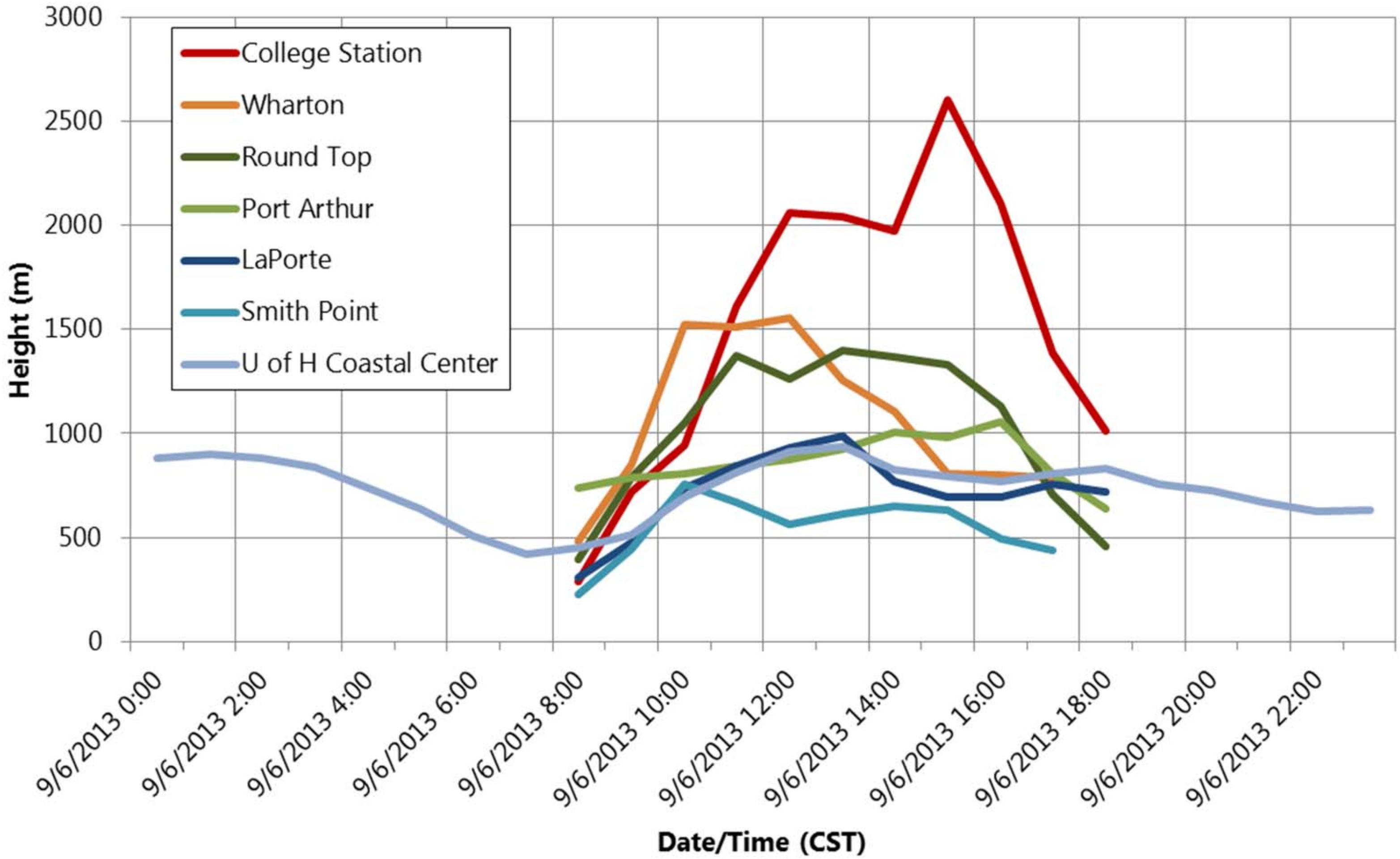


Figure 54. Hourly mixing heights on September 6, 2013.

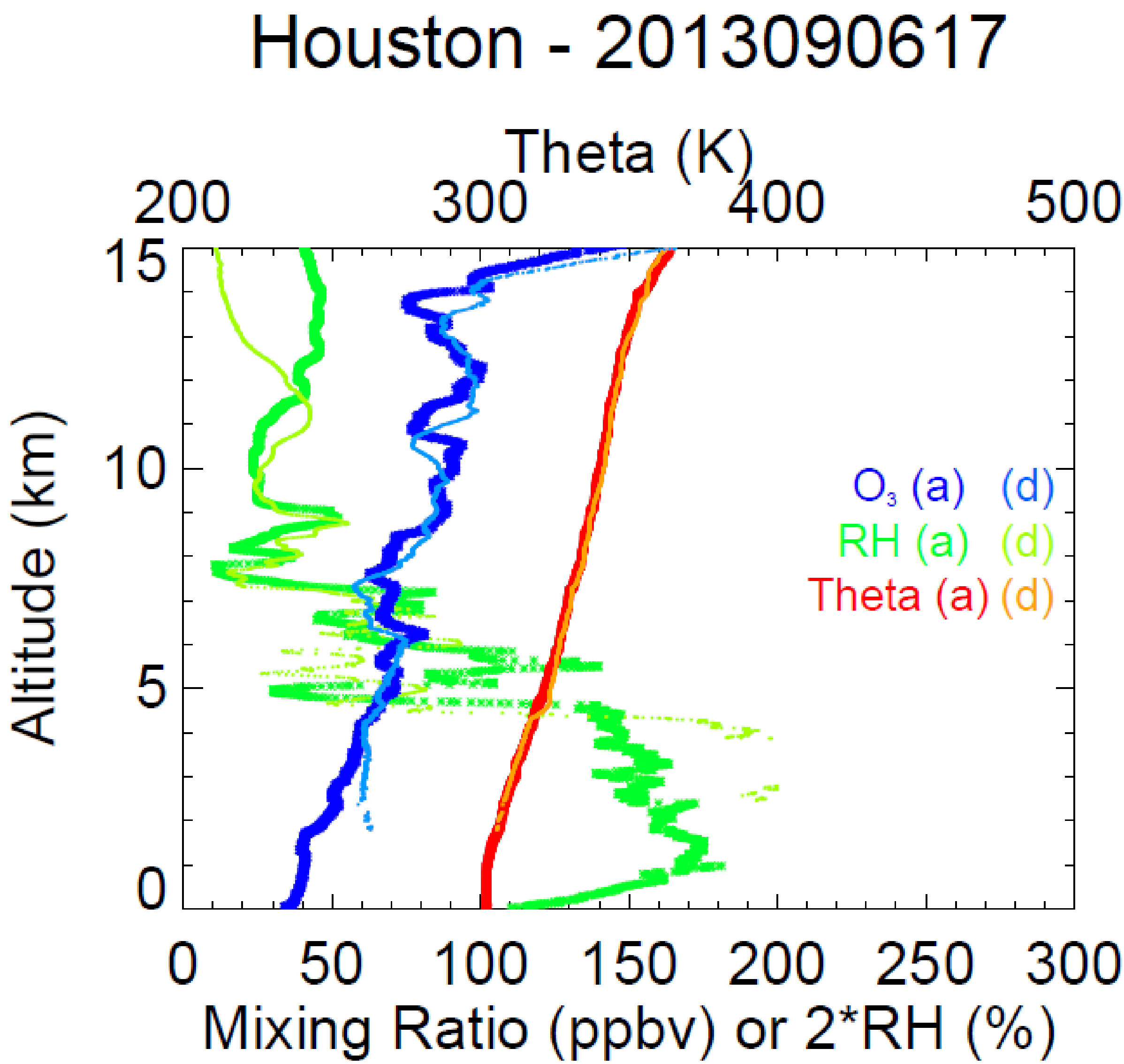


Figure 55. Ozonesonde data on September 6, 2013, launched from the University of Houston at 11:18 a.m. CST.

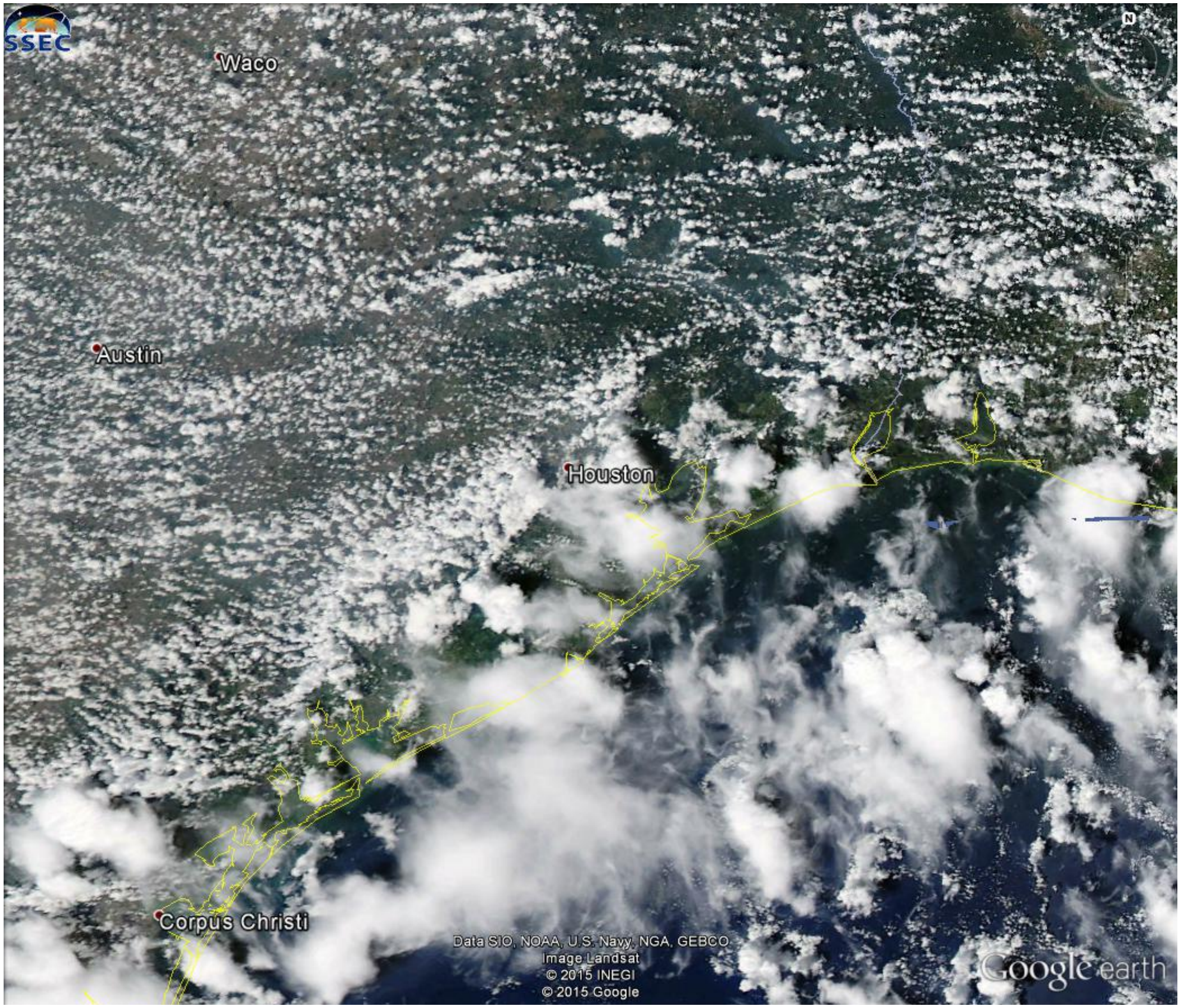


Figure 56. MODIS-AQUA image from September 6, 2013. Widespread convective clouds developed along the Texas coastline, resulting in mostly cloudy skies in the Houston area.

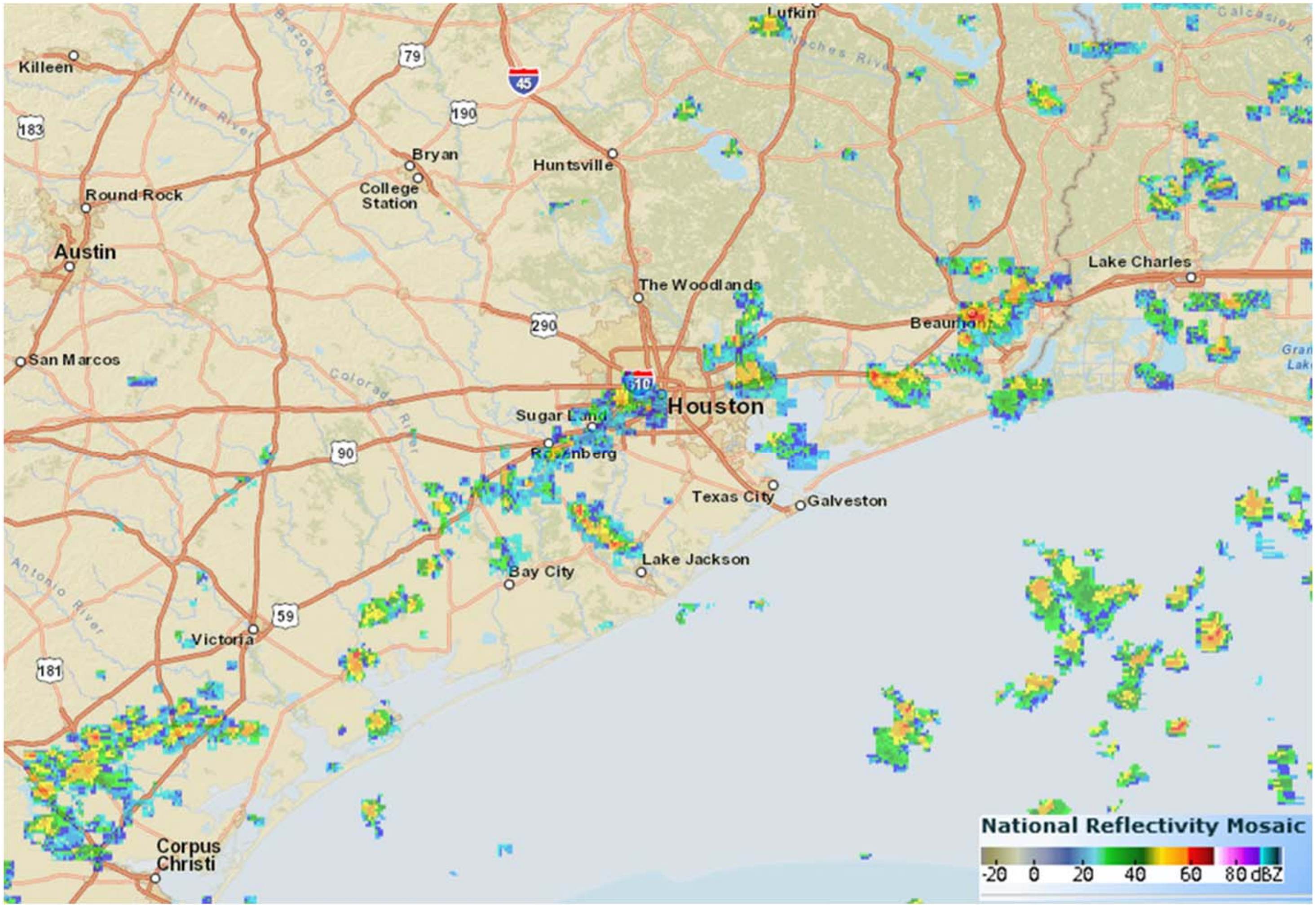


Figure 57. Regional radar image from 1:00 p.m. CST on September 6, 2013. Scattered showers and thunderstorms were detected throughout the Houston area.

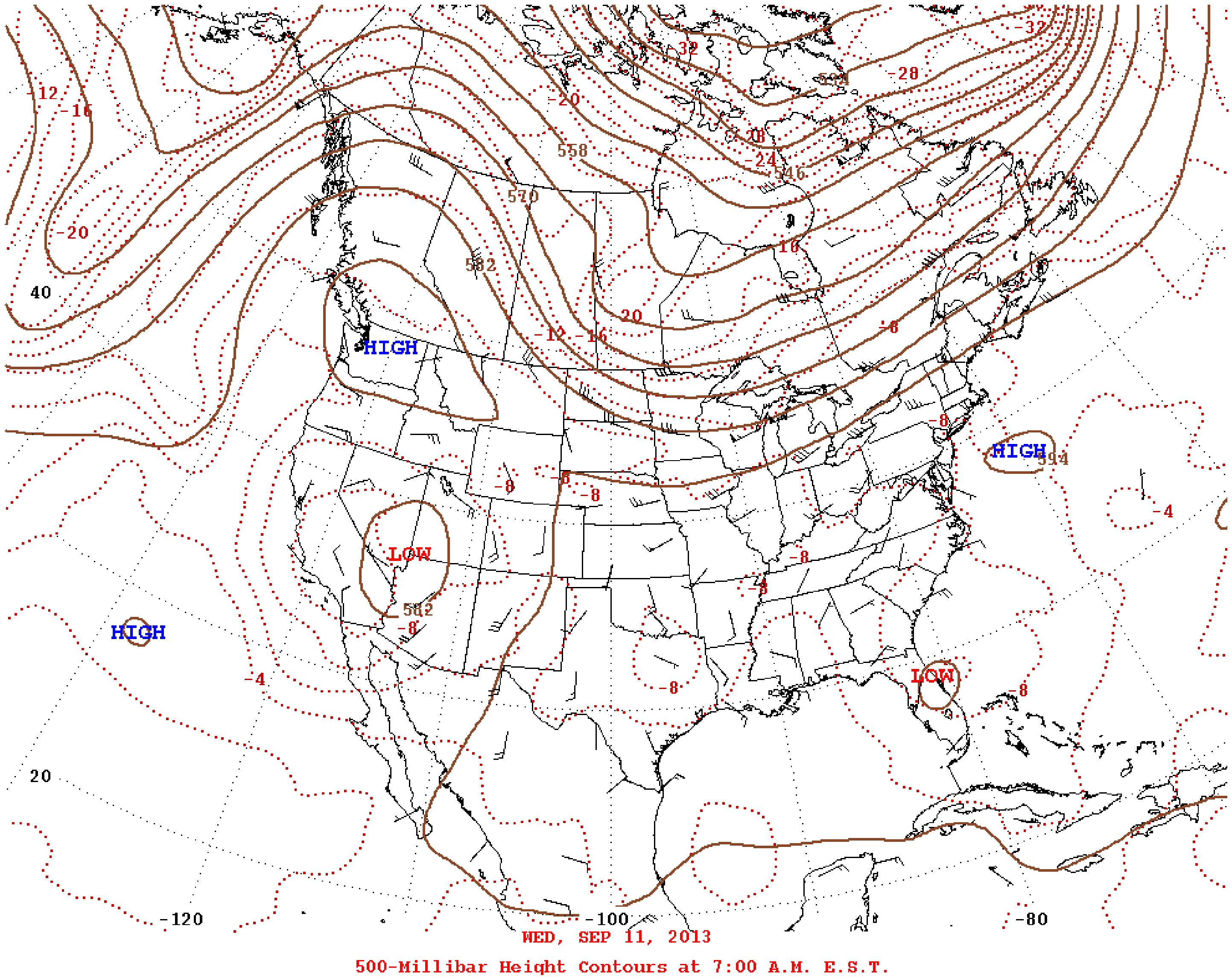


Figure 58. A map showing the height of the 500 mb pressure surface at 6:00 a.m. CST on September 11, 2013. A broad upper-level high-pressure system was located over the southeastern United States.

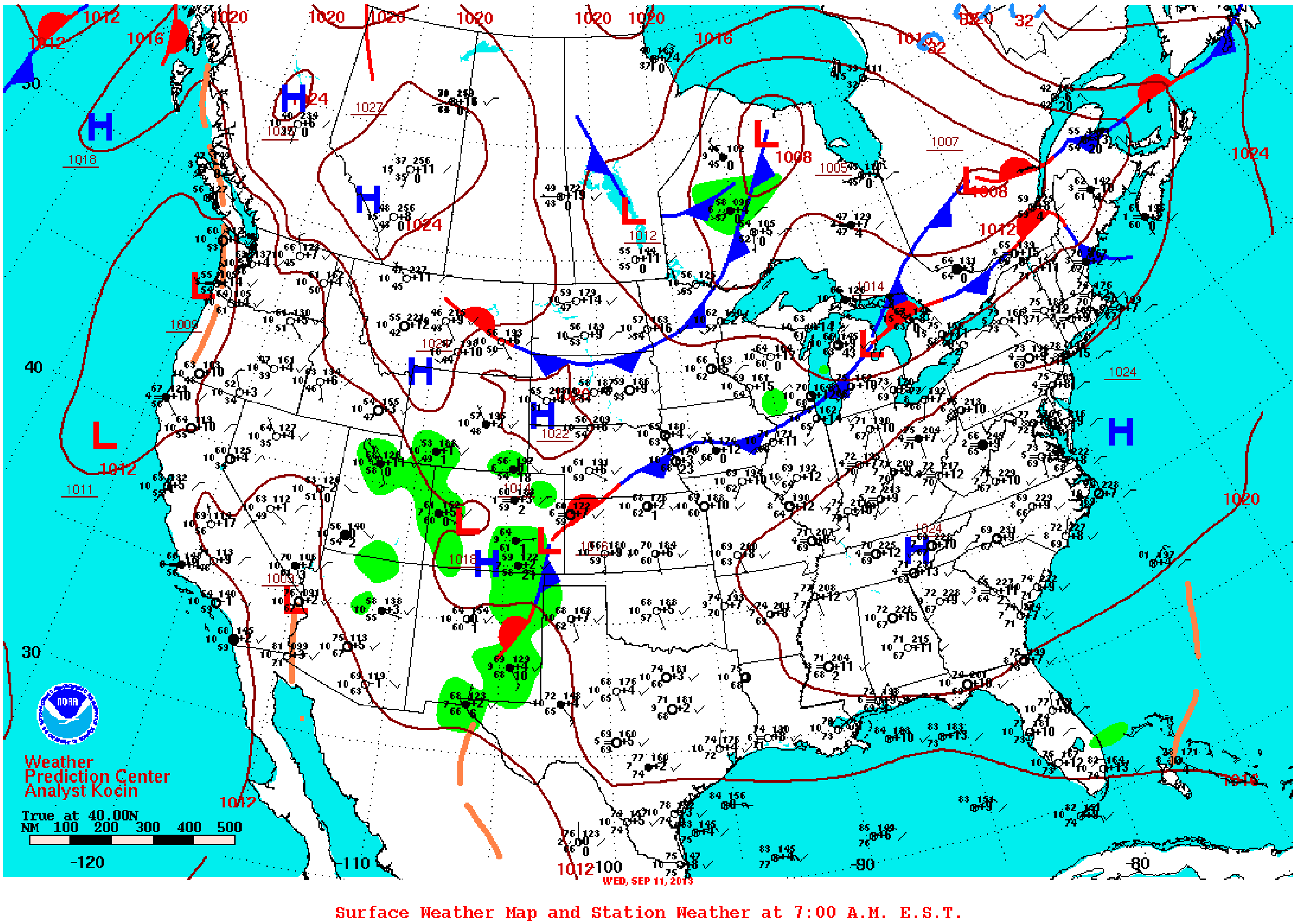


Figure 59. Surface pressure map at 6:00 a.m. CST on September 11, 2013. A surface high-pressure system was located over the southeastern United States, resulting in a moderate easterly large-scale pressure gradient in the Houston area.

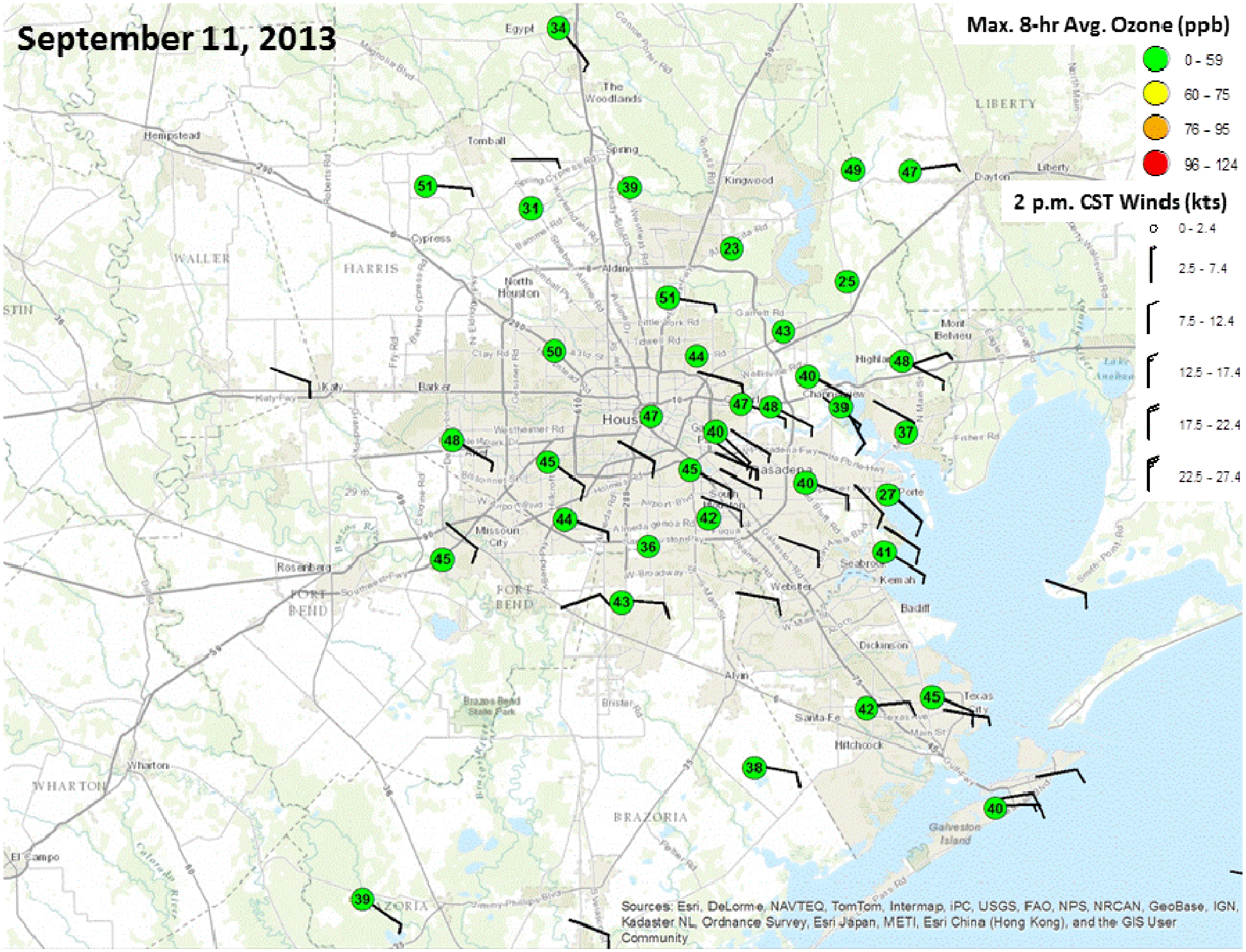


Figure 60. Daily maximum 8-hr average ozone concentrations and surface wind observations from Houston-area monitors on September 11, 2013. Moderate east-southeasterly winds transported pollutants west-northwestward across the Houston area. As a result, 8-hr ozone concentrations were highest on the west side of Houston. Cloud cover kept ozone levels low regionwide, however.

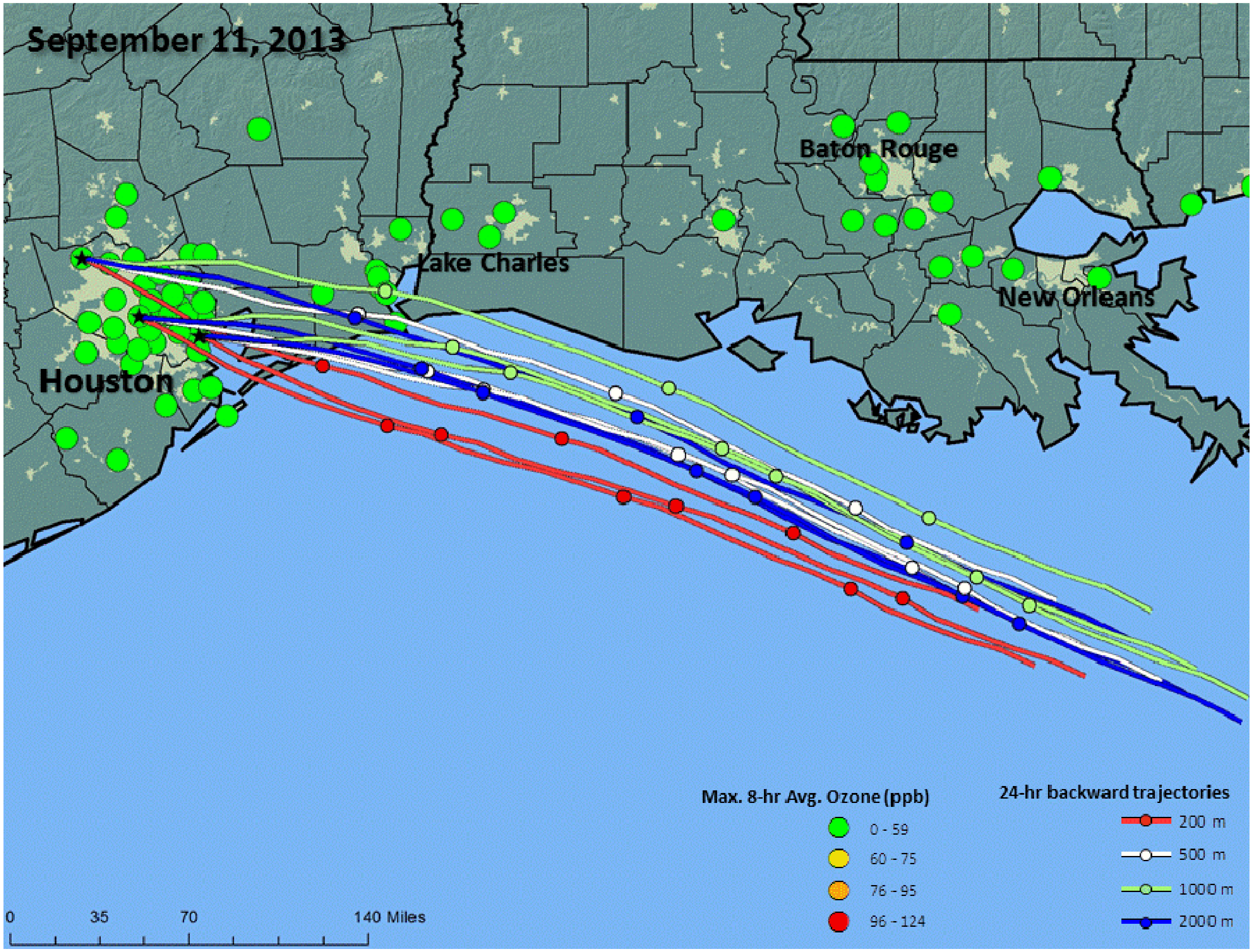


Figure 61. Daily maximum 8-hr average ozone concentrations and 24-hr backward trajectories ending at 6:00 p.m. CST on September 11, 2013. Deep east-southeasterly winds dispersed pollutants and transported relatively cleaner maritime air into the Houston area. Dots along the trajectories are at 6-hr intervals.

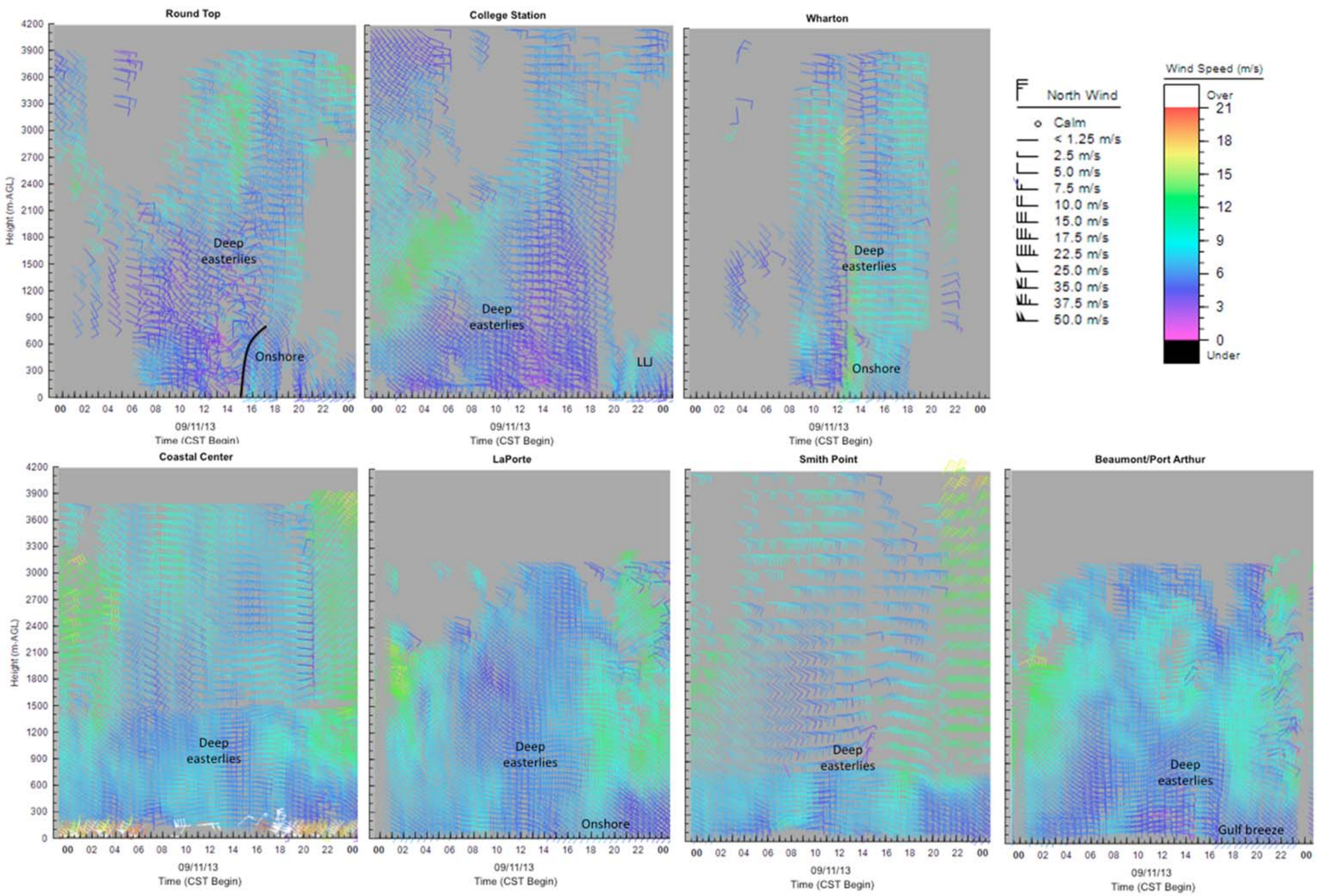


Figure 62. Wind profiler data on September 11, 2013. Deep easterly to southeasterly flow was present throughout southeast Texas on September 11.

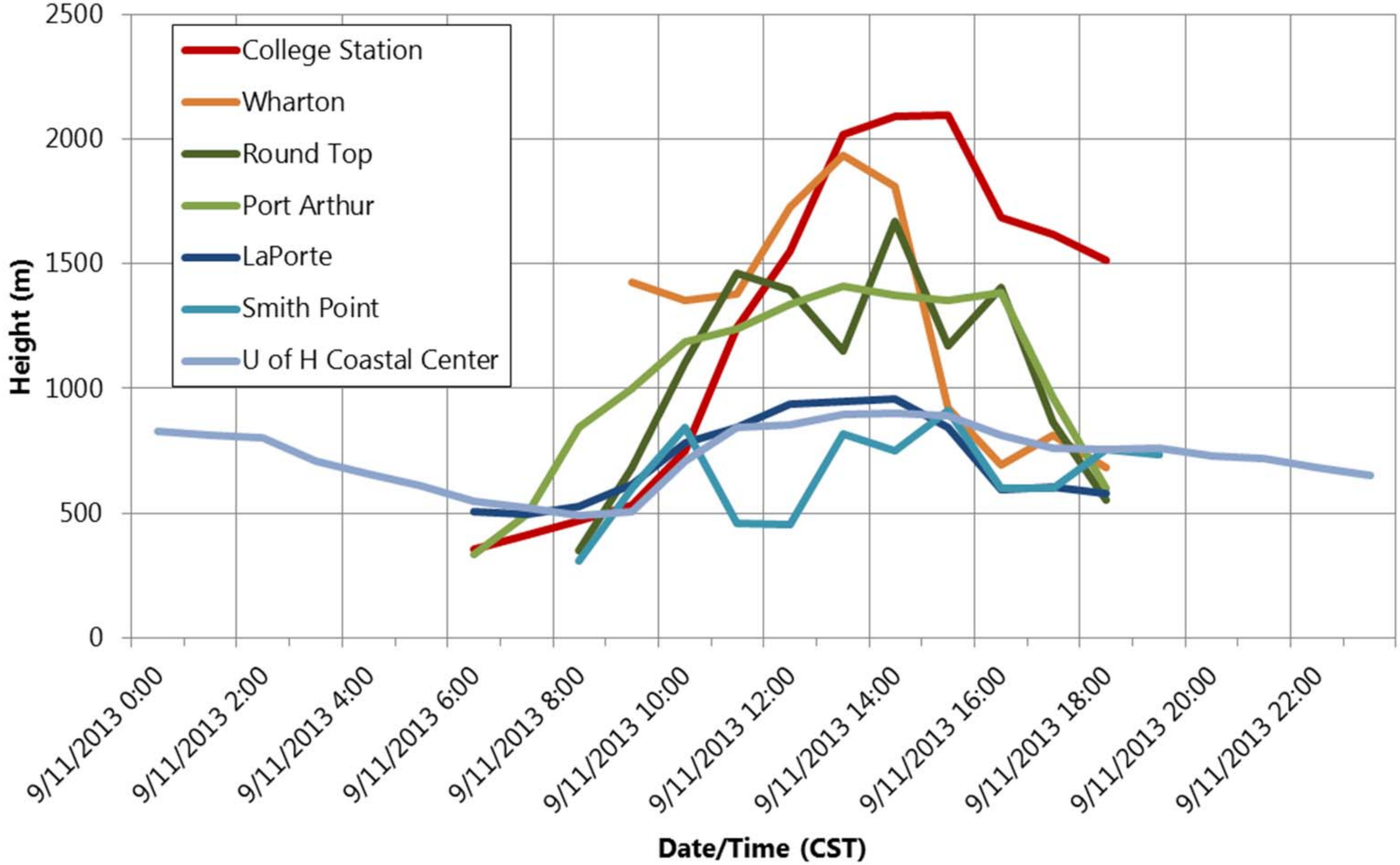


Figure 63. Hourly mixing heights on September 11, 2013.

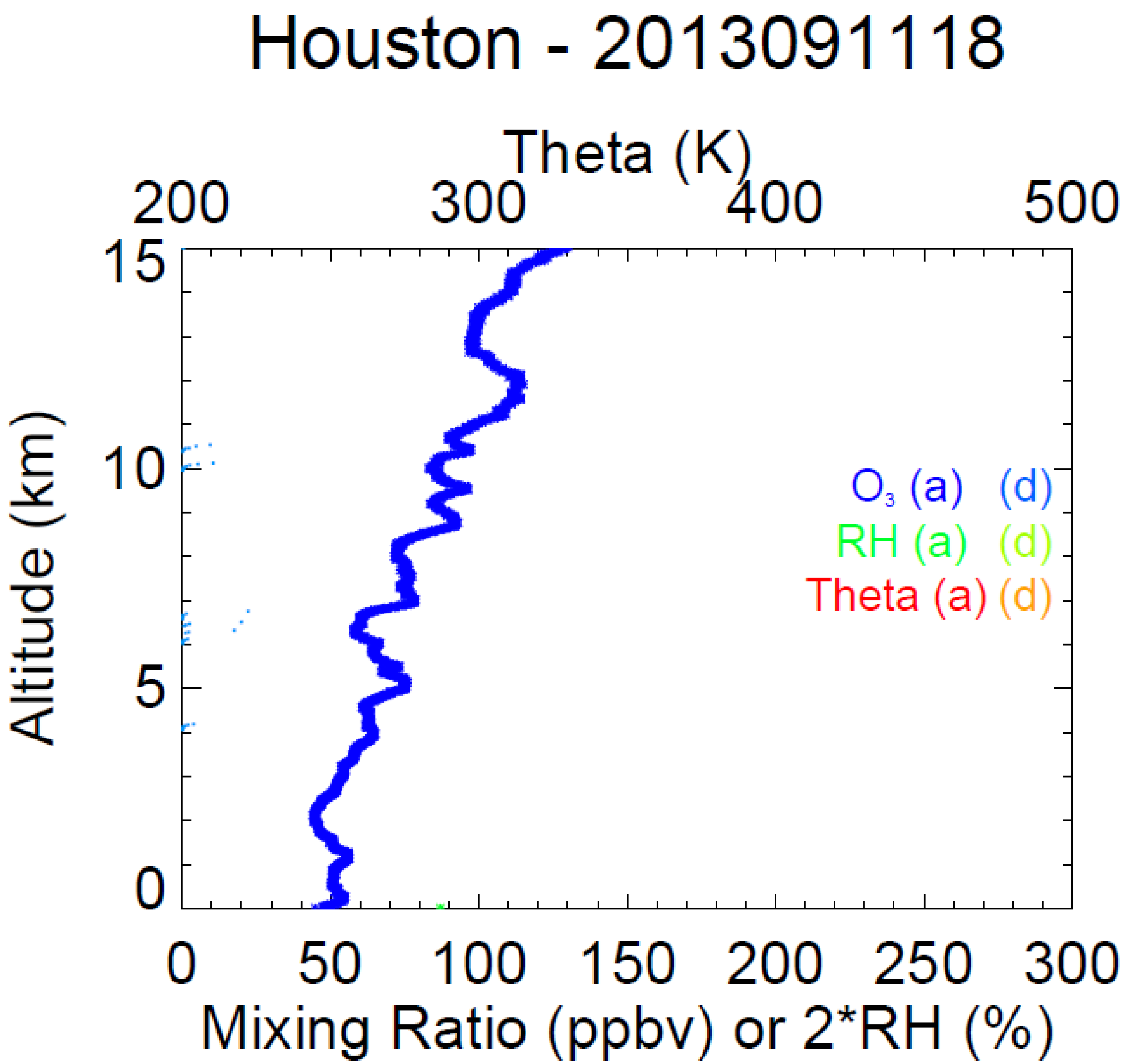


Figure 64. Ozonesonde data on September 11, 2013, launched from the University of Houston at 12:00 p.m. CST.

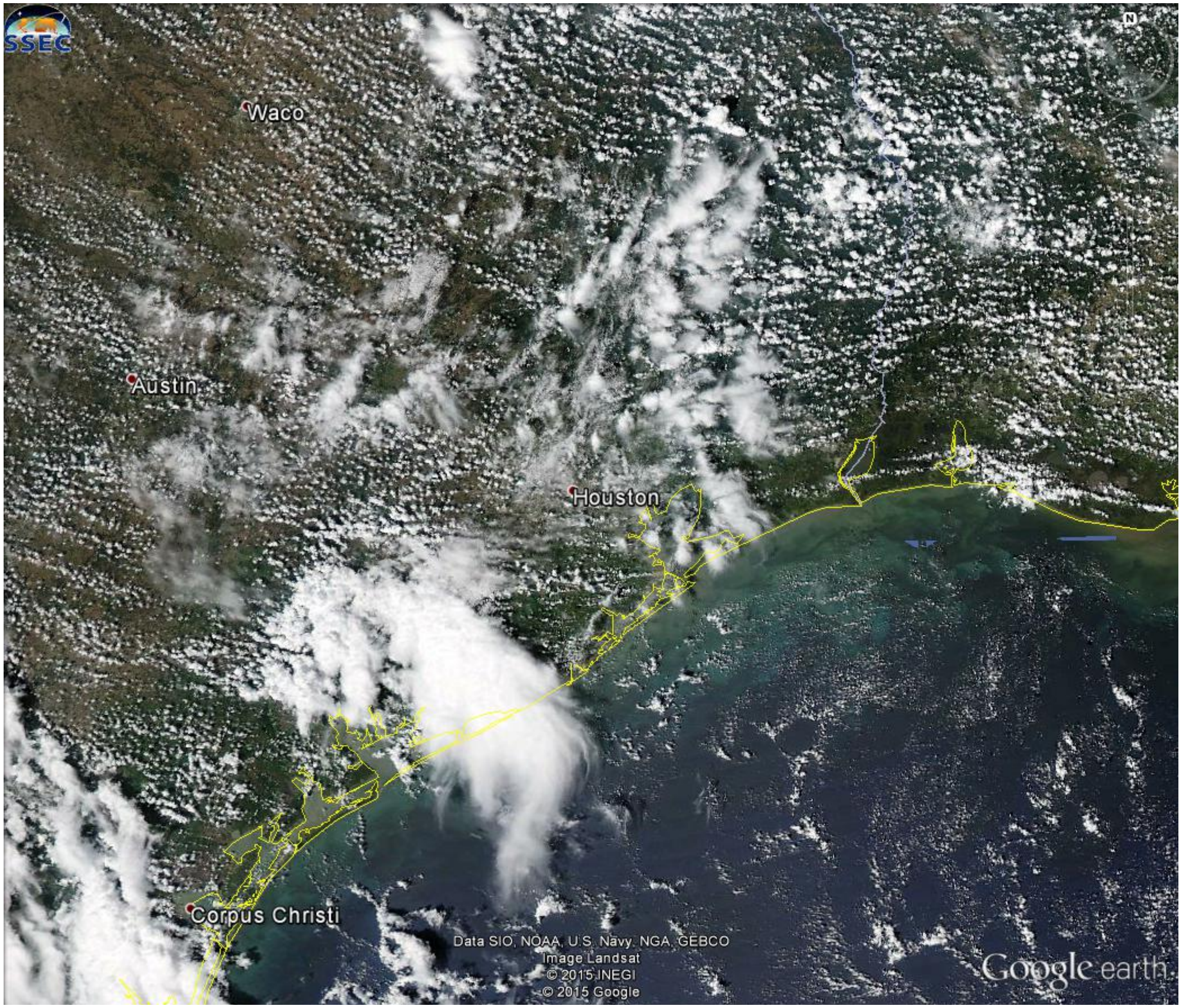


Figure 65. MODIS-AQUA image from September 11, 2013. Scattered fair weather cumulus clouds and areas of cirrus clouds from nearby convection moved over the Houston area, resulting in partly cloudy skies.

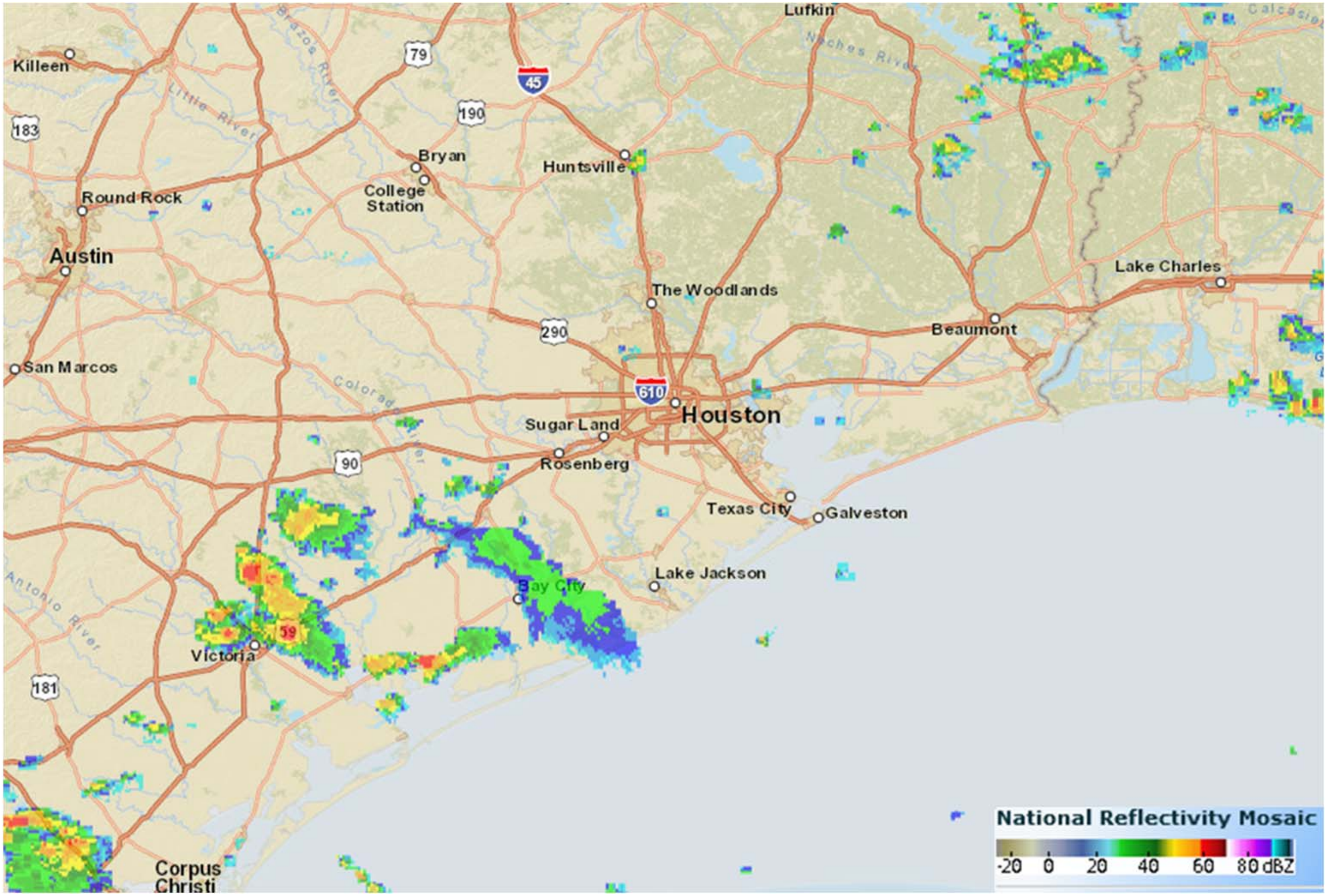


Figure 66. Regional radar image from 2:00 p.m. CST on September 11, 2013. Several thunderstorms were detected southwest of Houston.

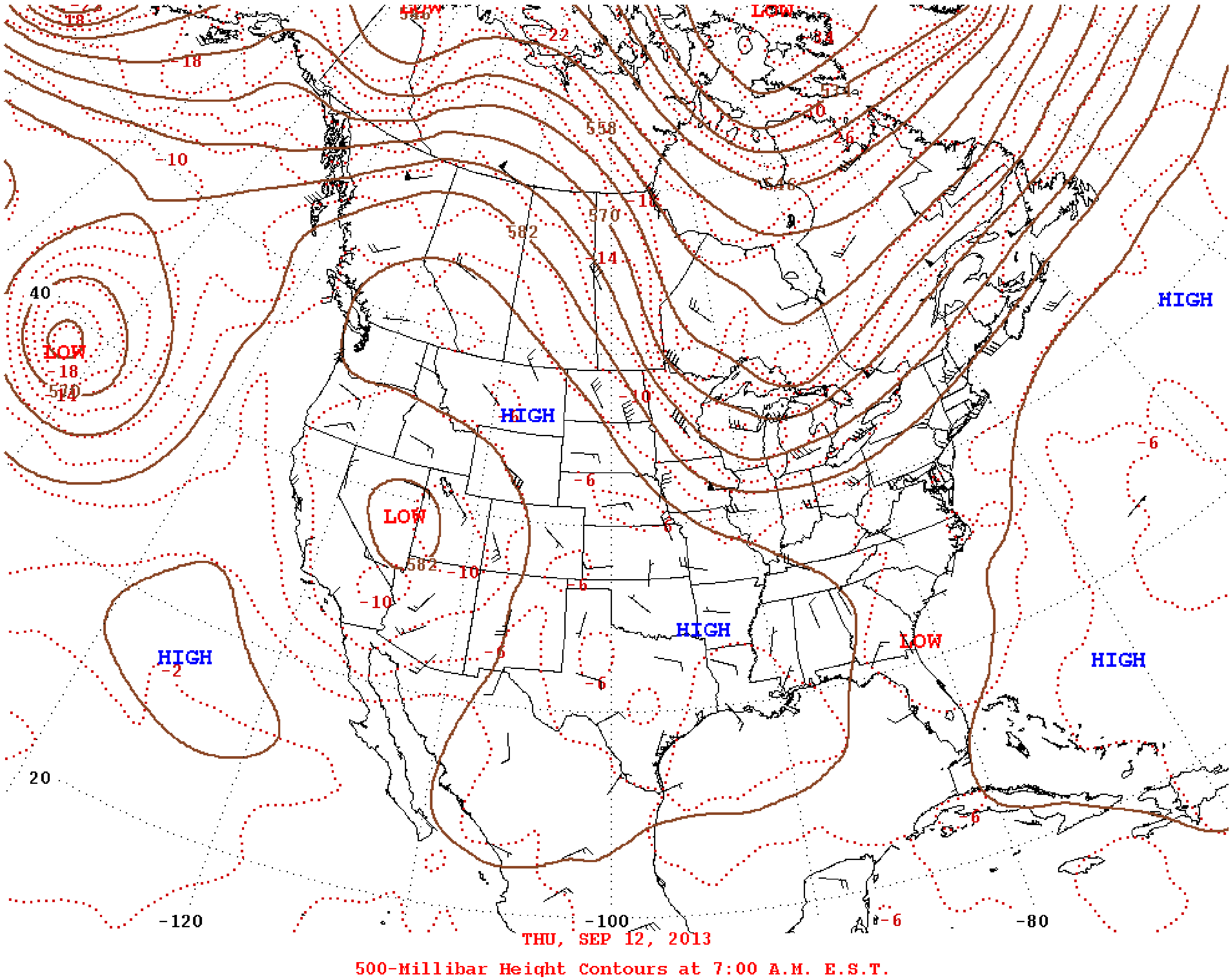
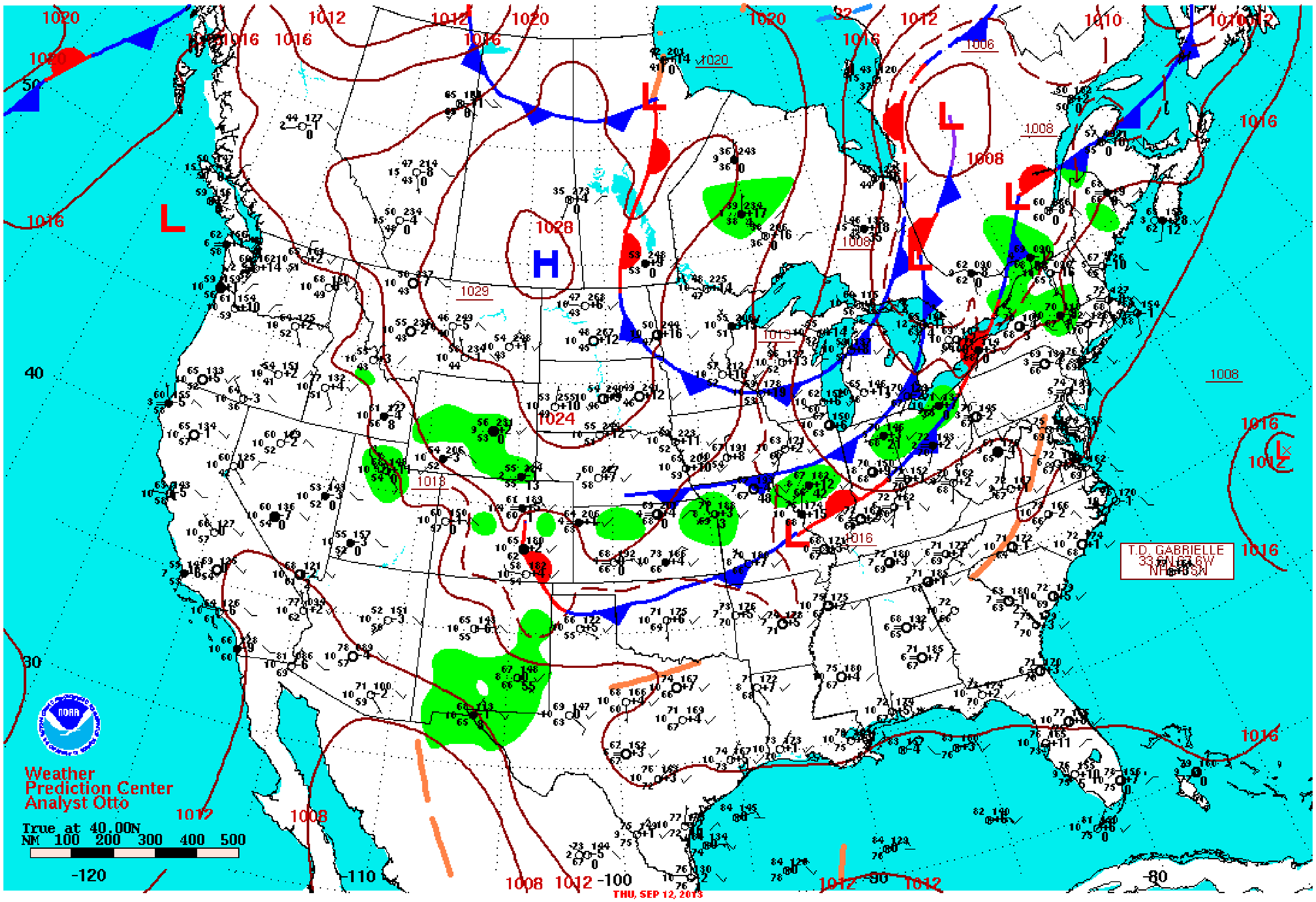


Figure 67. A map showing the height of the 500 mb pressure surface at 6:00 a.m. CST on September 12, 2013. An upper-level high-pressure system was located over the southern Plains.



Surface Weather Map and Station Weather at 7:00 A.M. E.S.T.

Figure 68. Surface pressure map at 6:00 a.m. CST on September 12, 2013. A broad surface high-pressure system was located over the southeastern United States, resulting in a weak easterly large-scale pressure gradient in the Houston area.

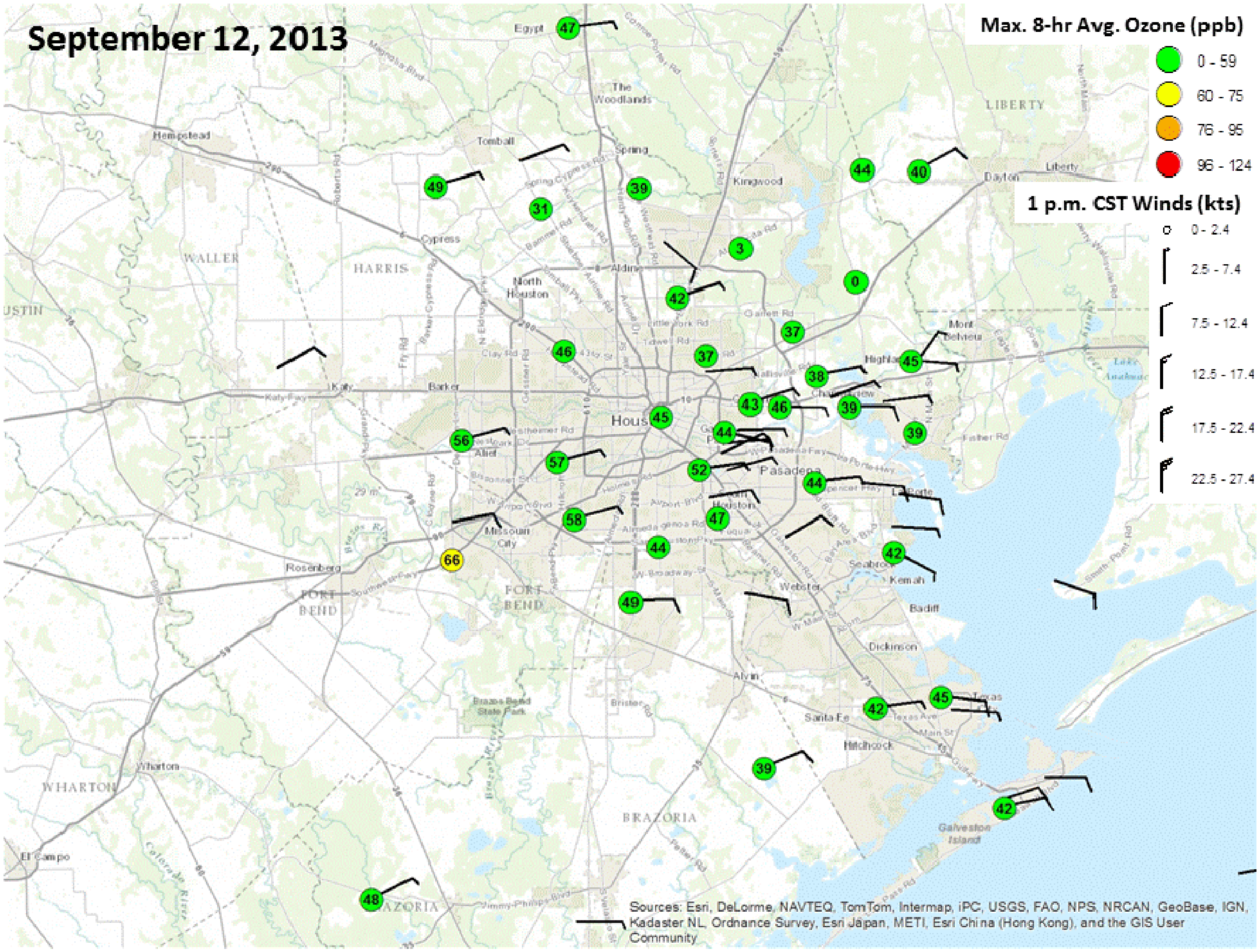


Figure 69. Daily maximum 8-hr average ozone concentrations and surface wind observations from Houston-area monitors on September 12, 2013. Moderate east-northeasterly winds transported pollutants west-southwestward across the Houston area. As a result, 8-hr ozone concentrations were highest on the west side of Houston.

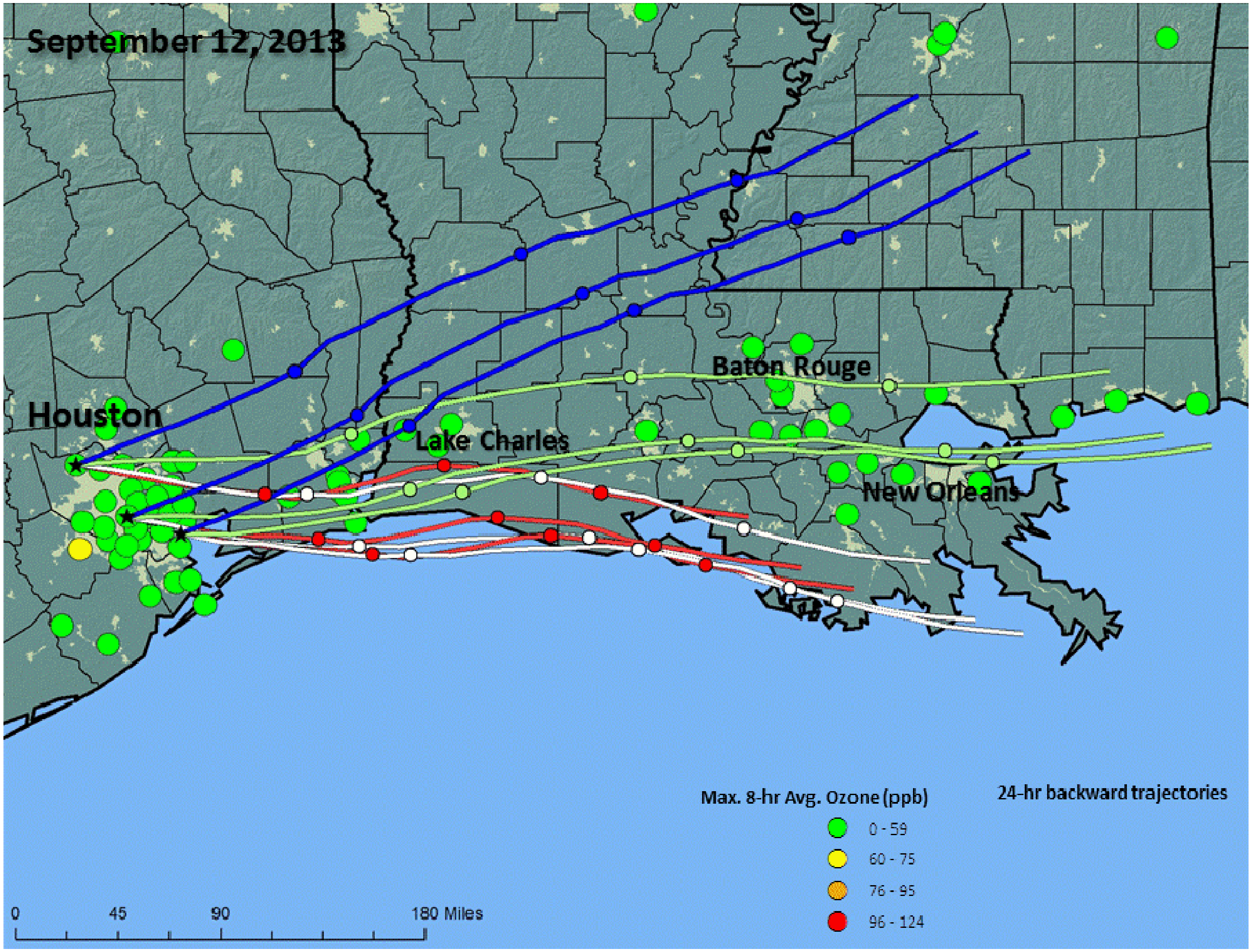


Figure 70. Daily maximum 8-hr average ozone concentrations and 24-hr backward trajectories ending at 6:00 p.m. CST on September 12, 2013. Deep easterly winds transported relatively cleaner air into the Houston area, and transported urban pollutants westward across the Houston area. Dots along the trajectories are at 6-hr intervals.

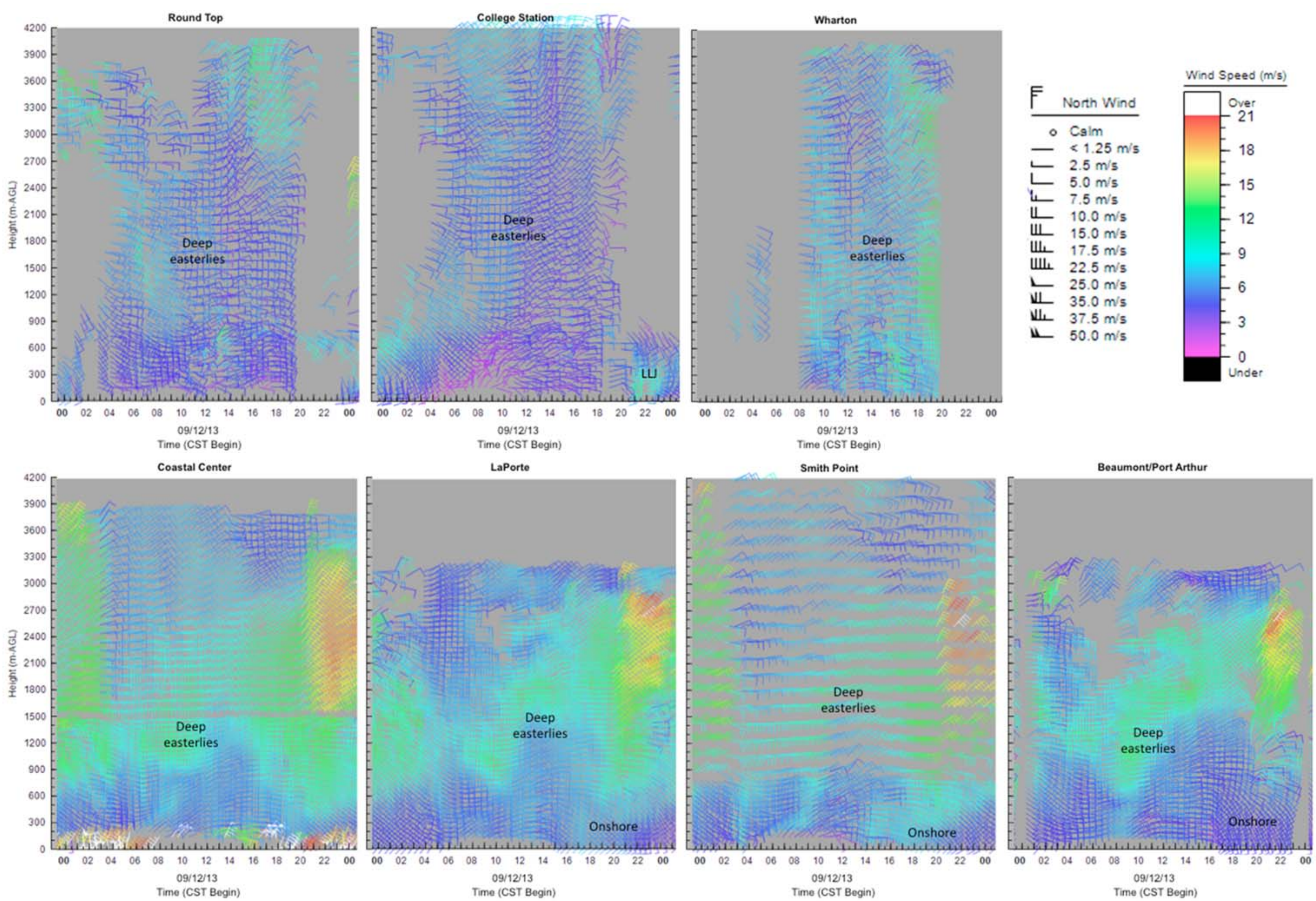


Figure 71. Wind profiler data on September 12, 2013. Deep easterly flow was present throughout southeast Texas on September 12. Winds shifted to southerly at coastal locations as a Bay/Gulf breeze developed during the afternoon hours.

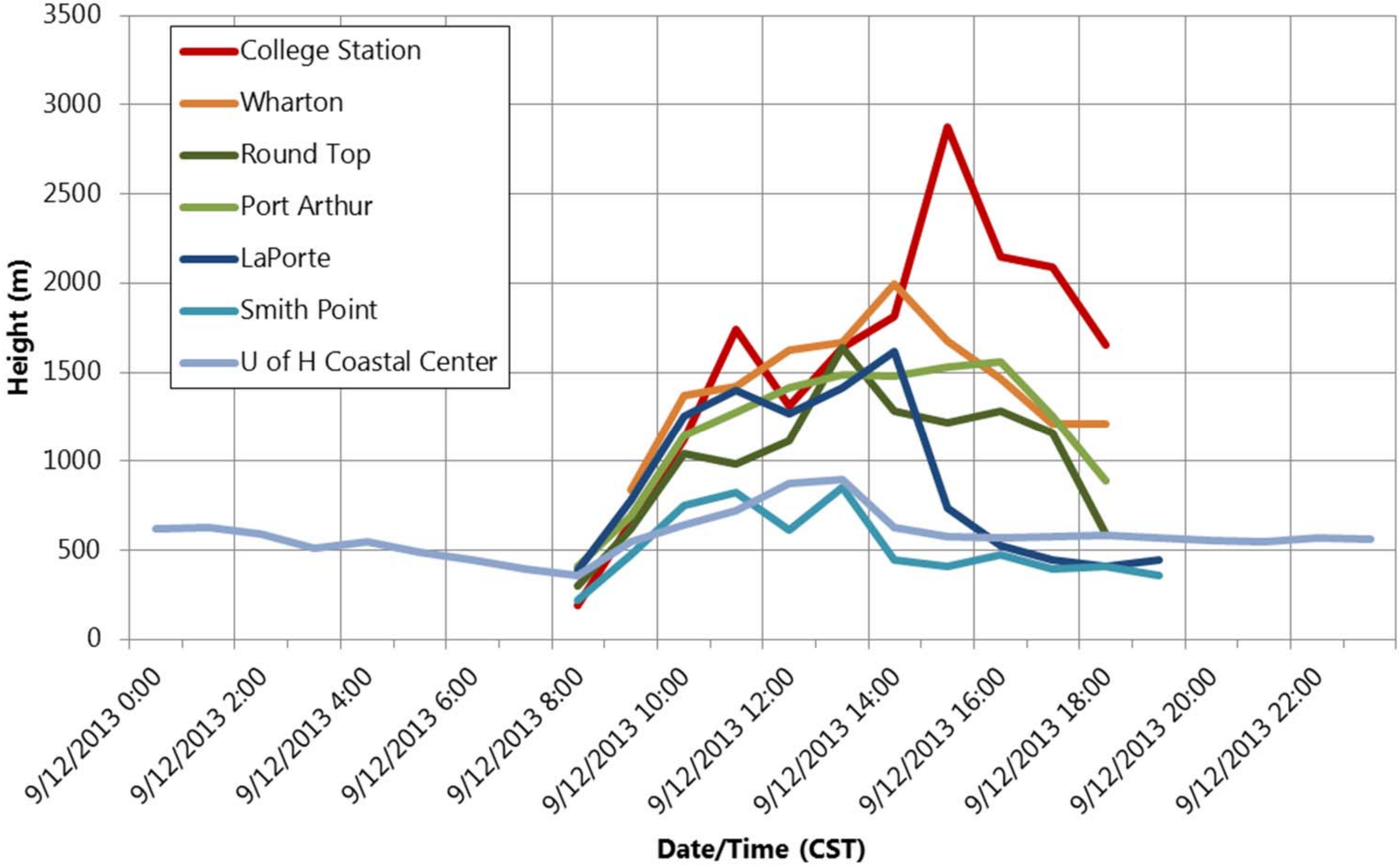


Figure 72. Hourly mixing heights on September 12, 2013.

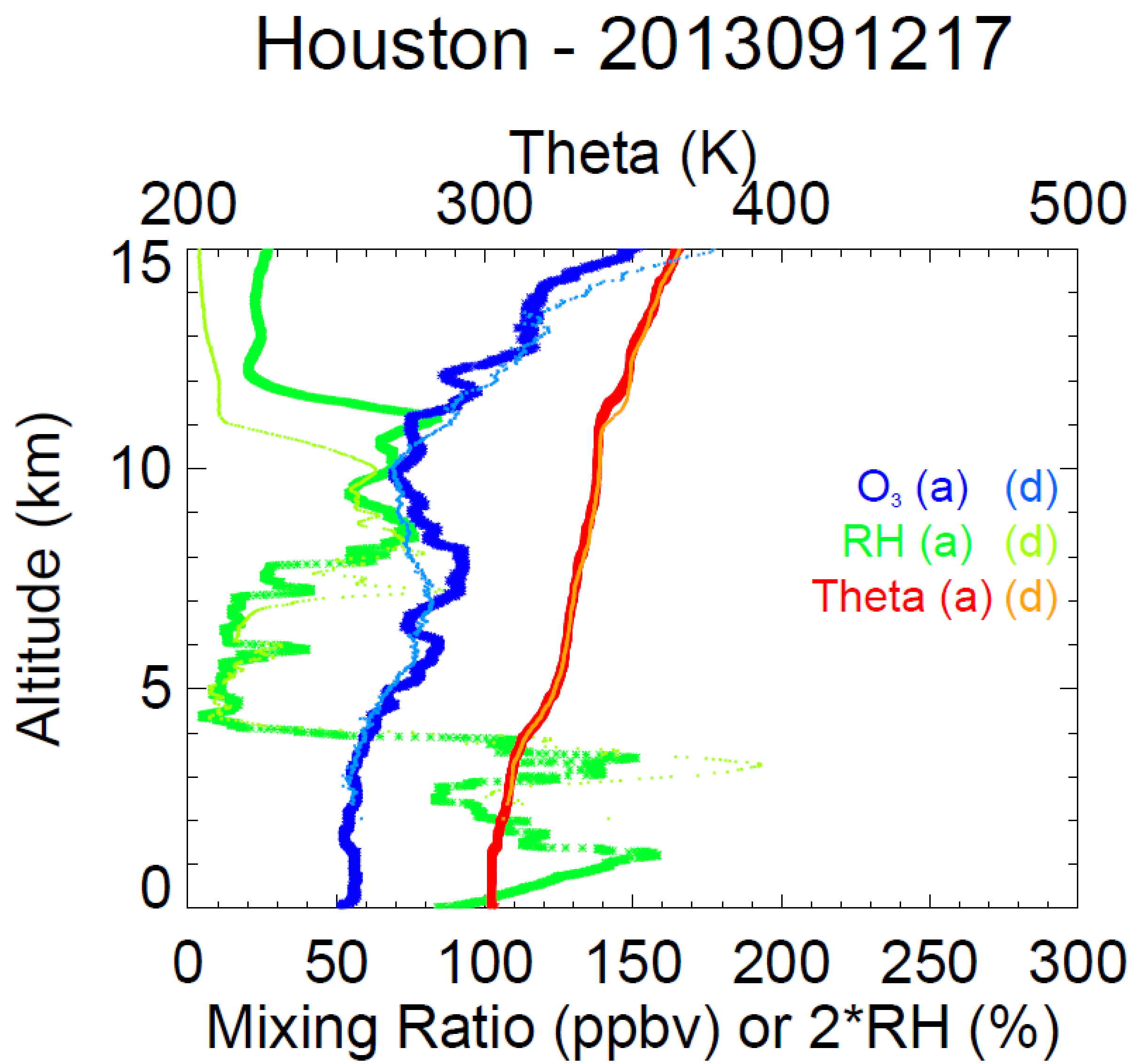


Figure 73. Ozonesonde data on September 12, 2013, launched from the University of Houston at 11:00 a.m. CST.

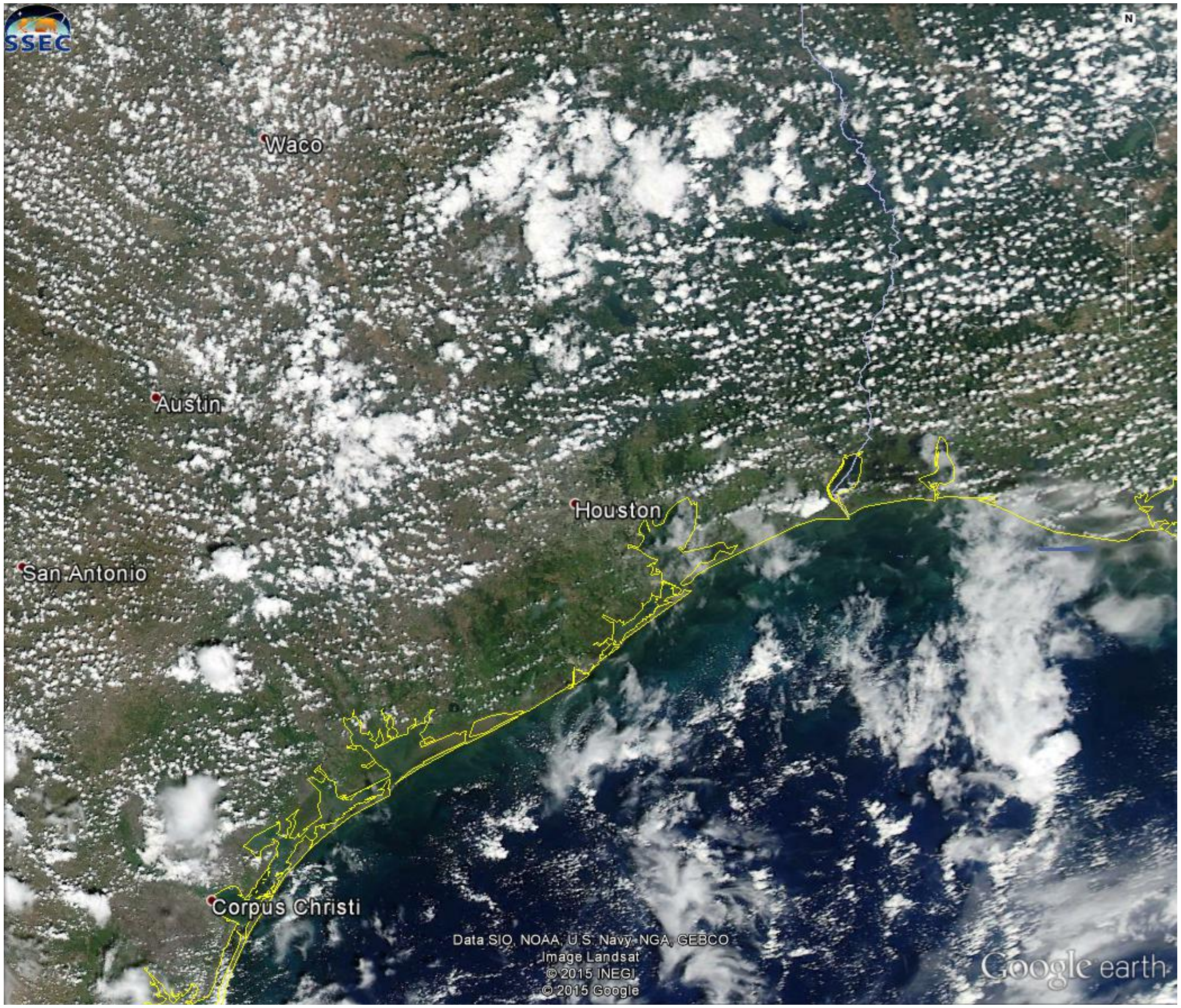


Figure 74. MODIS-AQUA image from September 12, 2013. A few fair weather cumulus clouds developed over inland areas while coastal locations were clear. Skies were mostly sunny throughout the Houston area.

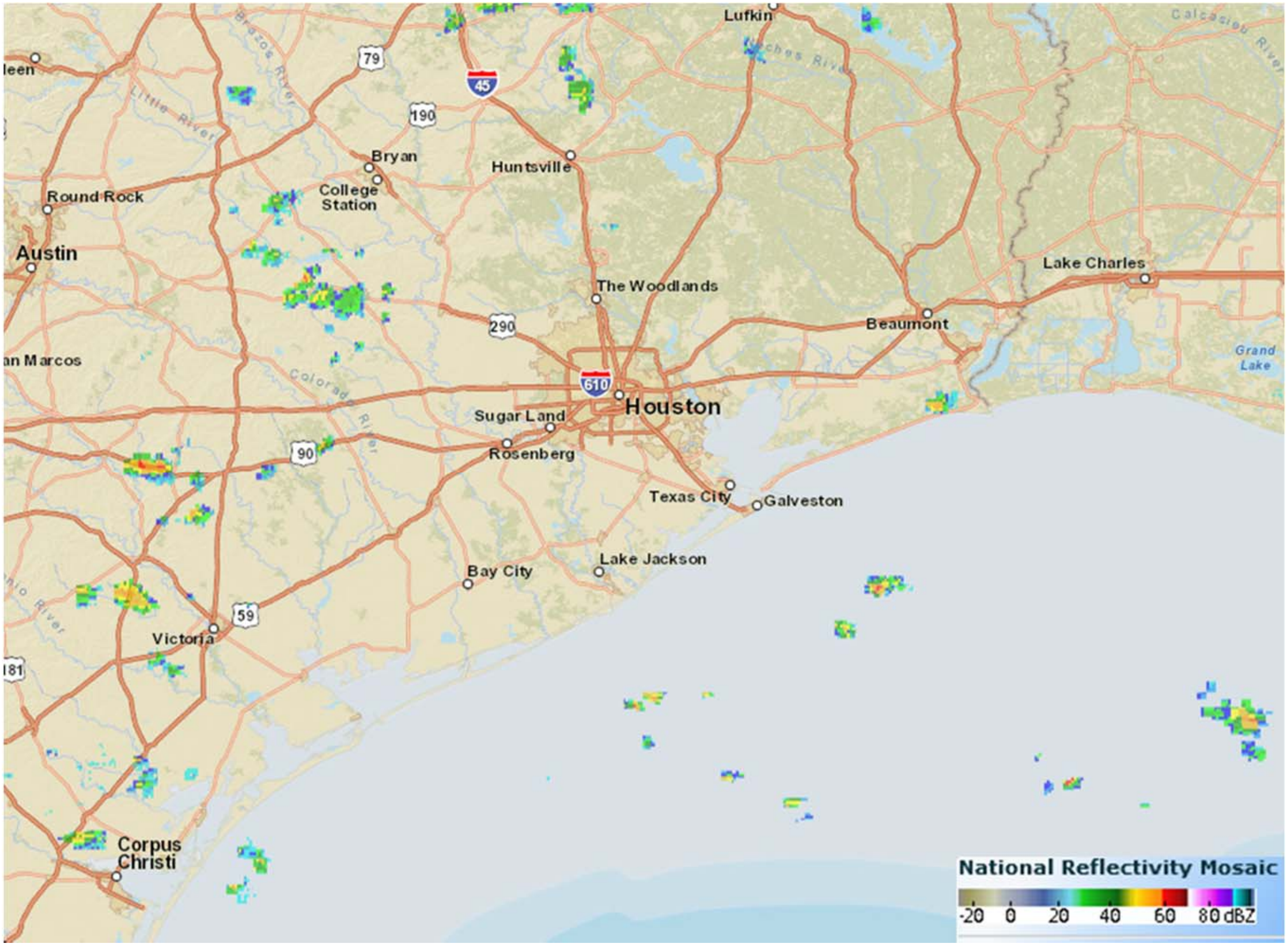


Figure 75. Regional radar image from 2:00 p.m. CST on September 12, 2013. Widely scattered showers were detected across parts of southeastern Texas, but were not affecting the immediate Houston area.

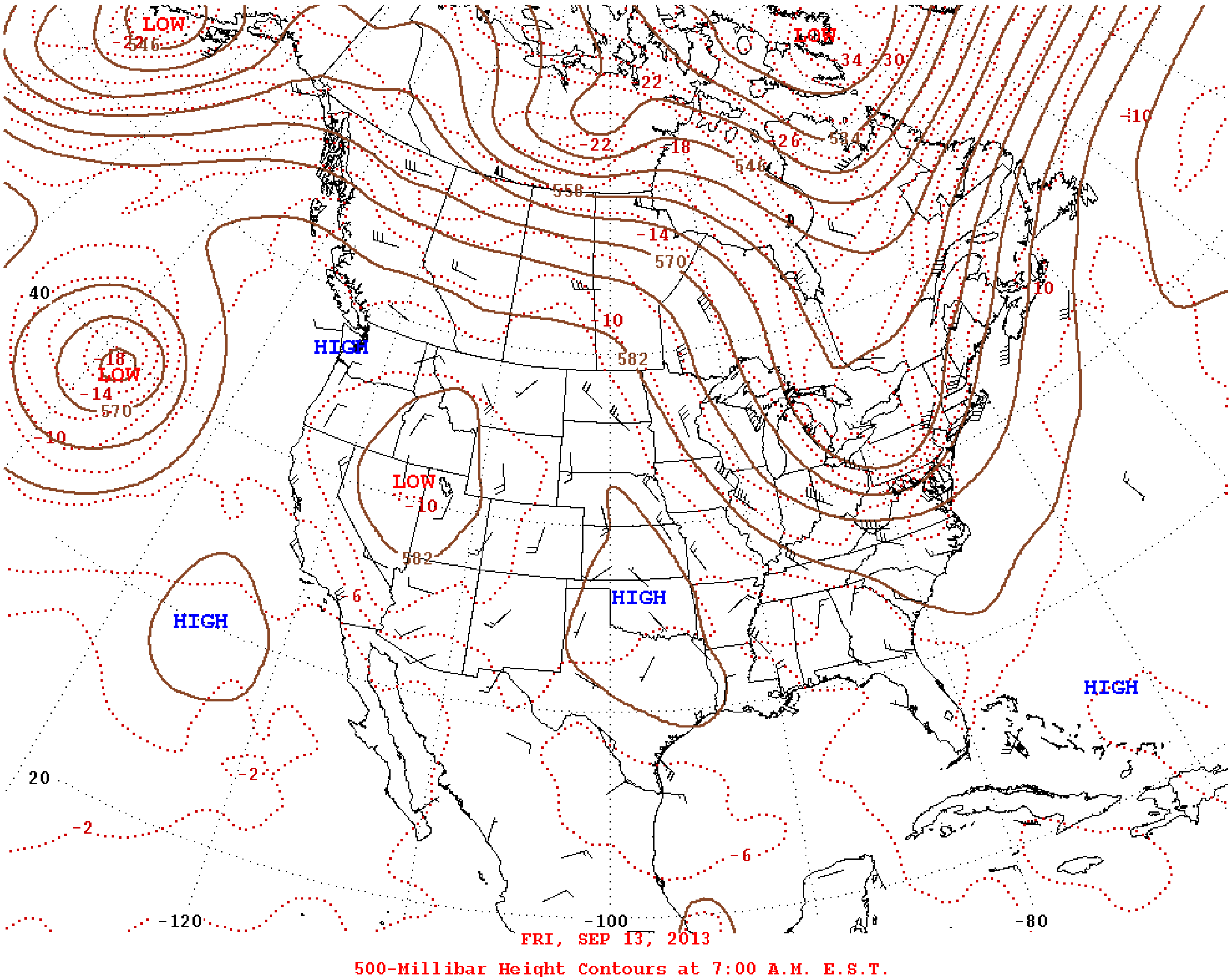
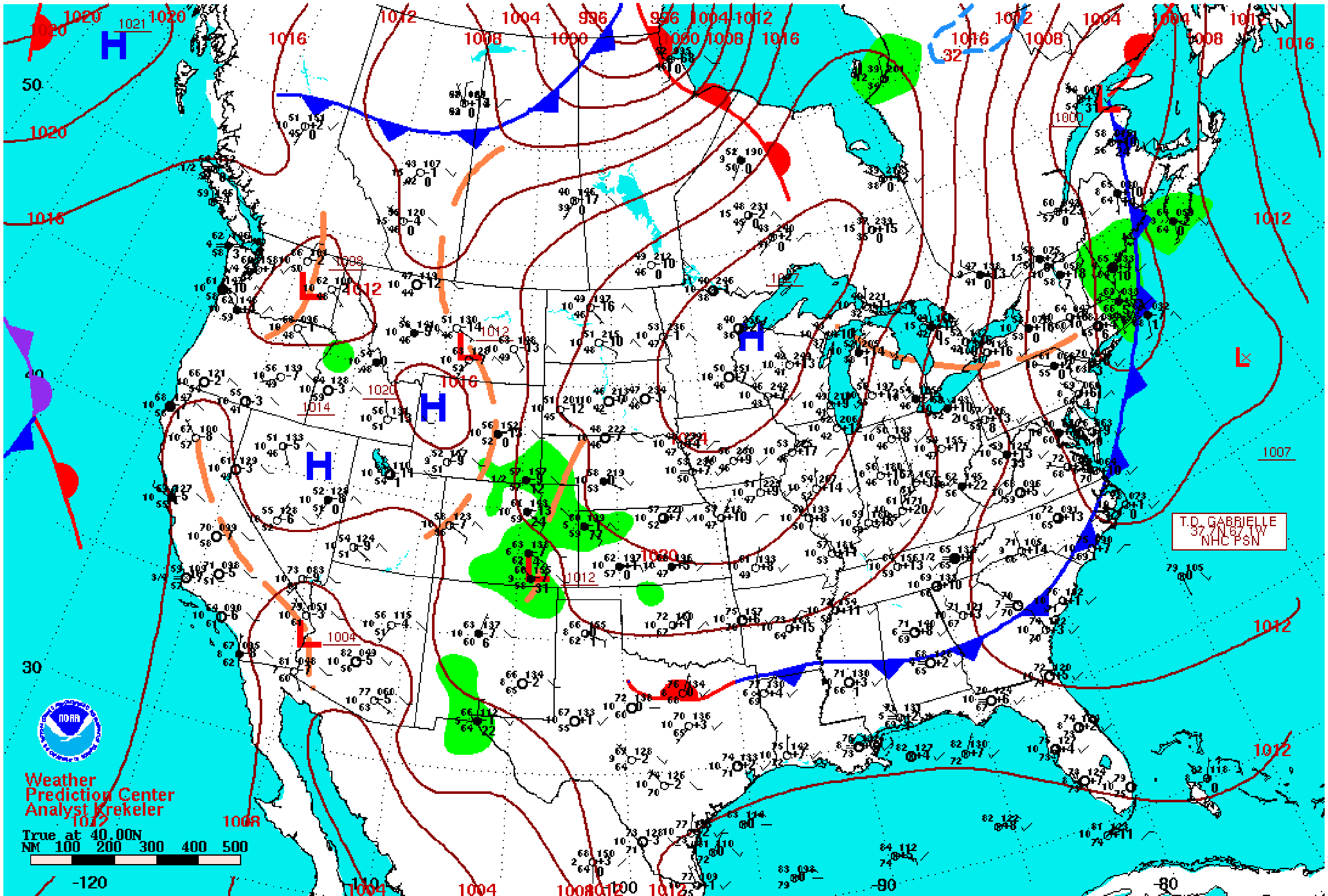


Figure 76. A map showing the height of the 500 mb pressure surface at 6:00 a.m. CST on September 13, 2013. An upper-level high-pressure system was located over the southern Plains.



Surface Weather Map and Station Weather at 7:00 A.M. E.S.T.

Figure 77. Surface pressure map at 6:00 a.m. CST on September 13, 2013. A weak cold front was located north of Houston, resulting in a very weak onshore pressure gradient in the Houston area.

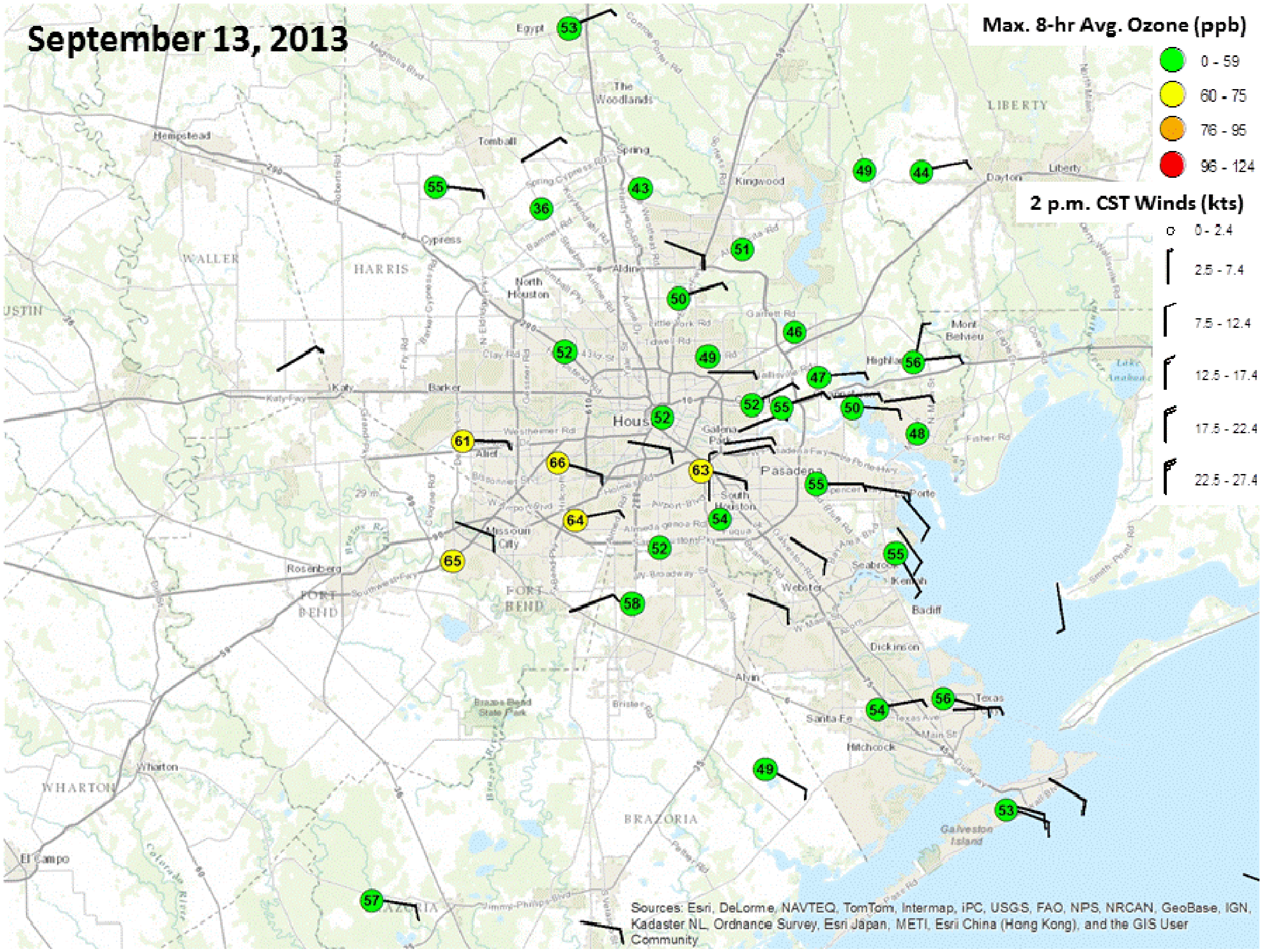


Figure 78. Daily maximum 8-hr average ozone concentrations and surface wind observations from Houston-area monitors on September 13, 2013. Moderate easterly winds transported pollutants westward across the Houston area. As a result, 8-hr ozone concentrations were highest on the west side of Houston. A Bay breeze also developed, shifting winds to southeasterly along Galveston Bay.

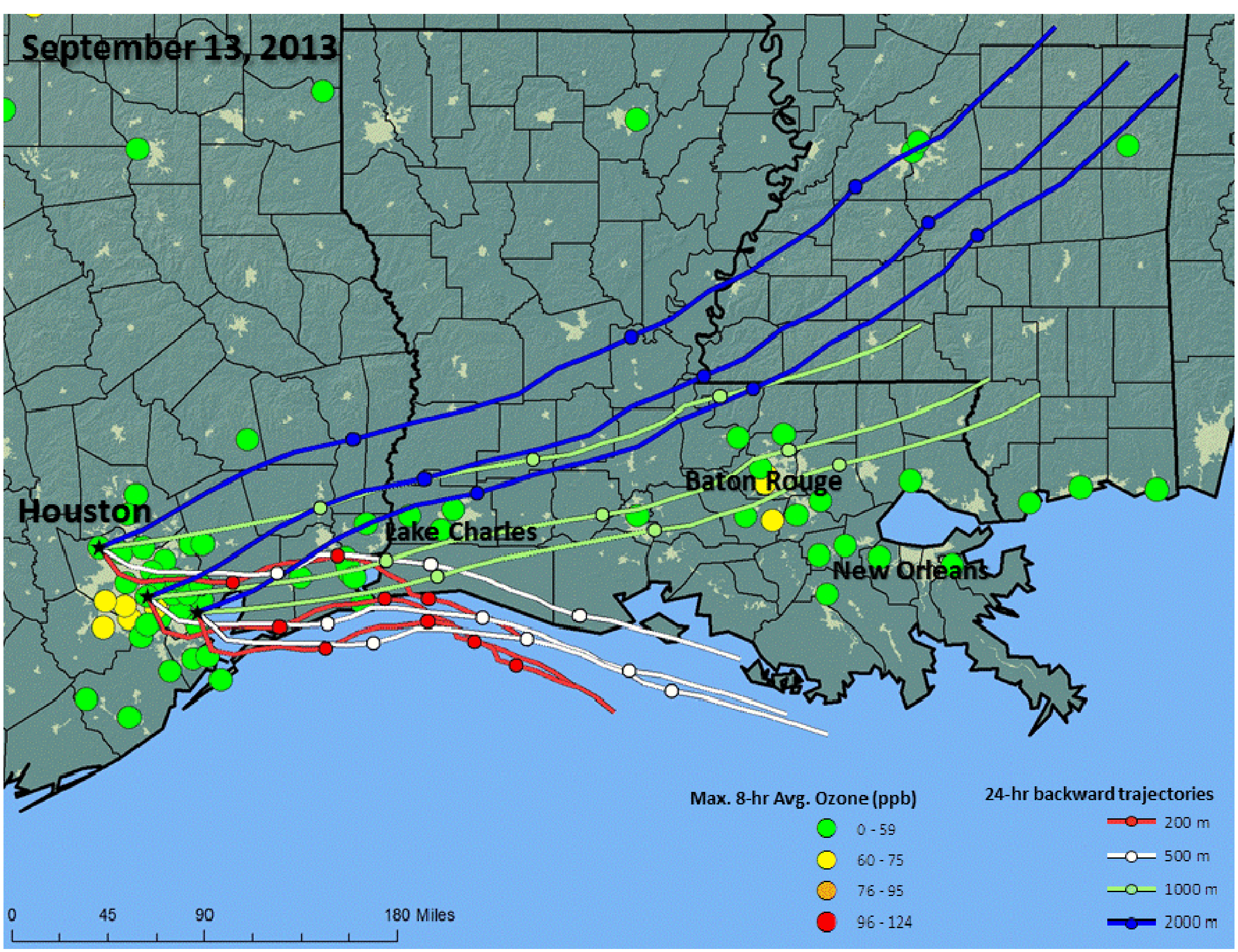


Figure 79. Daily maximum 8-hr average ozone concentrations and 24-hr backward trajectories ending at 6:00 p.m. CST on September 13, 2013. Deep east-northeasterly winds transported urban pollutants westward across the Houston area. A weak Bay/Gulf breeze developed during the late afternoon hours below 500 m. Dots along the trajectories are at 6-hr intervals.

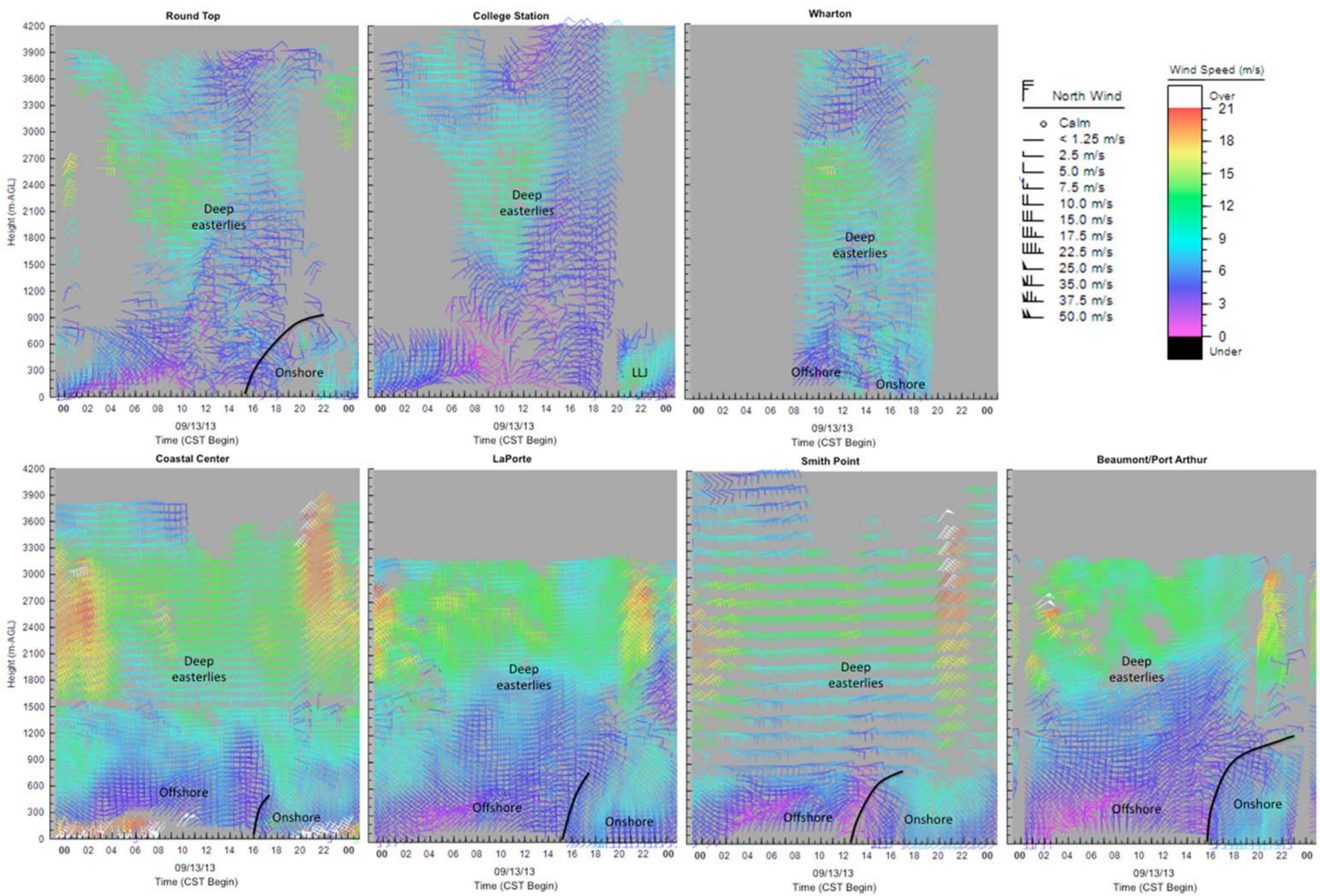


Figure 80. Wind profiler data on September 13, 2013. Light to moderate east-northeasterly winds shifted to southeasterly as a Bay/Gulf breeze developed.

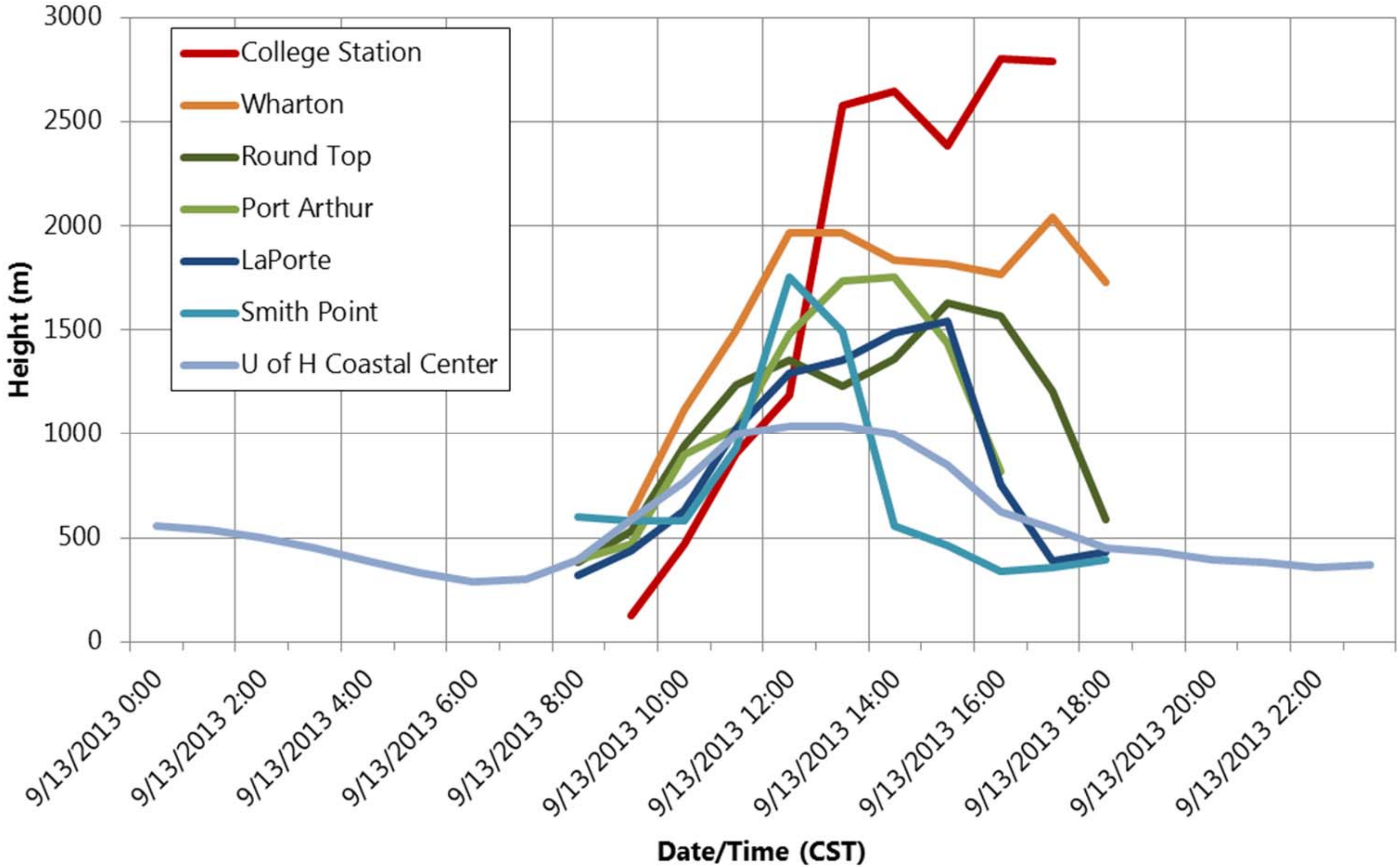


Figure 81. Hourly mixing heights on September 13, 2013.

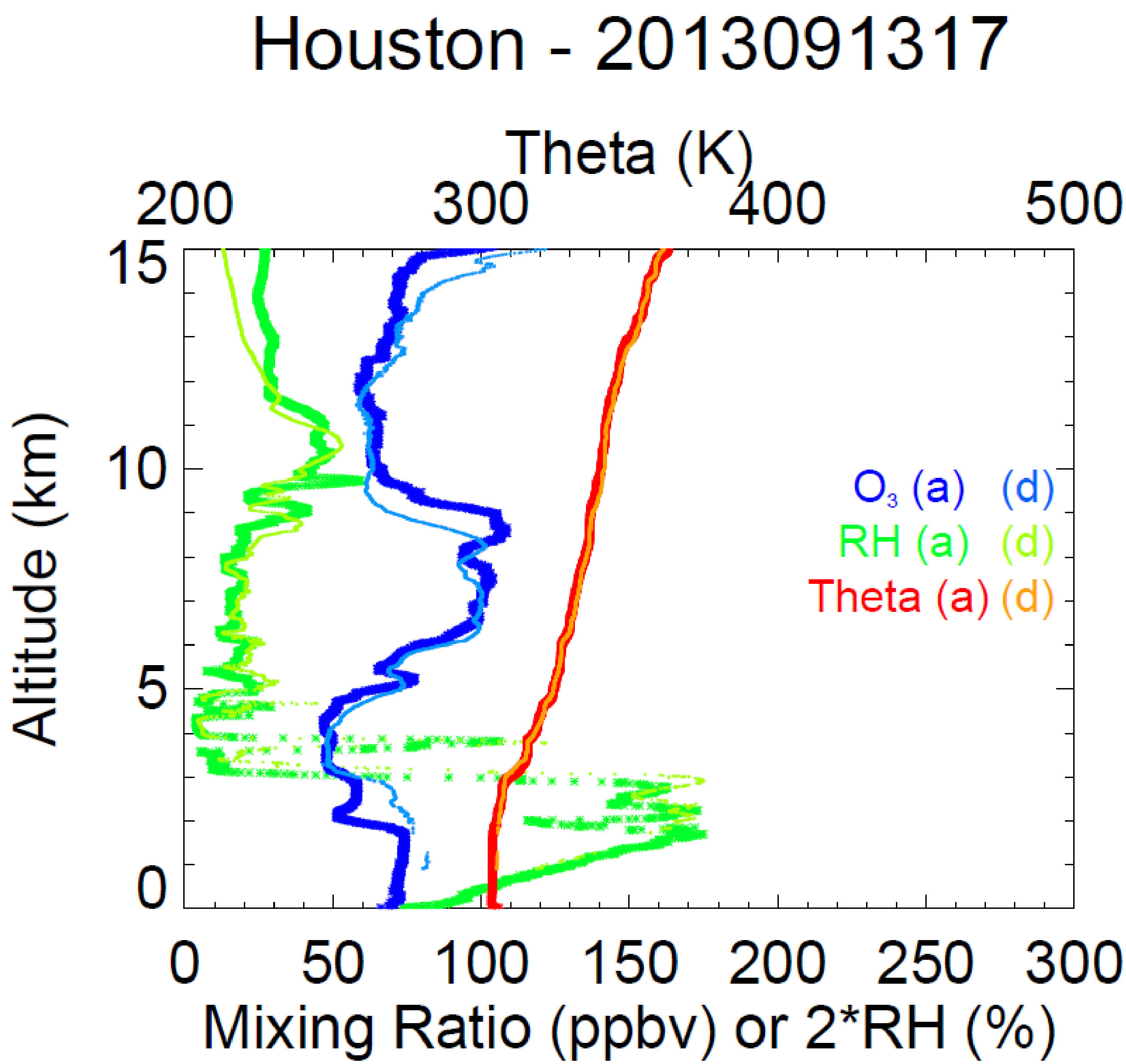


Figure 82. Ozonesonde data on September 13, 2013, launched from the University of Houston at 11:00 a.m. CST.

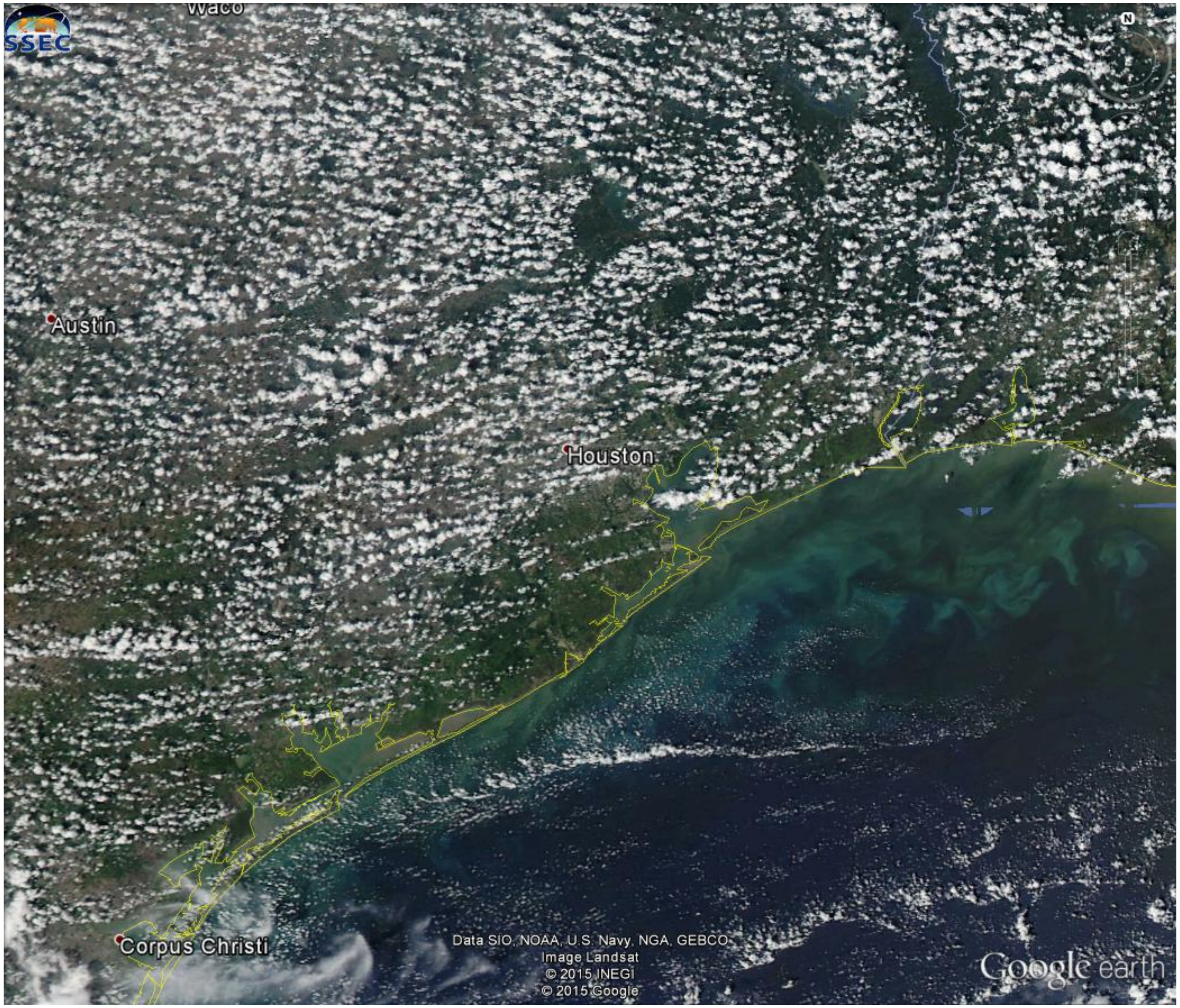


Figure 83. MODIS-AQUA image from September 13, 2013. Scattered fair weather cumulus clouds developed throughout the region, especially over inland areas.

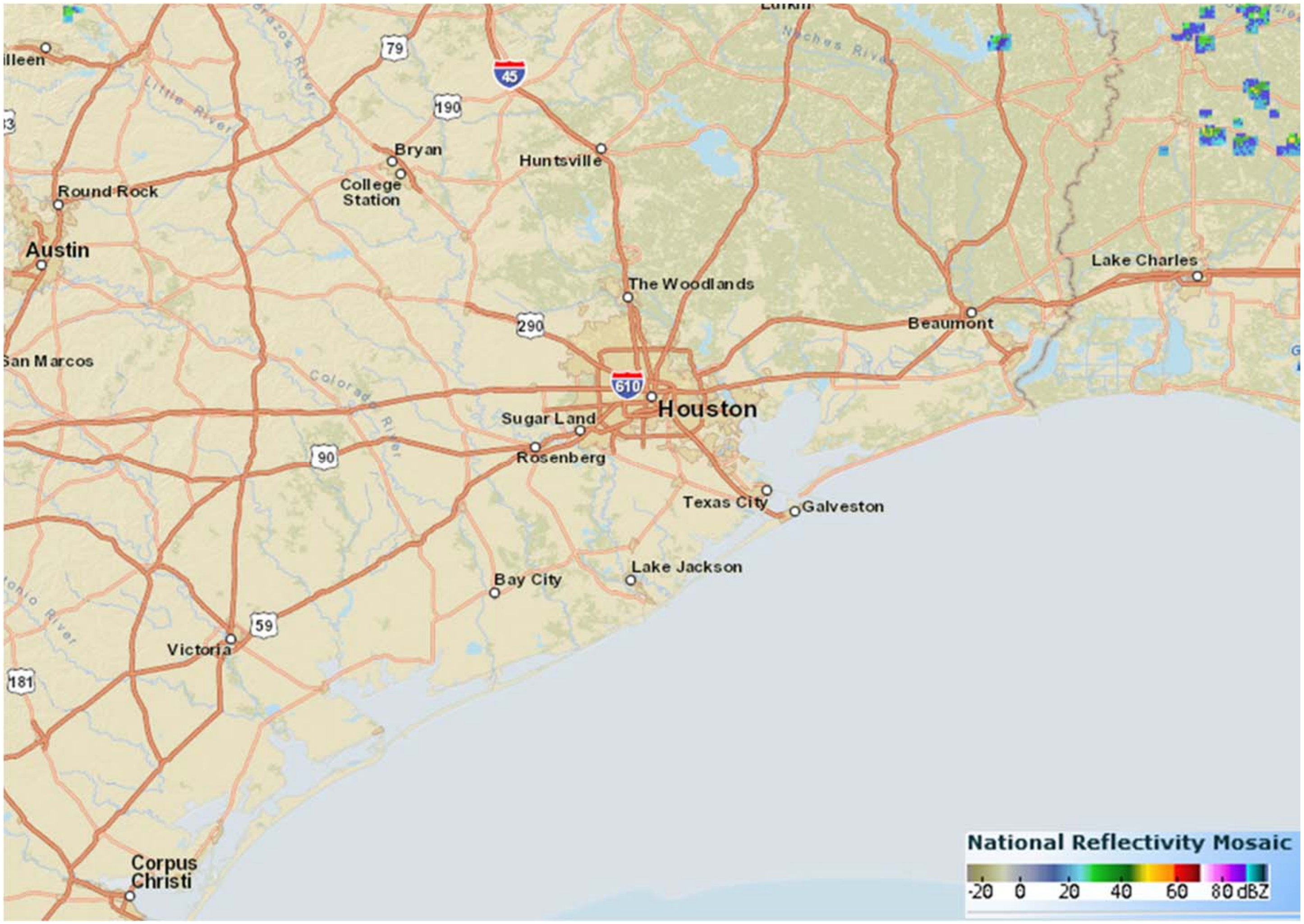


Figure 84. Regional radar image from 2:00 p.m. on September 13, 2013. No precipitation was detected throughout the Houston area.

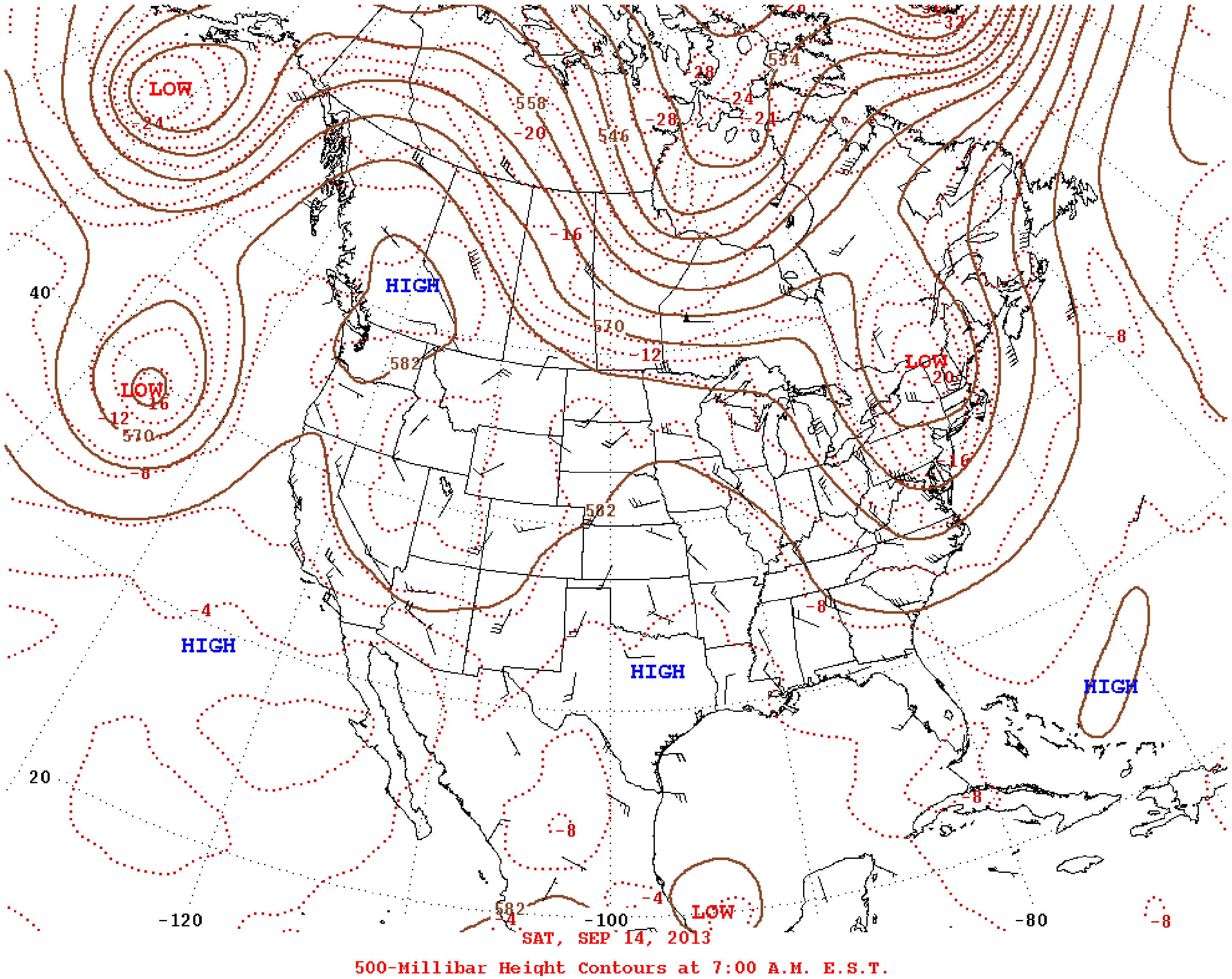
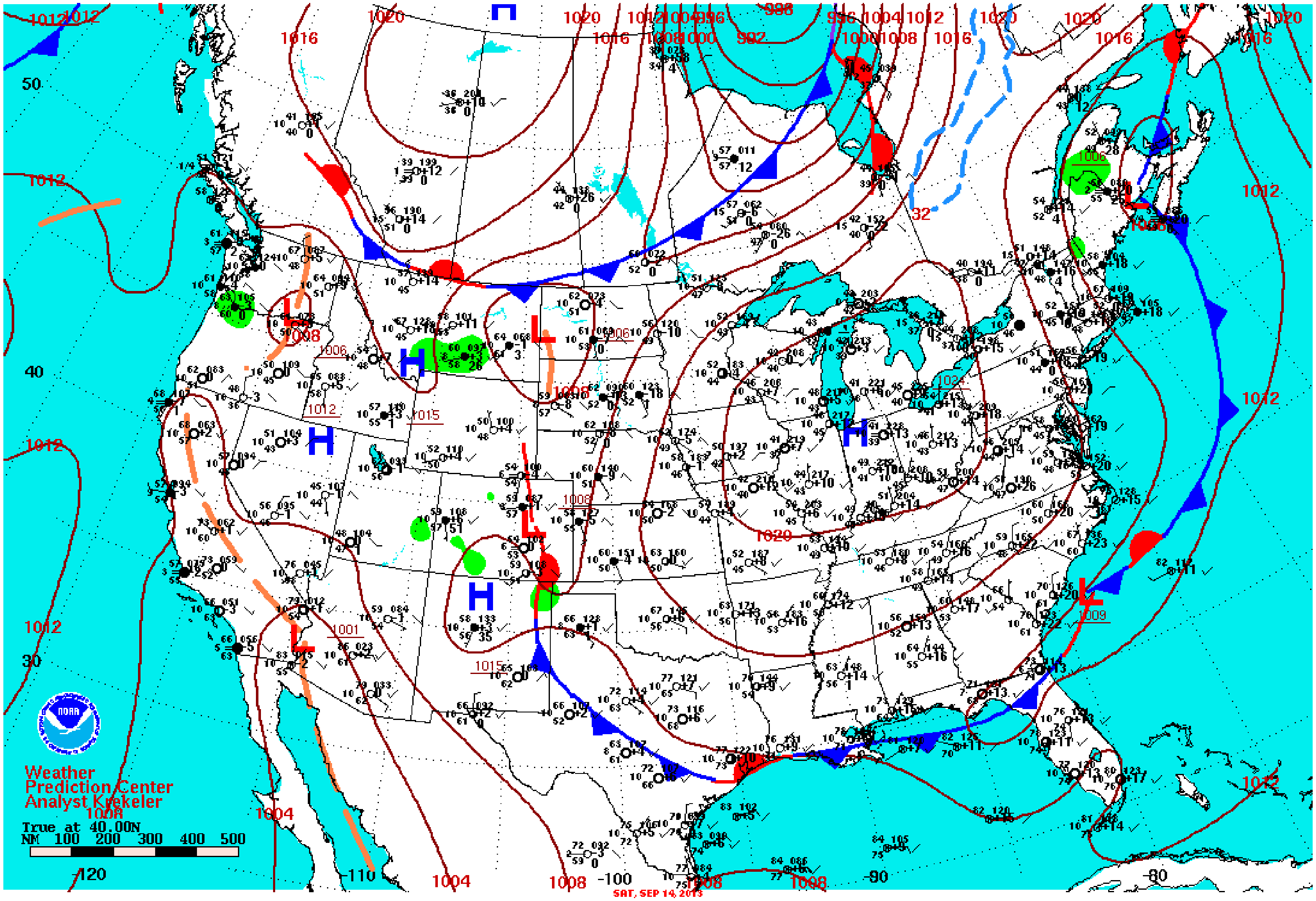


Figure 85. A map showing the height of the 500 mb pressure surface at 6:00 a.m. CST on September 14, 2013. An upper-level high-pressure system was located over the southern Plains.



Surface Weather Map and Station Weather at 7:00 A.M. E.S.T.

Figure 86. Surface pressure map at 6:00 a.m. CST on September 14, 2013. A cold front was located just south of Houston, resulting in a weak northeasterly (offshore) large-scale pressure gradient in the Houston area.

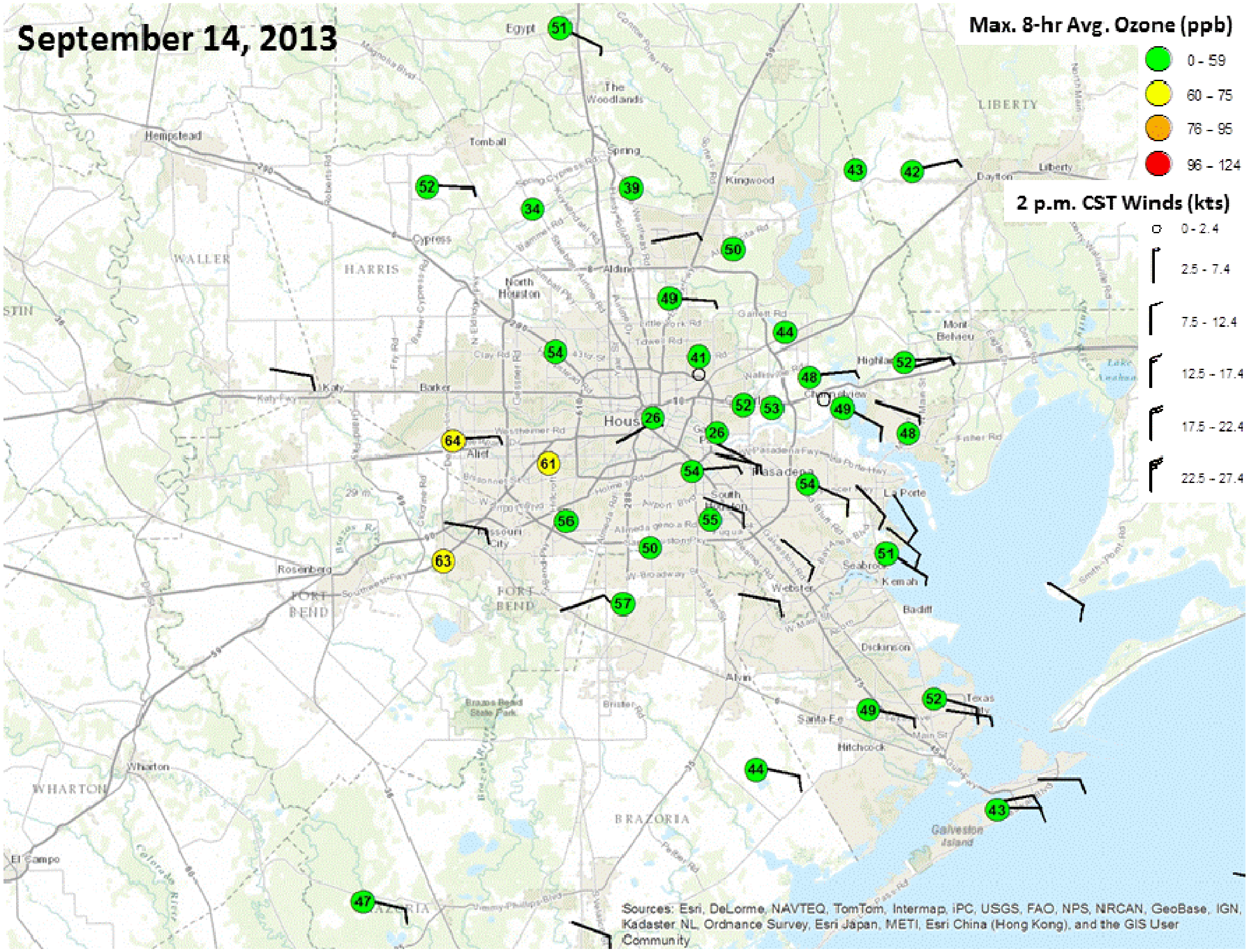


Figure 87. Daily maximum 8-hr average ozone concentrations and surface wind observations from Houston-area monitors on September 14, 2013. Moderate easterly winds transported pollutants westward across the Houston area. As a result, 8-hr ozone concentrations were highest on the west side of Houston. A Bay breeze also developed, shifting winds to southeasterly along Galveston Bay.

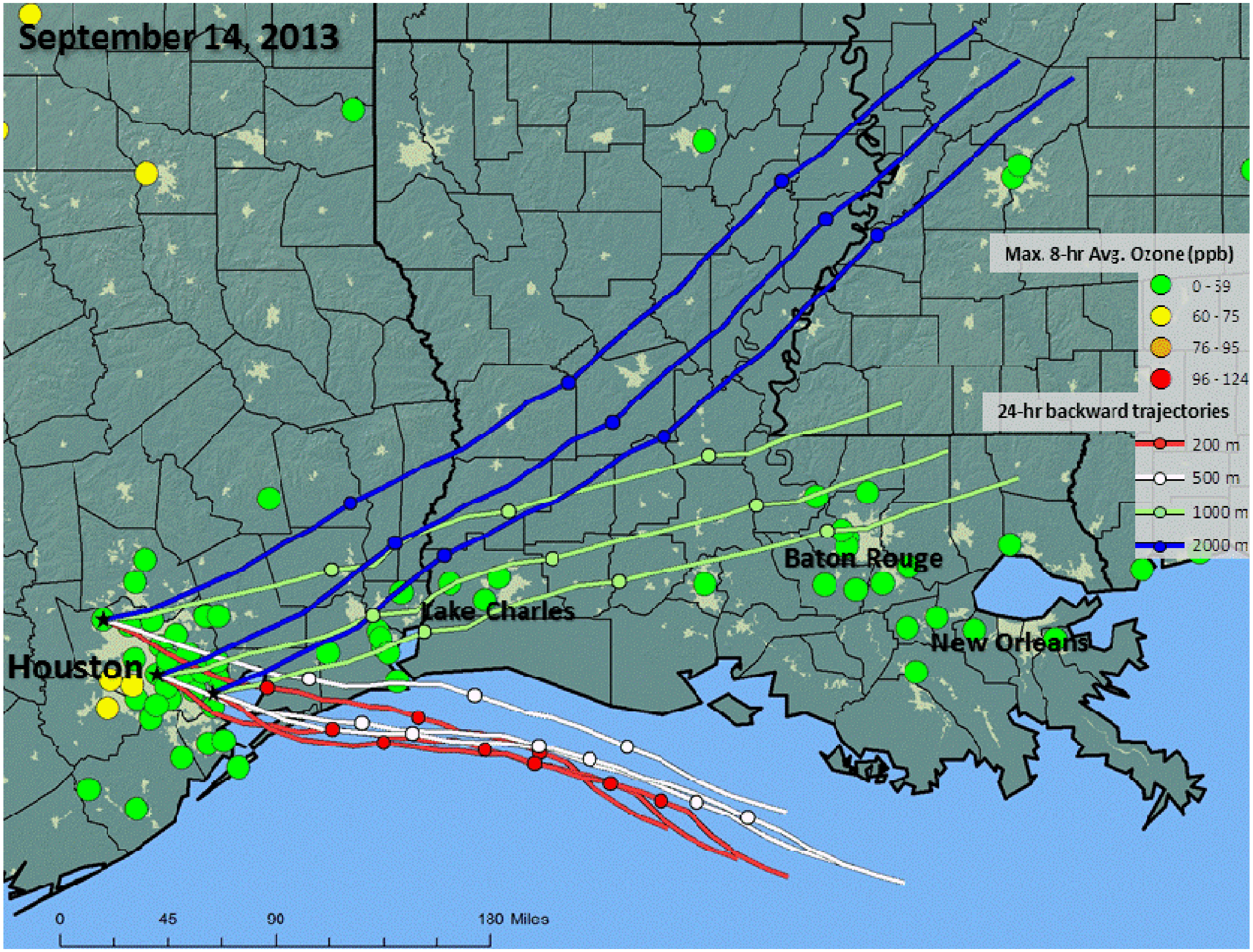


Figure 88. Daily maximum 8-hr average ozone concentrations and 24-hr backward trajectories ending at 6:00 p.m. CST on September 14, 2013. Easterly winds transported urban pollutants westward across the Houston area. Dots along the trajectories are at 6-hr intervals.

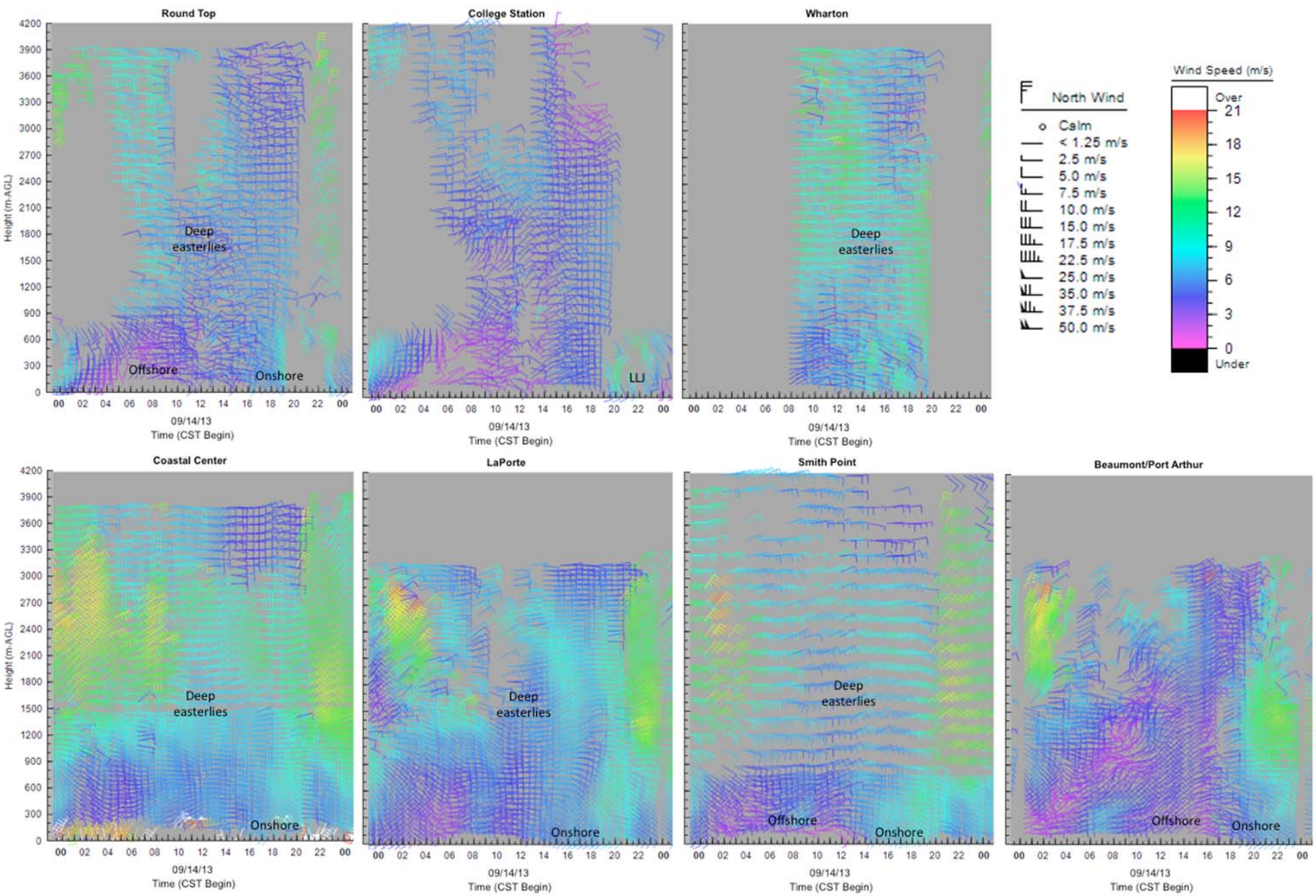


Figure 89. Wind profiler data on September 14, 2013. Light east-northeasterly winds shifted to southeasterly as a Bay/Gulf breeze developed, similar to conditions observed on the previous day.

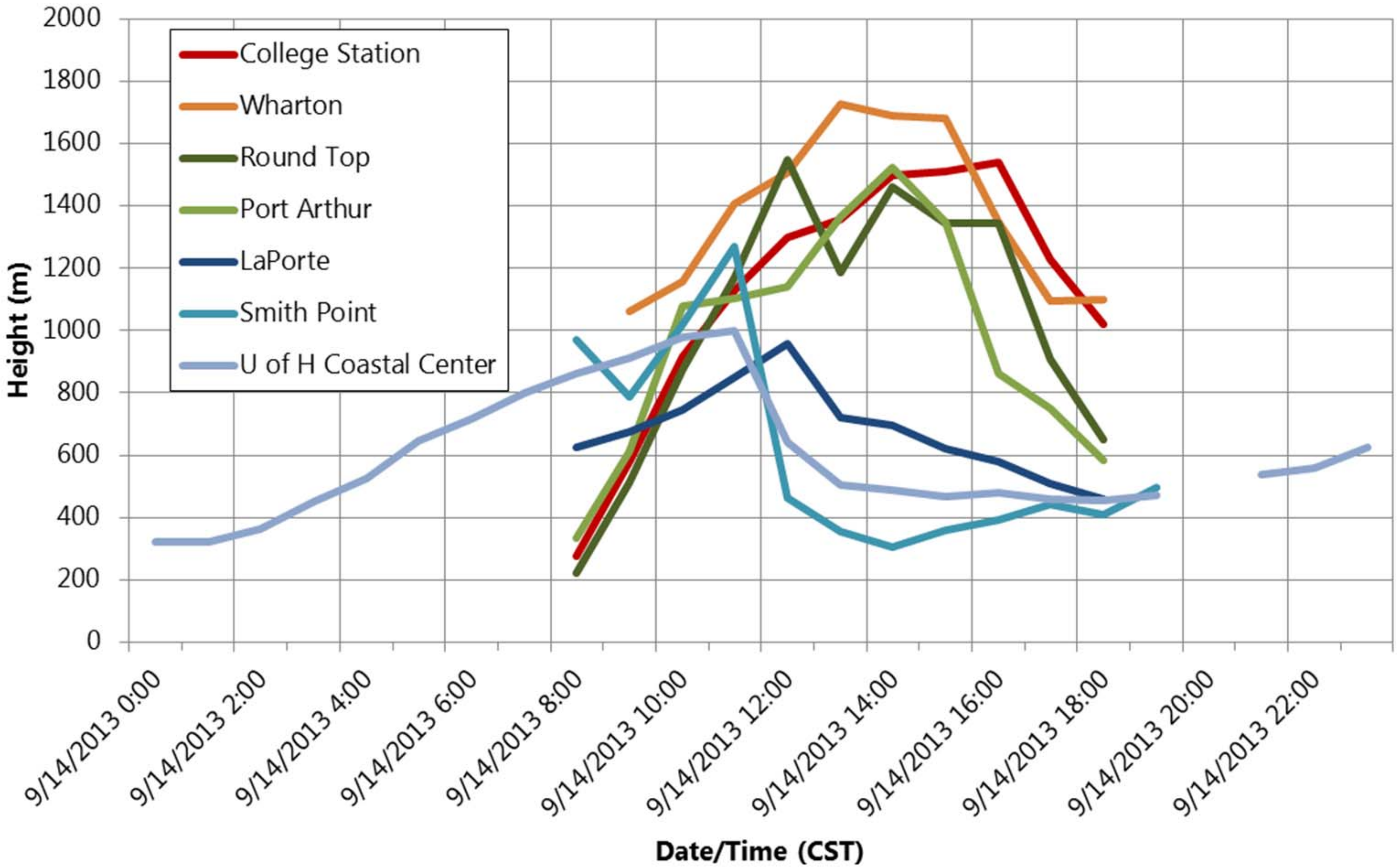


Figure 90. Hourly mixing heights on September 14, 2013.

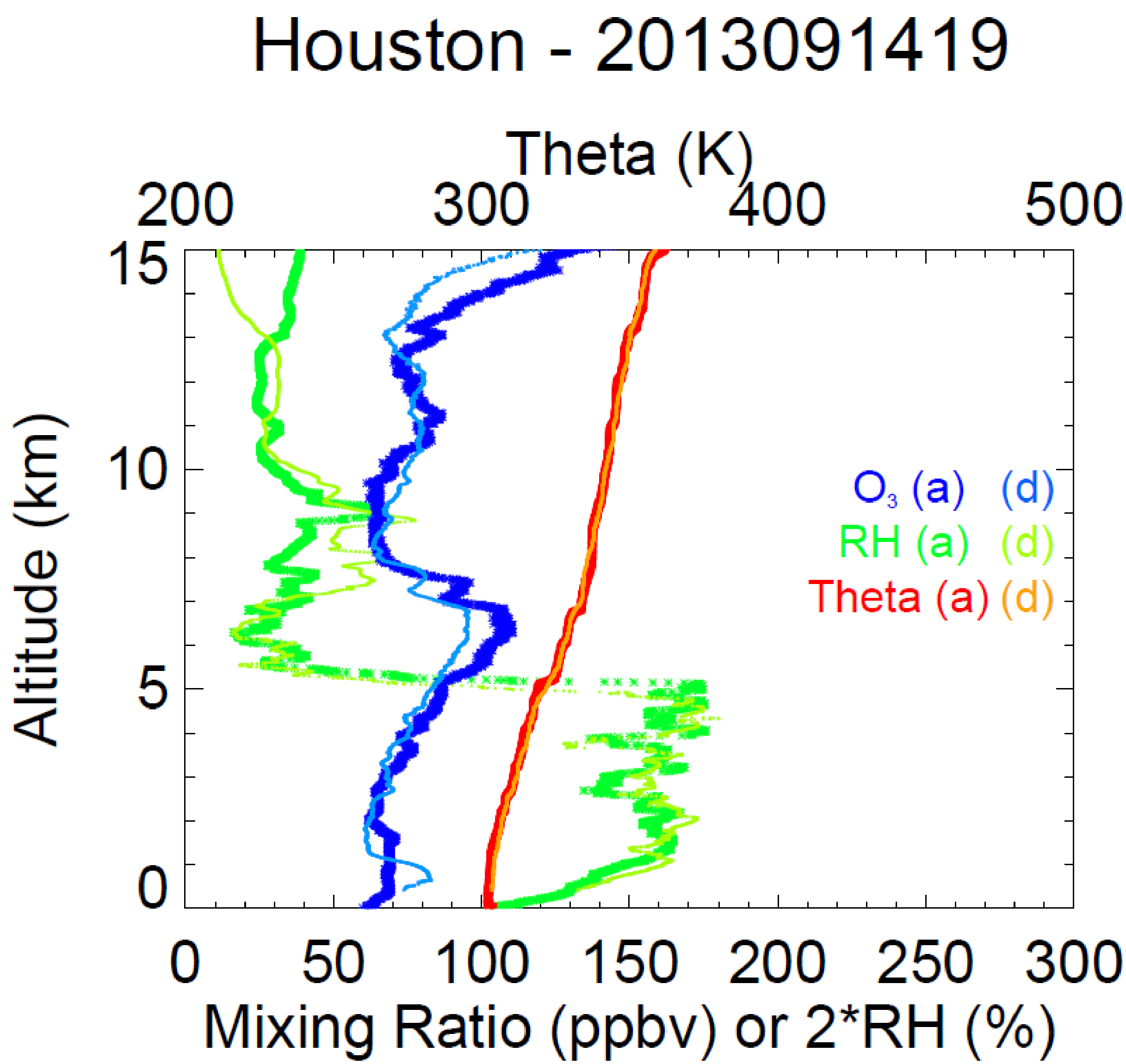


Figure 91. Ozonesonde data on September 14, 2013, launched from the University of Houston at 1:00 p.m. CST.

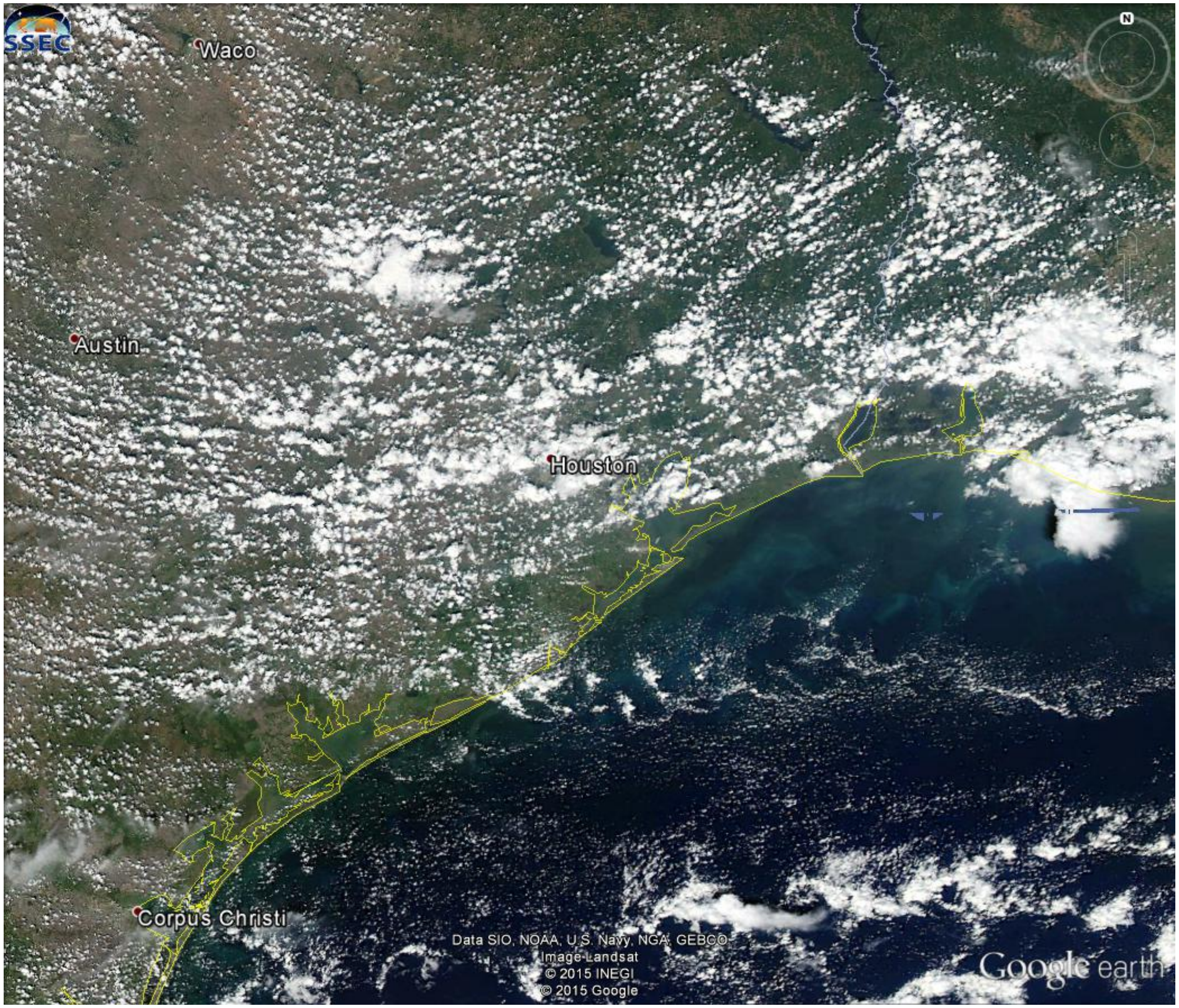


Figure 92. MODIS-AQUA image from September 14, 2013. Scattered fair weather cumulus clouds developed throughout the region, especially over inland areas.

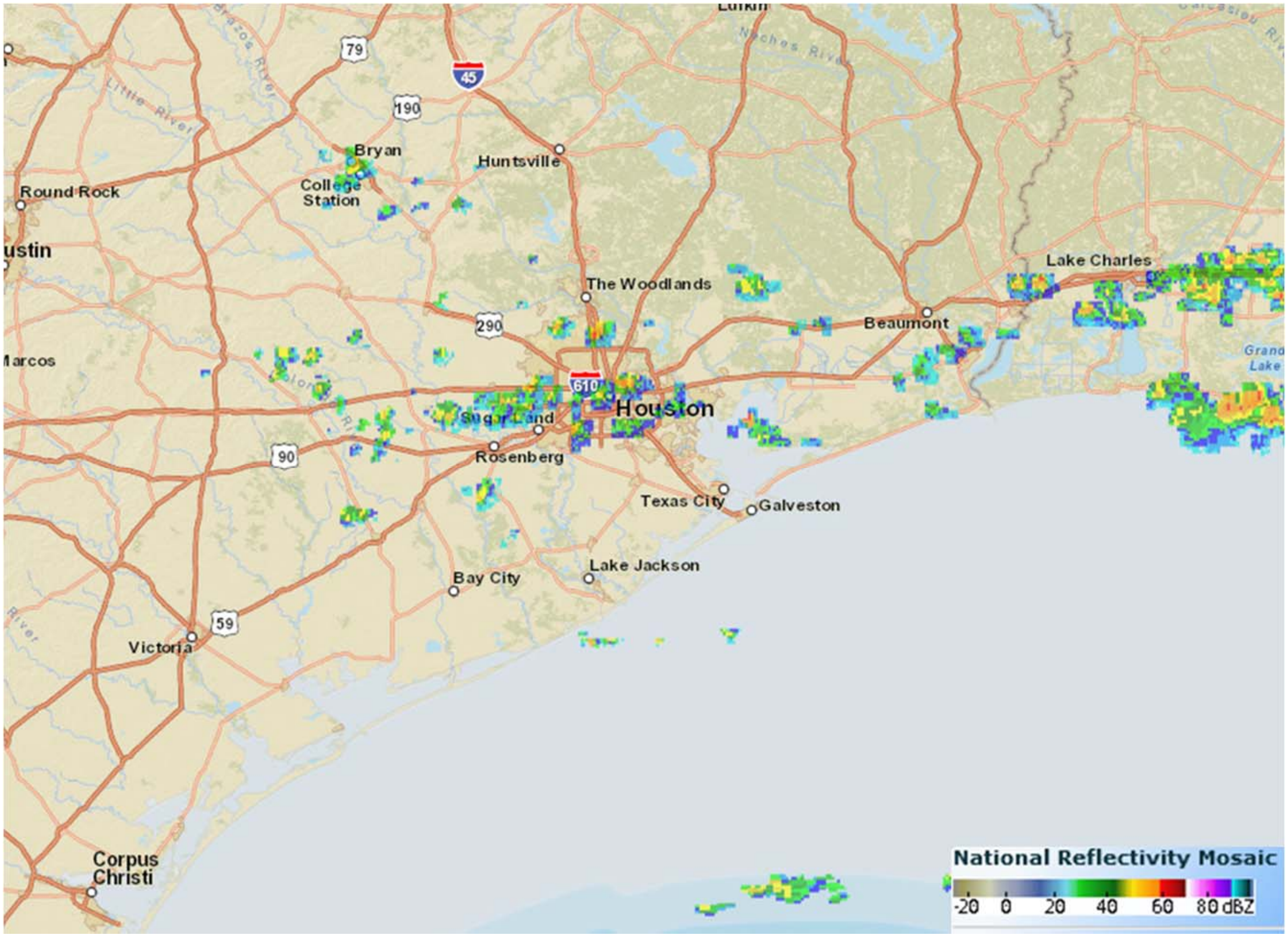


Figure 93. Regional radar image from 2:00 p.m. CST on September 14, 2013. Scattered showers were moving through the Houston area.

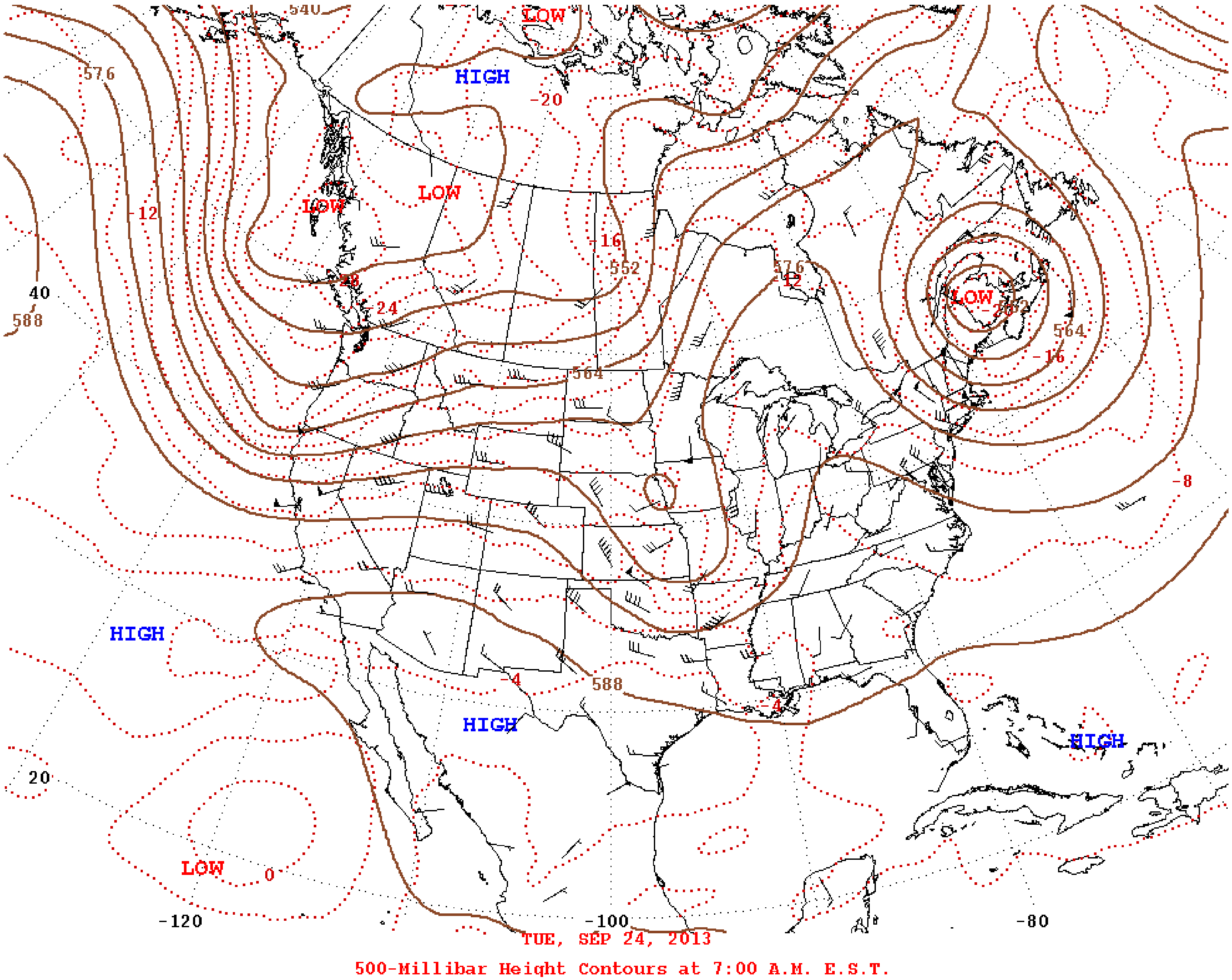
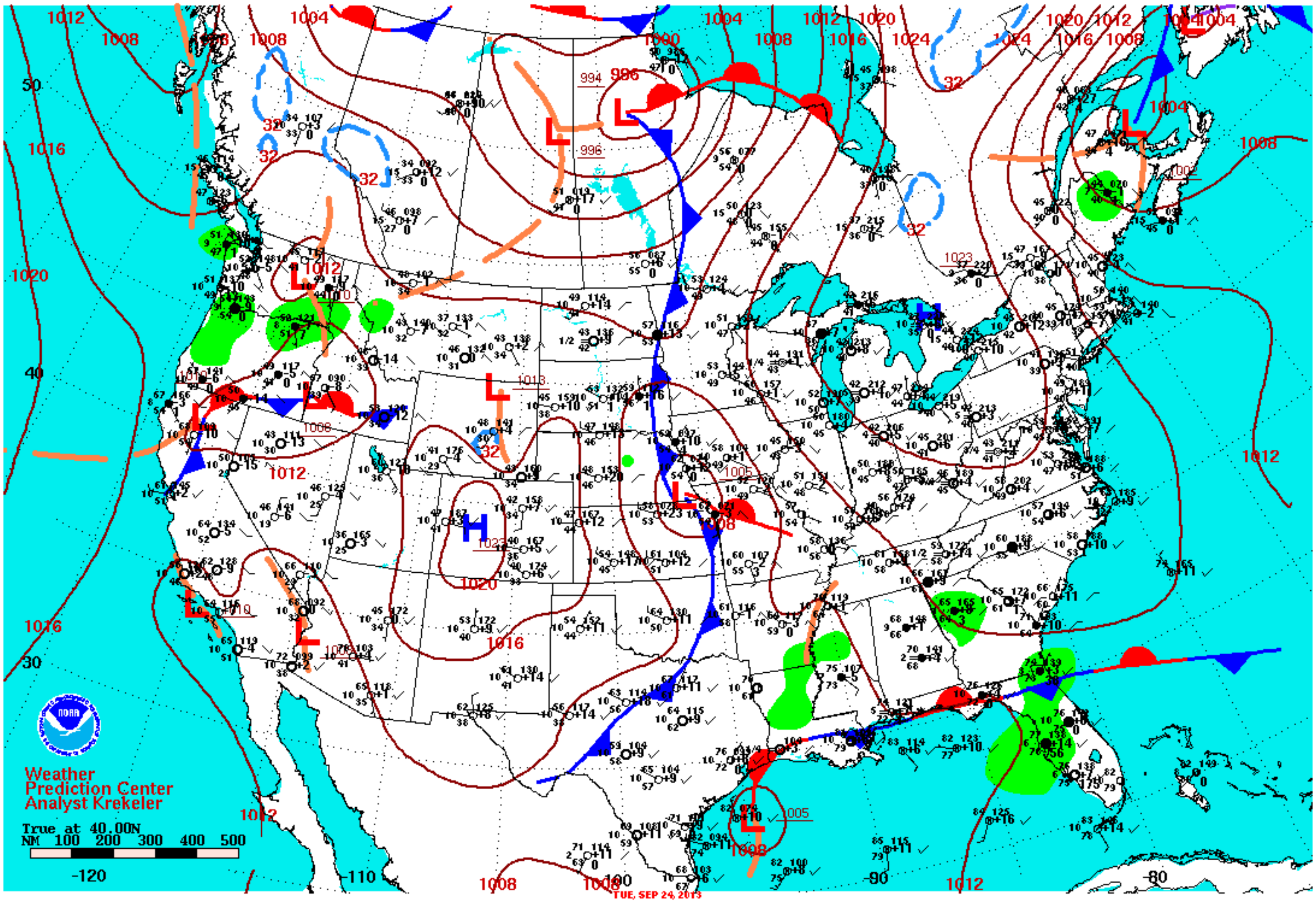


Figure 94. A map showing the height of the 500 mb pressure surface at 6:00 a.m. CST on September 24, 2013. An upper-level trough of low pressure was located over the central and southern Plains.



Surface Weather Map and Station Weather at 7:00 A.M. E.S.T.

Figure 95. Surface pressure map at 6:00 a.m. CST on September 24, 2013. A surface low-pressure system was located south of Houston, and a cold front was located northwest of Houston. A moderate northerly (offshore) pressure gradient developed as the cold front moved through southeast Texas.

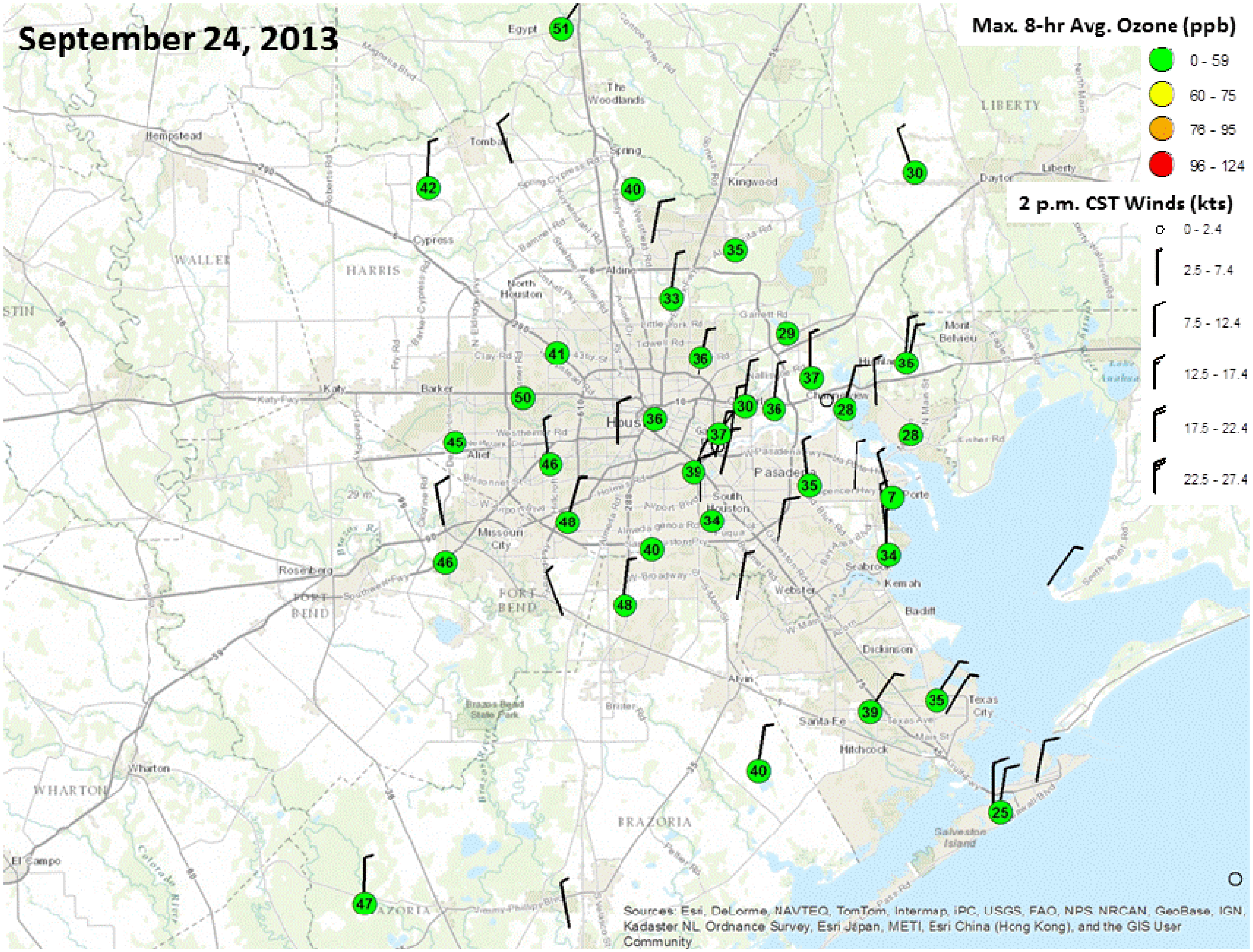


Figure 96. Daily maximum 8-hr average ozone concentrations and surface wind observations from Houston-area monitors on September 24, 2013. Moderate northerly (offshore) winds were reported throughout the Houston area behind a departing cold front.

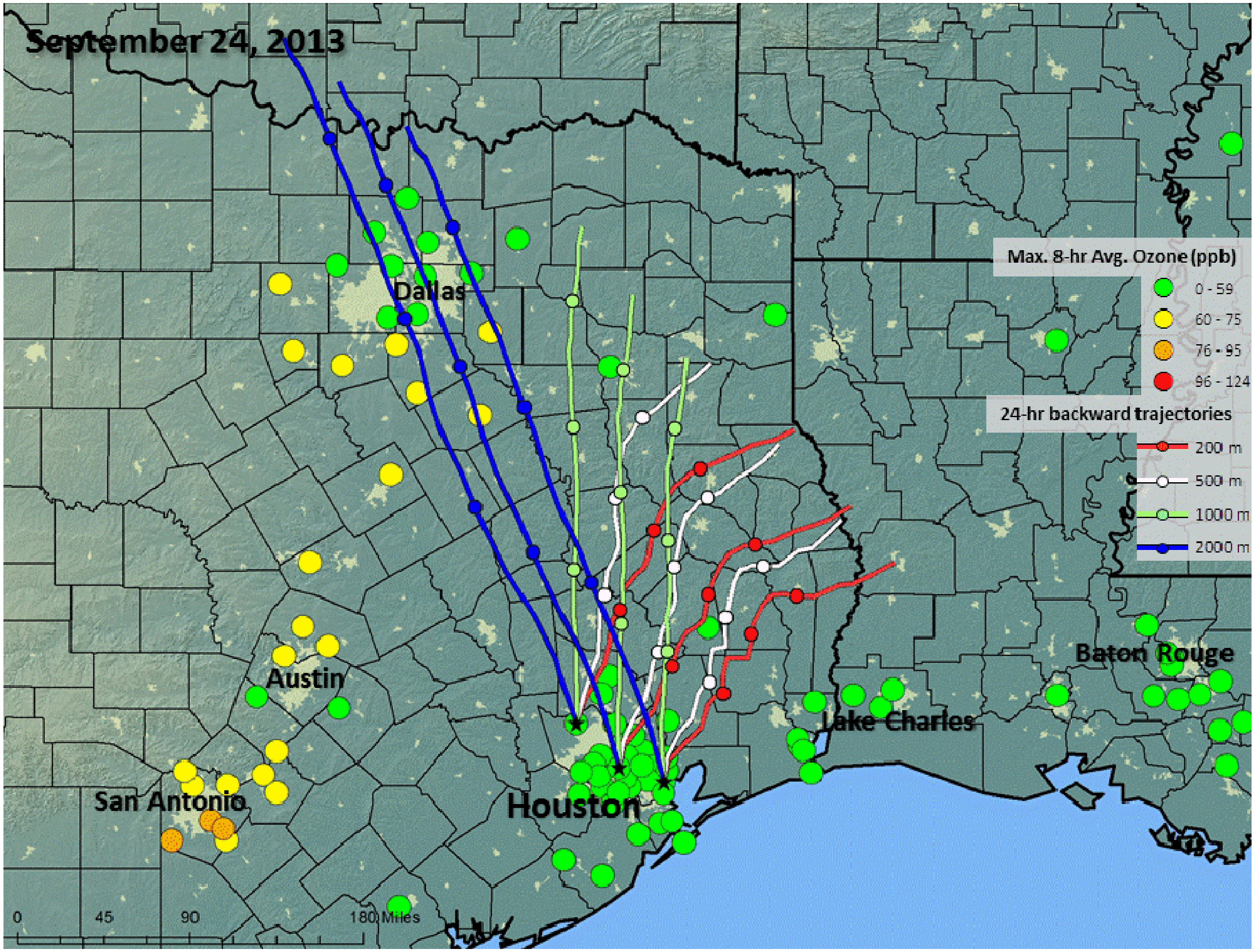


Figure 97. Daily maximum 8-hr average ozone concentrations and 24-hr backward trajectories ending at 6:00 p.m. CST on September 24, 2013. The trajectories indicate northeasterly winds in the low levels and north-northwesterly winds aloft; this backing of winds with height is consistent with cold air advection behind a departing low-pressure system. Dots along the trajectories are at 6-hr intervals.

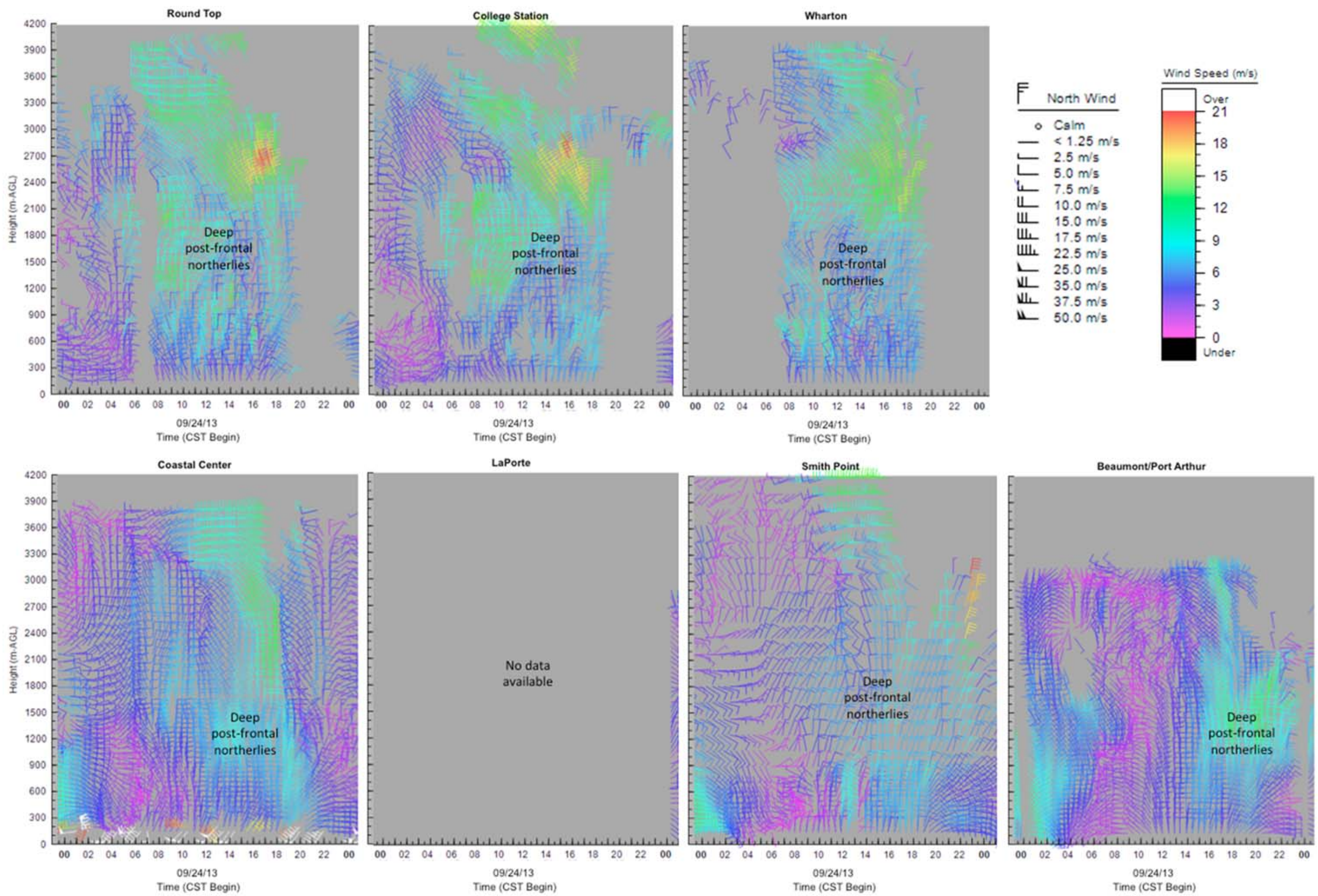


Figure 98. Wind profiler data on September 24, 2013. Deep northerly flow was observed behind a departing cold front on September 24.

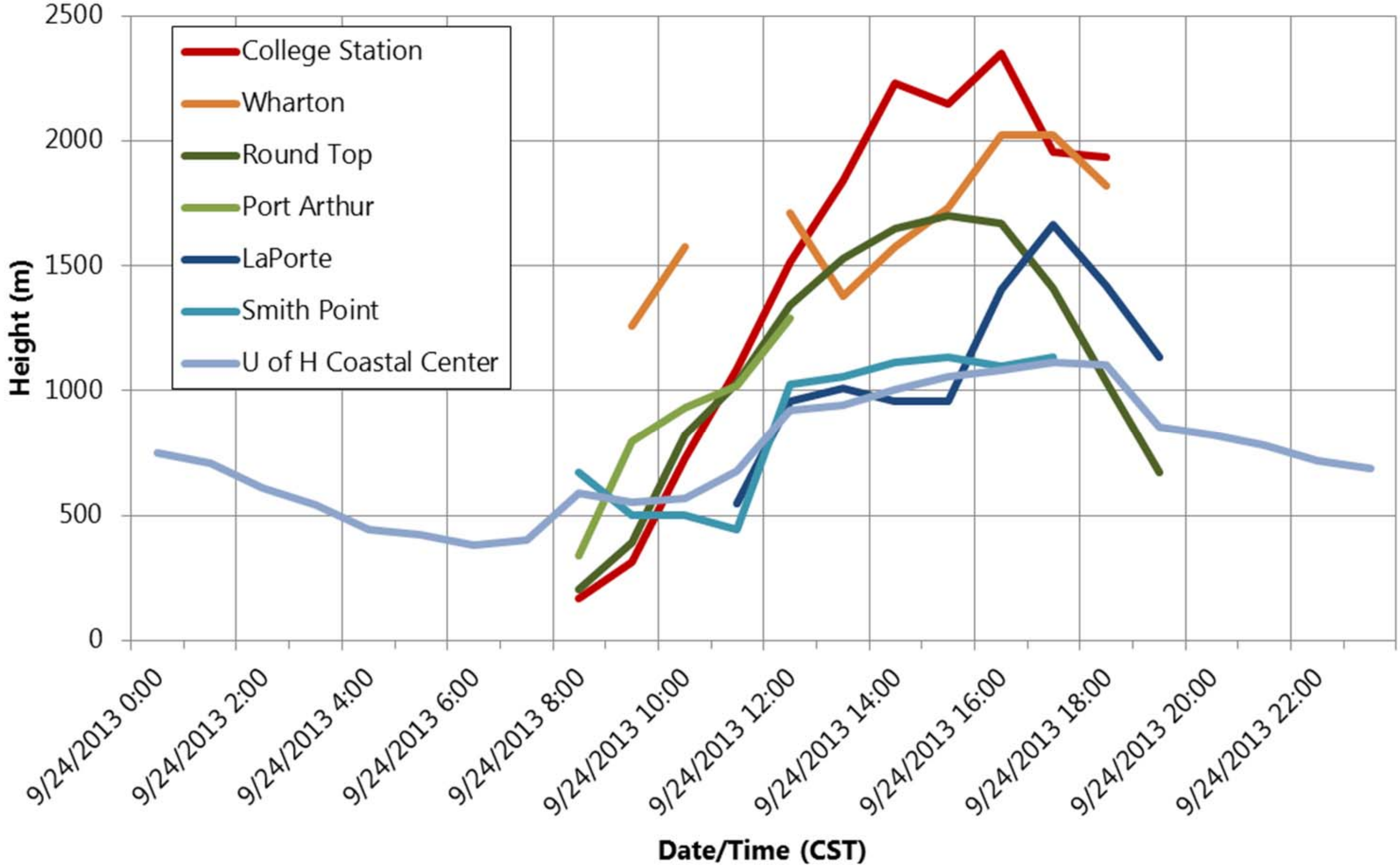


Figure 99. Hourly mixing heights on September 24, 2013.

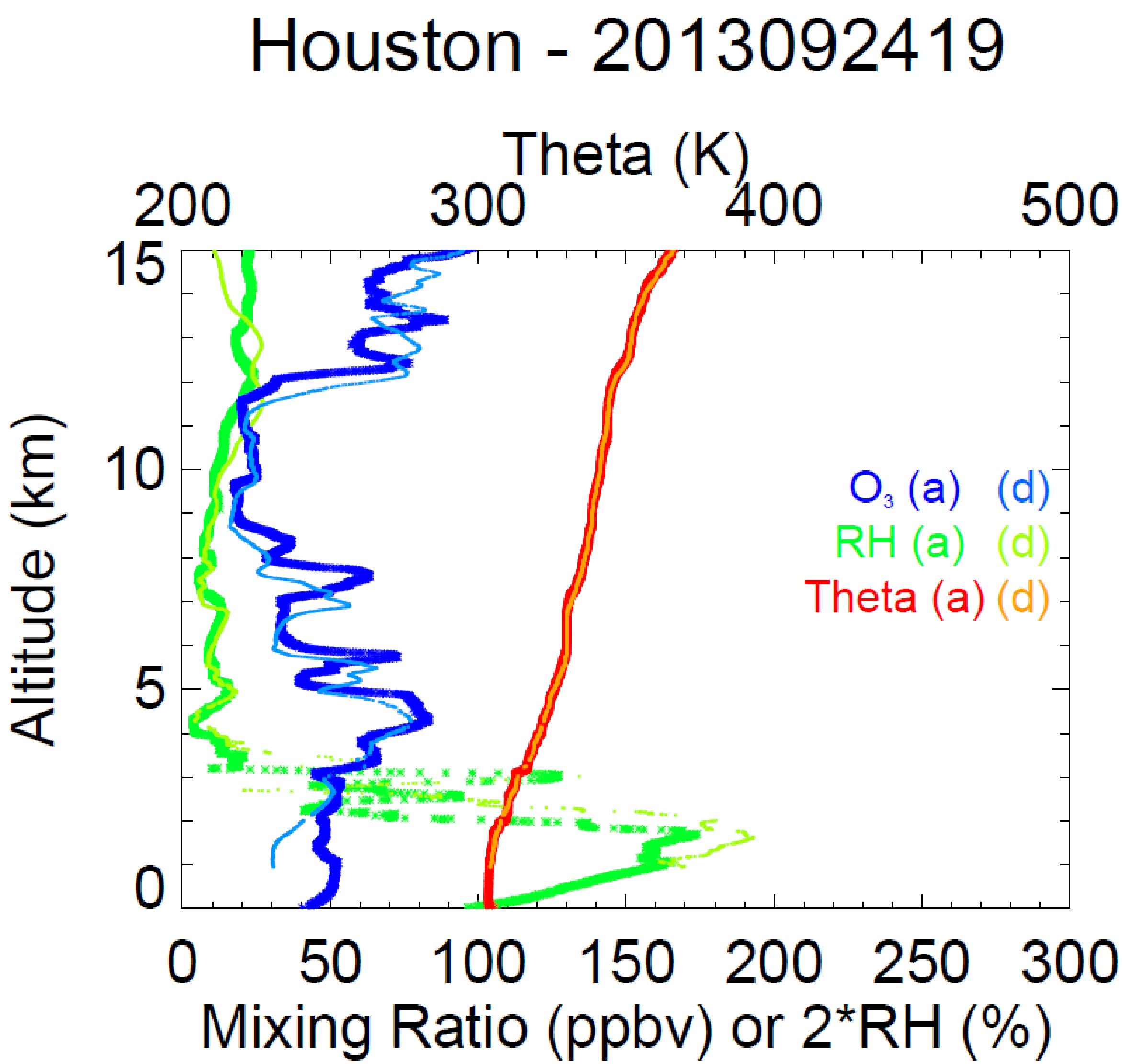


Figure 100. Ozonesonde data on September 24, 2013, launched from the University of Houston at 1:13 p.m. CST.

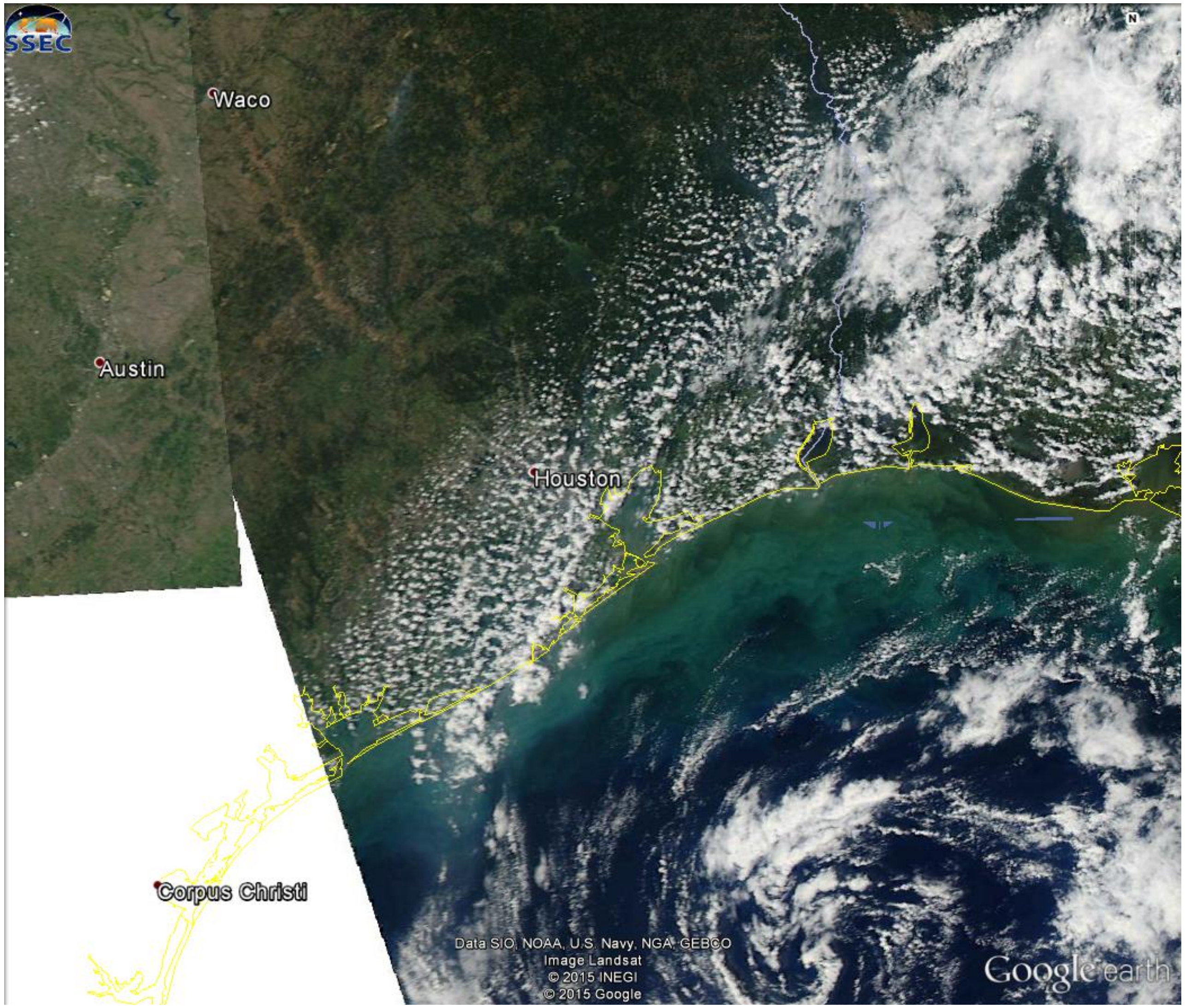


Figure 101. MODIS-AQUA image from September 24, 2013. Scattered fair weather cumulus clouds developed throughout southeast Texas behind a departing low-pressure system.

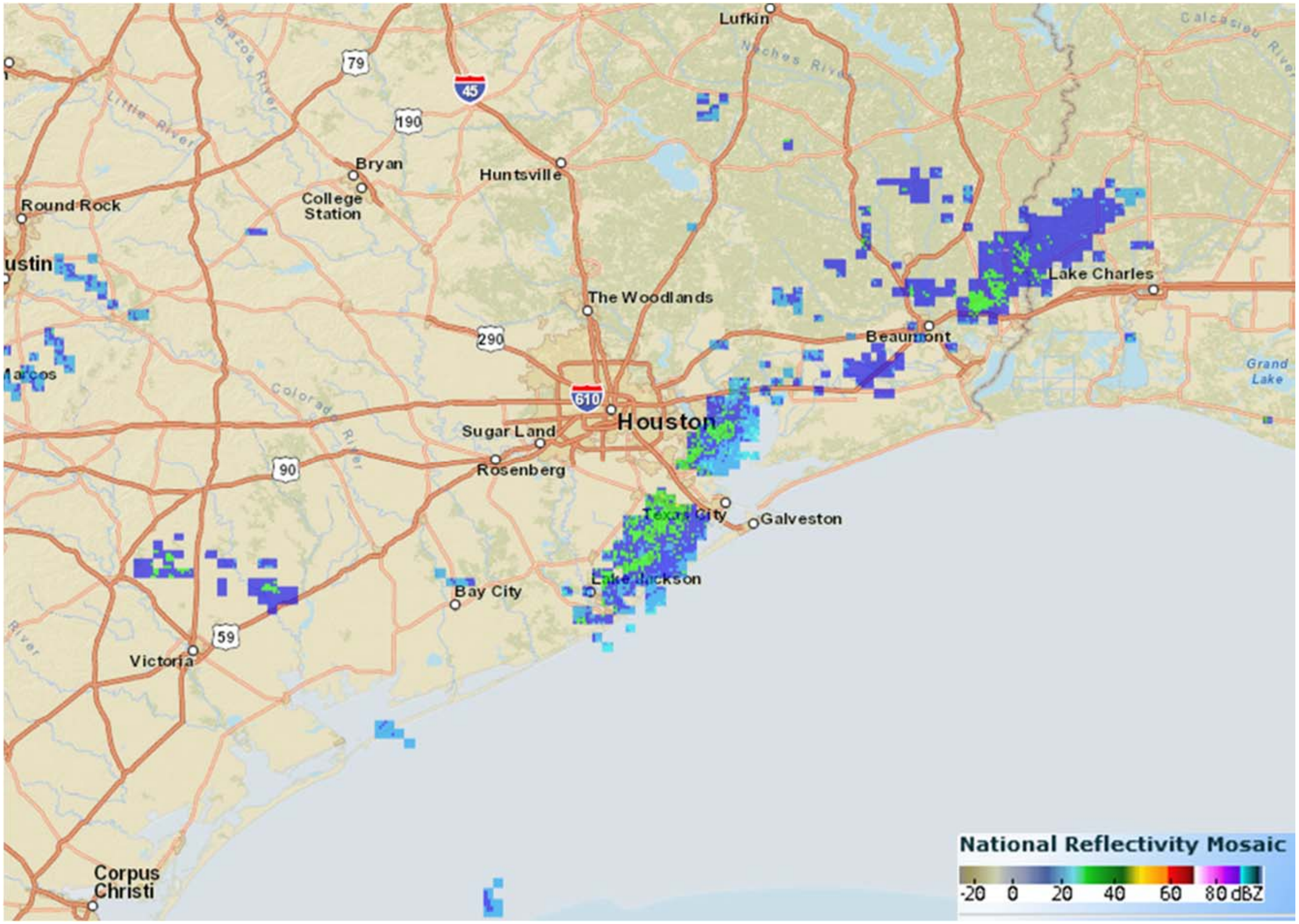


Figure 102. Regional radar image from 2:00 p.m. CST on September 24, 2013. Areas of light precipitation were detected south and east of Houston.

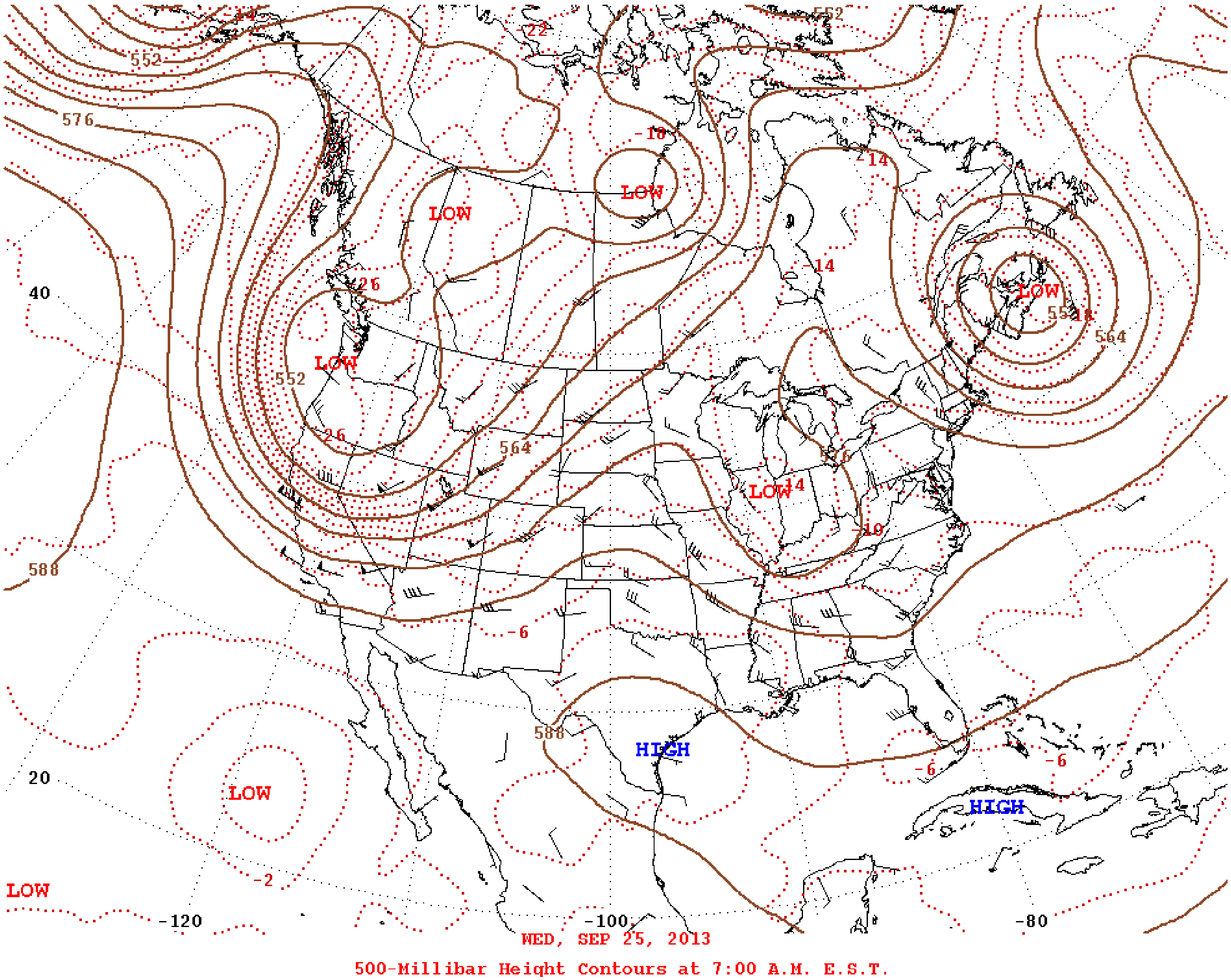
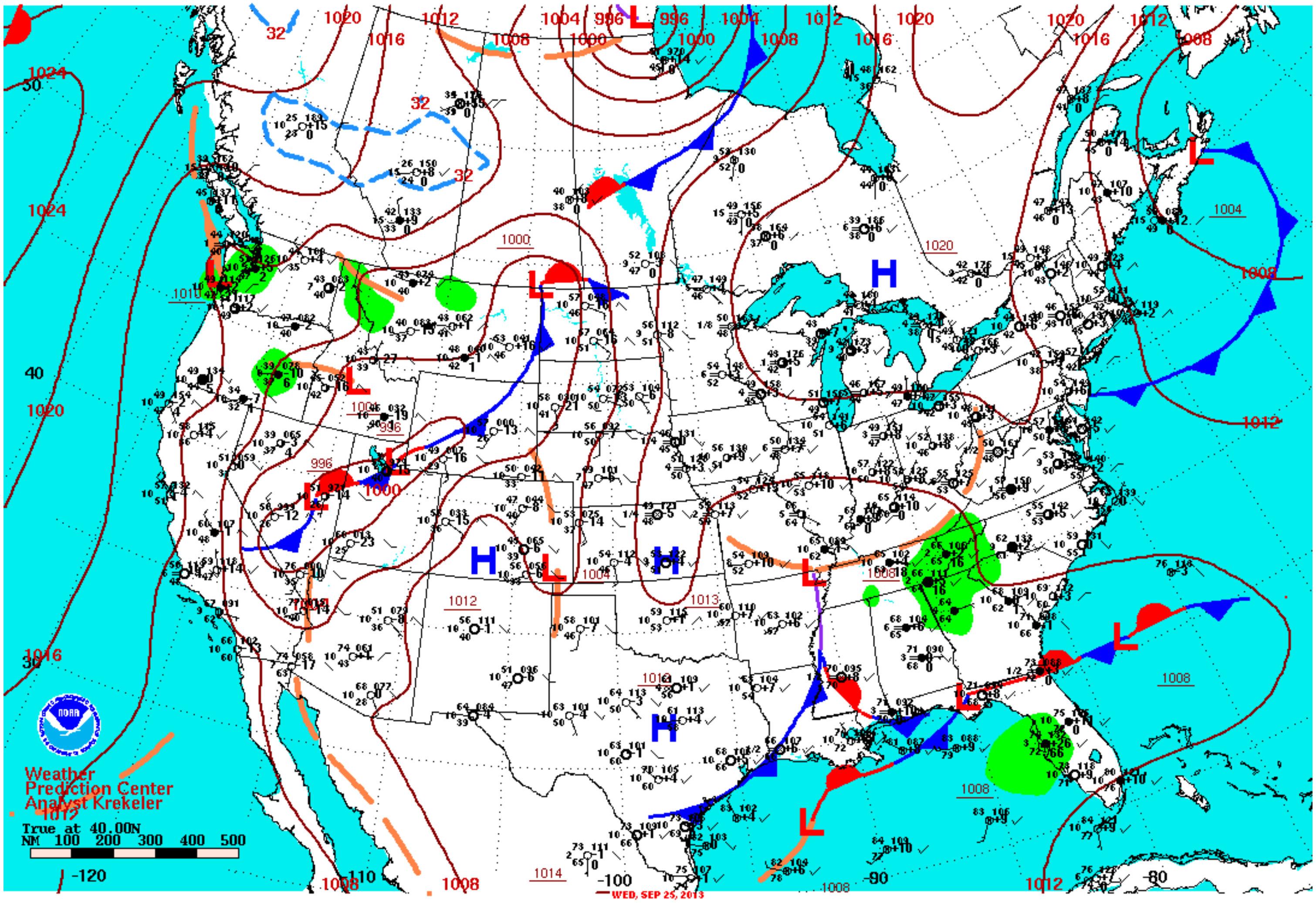


Figure 103. A map showing the height of the 500 mb pressure surface at 6:00 a.m. CST on September 25, 2013. An upper-level high-pressure system was located over the southern Plains.



Surface Weather Map and Station Weather at 7:00 A.M. E.S.T.

Figure 104. Surface pressure map at 6:00 a.m. CST on September 25, 2013. A cold front was located southeast of Houston and a surface high-pressure system was located over the southern Plains, resulting in a northerly (offshore) large-scale pressure gradient in the Houston area.

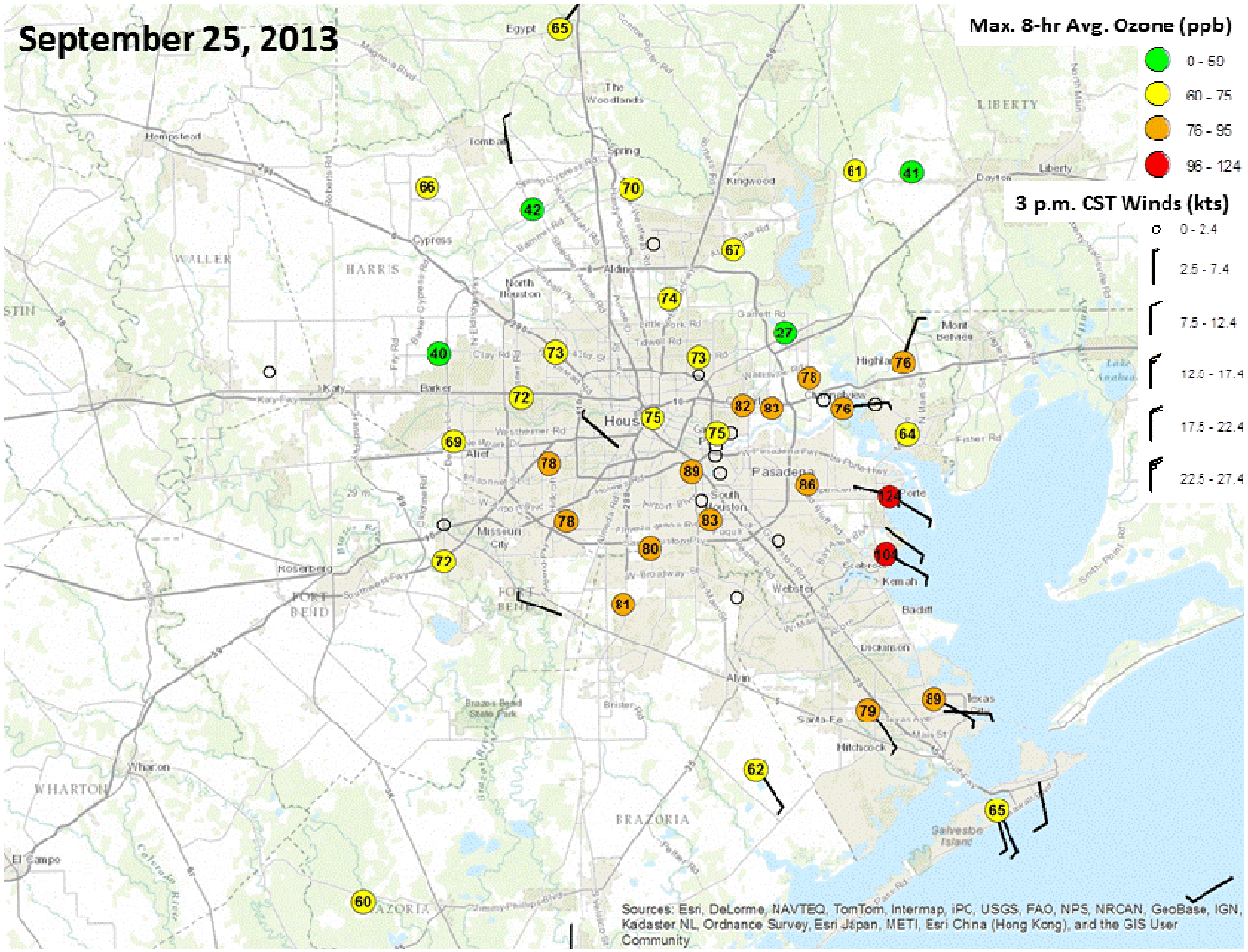


Figure 105. Daily maximum 8-hr average ozone concentrations and surface wind observations from Houston area monitors on September 25, 2013. Winds were calm or light northerly (offshore) over inland areas, while a weak Bay breeze developed along Galveston Bay and a weak Gulf breeze developed along the coast. The light winds limited pollutant dispersion. 8-hr ozone concentrations were high across the southern half of the Houston area, but were highest along the west side of Galveston Bay near the interface of the continental and maritime air masses.

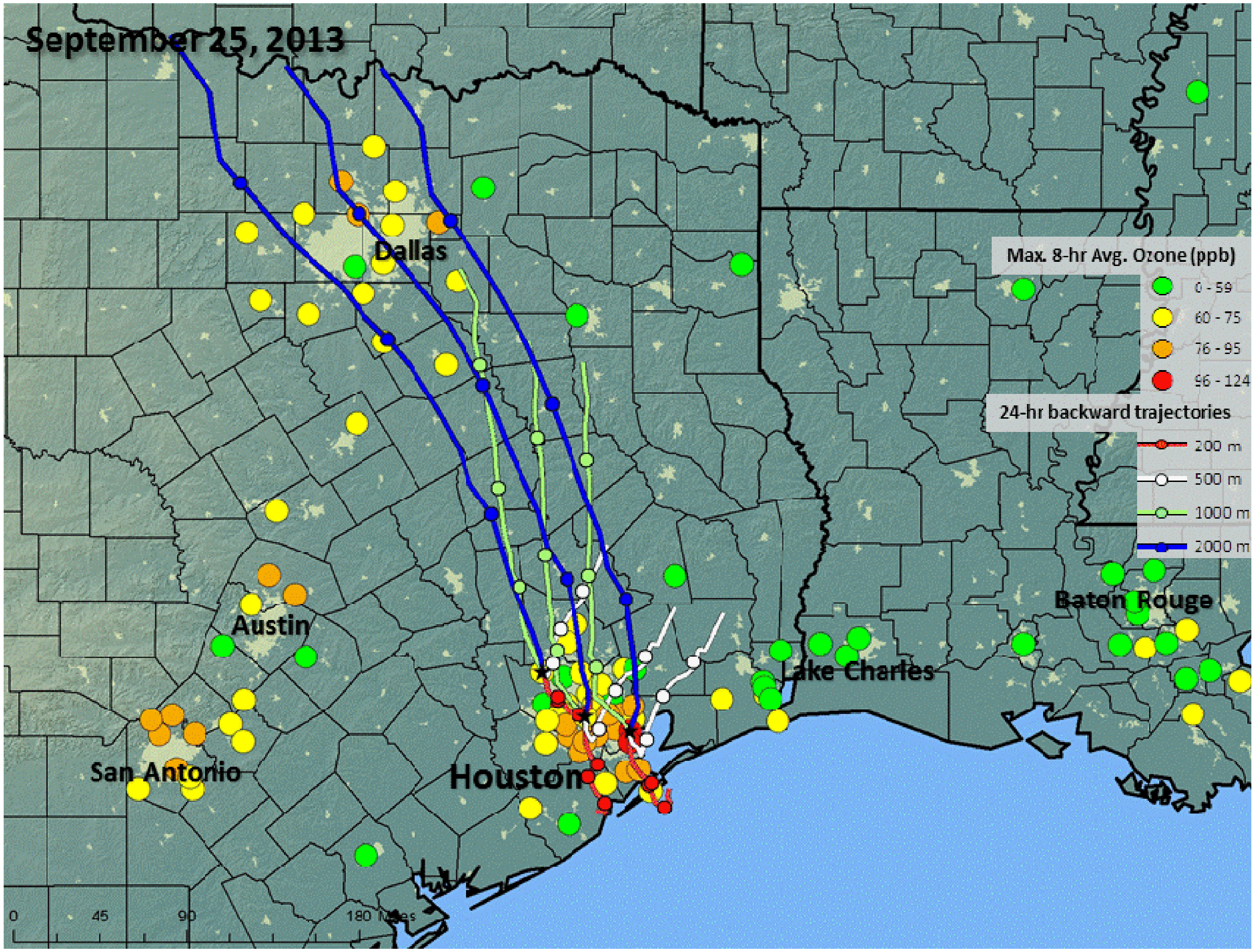


Figure 106. Daily maximum 8-hr average ozone concentrations and 24-hr backward trajectories ending at 6:00 p.m. CST on September 25, 2013. The trajectories depicted northerly (offshore) winds at and above 500 m; these winds transported polluted continental air into the Houston area. Trajectories at 200 m depicted very light southeasterly to southerly (onshore) winds, illustrating the development of a very shallow marine layer. The low-level wind shift from offshore to onshore indicates potential for recirculation of pollutants and cross-city pollutant transport. Dots along the trajectories are at 6-hr intervals.

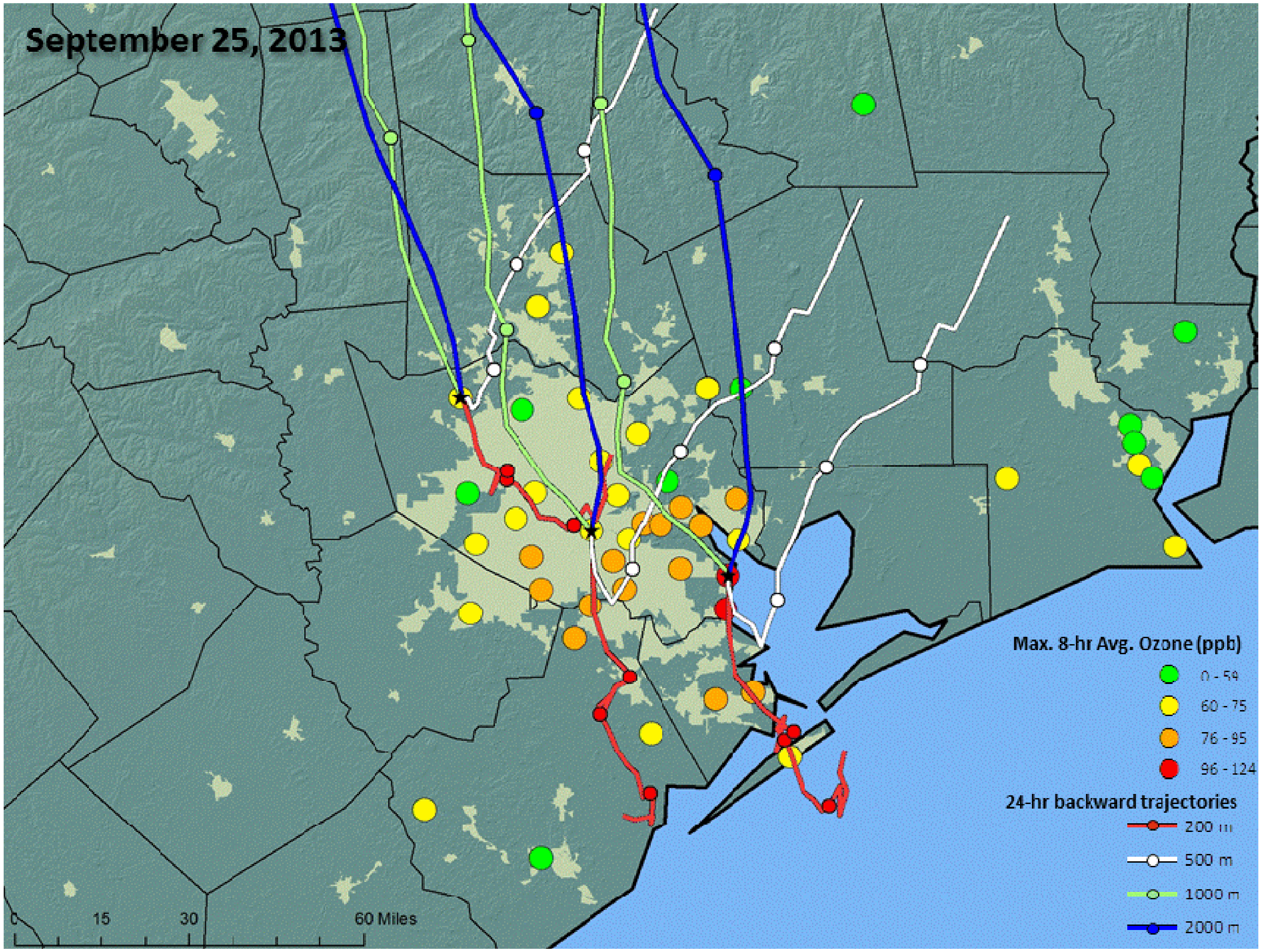


Figure 107. Daily maximum 8-hr average ozone concentrations and 24-hr backward trajectories ending at 6:00 p.m. CST on September 25, 2013. This figure is similar to Figure 106, but is zoomed in on the Houston area. The trajectories depicted northerly (offshore) winds at and above 500 m; these winds transported polluted continental air into the Houston area. Trajectories at 200 m depicted very light southeasterly to southerly (onshore) winds, illustrating the development of a very shallow marine layer. The low-level wind shift from offshore to onshore indicates potential for recirculation of pollutants and cross-city pollutant transport.

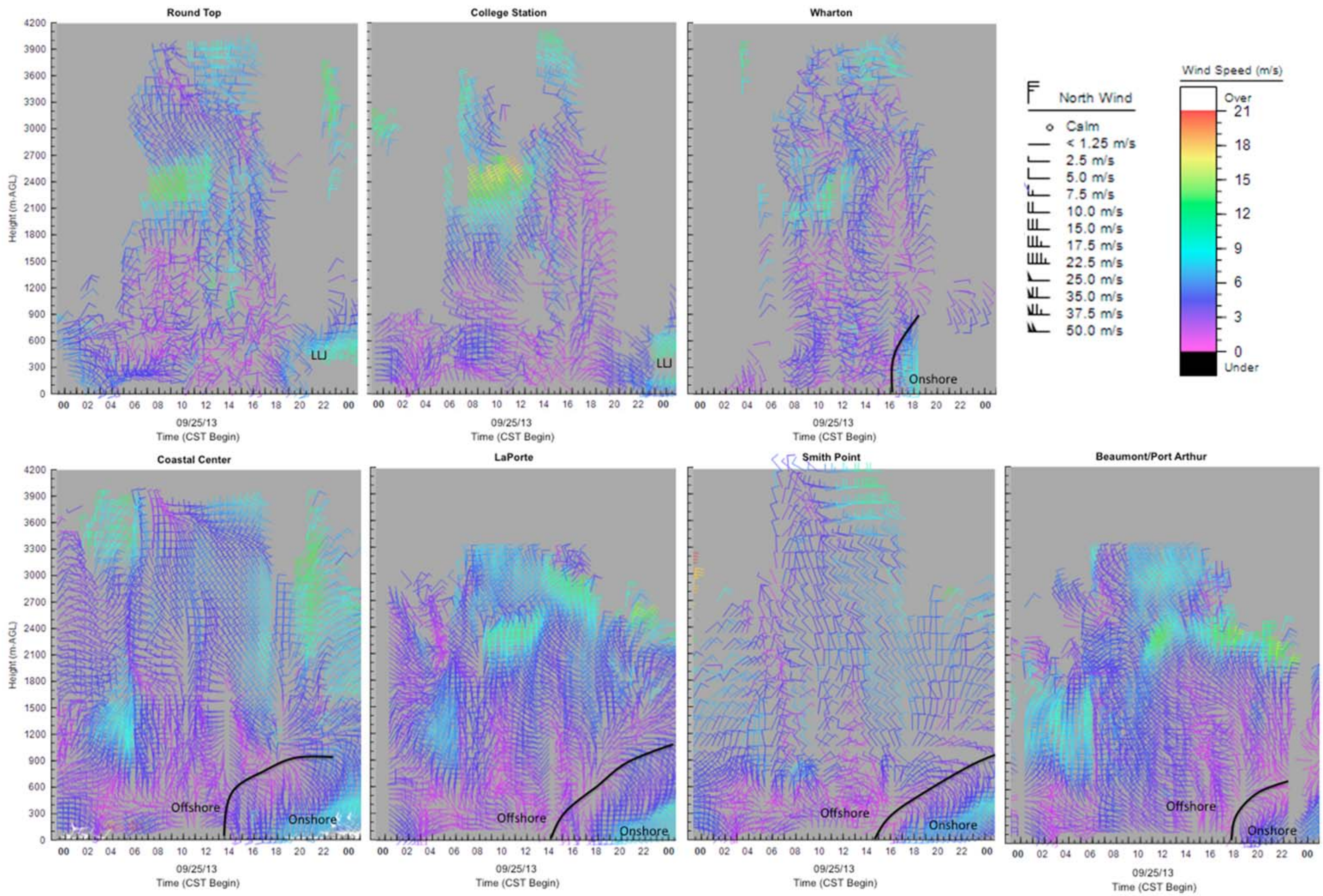


Figure 108. Wind profiler data on September 25, 2013. Light offshore winds were reported on September 25 through the early afternoon, until a weak shallow Bay breeze developed.

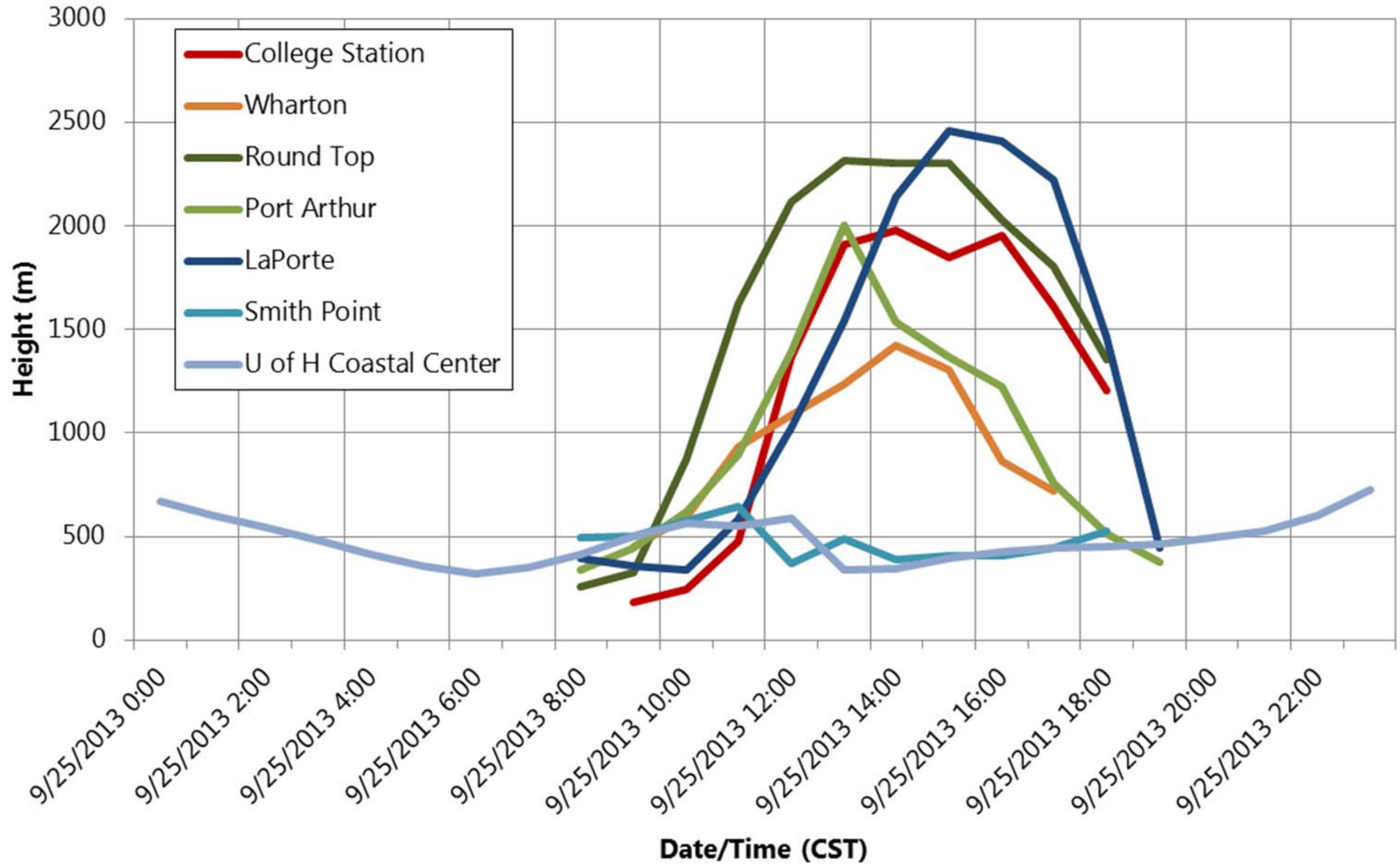


Figure 109. Hourly mixing heights on September 25, 2013.

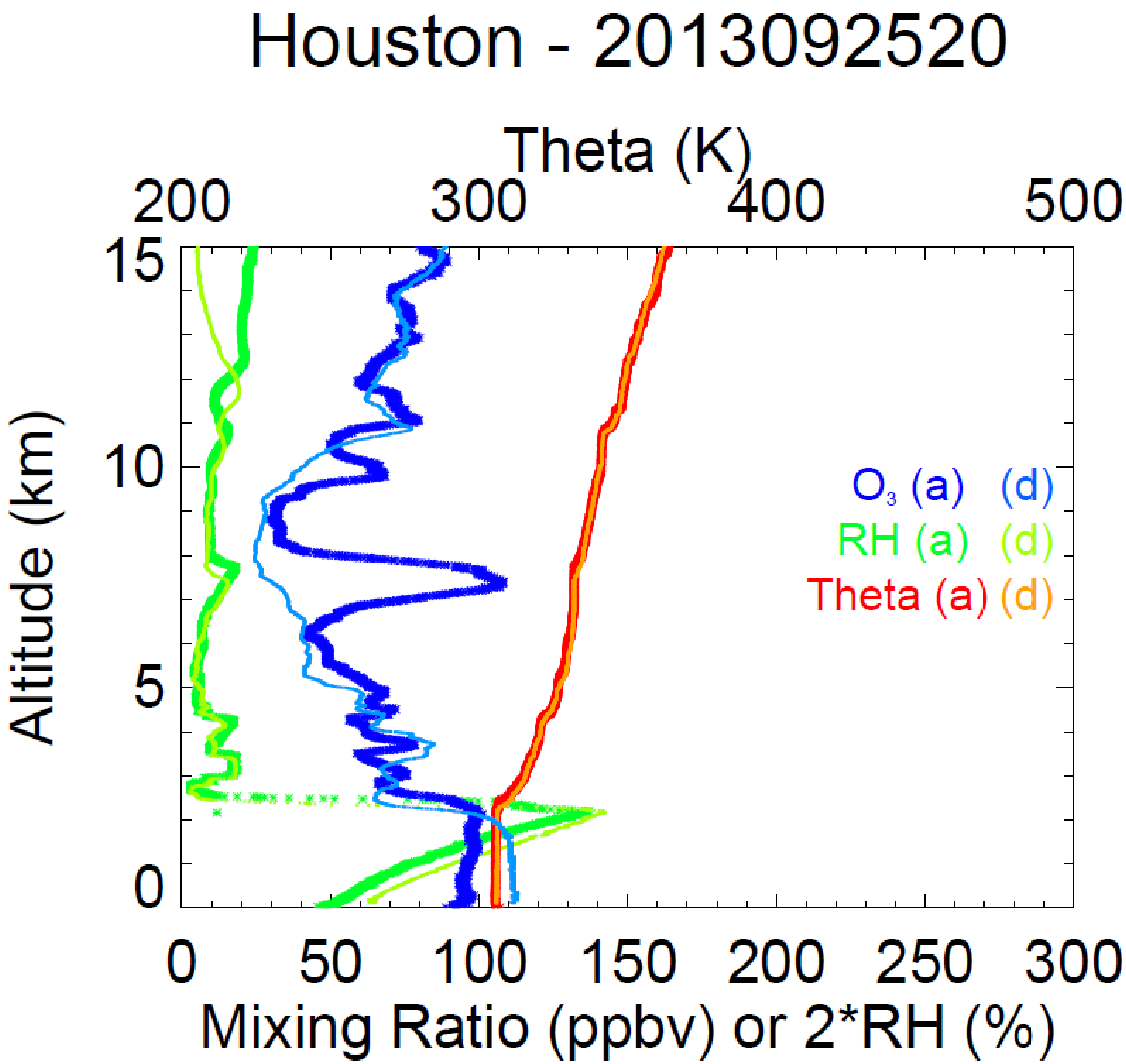


Figure 110. Ozonesonde data on September 25, 2013, launched from the University of Houston at 2:32 p.m. CST.

Figure 111. MODIS-AQUA image from September 25, 2013. Skies were clear throughout southeastern Texas.

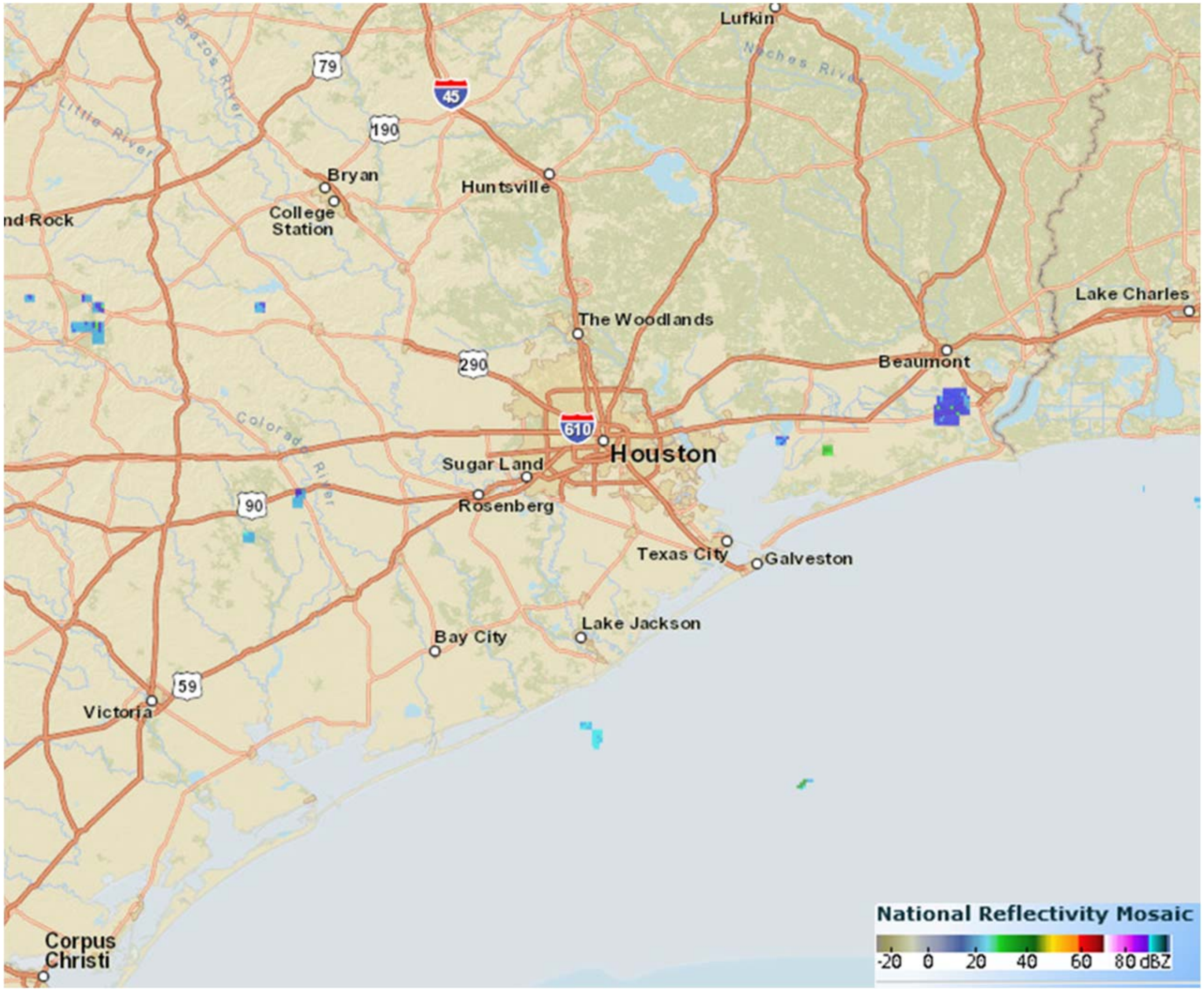


Figure 112. Regional radar image from 2:00 p.m. CST on September 25, 2013. No precipitation was detected throughout the Houston area.

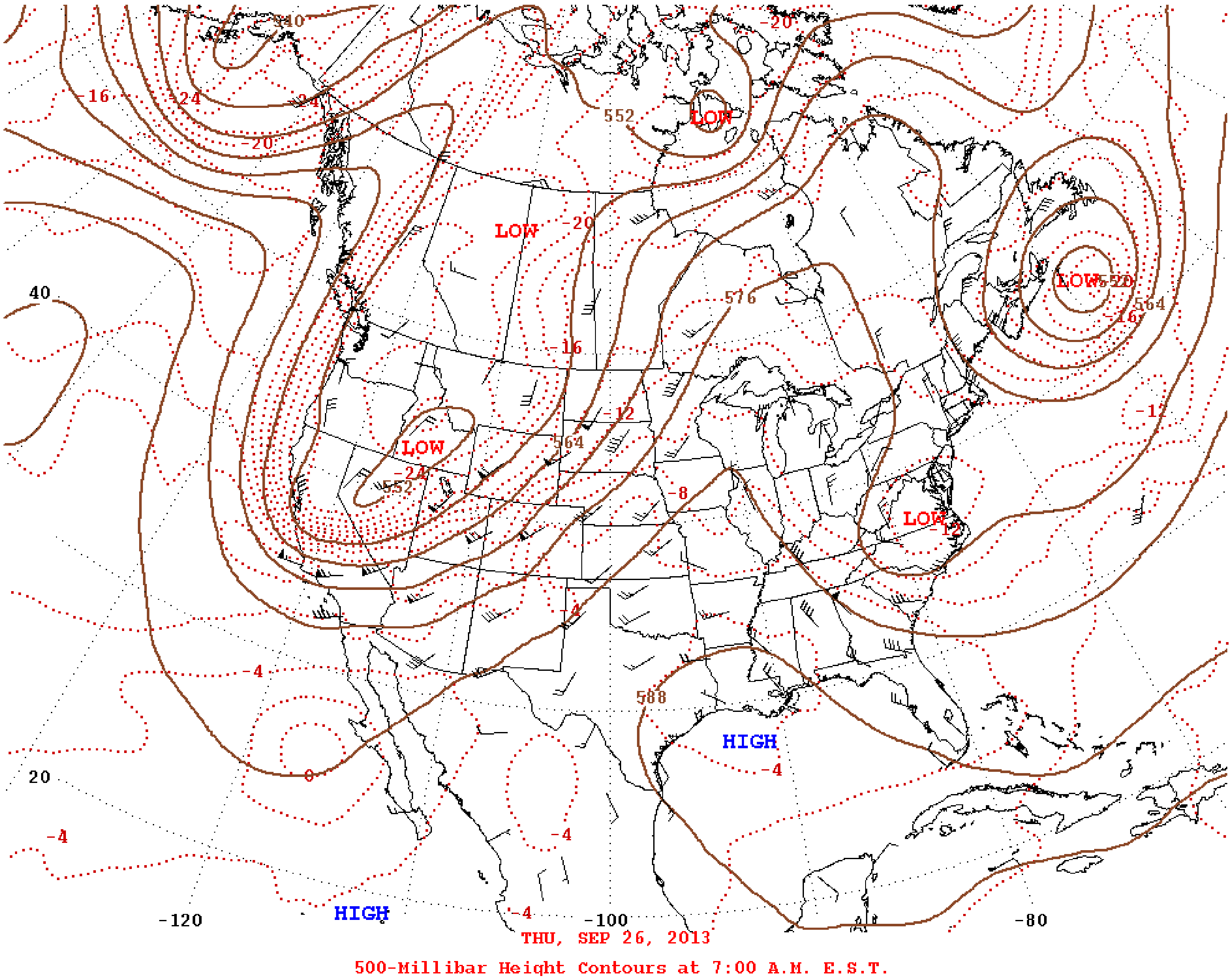


Figure 113. A map showing the height of the 500 mb pressure surface at 6:00 a.m. CST on September 26, 2013. An upper-level high-pressure system was located over the southern Plains.

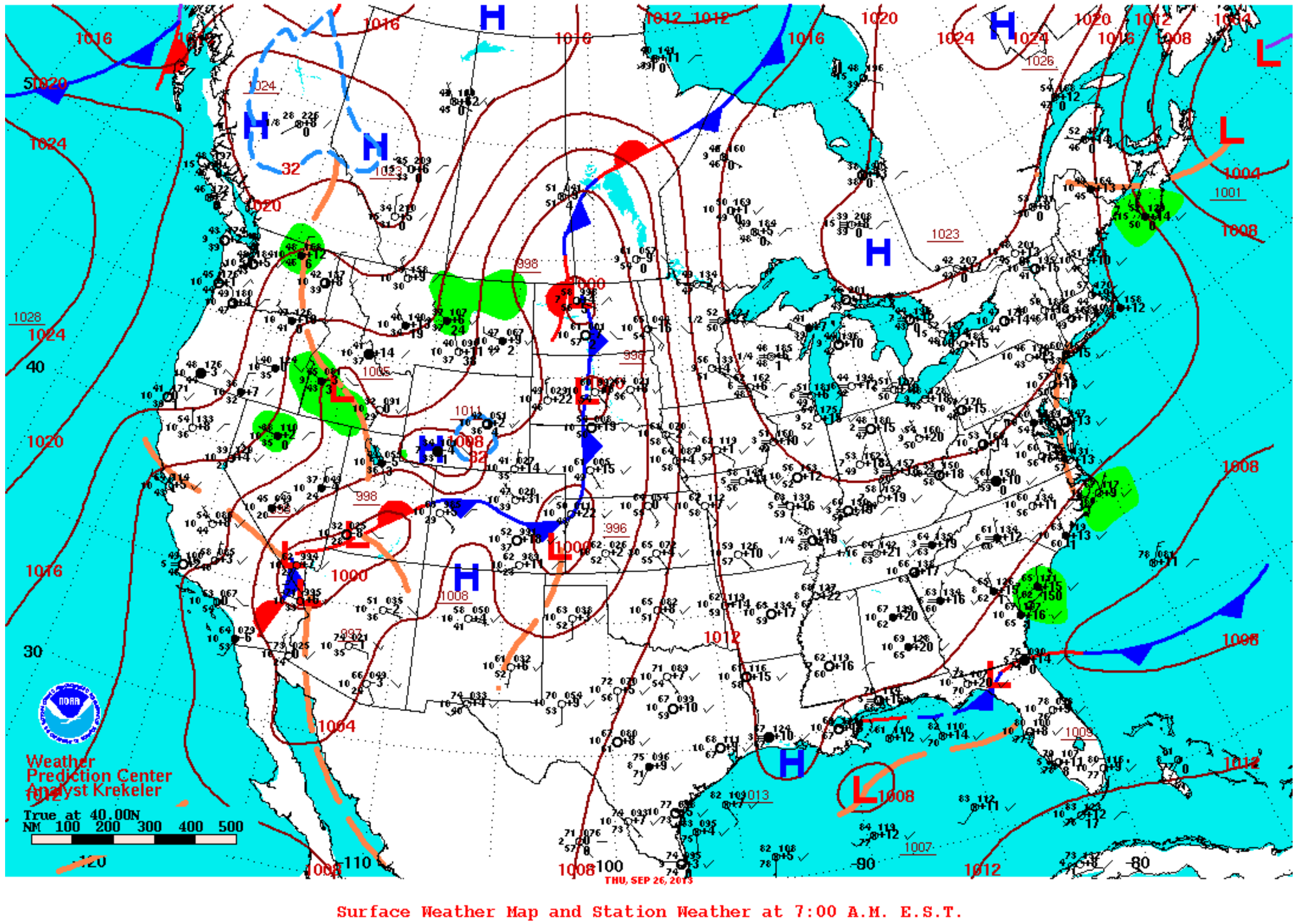


Figure 114. Surface pressure map at 6:00 a.m. CST on September 26, 2013. A broad surface high-pressure system was located from the southeastern United States northward through the Great Lakes, resulting in a weak southeasterly (onshore) pressure gradient in the Houston area.

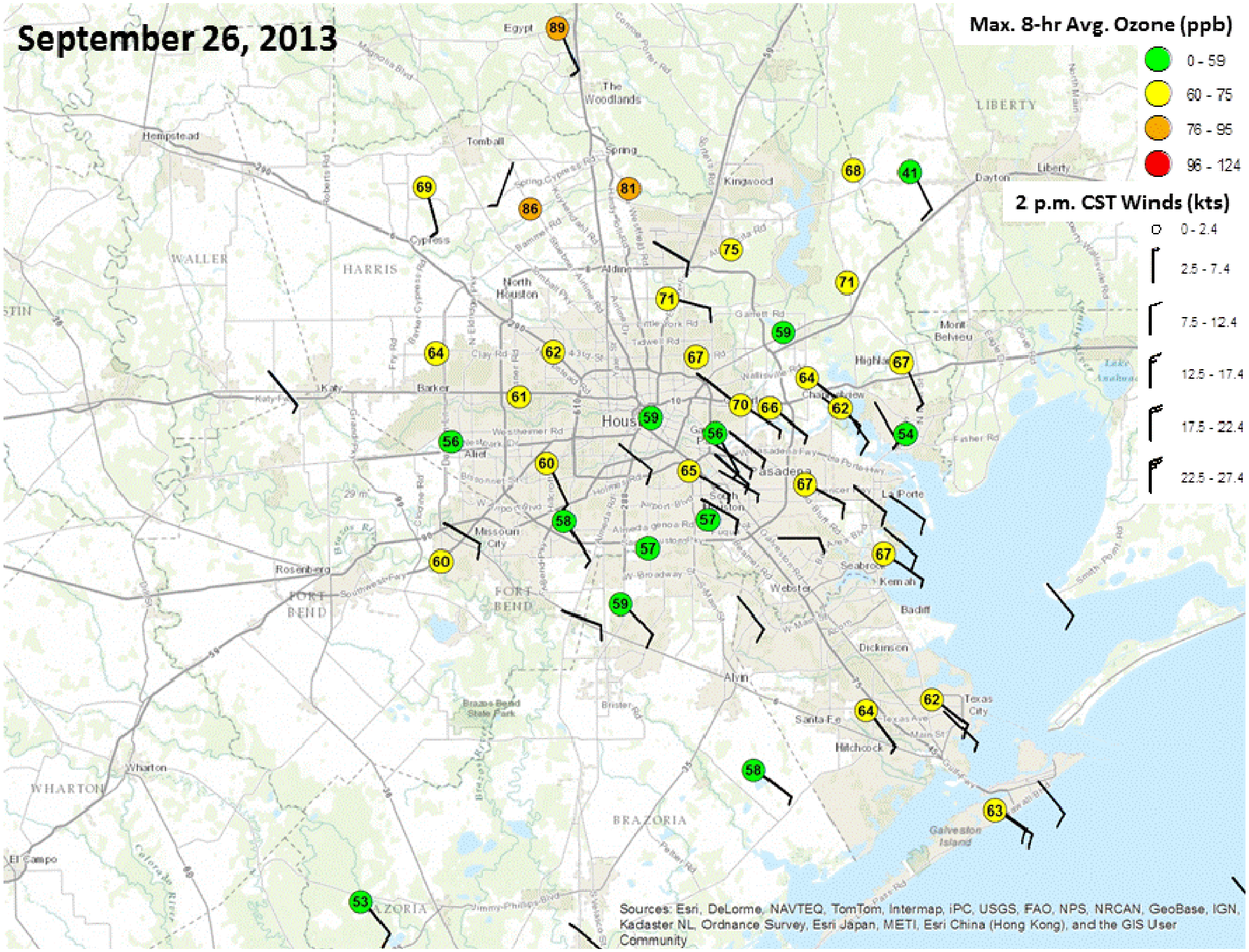


Figure 115. Daily maximum 8-hr average ozone concentrations and surface wind observations from Houston area monitors on September 26, 2013. Light to moderate southeasterly (onshore) winds transported pollutants northwestward across the Houston area. As a result, 8-hr ozone concentrations were highest on the northwest side of Houston.

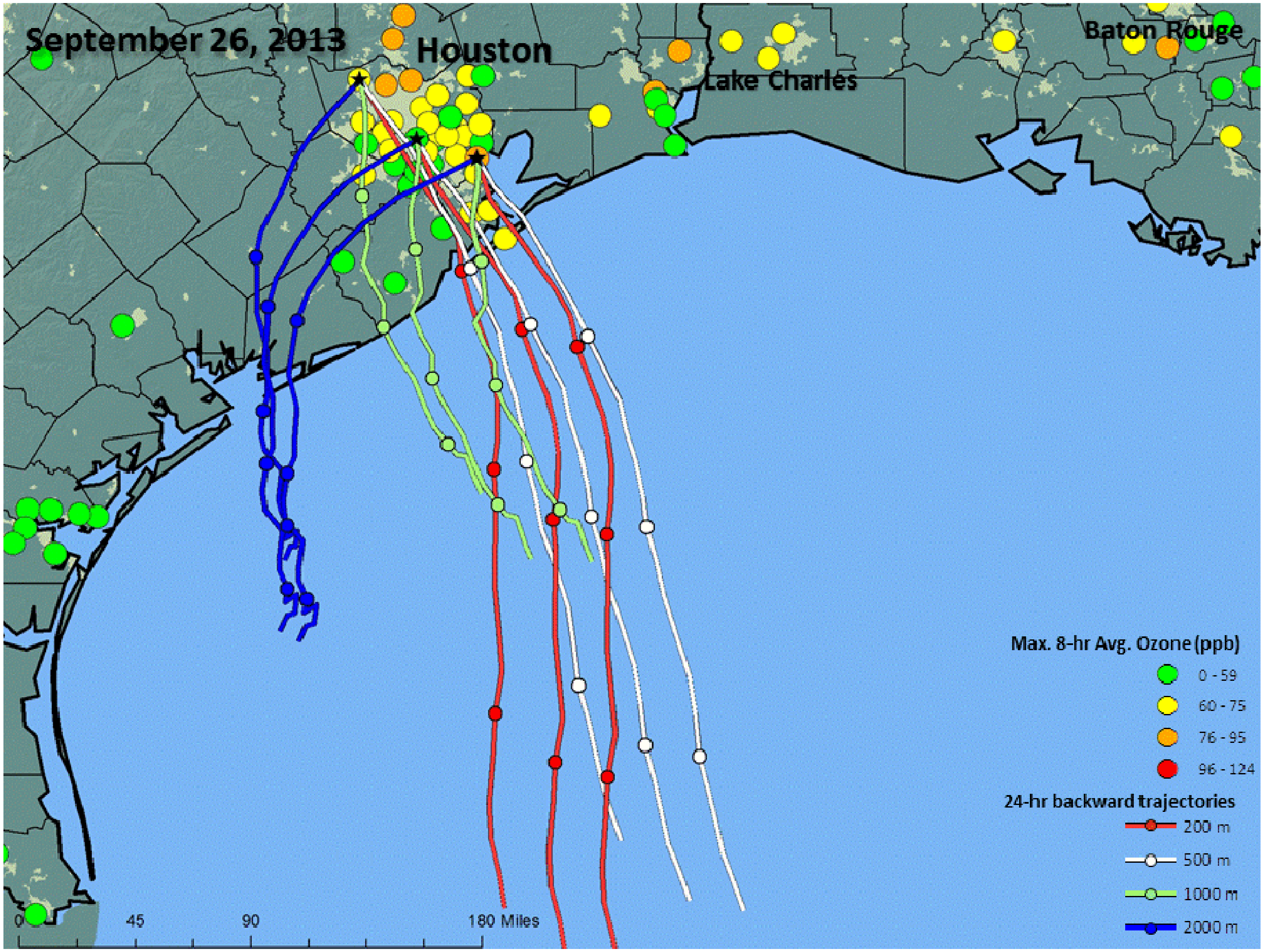


Figure 116. Daily maximum 8-hr average ozone concentrations and 24-hr backward trajectories ending at 6:00 p.m. CST on September 26, 2013. The trajectories depict stronger and deeper onshore winds compared to the previous day. These winds transported higher ozone levels to the north side of Houston. Dots along the trajectories are at 6-hr intervals.

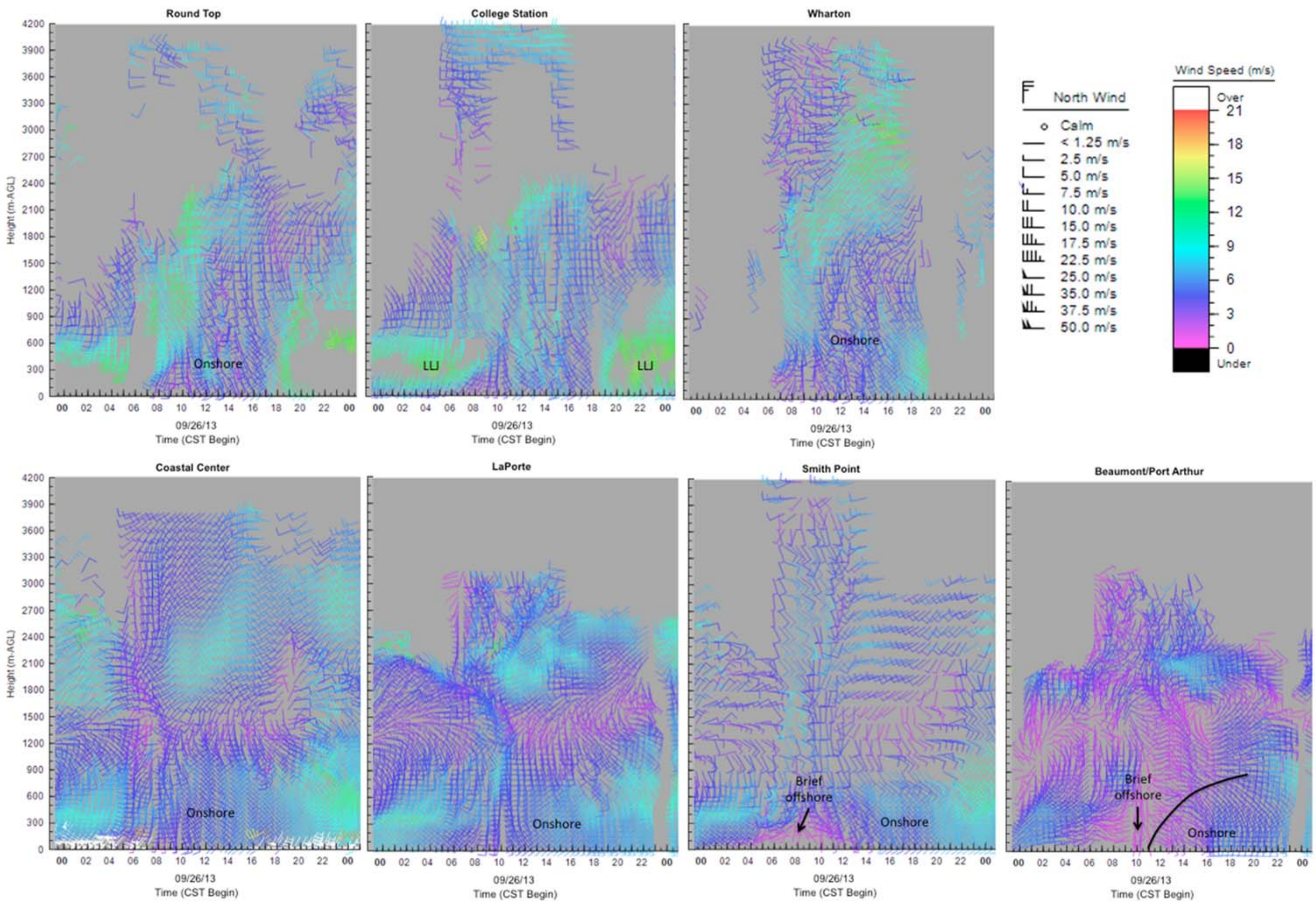


Figure 117. Wind profiler data from the LaPorte radar wind profiler on September 26, 2013. Onshore flow deepened on September 26 in response to a strengthening onshore pressure gradient. As a result, higher ozone levels occurred on the north (downwind) side of Houston.

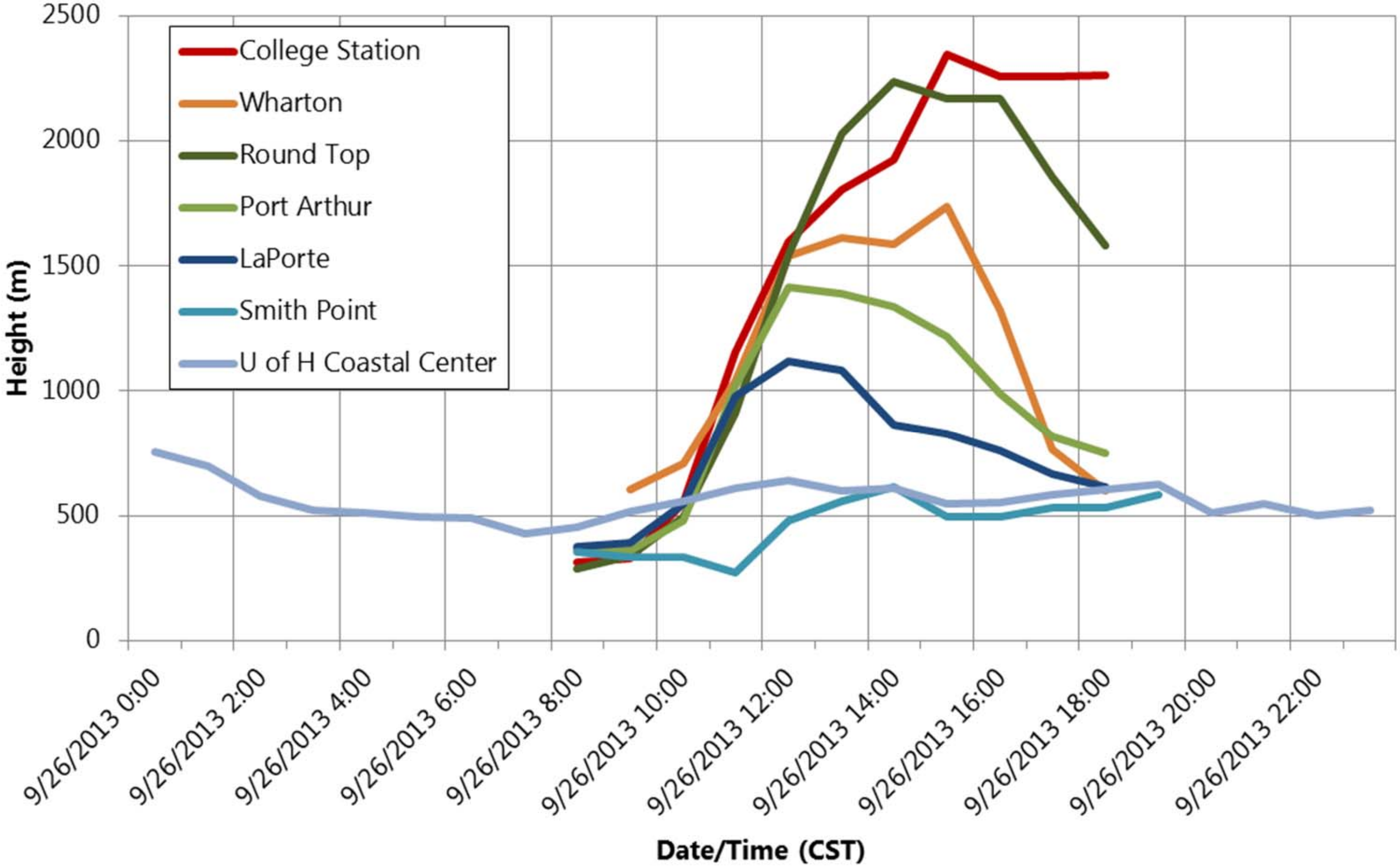


Figure 118. Hourly mixing heights on September 26, 2013.

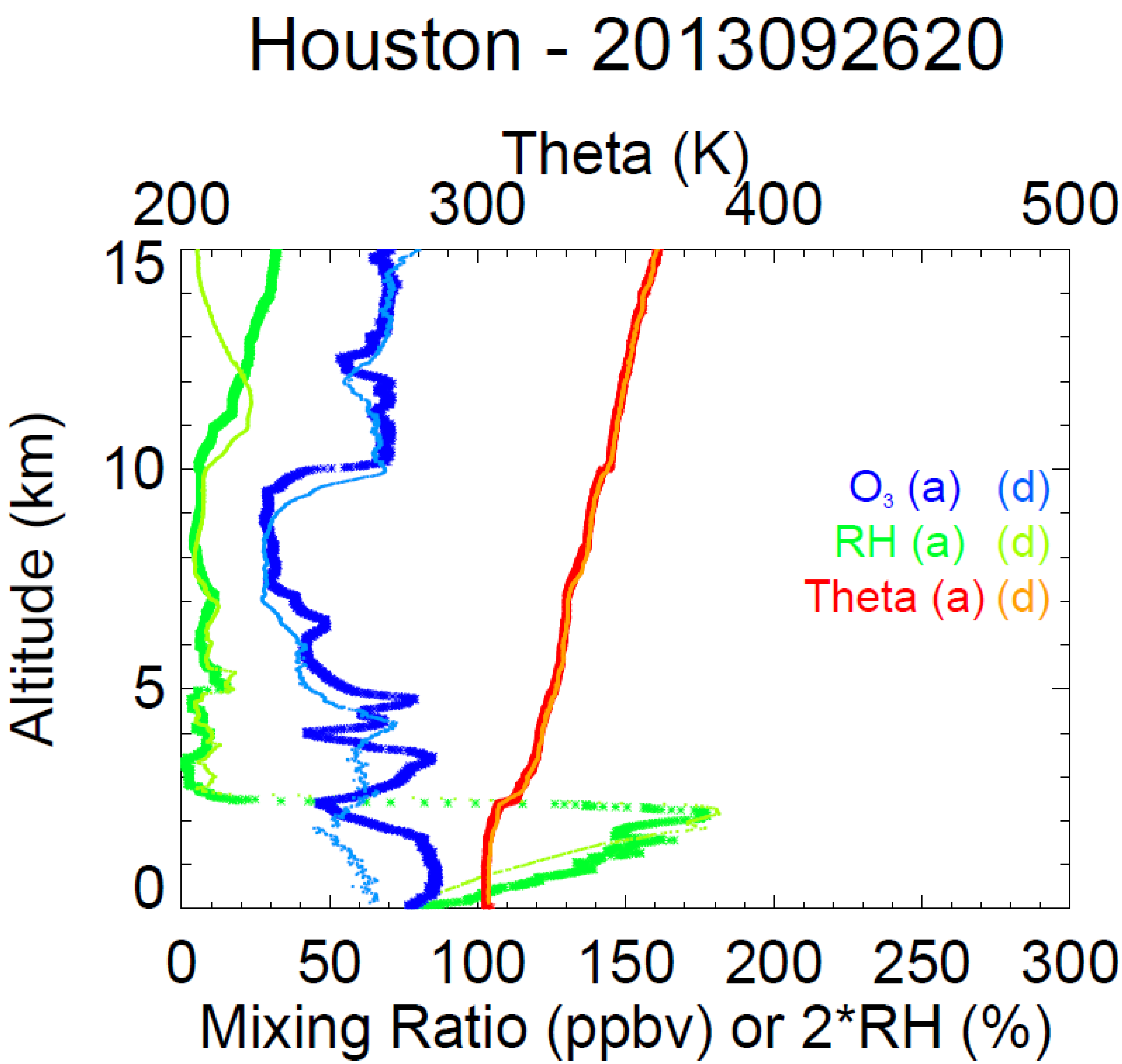


Figure 119. Ozonesonde data on September 26, 2013, launched from the University of Houston at 2:20 p.m. CST.

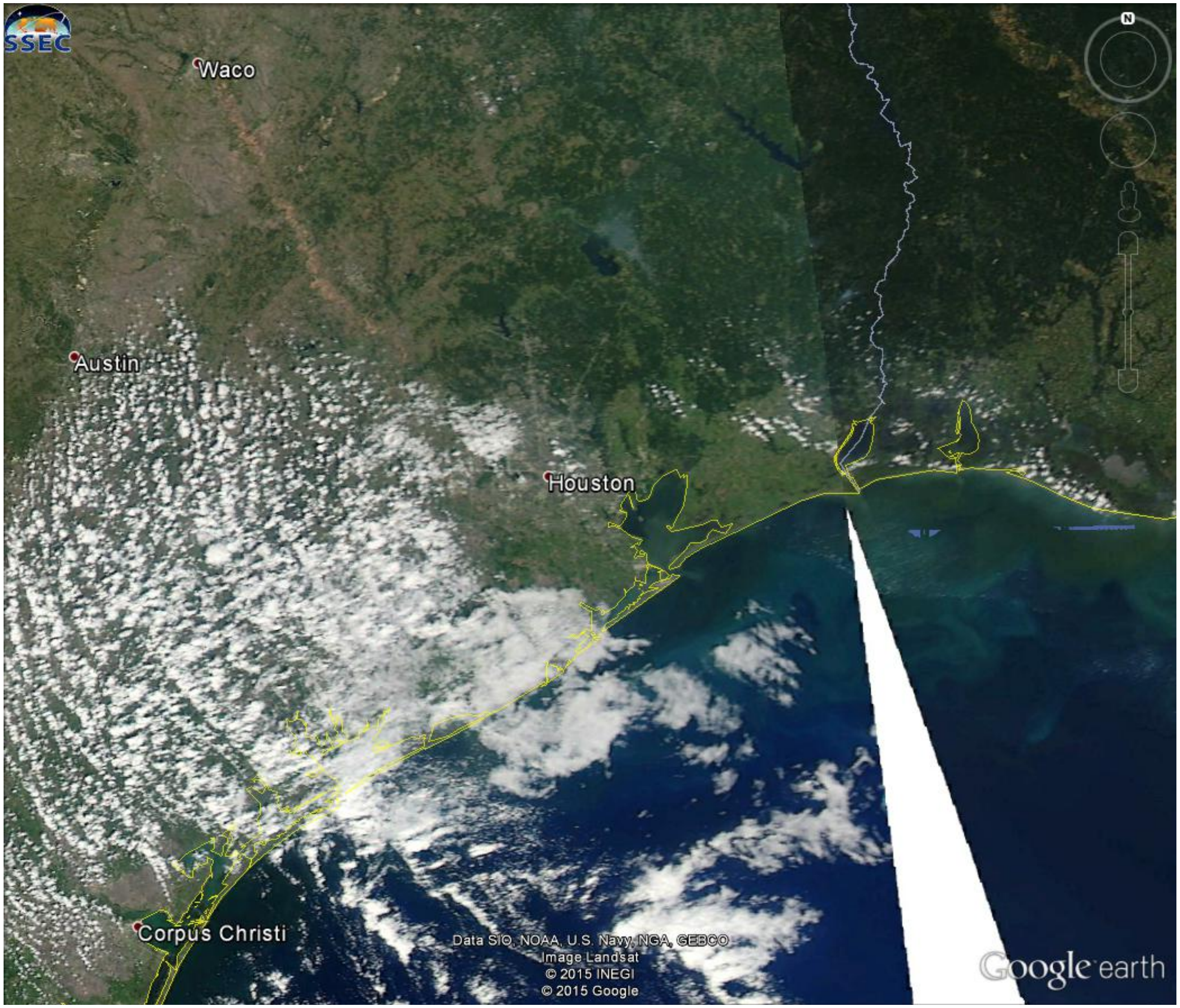


Figure 120. MODIS-AQUA image from September 26, 2013. Scattered cloud cover developed southwest of Houston, but skies in the immediate Houston area were mostly clear.

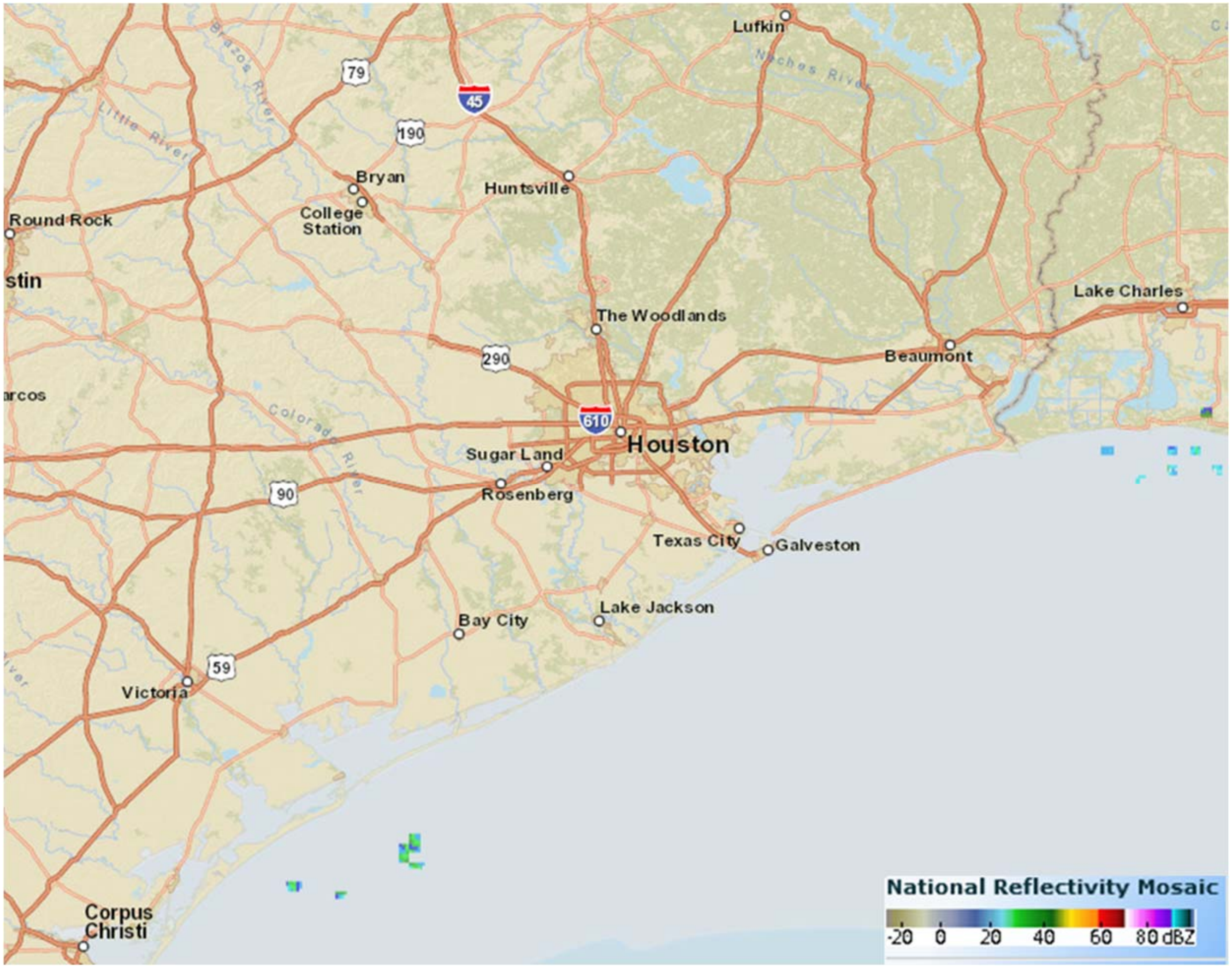


Figure 121. Regional radar image from 2:00 p.m. CST on September 26, 2013. No precipitation was detected throughout the Houston area.

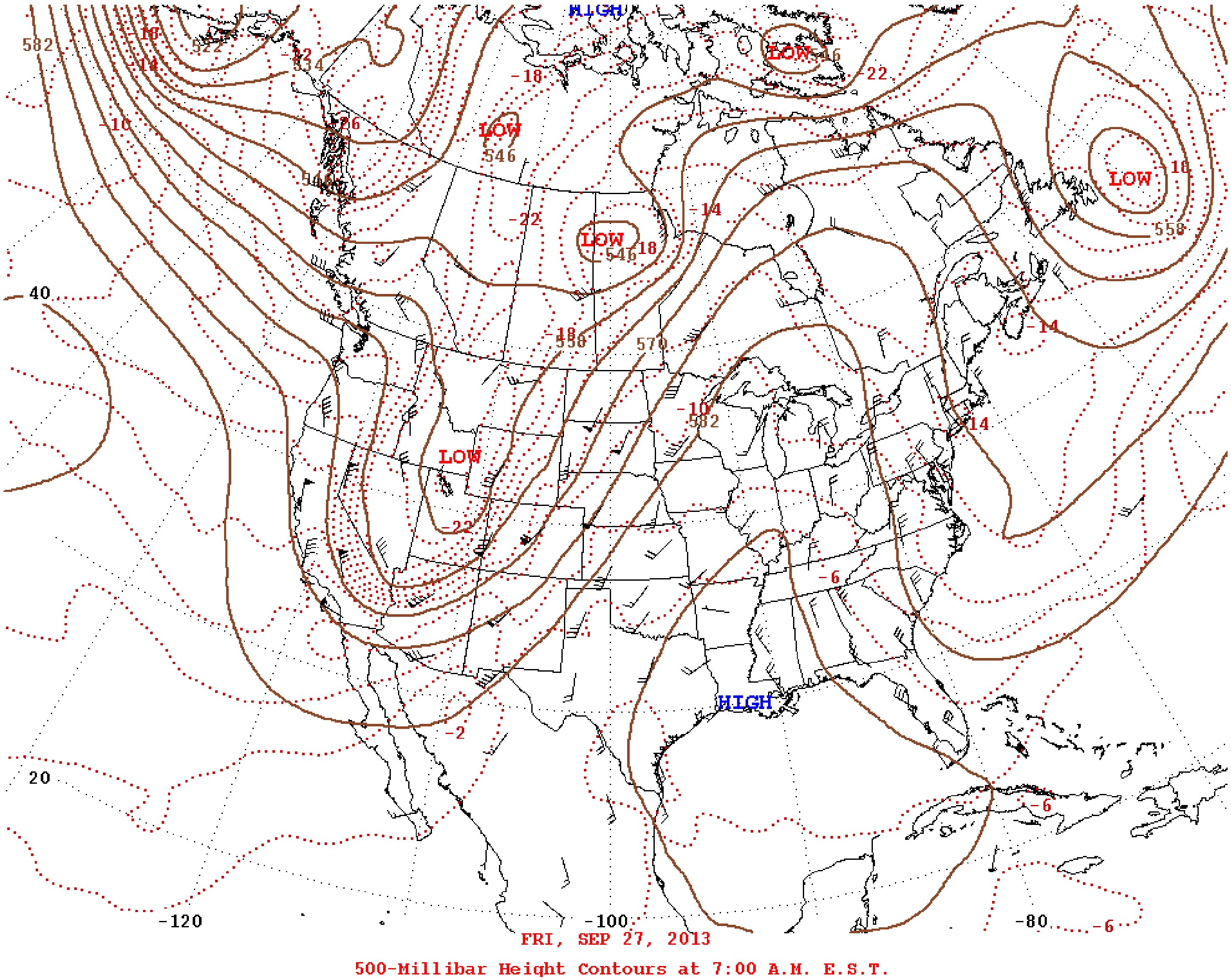
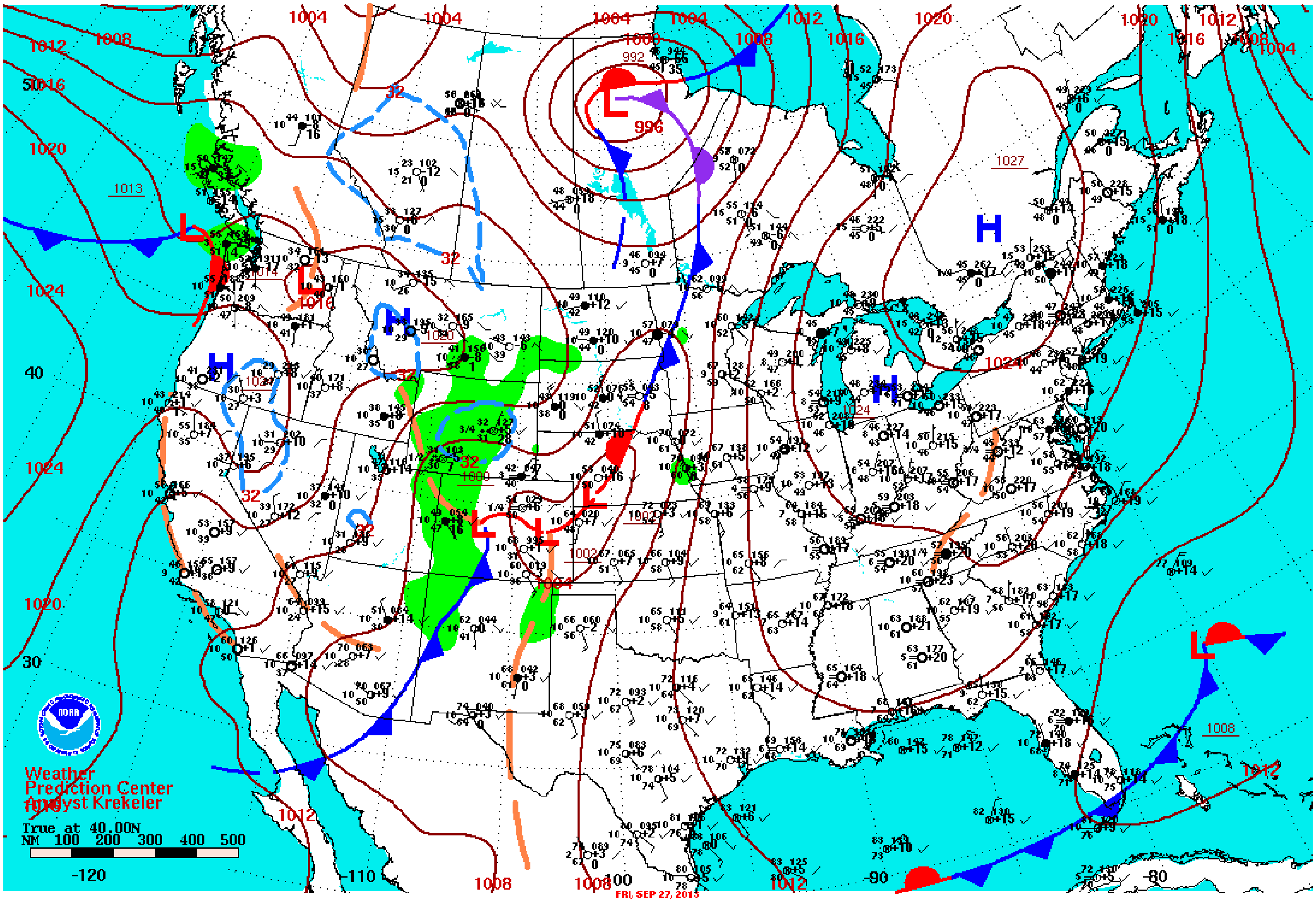


Figure 122. A map showing the height of the 500 mb pressure surface at 6:00 a.m. CST on September 27, 2013. An upper-level high-pressure system was located over the Lower Mississippi River Valley.



Surface Weather Map and Station Weather at 7:00 A.M. E.S.T.

Figure 123. Surface pressure map at 6:00 a.m. CST on September 27, 2013. A broad surface high-pressure system over the eastern United States produced a moderate easterly large-scale pressure gradient in the Houston area.

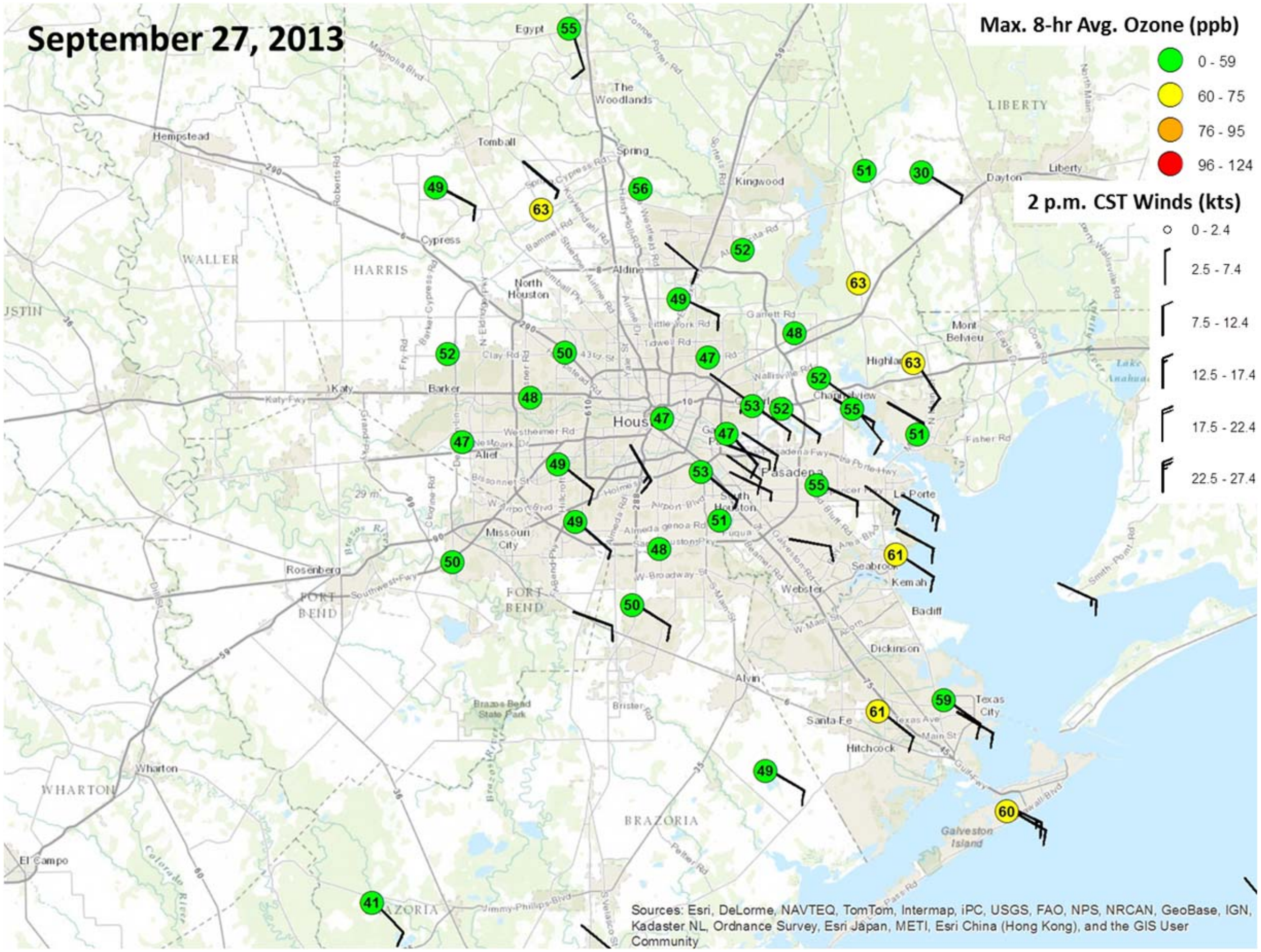


Figure 124. Daily maximum 8-hr average ozone concentrations and surface wind observations from Houston-area monitors on September 27, 2013. Light to moderate southeasterly (onshore) winds transported pollutants northwestward across the Houston area; however, deeper onshore winds resulted in stronger atmospheric mixing and more-uniform ozone concentrations regionally. These winds also transported cleaner, maritime air into the Houston area.

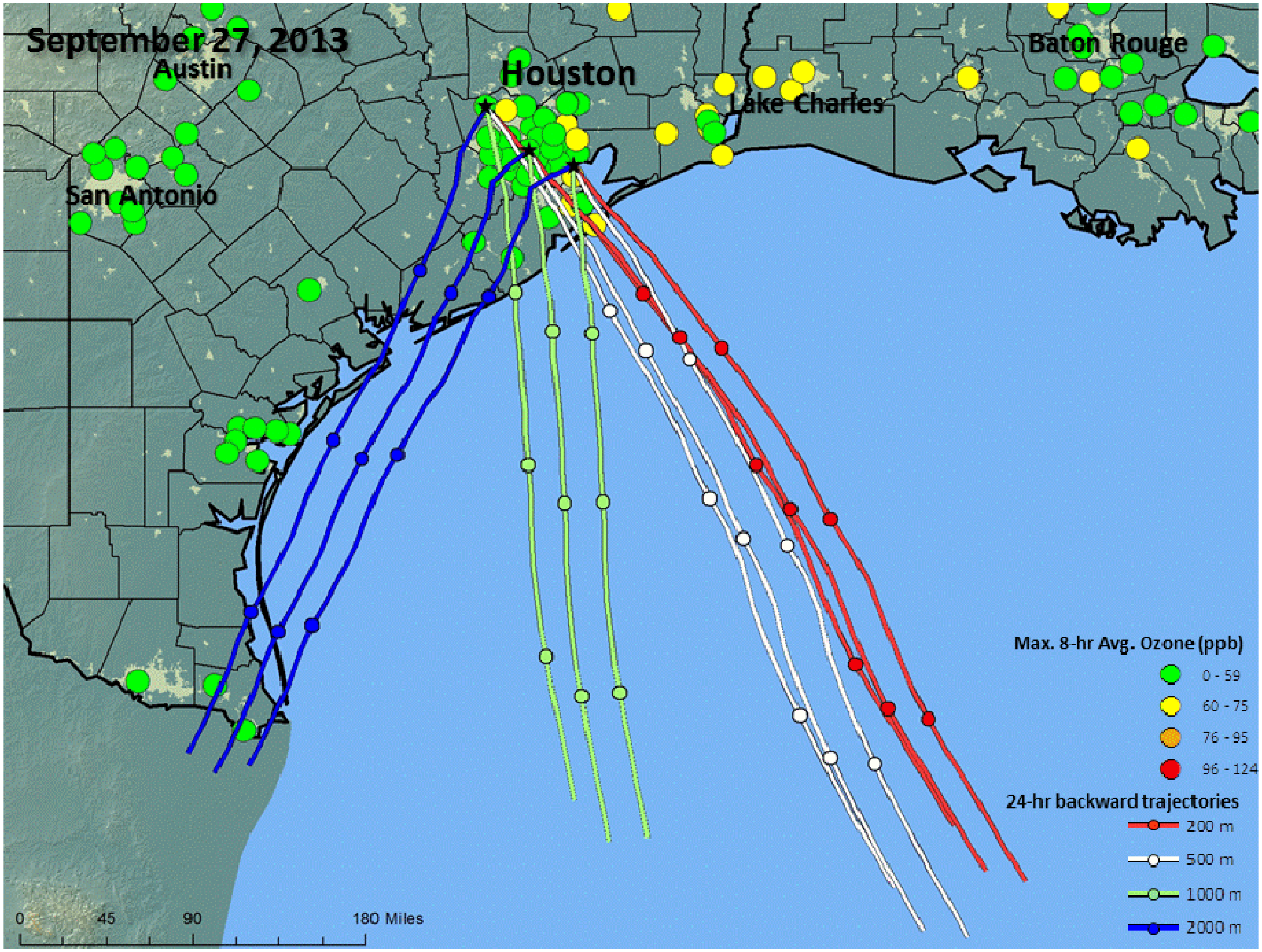


Figure 125. Daily maximum 8-hr average ozone concentrations and 24-hr backward trajectories ending at 6:00 p.m. CST on September 27, 2013. Deep onshore winds transported cleaner maritime air into the Houston area. Extensive cloud cover on this day also limited ozone formation in the Houston area. Dots along the trajectories are at 6-hr intervals.

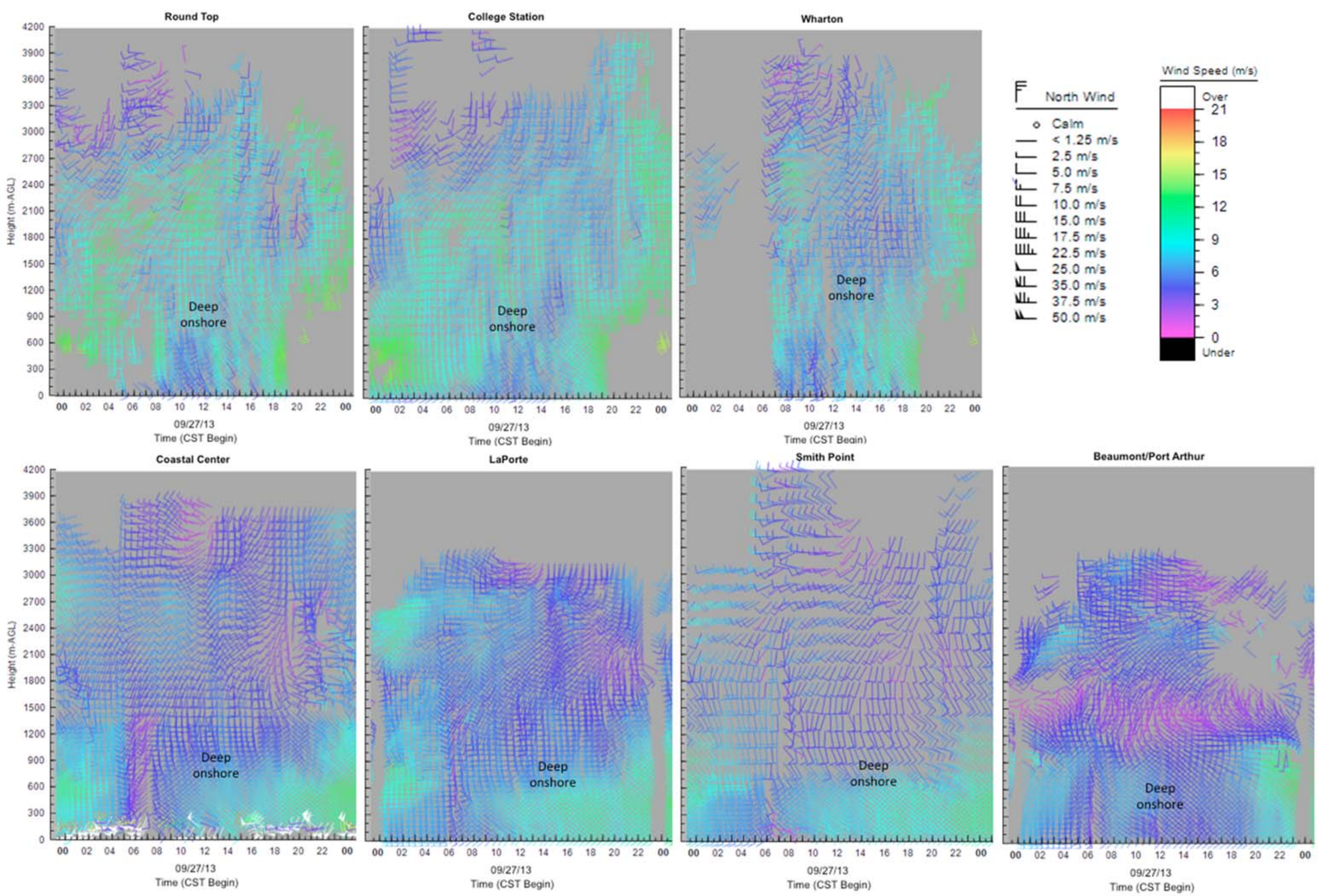


Figure 126. Wind profiler data on September 27, 2013. Onshore flow continued to deepen and intensify on September 27 in response to a strengthening onshore pressure gradient.

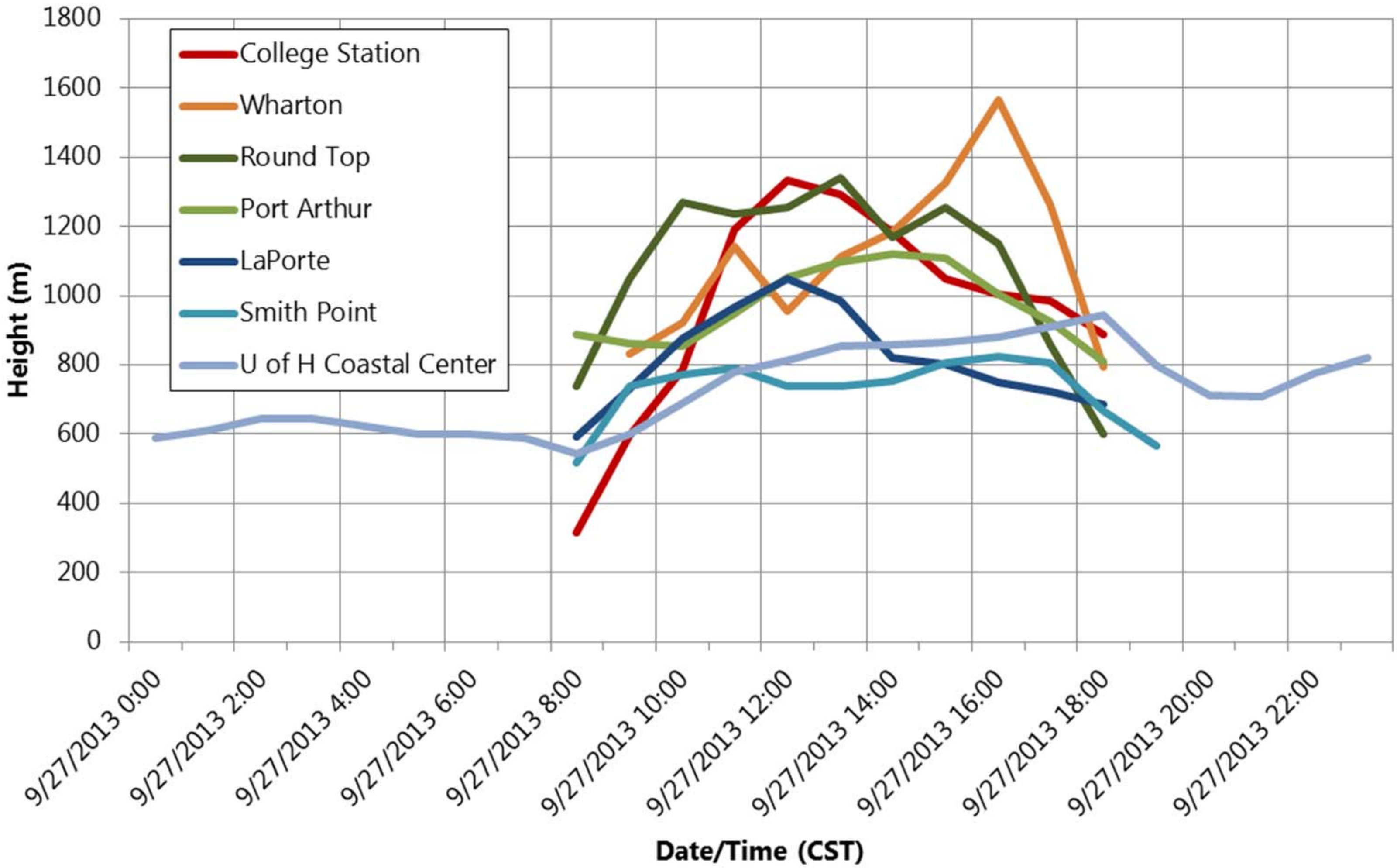


Figure 127. Hourly mixing heights on September 27, 2013.

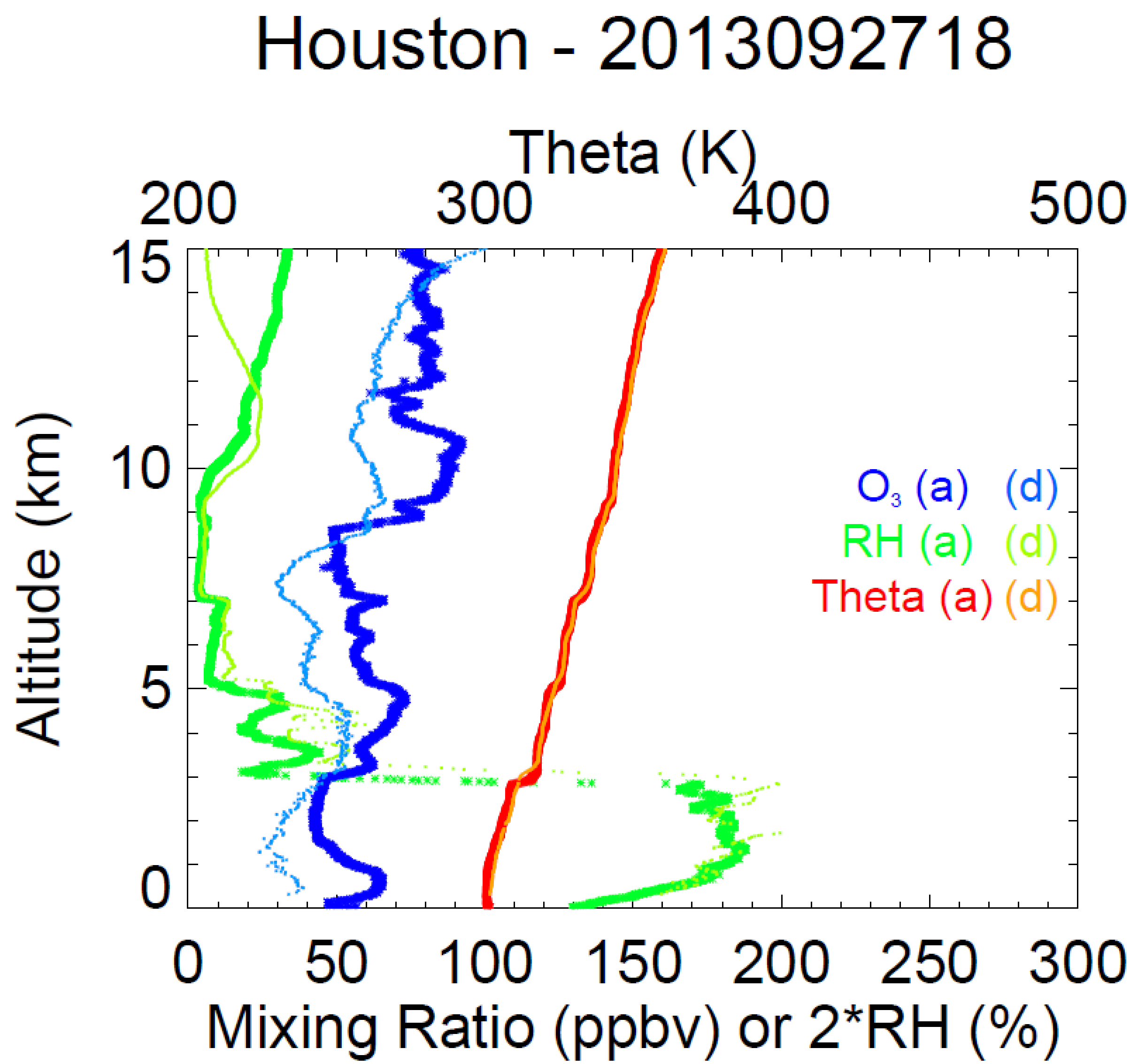


Figure 128. Ozonesonde data on September 27, 2013, launched from the University of Houston at 12:13 p.m. CST.

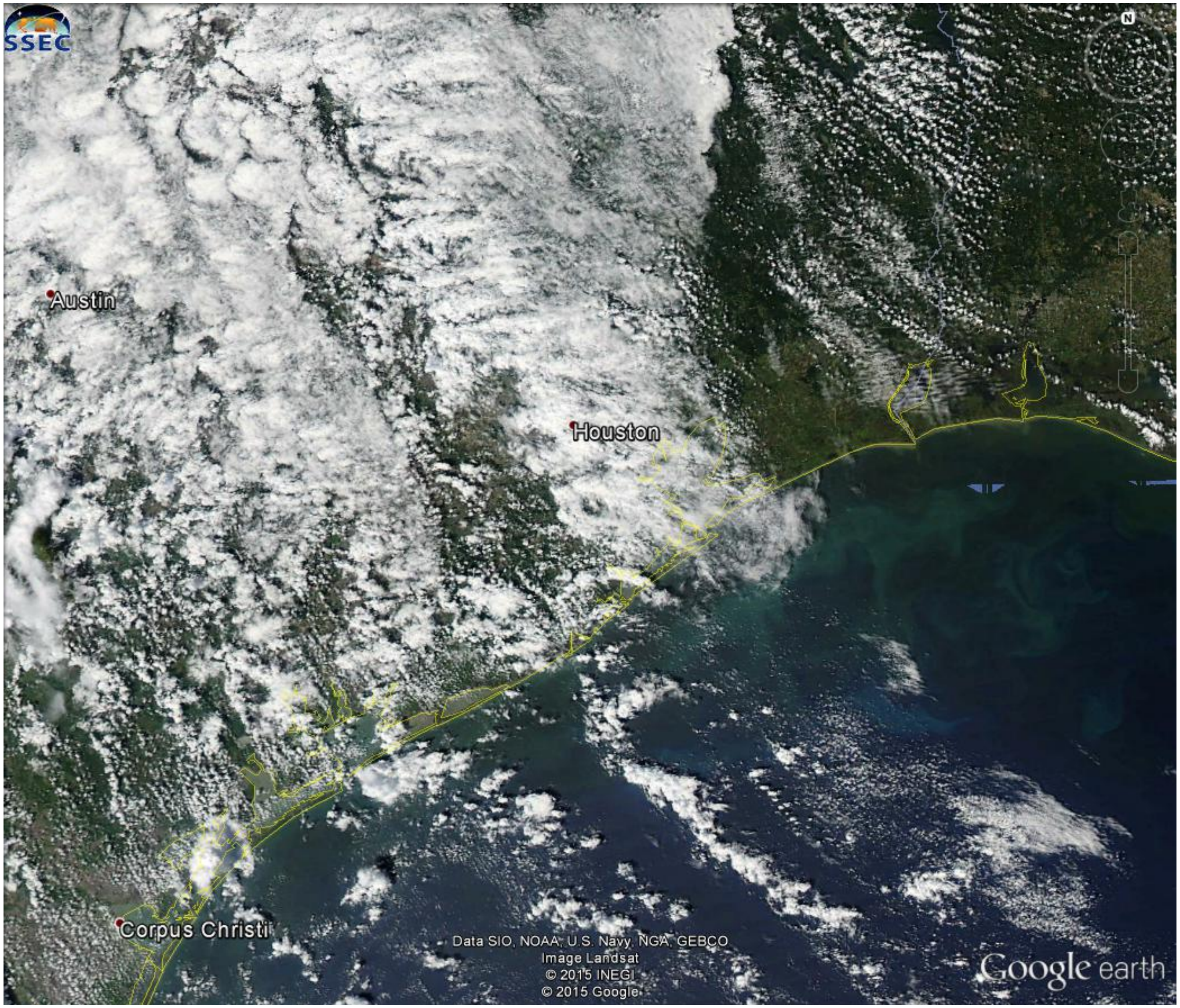


Figure 129. MODIS-AQUA image from September 27, 2013. Widespread cloud cover was present over the Houston area.

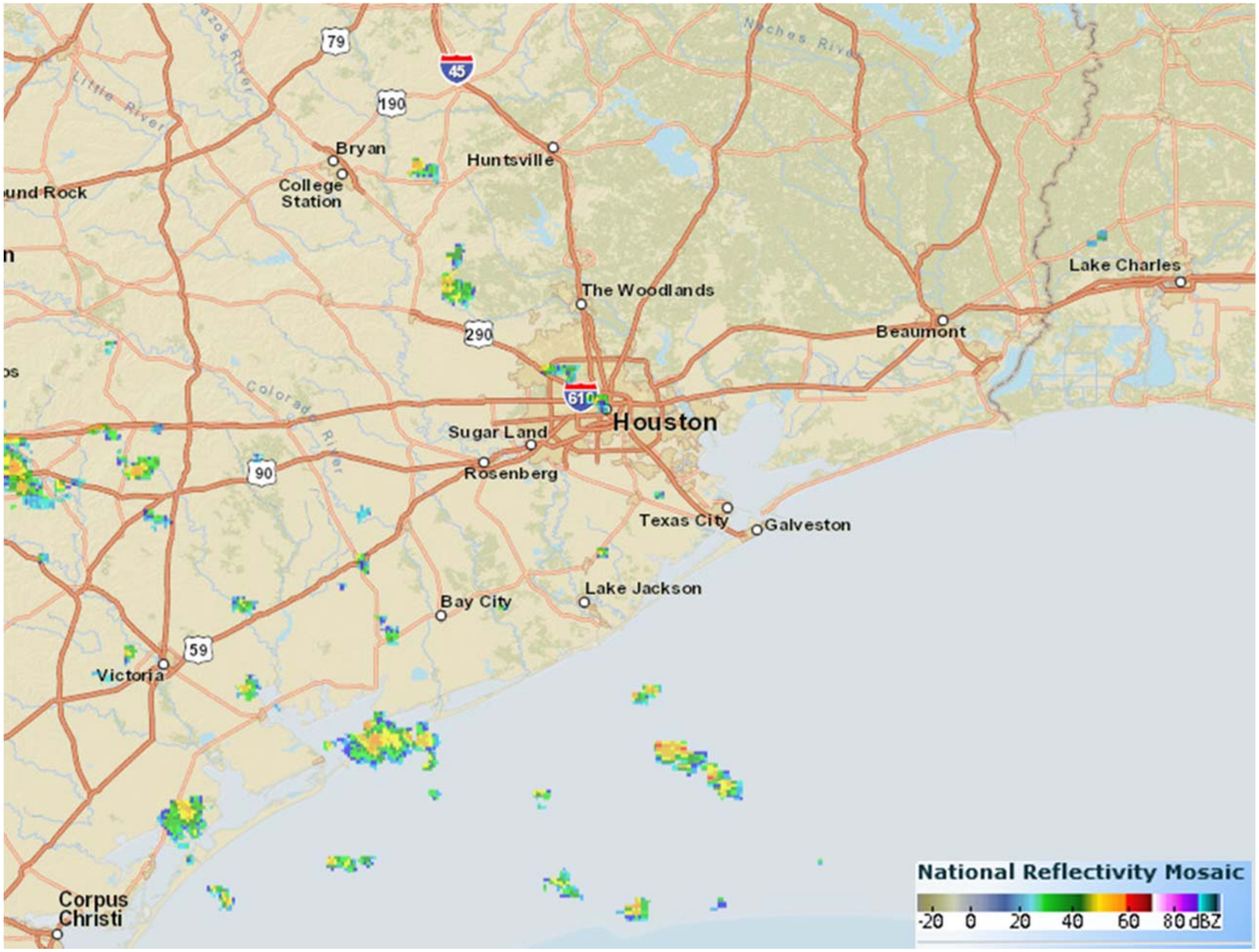


Figure 130. Regional radar image from 2:00 p.m. CST on September 27, 2013. A few light showers were detected in the Houston area.

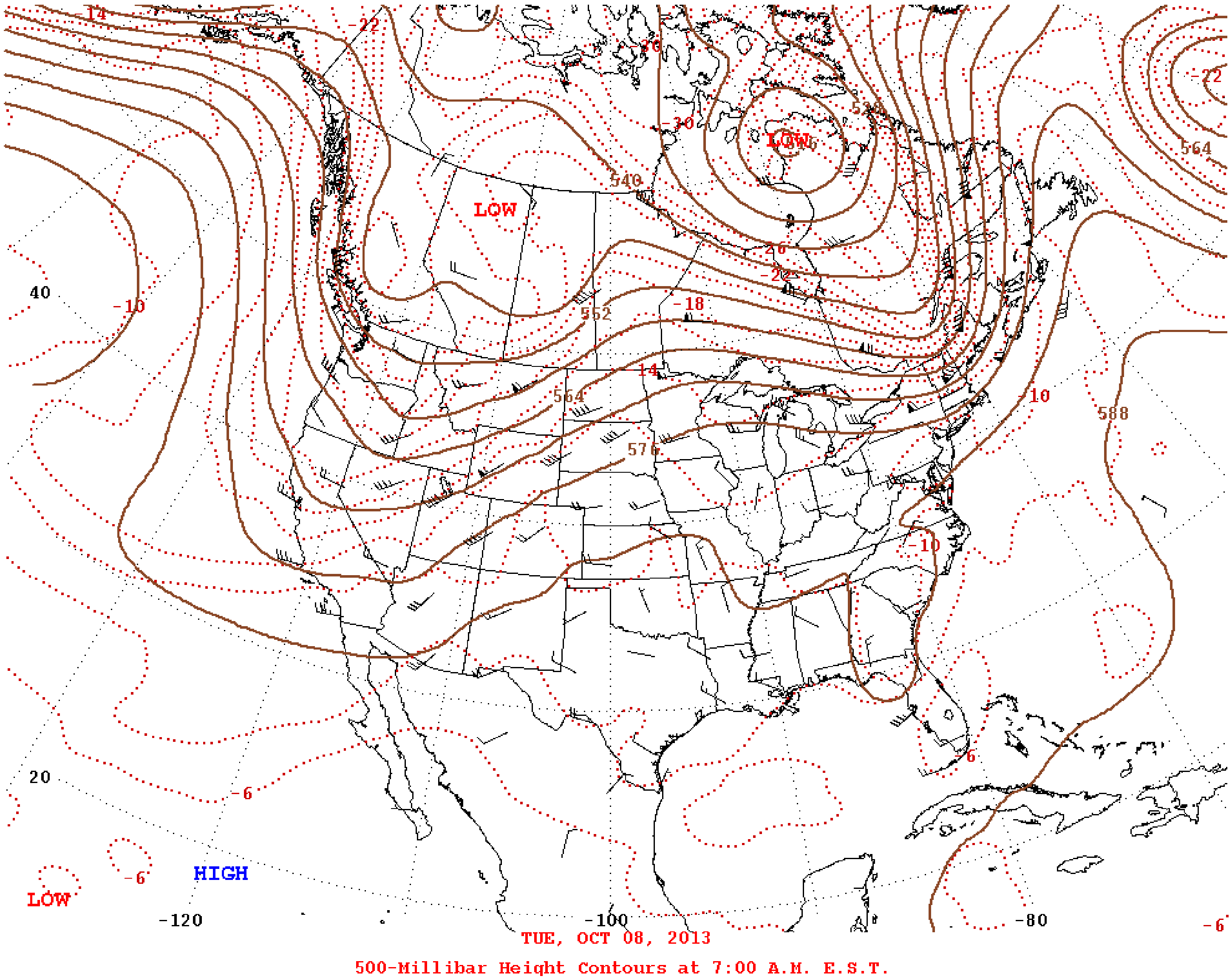
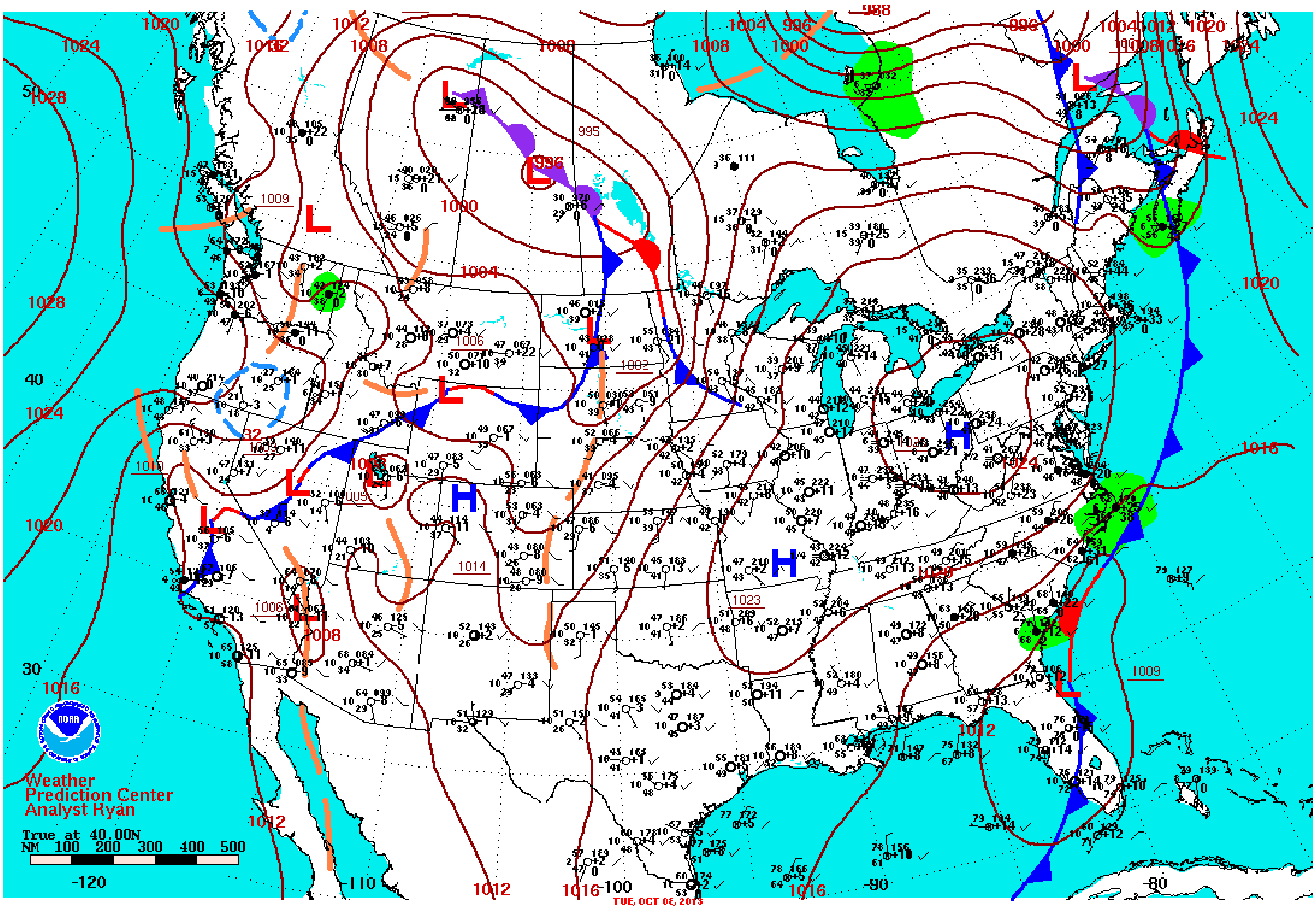


Figure 131. A map showing the height of the 500 mb pressure surface at 6:00 a.m. CST on October 8, 2013. An upper-level ridge of high pressure was located over Texas.



Surface Weather Map and Station Weather at 7:00 A.M. E.S.T.

Figure 132. Surface pressure map at 6:00 a.m. CST on October 8, 2013. A broad surface high-pressure system was located from Texas northeastward through the Great Lakes, resulting in a weak northeasterly (offshore) pressure gradient in the Houston area.

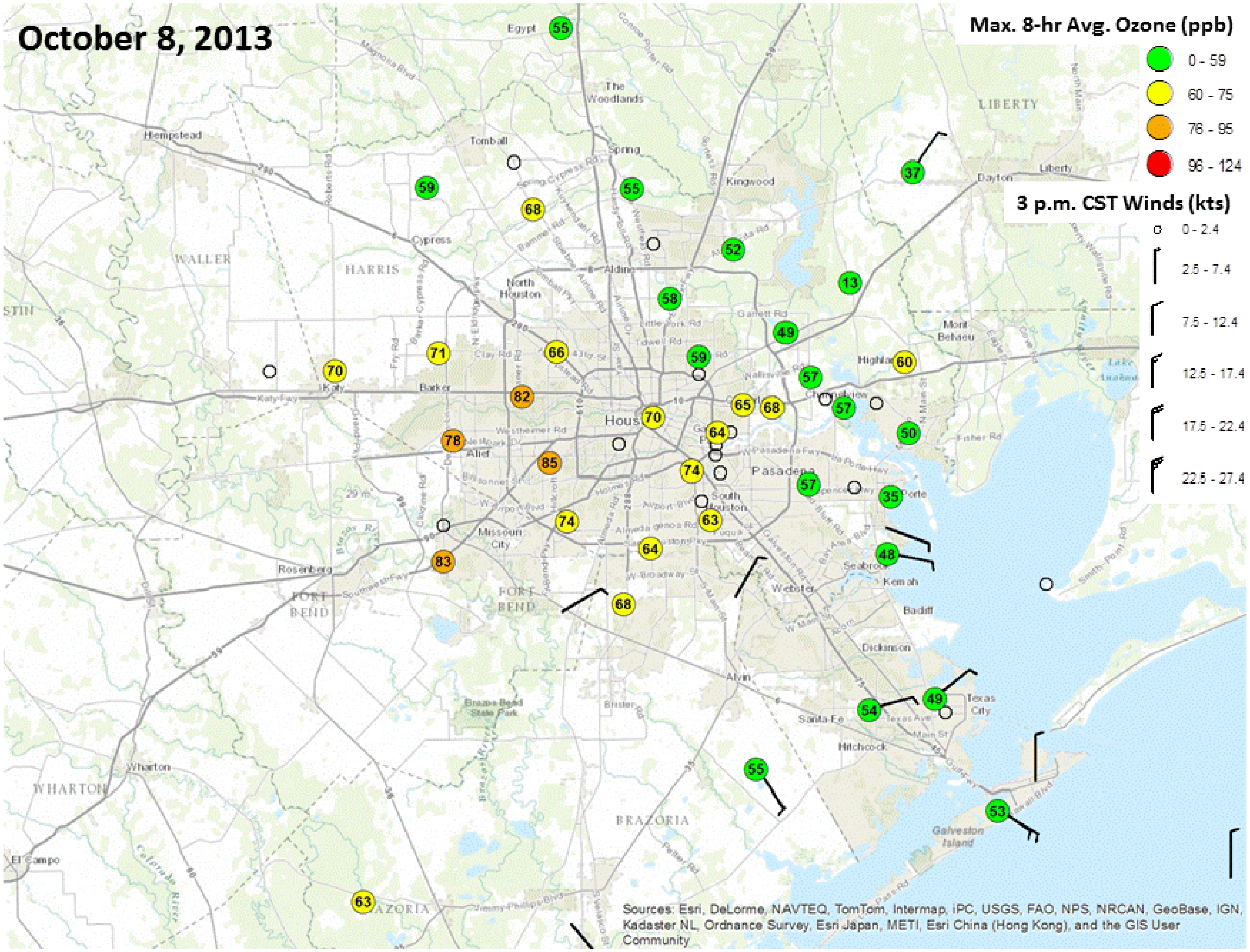


Figure 133. Daily maximum 8-hr average ozone concentrations and surface wind observations from Houston-area monitors on October 8, 2013. Winds were calm or light northeasterly over inland areas, while a weak Bay breeze developed along Galveston Bay. These winds transported pollutants westward across the Houston area. As a result, 8-hr ozone concentrations were highest on the west side of Houston.

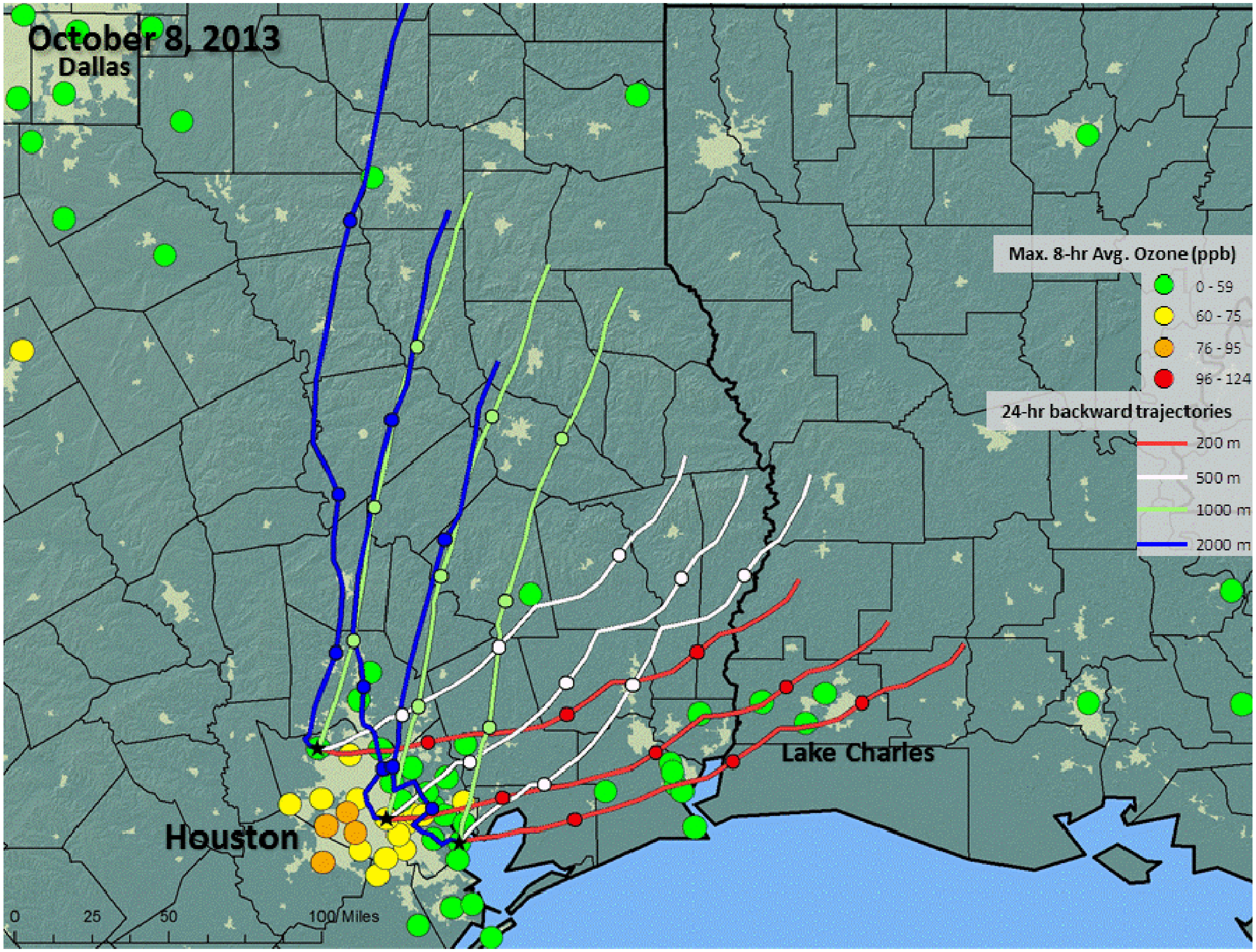


Figure 134. Daily maximum 8-hr average ozone concentrations and 24-hr backward trajectories ending at 6:00 p.m. CST on October 8, 2013. Light northeasterly winds at and below 500 m transported urban pollutants southwestward across the Houston area. The offshore winds also limited inland progression of the afternoon Bay/Gulf breeze. Dots along the trajectories are at 6-hr intervals.

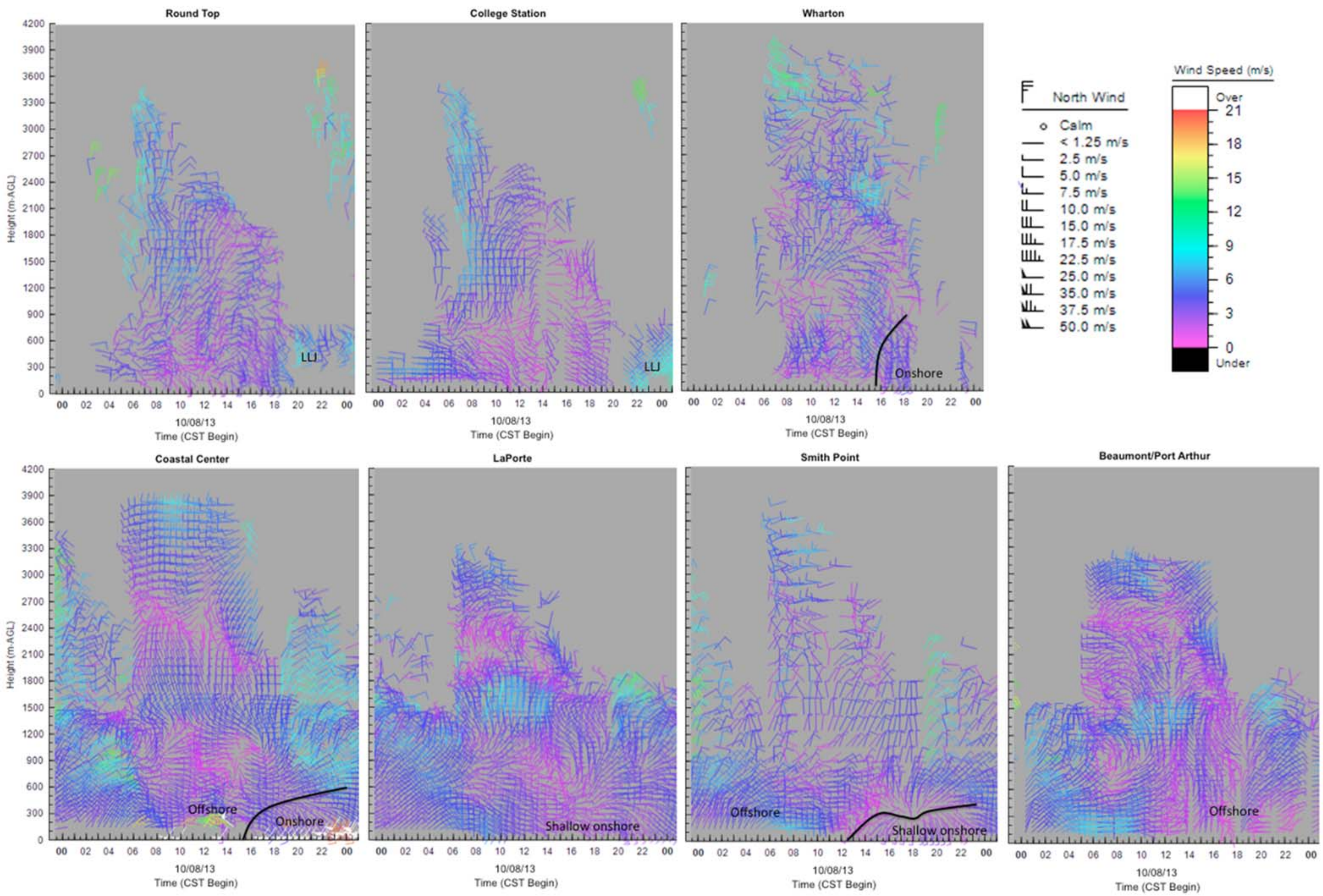


Figure 135. Wind profiler data on October 8, 2013. Offshore flow during the morning shifted to a weak, shallow onshore flow during the afternoon.

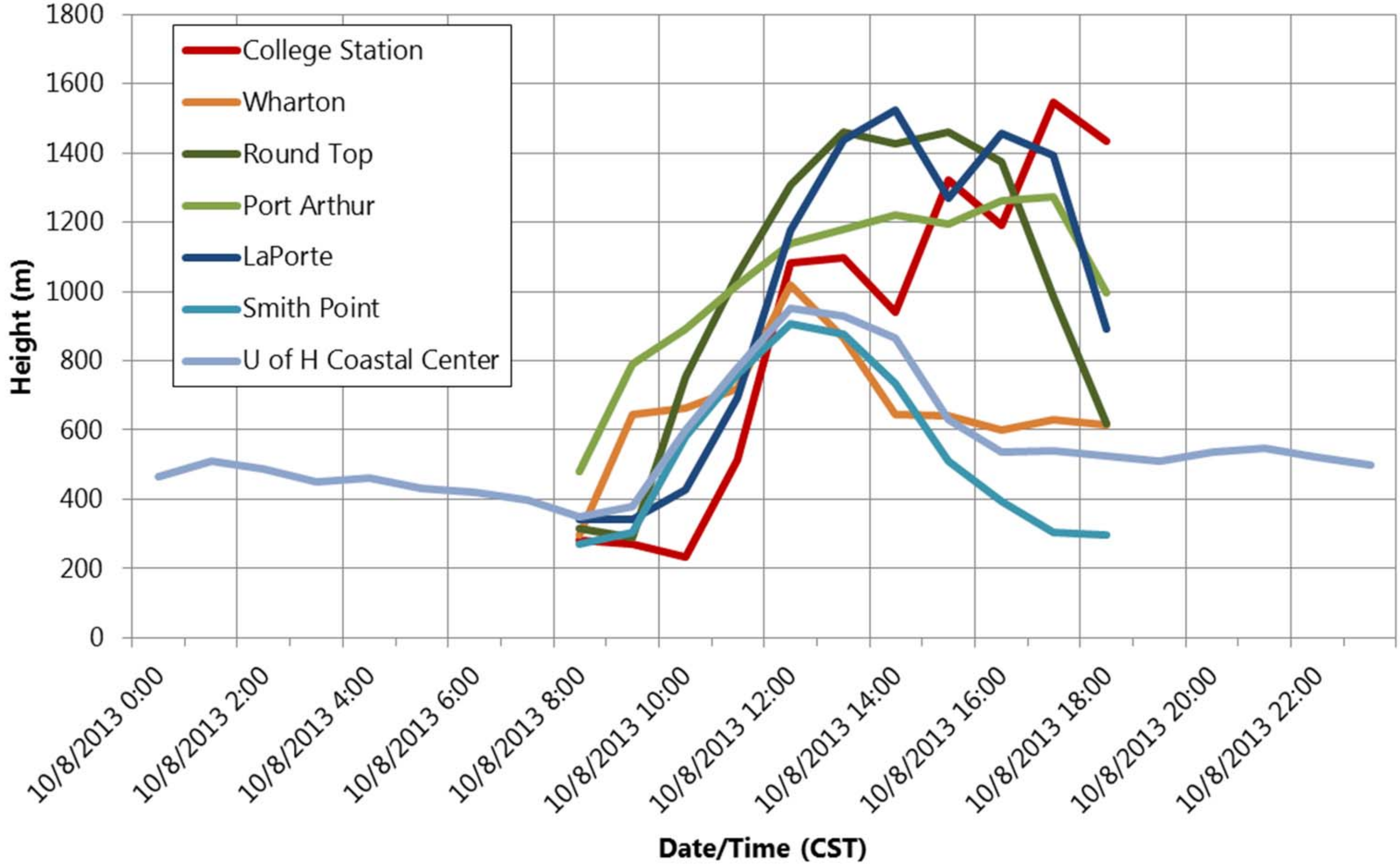


Figure 136. Hourly mixing heights on October 8, 2013.

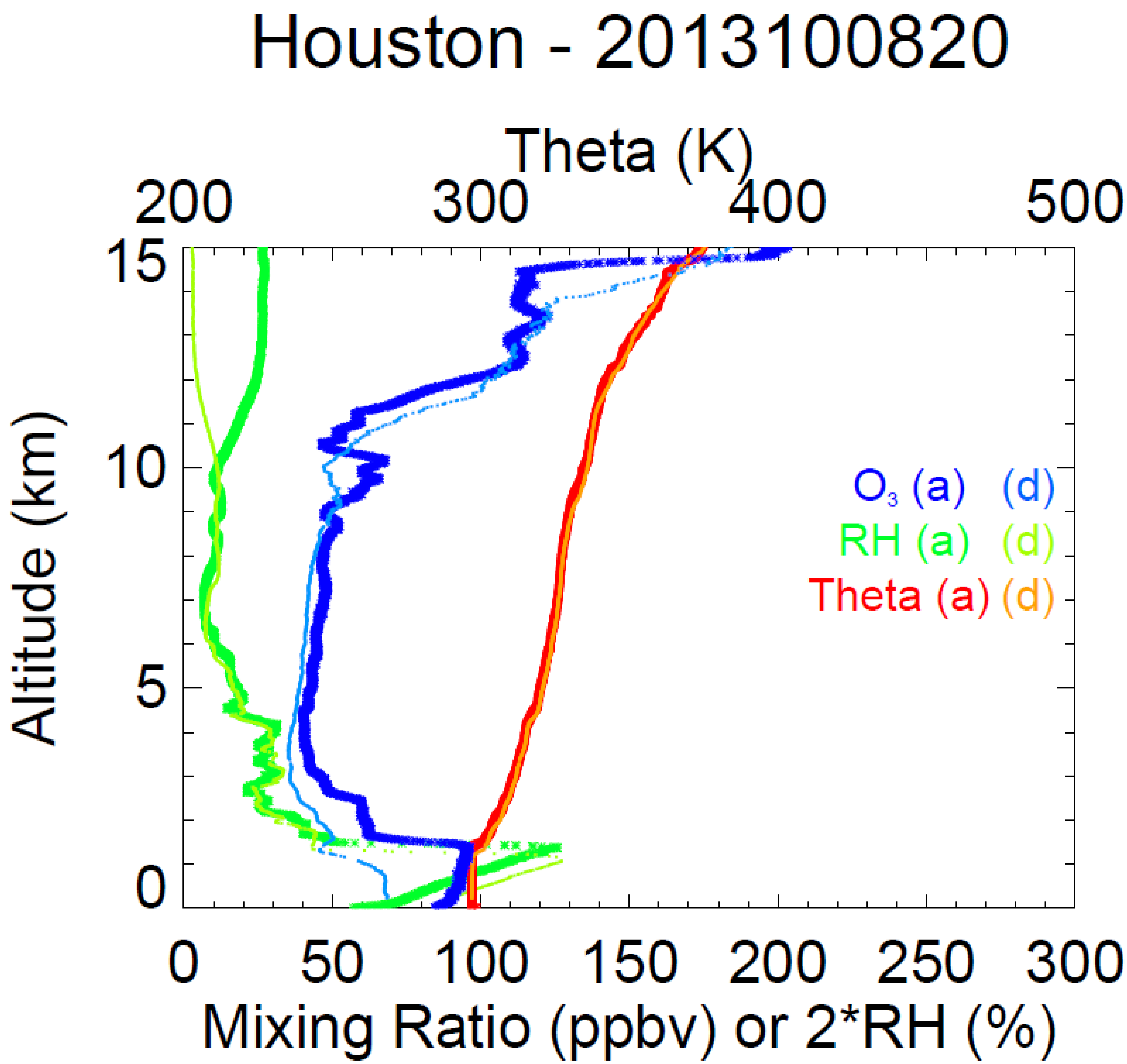


Figure 137. Ozonesonde data on October 8, 2013, launched from the University of Houston at 2:01 p.m. CST.

Figure 138. MODIS-AQUA image from October 8, 2013. Skies were clear throughout the Houston area.

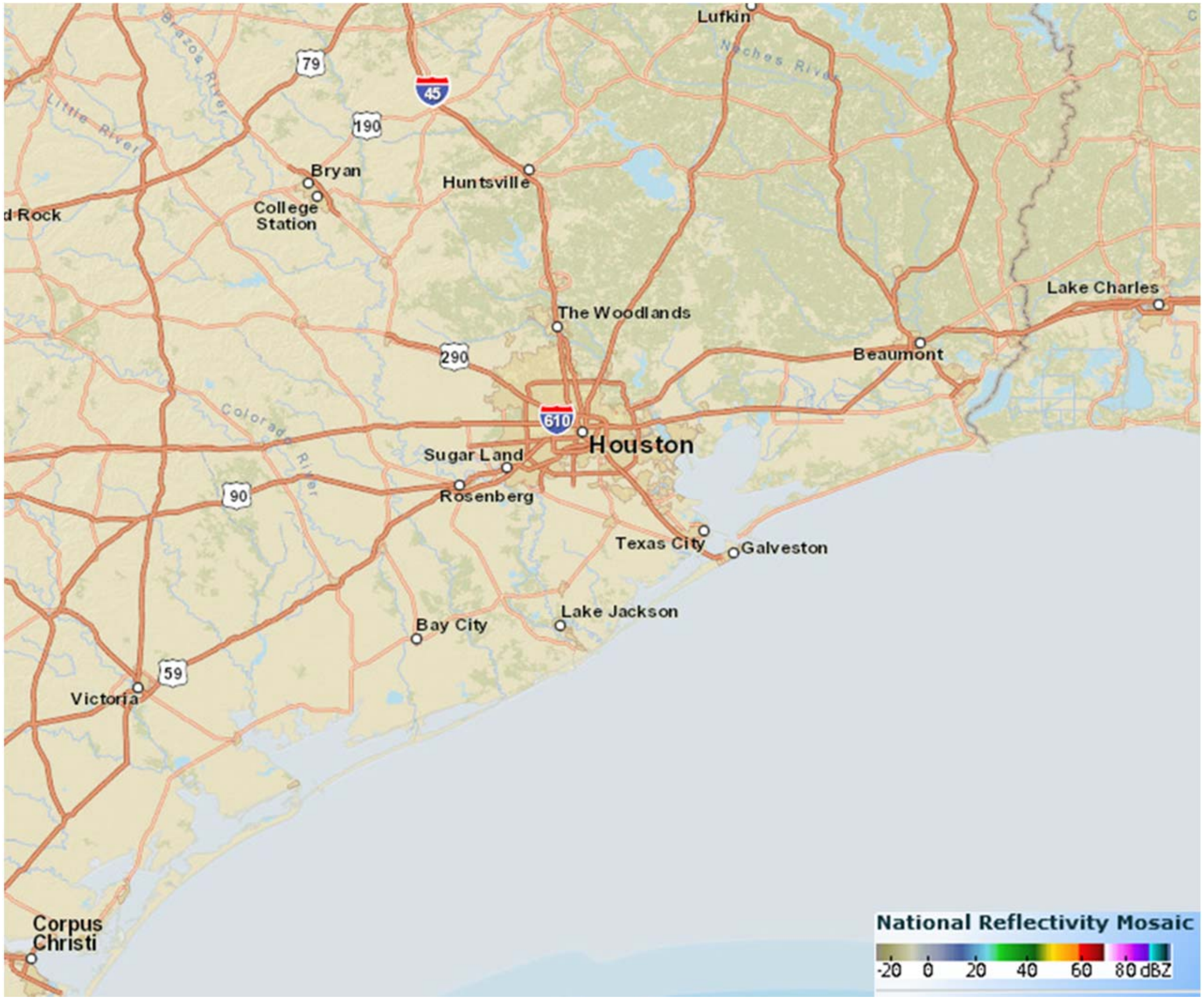


Figure 139. Regional radar image from 2:00 p.m. CST on October 8, 2013. No precipitation was observed throughout the Houston area.

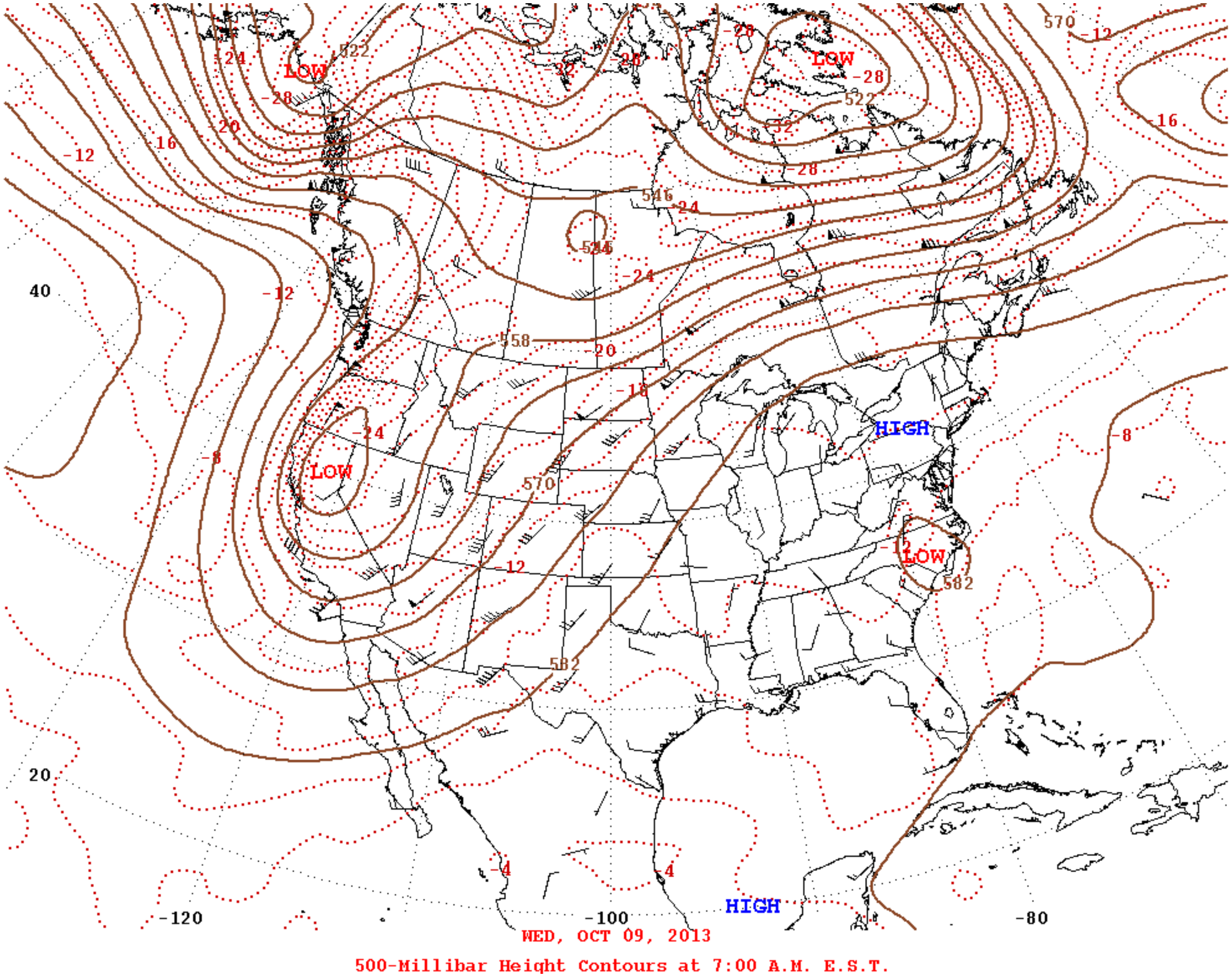
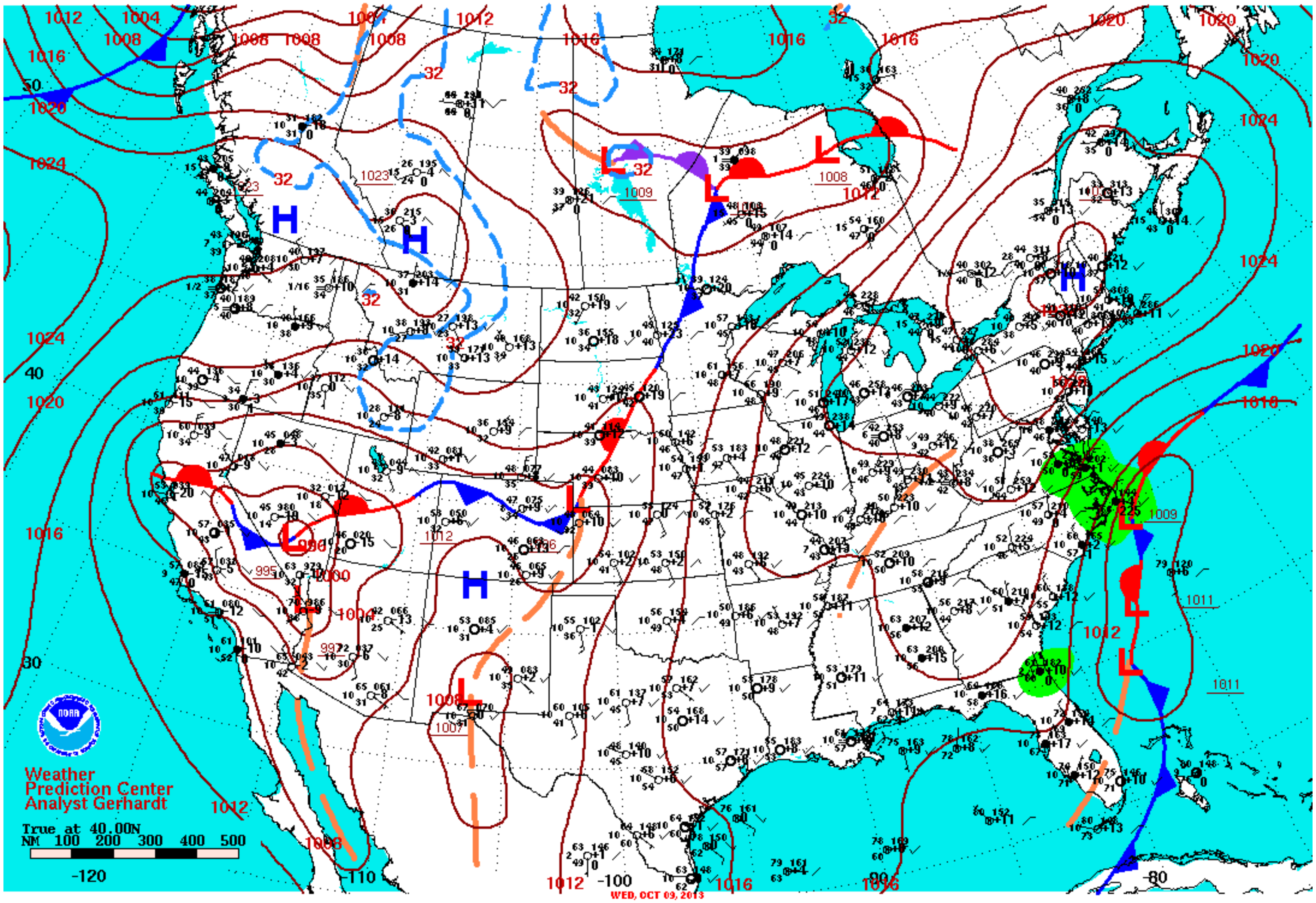


Figure 140. A map showing the height of the 500 mb pressure surface at 6:00 a.m. CST on October 9, 2013. A broad upper-level ridge of high pressure was located over the eastern United States.



Surface Weather Map and Station Weather at 7:00 A.M. E.S.T.

Figure 141. Surface pressure map at 6:00 a.m. CST on October 9, 2013. A broad surface high-pressure system was located from the Gulf Coast northeastward through New England, resulting in a weak easterly large-scale pressure gradient in the Houston area.

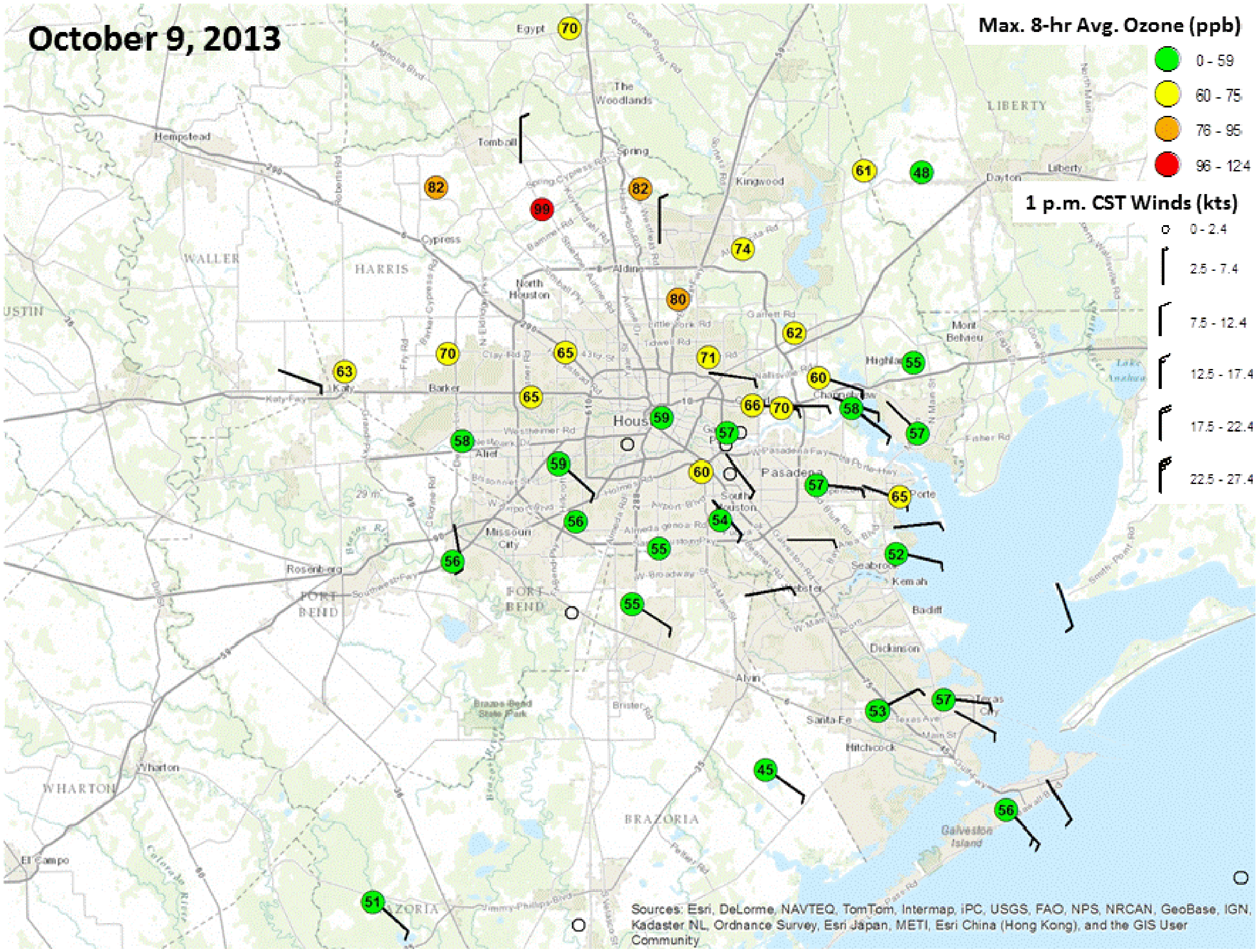


Figure 142. Daily maximum 8-hr average ozone concentrations and surface wind observations from Houston-area monitors on October 9, 2013. Winds were light northerly (offshore) north of Houston, and were light to moderate southeasterly (onshore) across the rest of the Houston area. These winds transported pollutants northwestward across the Houston area; as a result, 8-hr ozone concentrations were highest on the northwest side of Houston. These winds also transported cleaner, maritime air into the southern half of the Houston area.

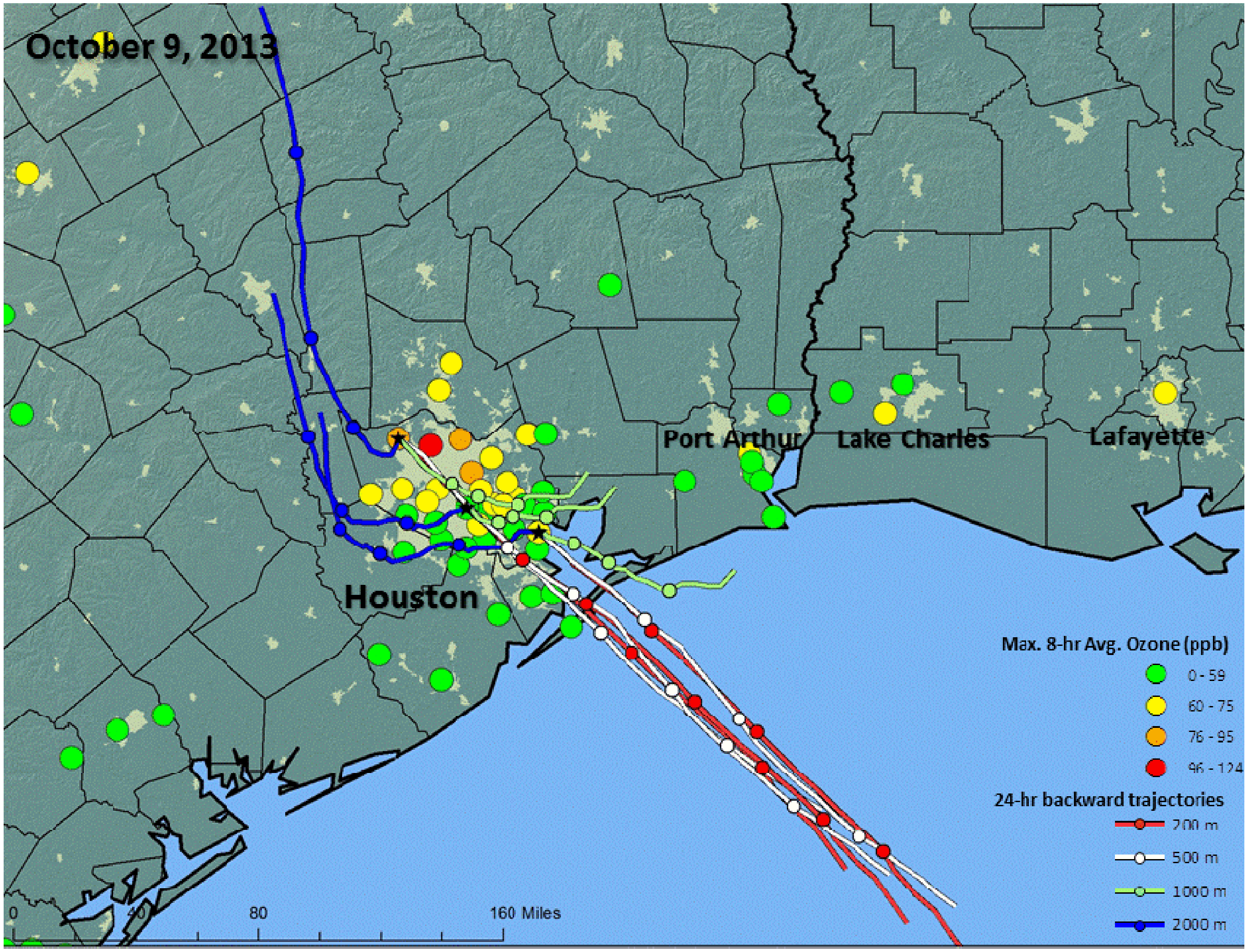


Figure 143. Daily maximum 8-hr average ozone concentrations and 24-hr backward trajectories ending at 6:00 p.m. CST on October 9, 2013. The trajectories depict air flow from the southeast (onshore) at 200 m, 500 m, and 1000 m, consistent with the development of a weak Bay and Gulf breeze. Trajectories at 2000 m showed light northerly (offshore) winds. The northwest side of Houston was more affected by pollutant transport, as trajectories ending there passed through and resided longer over the urban Houston area. Dots along the trajectories are at 6-hr intervals.

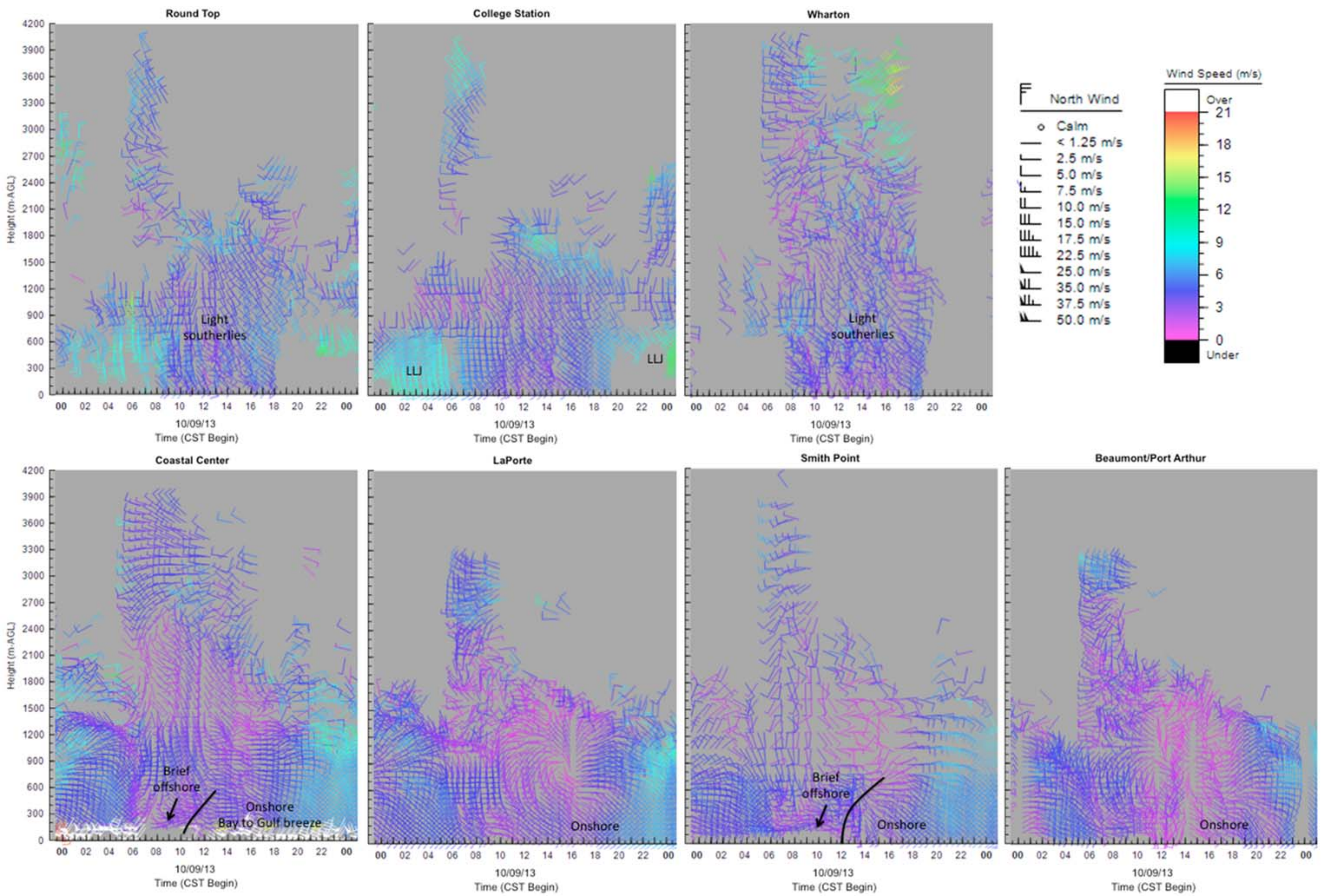


Figure 144. Wind profiler data from the Smith Point radar wind profiler on October 9, 2013. Weak, shallow offshore flow early on October 9 switched to onshore flow during the afternoon in response to a strengthening onshore pressure gradient. As a result, higher ozone concentrations were transported to the north side of Houston.

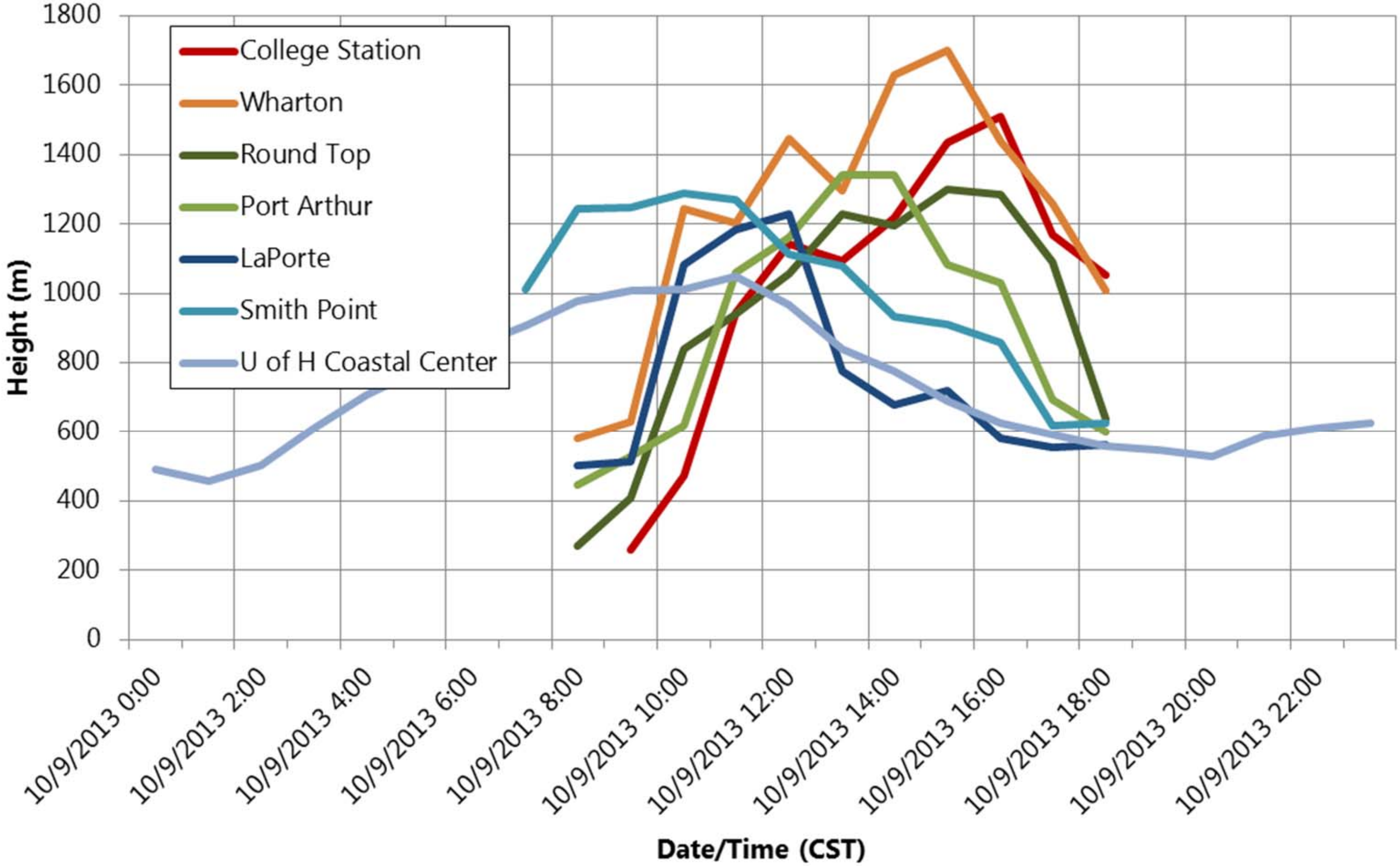


Figure 145. Hourly mixing heights on October 9, 2013.

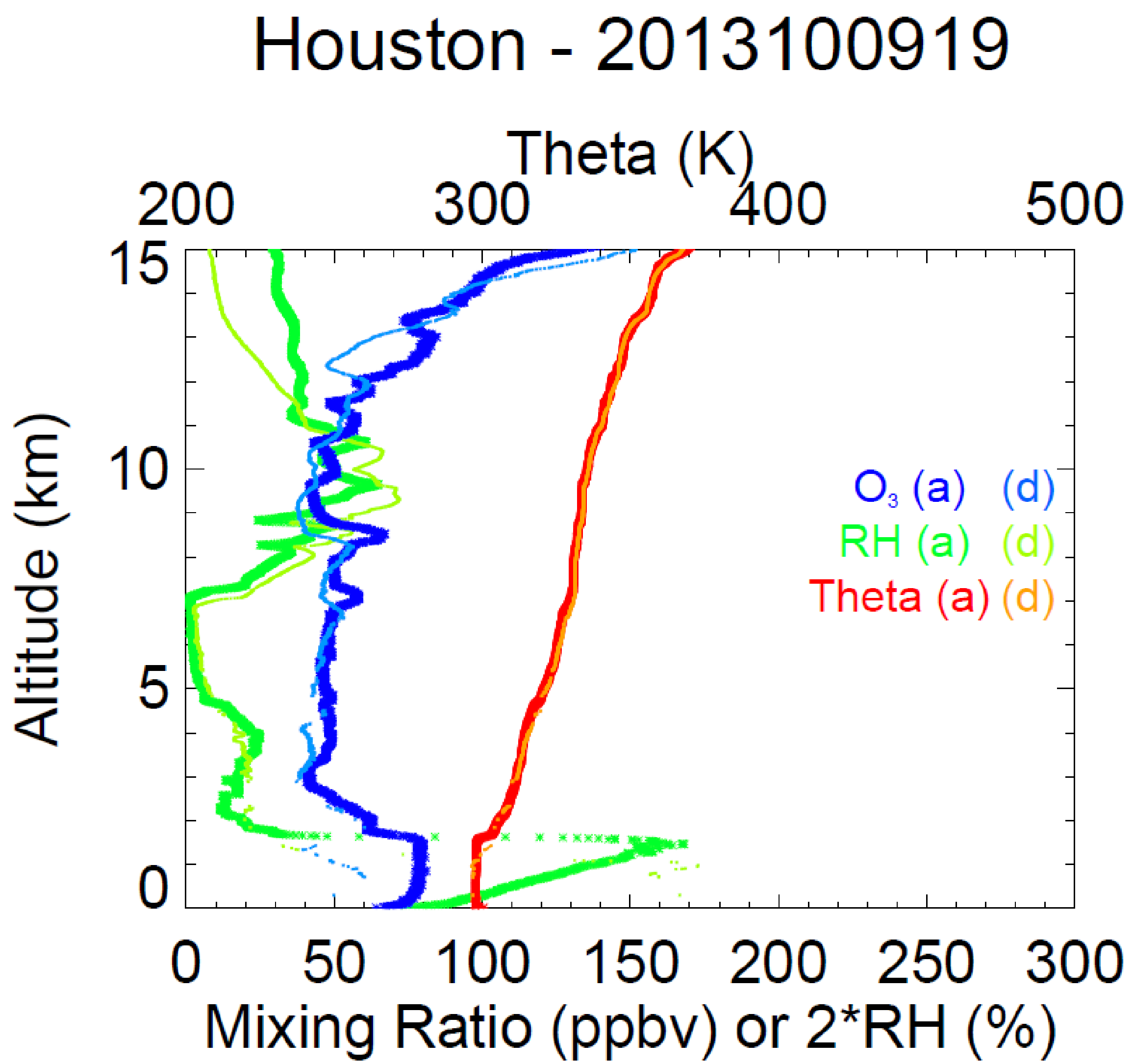


Figure 146. Ozonesonde data on October 9, 2013, launched from the University of Houston at 1:34 p.m. CST.

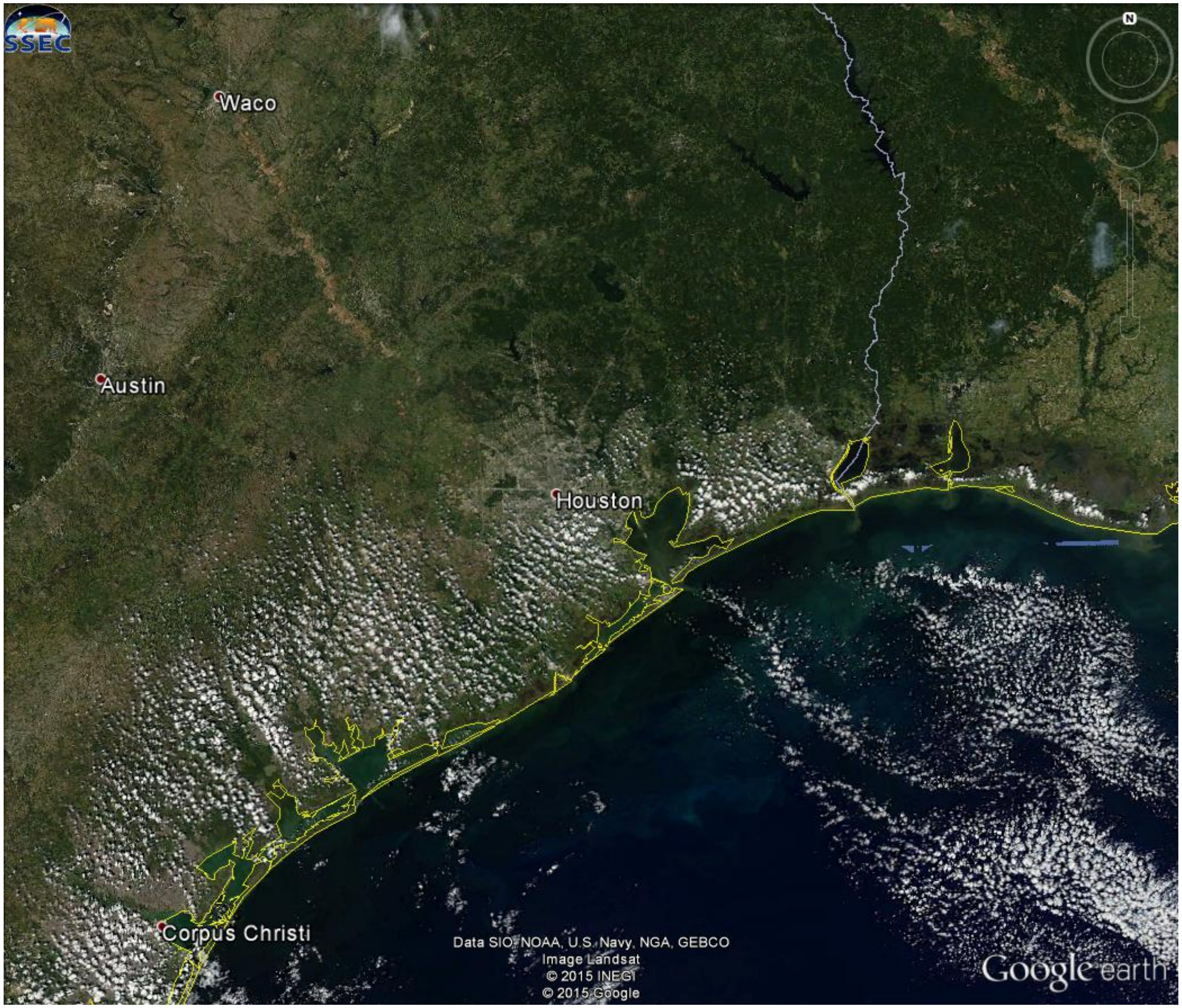


Figure 147. MODIS-AQUA image from October 9, 2013. A few fair weather cumulus clouds developed over the southern half of the Houston area, but skies remained mostly clear.

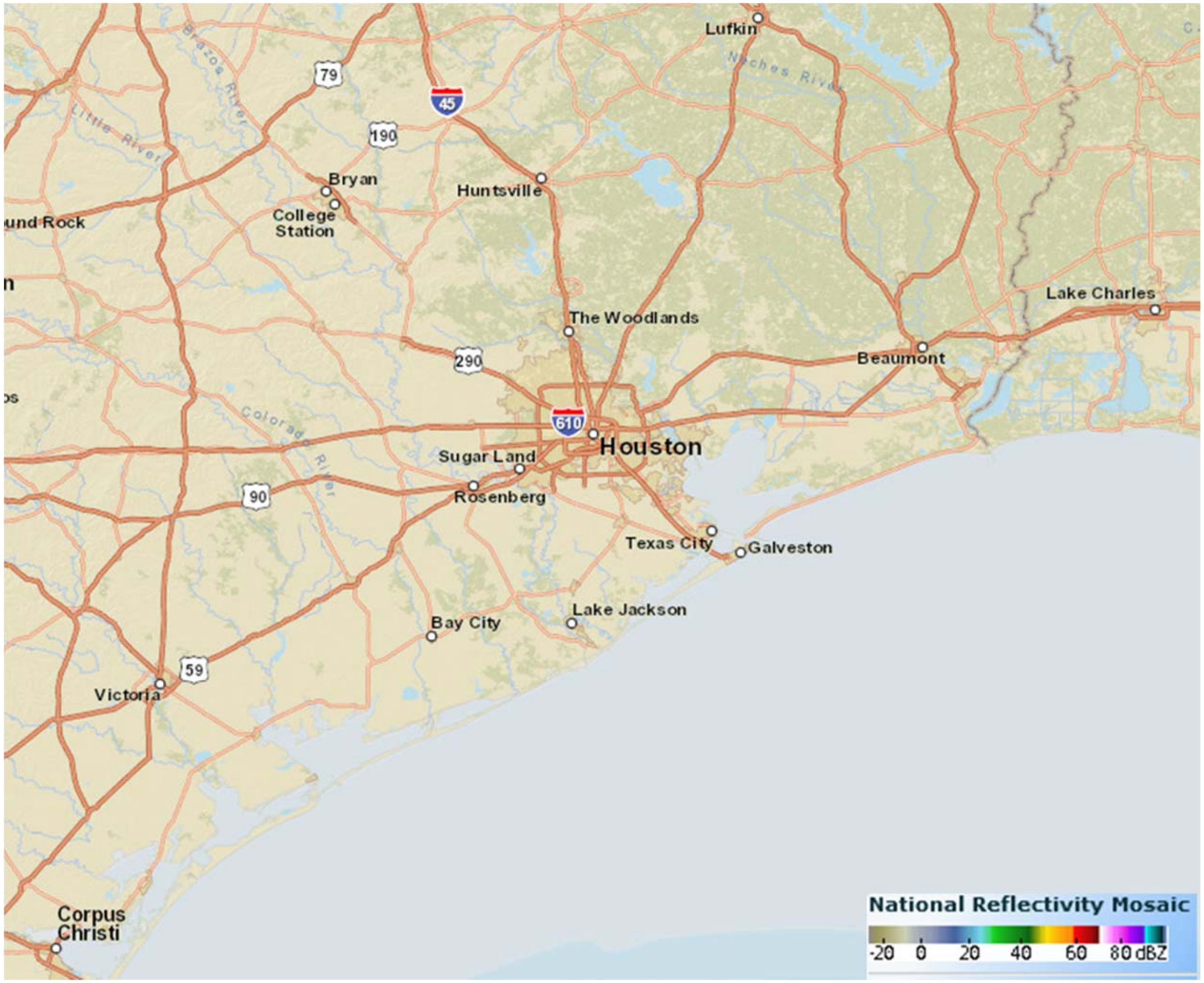


Figure 148. Regional radar image from October 9, 2013. No precipitation was observed throughout the Houston area

2. Representativeness of Meteorological Conditions During the DISCOVER-AQ Campaign

This section provides context to the DISCOVER-AQ boundary layer characteristics described in Section 1 by comparing them to boundary layer characteristics observed (1) on days with high ozone concentrations during the 2005-2006 Texas Air Quality Study II[3] (TexAQS-II) and (2) generally over the past 10 years, in regards to the vertical ozone structure and meteorological conditions.

2.1 Comparison of Meteorological Conditions in DISCOVER-AQ and TexAQS-II

The TexAQS-II field study was conducted from April 2005 through October 2006, to examine regional ozone formation, transport of ozone and ozone precursors, meteorological and photochemical modeling, issues related to ozone formation by highly reactive emissions, and particulate matter formation across roughly the eastern half of Texas. As part of the TexAQS-II study, STI quality controlled radar wind profiler data from several sites across Texas, completed mixing-height derivations, and investigated and summarized meteorological boundary layer conditions. STI closely assessed 10 of the days that were a focus of TCEQ modeling efforts during the TexAQS-II study, and those 10 days were used for comparison with meteorological boundary layer conditions observed on high-ozone days during the 2013 DISCOVER-AQ study in Houston. The 10 analysis days from TexAQS-II include June 22-25, 2005; July 31–August 2, 2005; and August 31-September 2, 2006.

The following tasks were completed to note similarities and differences between the selected TexAQS-II days and DISCOVER-AQ days:

- Assessment of diurnal and spatial characteristics of boundary layer winds and mixing heights.
- Analysis of general transport patterns.
- Analysis of aloft ozone patterns using sounding data.
- Identification of days with similar large-scale and mesoscale meteorological patterns between TexAQS-II and DISCOVER-AQ.

2.1.1 Boundary Layer Characteristics

In general, meteorological conditions during the 10 TexAQS-II study days featured weaker onshore winds and higher ozone levels compared to conditions on most of the DISCOVER-AQ study days. An

[3] TexAQS-II website: https://www.tceq.texas.gov/airquality/research/texaqs.

important distinction between the two studies in this analysis is the fact that the DISCOVER-AQ study days were later in the year (late August through early October) compared to the TexAQS-II study days (late June through early September). Thus, in general, 500 mb heights were lower, surface pressure gradients were stronger, and mixing heights were lower during the DISCOVER-AQ study days, as would generally be expected across the southern and southeastern United States during late summer and early fall.

Similar to findings from the TexAQS-II study period, ozone levels were highest in the Houston area on days with generally light winds through the depth of the boundary layer and a gradual shift in winds from light offshore (land breeze) during the overnight and morning to light easterly/onshore (Bay breeze) during the late morning and early afternoon, and then light to moderate southeasterly/onshore (Gulf breeze) during the late afternoon and evening. Figures 149 and 150 show wind data in UTC from the LaPorte profiler on September 1, 2006 (TexAQS-II), and on September 25, 2013 (DISCOVER-AQ); 8-hr maximum ozone concentrations were 121 ppb and 124 ppb on these days, respectively. The wind data at LaPorte clearly illustrate the cyclical pattern of offshore to onshore winds, which is conducive to recirculation of pollutants and that was noted on many of the high-ozone days in both studies.

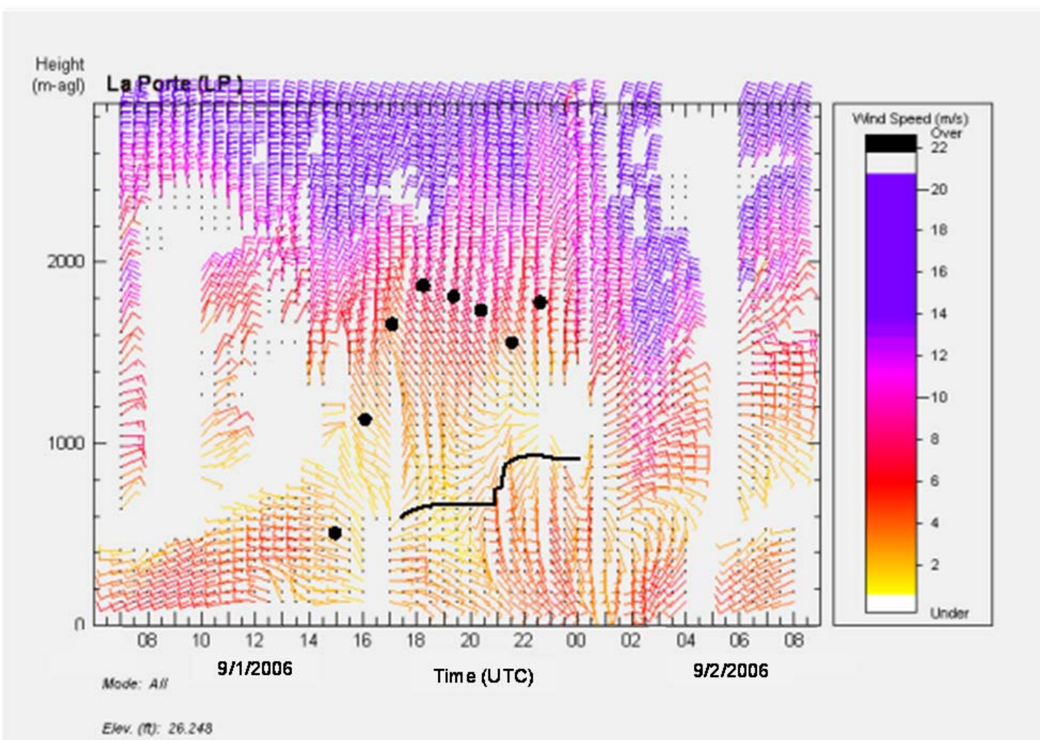


Figure 149. Wind data from the LaPorte radar wind profiler on September 1, 2006. Black dots indicate estimated hourly mixing heights; the black line denotes the depth of the marine layer.

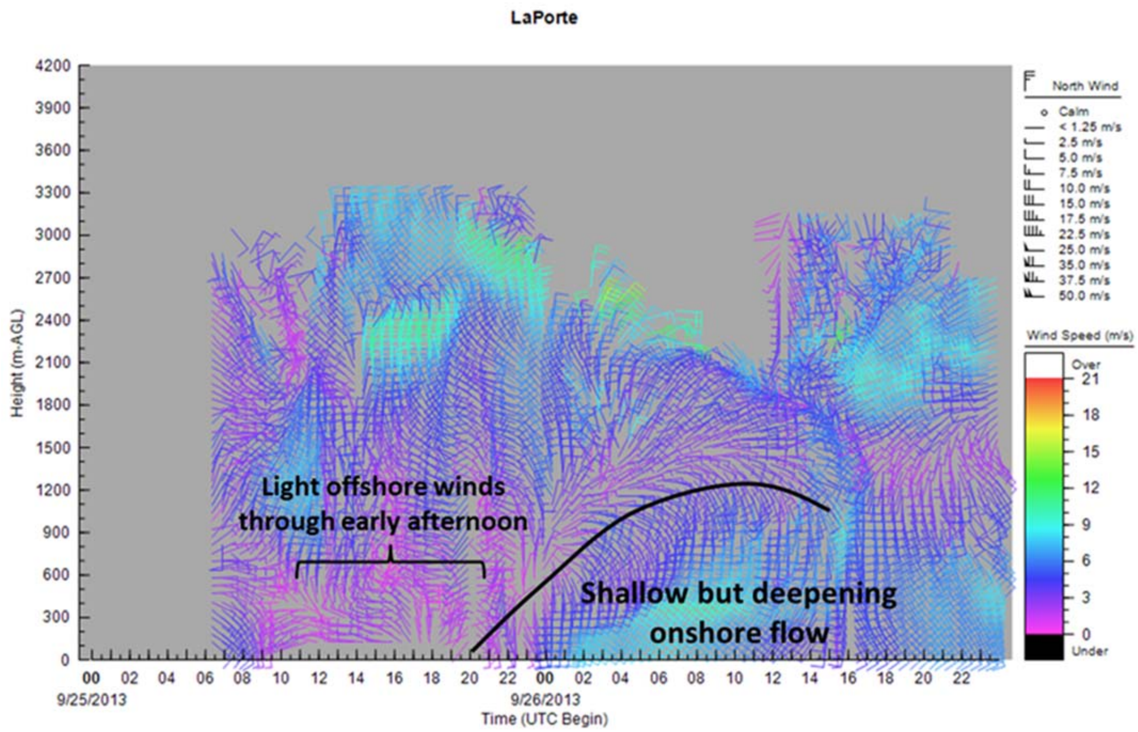


Figure 150. Wind data from the LaPorte radar wind profiler on September 25 and 26, 2013.

In addition, mixing heights at the LaPorte radar wind profiler during the morning hours were generally lower on high-ozone days (days with a regional maximum 8-hr ozone average of at least 76 ppb) compared to low-ozone days, and mixing heights were higher during the afternoon hours on high-ozone days compared to low-ozone days (Table 8). This is consistent with stronger onshore flow on low-ozone days.

Table 8. Comparison of mixing heights at the LaPorte radar wind profiler on high- and low-ozone days during the TexAQS-II and DISCOVER-AQ studies.

Study Period	Average Morning (9:00 a.m. to 12:00 p.m. CST) Mixing Height		Average Peak Mixing Height	
	High-Ozone Days	Low-Ozone Days	High-Ozone Days	Low-Ozone Days
TexAQS-II (368 days)	~825 m	~975 m	~1500 m	~1400 m
DISCOVER-AQ (16 days)	~850 m	~1000 m	~1600 m	~1200 m

2.1.2 General Transport Patterns

The 24-hr backward trajectories generated to assess boundary layer transport during the DISCOVER-AQ study period (described in Section 1) were compared to HYSPLIT trajectories created for a previous analysis of general transport patterns during the TexAQS-II study period. That previous analysis found that winds were primarily south-southeasterly with longer transport distances on non-episode days, and were primarily southeasterly with shorter transport distances on episode days, demonstrating that lighter winds, recirculation, and reduced pollutant dispersion coincided with higher ozone concentrations (Table 9). Similarly, during the DISCOVER-AQ study, transport distances were longer on low-ozone days and shorter on high-ozone days. Winds on low-ozone days during the DISCOVER-AQ study were primarily east-southeasterly, compared to south-southeasterly during the TexAQS-II study.

Table 9. Comparison of 24-hr average scalar transport distance and transport direction on high- and low-ozone days during the TexAQS-II and DISCOVER-AQ studies.

Study Period	24-hr Average Transport Distance		Predominant Transport Direction	
	High-Ozone Days	Low-Ozone Days	High-Ozone Days	Low-Ozone Days
TexAQS-II (368 days)	267 km	450 km	Southeast	South-southeast
DISCOVER-AQ (16 days)	330 km	430 km	South-southeast	East-southeast

2.1.3 Aloft Ozone Patterns

Daily ozonesonde data from the TexAQS-II and DISCOVER-AQ studies were viewed to compare and contrast aloft ozone patterns. Ozonesondes during both studies were launched during the late afternoon at the University of Houston. Some of the features in the daily ozonesonde data that were noted for this analysis include boundary layer height, average ozone concentration in the surface mixed layer, relative humidity above and below the mixed layer, the presence and height of aloft layers of higher ozone mixing ratios, and tropopause height. Figure 151 shows these features annotated on ozonesonde plots as an example. Ozonesonde data were available for only 6 of the 10 TexAQS-II days being analyzed in this project.

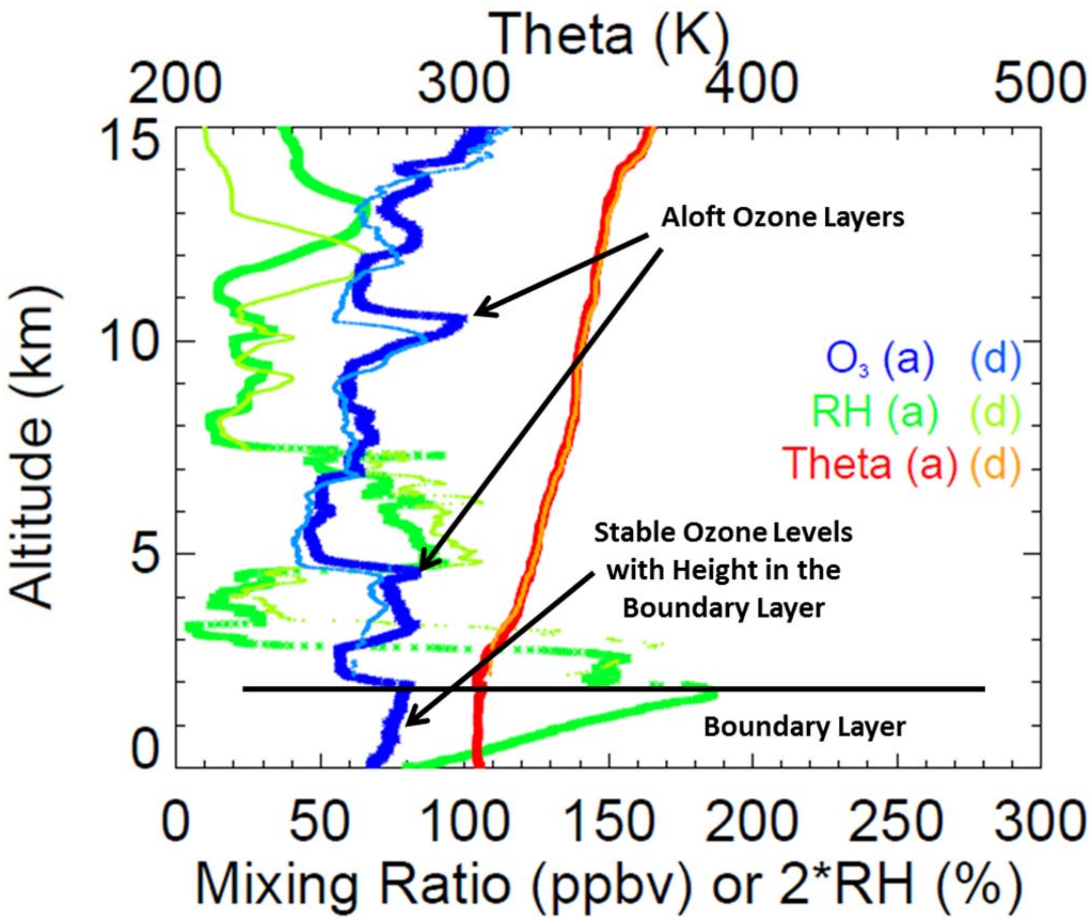


Figure 151. Ozonesonde data from August 28, 2013, with key features annotated. Colored lines indicate ozone mixing ratio (blue), relative humidity (green), and potential temperature (red). (a) denotes ascending profiles; (d) denotes descending profiles.

Some general observations noted in the daily ozonesonde data during the TexAQS-II and DISCOVER-AQ studies include:

- Homogeneous ozone concentrations through the depth of the boundary layer.
- A rapid increase in relative humidity with height from the surface to the top of the boundary layer, followed by a decrease in relative humidity.
- Relative humidity levels were lower both above and below the top of the boundary layer on the days with the highest ozone concentrations (August 31, 2006, and September 25, 2013) compared to days with lower ozone levels. Relative humidity also dropped more rapidly above the boundary layer on the highest-ozone days. Ozone levels are typically highest in Houston with a dry, continental air mass in place following passage of a cold front/low-pressure system.

- Mixing heights derived from the daily ozonesondes were all between 1000 and 2200 m. There was some correlation between higher mixing heights and higher ozone concentrations; this relationship is likely attributable to the dry, continental air mass typically in place on high-ozone days that is conducive to rapid boundary layer growth during the afternoon hours.

- Tropopause heights were consistently between 15 and 17 km in both studies with little day-to-day change.

2.1.4 Days with Similar Synoptic and Mesoscale Patterns

Synoptic weather maps, local surface weather conditions from Houston Hobby Airport (KHOU), radar wind profiler data, and data from the Ozone Monitoring Instrument (OMI) were used to compare the TexAQS-II study days and the DISCOVER-AQ days to identify days with similar meteorological patterns across the two study periods, and then to explain differences in observed ozone concentrations on those days. **Table 10** lists the TexAQS-II and DISCOVER-AQ study days with comparable meteorological conditions (referred to as analog days). In general, on days with similar meteorological conditions during the TexAQS-II and DISCOVER-AQ studies, ozone concentrations were lower on the DISCOVER-AQ days, suggesting that the lower ozone concentrations are attributable to lower pollution emissions.

Table 10. TexAQS-II study days and analog days from the DISCOVER-AQ study.

TexAQS-II Study Days	DISCOVER-AQ Analog Days
June 23, 2005	August 28, 2013
June 25, 2005	September 11, 2013
August 2, 2005	October 8, 2013
September 1, 2006	September 25, 2013

Comparison #1: June 23, 2005, and August 28, 2013

Table 11 summarizes key synoptic and meteorological conditions observed on June 23, 2005, and August 28, 2013; **Figures 152 and 153** show 500 mb weather maps for both days; and **Figures 154 and 155** show surface weather maps for both days. Synoptic meteorological conditions were closely matched on these days. Weak onshore winds developed during the afternoon hours, transporting higher ozone concentrations to the northwest side of Houston. Low-level trajectories were from the southeast with 24-hr transport distances of around 300 km. Peak 1-hr and 8-hr ozone concentrations were high but still lower on August 28, 2013, compared to June 23, 2005; this was found to be true generally when comparing the TexAQS-II and DISCOVER-AQ field studies, and is likely attributable, at least in part, to reductions in pollutant emissions.

Table 11. Comparison of meteorological conditions on June 23, 2005, and August 28, 2013.

Meteorological Parameter	June 23, 2005 (TexAQS-II)	August 28, 2013 (DISCOVER-AQ)
500 mb pattern	High over central Plains/Southwest	High over central Plains
Surface pattern	High over Mississippi; weak large-scale gradient	Broad surface high from Northeast United States to eastern Texas; weak large-scale gradient
Max./Min. Surface Temps.	94°F / 73°F	95°F / 73°F
Avg. Surface Dew Point	67°F	69°F
Local wind pattern	Weak overnight land breeze followed by afternoon sea breeze	Weak overnight land breeze followed by afternoon sea breeze
24-hr transport direction	From the southeast	From the southeast
24-hr transport distance	~350 km	~350 km
Mixing heights	N/A	1500–2000 m inland; less than 1000 m coast
Cloud cover	Mostly sunny	Mostly sunny
OMI Cloud Fraction (%)	36	36
OMI Total Ozone (Dobson Unit - DU)	308	294
Location of highest ozone	Northwest side of Houston	Northwest side of Houston
Peak 1-hr ozone	138 ppb	108 ppb
Peak 8-hr ozone	96 ppb	83 ppb

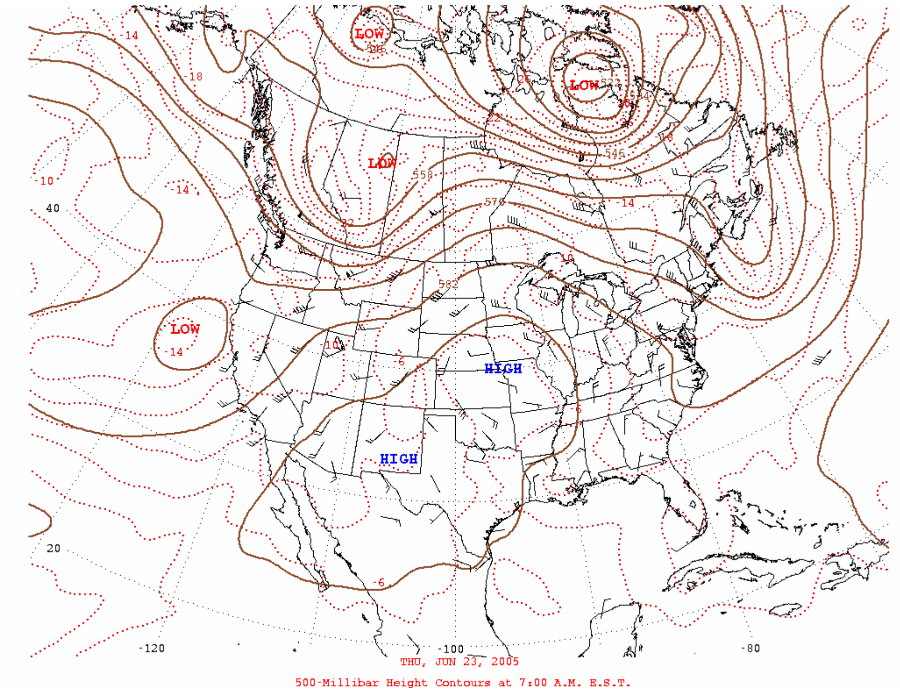


Figure 152. A map showing the height of the 500 mb pressure surface at 6:00 a.m. CST on June 23, 2005. An upper-level high-pressure system was located over the central Plains.

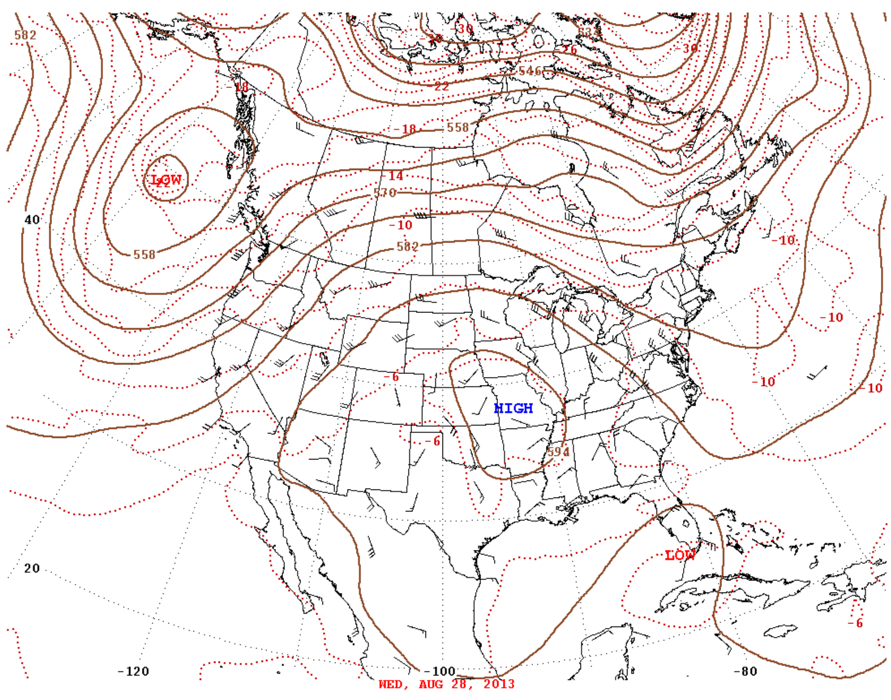


Figure 153. A map showing the height of the 500 mb pressure surface at 6:00 a.m. CST on August 28, 2013. An upper-level high-pressure system was located over the central Plains.

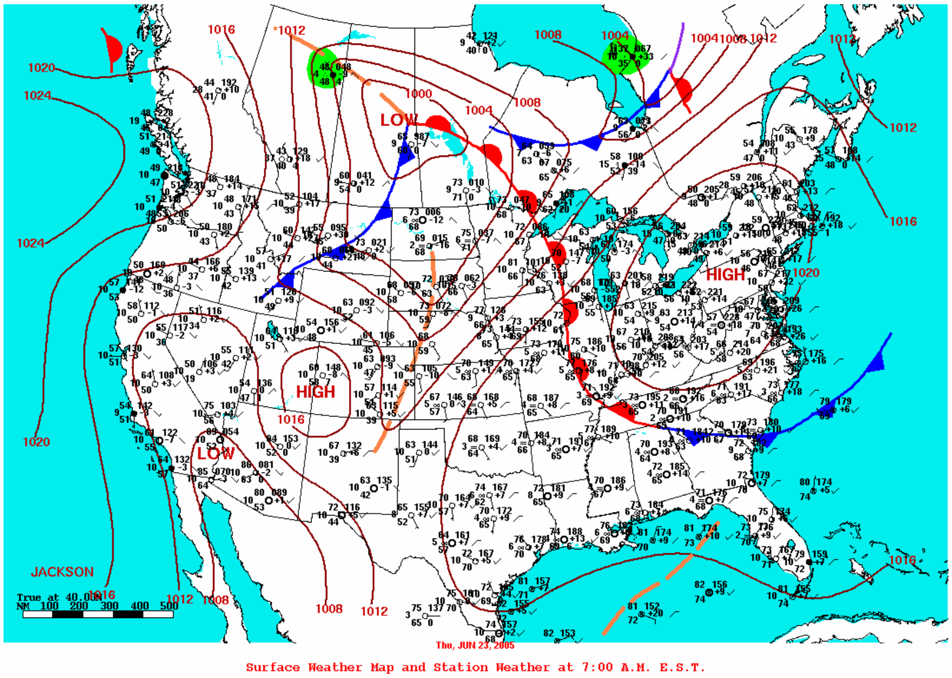


Figure 154. Surface pressure map at 6:00 a.m. CST on June 23, 2005. A broad surface high-pressure system extended from the northeastern United States southwestward to eastern Texas, resulting in a weak large-scale pressure gradient in the Houston area.

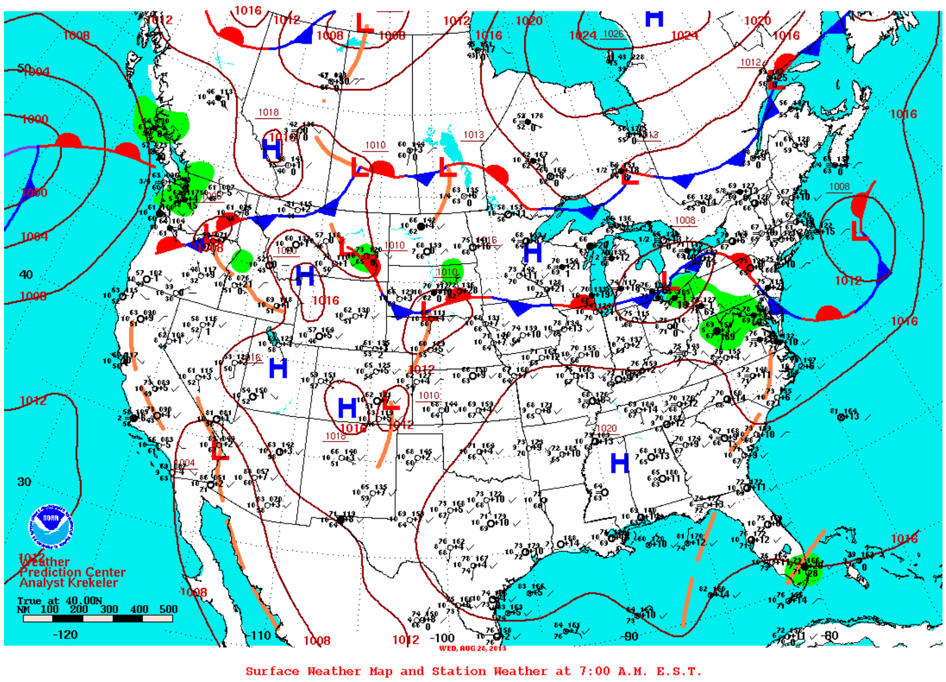


Figure 155. Surface pressure map at 6:00 a.m. CST on August 28, 2013. A broad surface high-pressure system was located over the southeastern United States, resulting in a weak large-scale pressure gradient in the Houston area.

Comparison #2: June 25, 2005, and September 11, 2013

Table 12 summarizes key synoptic and meteorological conditions observed on June 25, 2005, and September 11, 2013. Figures 156 and 157 show 500 mb weather maps for both days. Figures 158 and 159 show surface weather maps for both days. Synoptic meteorological conditions closely matched on both days. Moderate onshore winds helped to disperse pollutants and bring cleaner air into the Houston area. Low-level trajectories were from the east-southeast with 24-hr transport distances of at least 500 km on both days. Despite similarities in the large- and local-scale meteorological conditions, peak 1-hr and 8-hr ozone concentrations were much higher on June 25, 2005, compared to September 11, 2013. On the latter day, increased cloud cover likely reduced ozone formation somewhat, and slightly stronger onshore winds (as noted by the 24-hr transport distance) helped to further disperse pollutants and bring cleaner, maritime air inland. Because of differences in cloud cover on the two days, the benefit of emissions reductions on ozone concentrations is not clear.

Table 12. Comparison of meteorological conditions on June 25, 2005, and September 11, 2013.

Meteorological Parameter	June 25, 2005 (TexAQS-II)	September 11, 2013 (DISCOVER-AQ)
500 mb pattern	Broad high over the central and eastern united States; weak low near Florida	Broad high over the southeastern United States; weak low over Florida
Surface pattern	High over the Mid-Atlantic/Southeast; weak to moderate easterly gradient	High over the Southeast; moderate easterly gradient
Max./Min. Surface Temps.	94°F / 71°F	92°F / 72°F
Avg. Surface Dew Point	70°F	72°F
Local wind pattern	Light easterly winds during the overnight/morning, followed by moderate easterly winds with enhancement from a Gulf Breeze	Light east-northeasterly winds overnight, followed by moderate east-southeasterly winds with enhancement from a Gulf Breeze
24-hr transport direction	From the east-southeast	From the east-southeast
24-hr transport distance	~550 km	~650 km
Mixing heights	N/A	Uniform throughout the region, between 800 and 1200 m
Cloud cover	Partly cloudy	Partly to mostly cloudy
OMI Cloud Fraction (%)	32	17
OMI Total Ozone (DU)	301	284

Meteorological Parameter	June 25, 2005 (TexAQS-II)	September 11, 2013 (DISCOVER-AQ)
Location of highest ozone	Highest on west side of Houston, but fairly uniform regionally	Regionally uniform
Peak 1-hr ozone	93 ppb	63 ppb
Peak 8-hr ozone	82 ppb	51 ppb

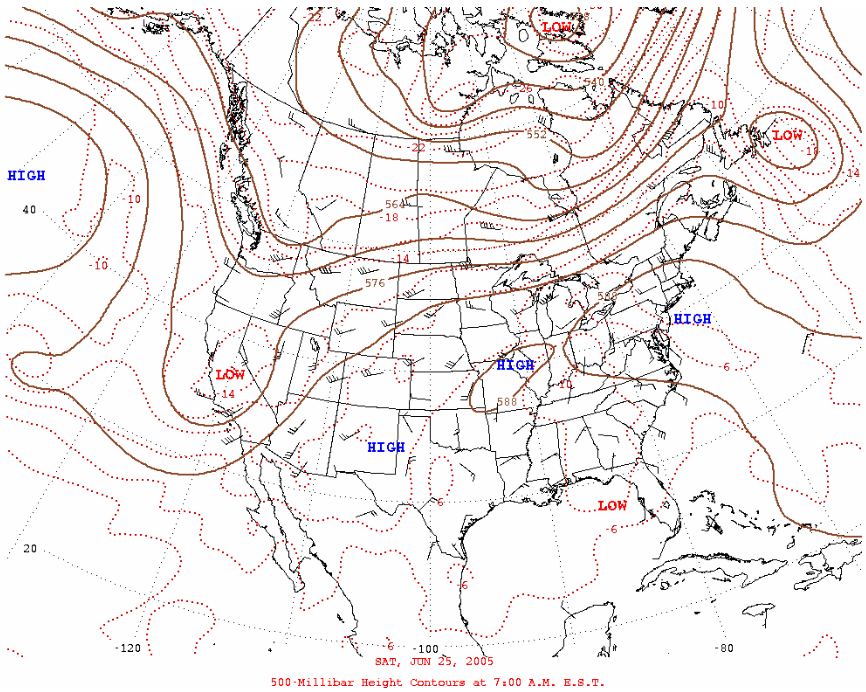


Figure 156. A map showing the height of the 500 mb pressure surface at 6:00 a.m. CST on June 25, 2005. A broad upper-level high-pressure system was located over the southern and eastern United States, and a weak upper-level low was located near Florida.

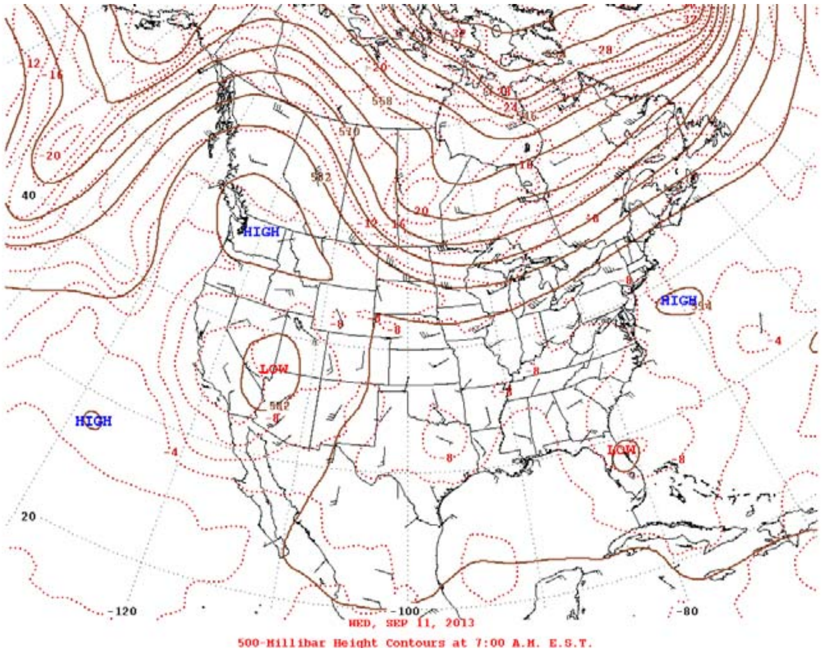


Figure 157. A map showing the height of the 500 mb pressure surface at 6:00 a.m. CST on September 11, 2013. A broad upper-level high-pressure system was located over the south-central and eastern United States, and a weak upper-level low was located over Florida.

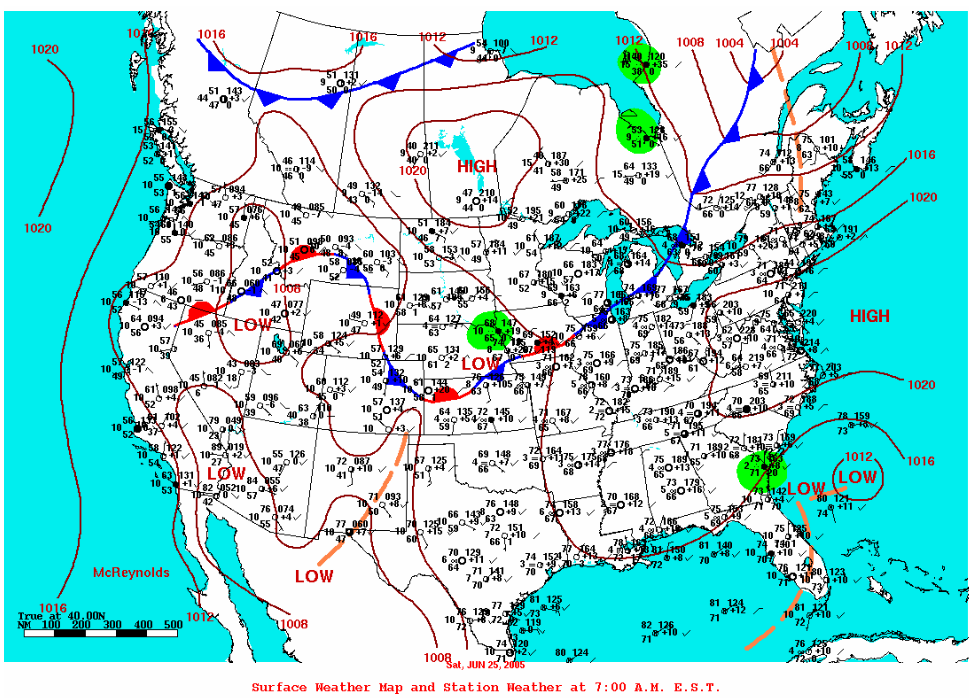
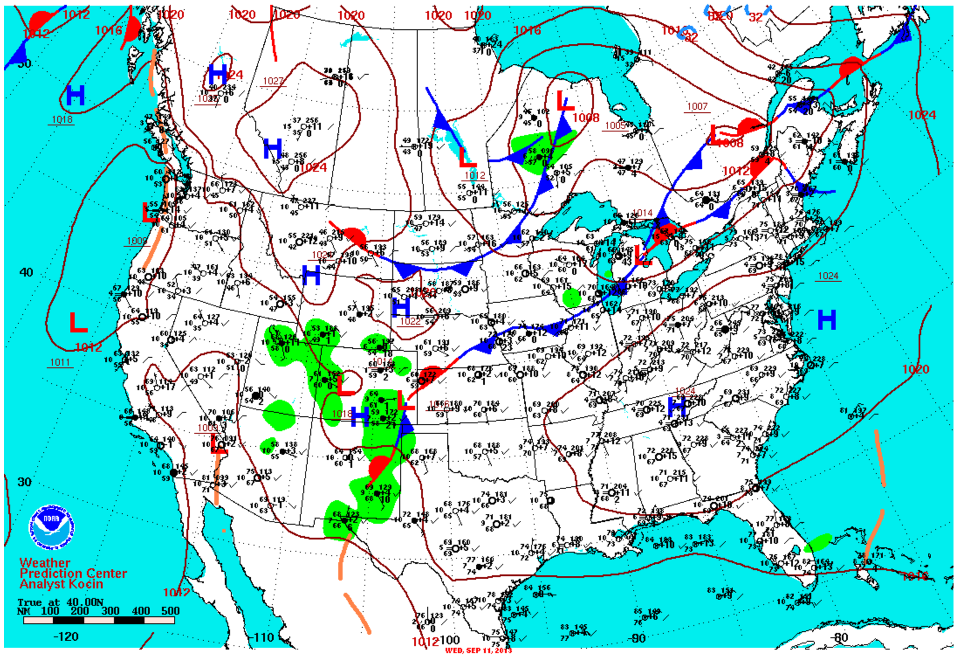


Figure 158. Surface pressure map at 6:00 a.m. CST on June 25, 2005. A surface high-pressure system was located over the Mid-Atlantic and Southeast, resulting in a weak to moderate easterly large-scale pressure gradient in the Houston area.



Surface Weather Map and Station Weather at 7:00 A.M. E.S.T.

Figure 159. Surface pressure map at 6:00 a.m. CST on September 11, 2013. A surface high-pressure system was located over the Southeast, resulting in a moderate easterly large-scale pressure gradient in the Houston area.

Comparison #3: August 2, 2005, and October 8, 2013

Table 13 summarizes key synoptic and meteorological conditions observed on August 2, 2005, and October 8, 2013. Figures 160 and 161 show 500 mb weather maps for both days. Figures 162 and 163 show surface weather maps for both days. Synoptic meteorological conditions closely matched on both days, but the upper-level ridge of high pressure over Texas was slightly weaker on October 8, 2013, compared to August 2, 2005. In addition, surface temperatures and dew point temperatures were lower on October 8, 2013, compared to August 2, 2005, indicative of the difference in season (autumn vs. summer). On both days, a weak synoptic pressure gradient allowed for a typical diurnal cycle of land breeze, Bay breeze, and Gulf breeze, indicating some recirculation of pollution was likely. Easterly to southeasterly winds during the afternoon hours transported higher concentrations to the west side of Houston. Peak 1-hr and 8-hr ozone concentrations were higher on August 2, 2005, compared to October 8, 2013, despite some cloud cover in the Houston area on August 2, 2005. However, slightly lower mixing heights and shorter transport distances on August 2, 2005, likely reduced vertical and horizontal dispersion of pollutants.

Table 13. Comparison of meteorological conditions on August 2, 2005, and October 8, 2013.

Meteorological Parameter	August 2, 2005 (TexAQS-II)	October 8, 2013 (DISCOVER-AQ)
500 mb pattern	High over the central and southern United States	High over the south-central United States
Surface pattern	High over the Mid-Atlantic/Southeast; weak easterly gradient	High centered over the Ohio River Valley, extending southwestward; weak easterly gradient
Max./Min. Surface Temps.	95°F / 75°F	81°F / 53°F
Avg. Surface Dew Point	74°F	52°F
Local wind pattern	Overnight/early-morning land breeze, followed by an early-afternoon Bay breeze and late-afternoon Gulf breeze	Overnight/early-morning land breeze, followed by an early-afternoon Bay breeze and late-afternoon Gulf breeze
24-hr transport direction	From the southeast with some recirculation	From the east with some recirculation
24-hr transport distance	~225 km	~275 km
Mixing heights	Started below 1000 m; then remained near or below 1000 m at coastal/bayside locations with passage of Bay breeze	Started below 1000 m; then remained near or below 1000 m at coastal locations with passage of Bay breeze, and increased to ~1500 m inland. Mixing heights were slightly higher compared to August 2, 2005.
Cloud cover	Partly sunny; some convection on northeast side of Houston	Sunny
OMI Cloud Fraction (%)	5	0
OMI Total Ozone (DU)	306	286
Location of highest ozone	Highest on west side of Houston	Highest on west side of Houston
Peak 1-hr ozone	135 ppb	115 ppb
Peak 8-hr ozone	104 ppb	85 ppb

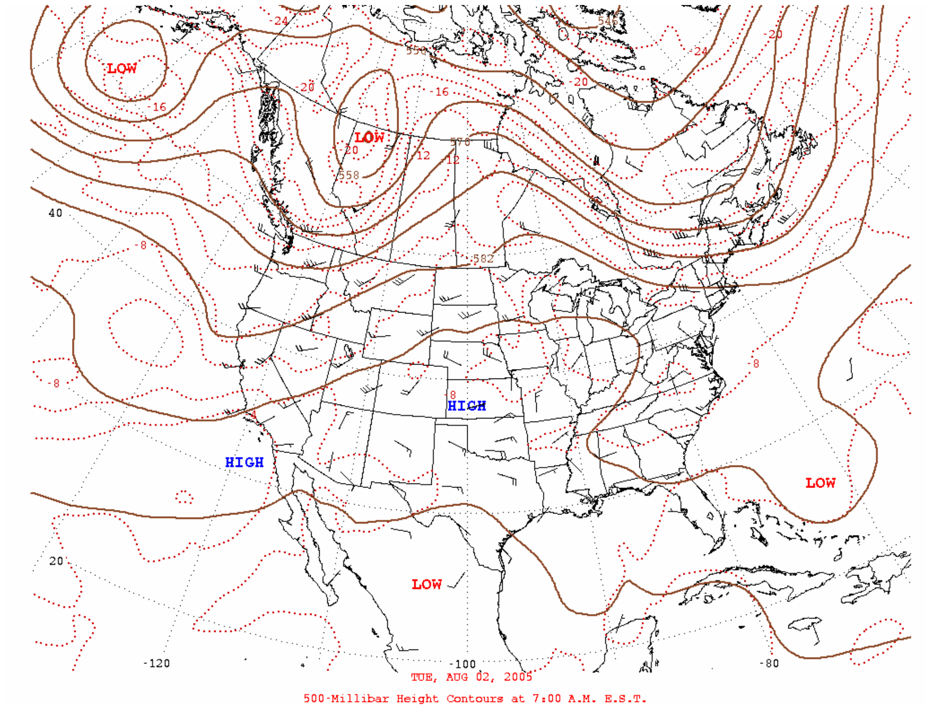


Figure 160. A map showing the height of the 500 mb pressure surface at 6:00 a.m. CST on August 2, 2005. A broad upper-level high-pressure system was located over the central United States.

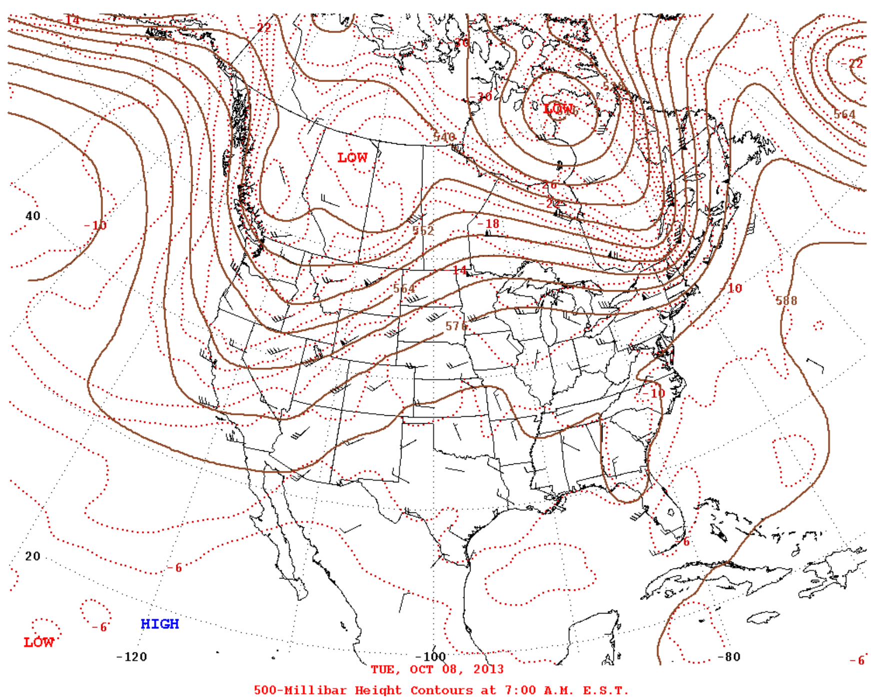


Figure 161. A map showing the height of the 500 mb pressure surface at 6:00 a.m. CST on October 8, 2013. An upper-level high-pressure system was located over the central United States.

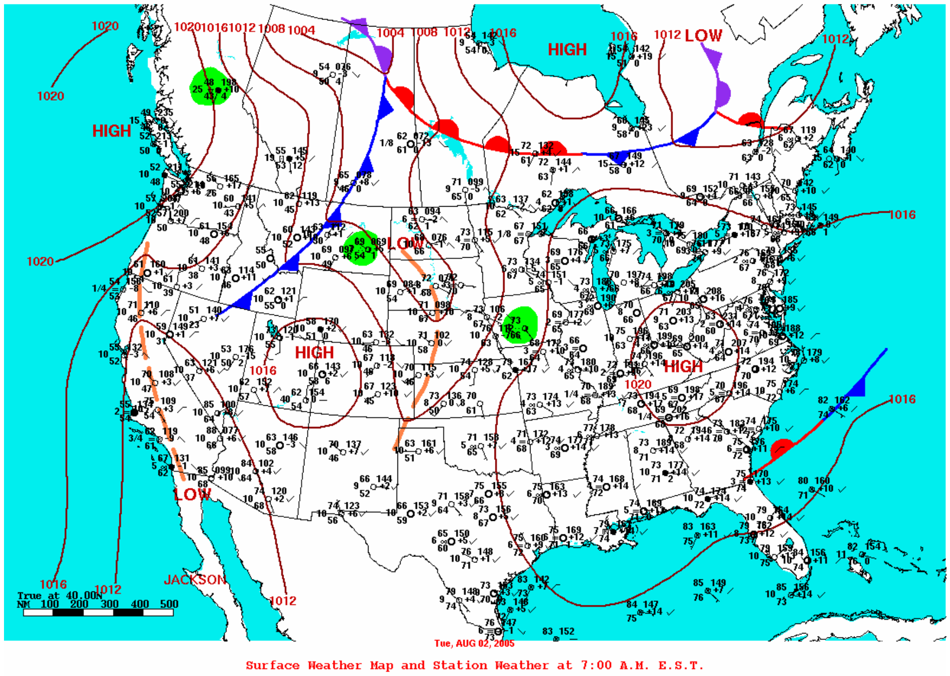


Figure 162. Surface pressure map at 6:00 a.m. CST on August 2, 2005. A surface high-pressure system was located over the Mid-Atlantic region, resulting in a weak easterly large-scale pressure gradient in the Houston area.

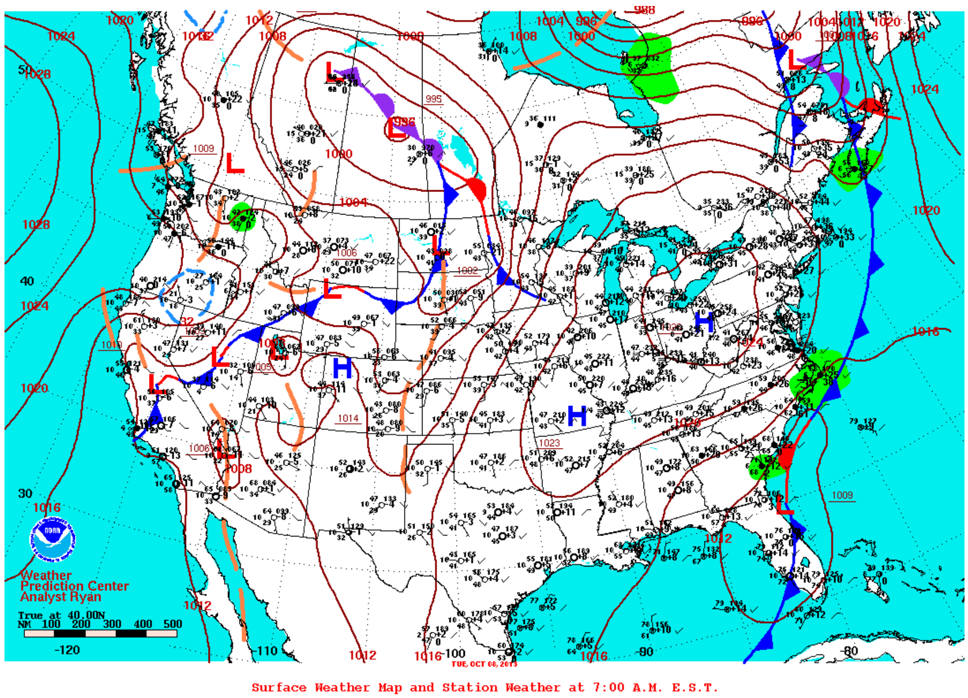


Figure 163. Surface pressure map at 6:00 a.m. CST on October 8, 2013. A surface high-pressure system was located over the Ohio River Valley, resulting in a moderate easterly large-scale pressure gradient in the Houston area.

Comparison #4: September 1, 2006, and September 25, 2013

Table 14 summarizes key synoptic and meteorological conditions observed on September 1, 2006, and September 25, 2013. Figures 164 and 165 show 500 mb weather maps for both days. Figures 166 and 167 show surface weather maps for both days. Synoptic meteorological conditions closely matched on both days, but the synoptic offshore gradient was slightly stronger on September 25, 2013, compared to September 1, 2006, due to a stronger preceding frontal passage. On both days, the weak synoptic pressure gradient allowed for a typical diurnal cycle of land breeze, Bay breeze, and Gulf breeze, indicating some recirculation. The offshore component to the pressure gradient delayed onset of the Bay breeze until mid-afternoon on both days. Low mixing heights during the morning hours increased rapidly by afternoon, before falling at immediate coastal areas due to passage of the Bay breeze. The very light winds resulted in higher ozone concentrations east and southeast of downtown Houston (near the Ship Channel). Peak 1-hr and 8-hr ozone concentrations were very similar on both days.

Table 14. Comparison of meteorological conditions on September 1, 2006, and September 25, 2013.

Meteorological Parameter	September 1, 2006 (TexAQS-II)	September 25, 2013 (DISCOVER-AQ)
500 mb pattern	High over Texas	High over Texas
Surface pattern	Weak high over the southern Plains and weak trough of low pressure across northern Gulf Coast; weak offshore gradient	High over the southern Plains and cold front southeast of Houston; weak offshore gradient
Max./Min. Surface Temps.	96°F / 73°F	95°F / 66°F
Avg. Surface Dew Point	70°F	64°F
Local wind pattern	Overnight/early-morning land breeze, followed by a mid-afternoon Bay breeze and evening Gulf breeze	Overnight/early-morning land breeze, followed by a mid-afternoon Bay breeze and evening Gulf breeze
24-hr transport direction	From the southeast with recirculation	From the southeast with recirculation
24-hr transport distance	~200 km	~150 km
Mixing heights	Started near 500 m; then increased rapidly to near 2000 m before falling back to near 1000 m late in the day with passage of the Bay breeze	Started near 500 m; then increased rapidly to over 2000 m before falling back to near 1000 m late in the day with passage of the Bay breeze
Cloud cover	Partly sunny; some convection on northeast side of Houston	Sunny

Meteorological Parameter	September 1, 2006 (TexAQS-II)	September 25, 2013 (DISCOVER-AQ)
OMI Cloud Fraction (%)	43	10
OMI Total Ozone (DU)	300	275
Location of highest ozone	Highest near the Ship Channel on southeast side of Houston	Highest near the Ship Channel on southeast side of Houston
Peak 1-hr ozone	161 ppb	151 ppb
Peak 8-hr ozone	121 ppb	124 ppb

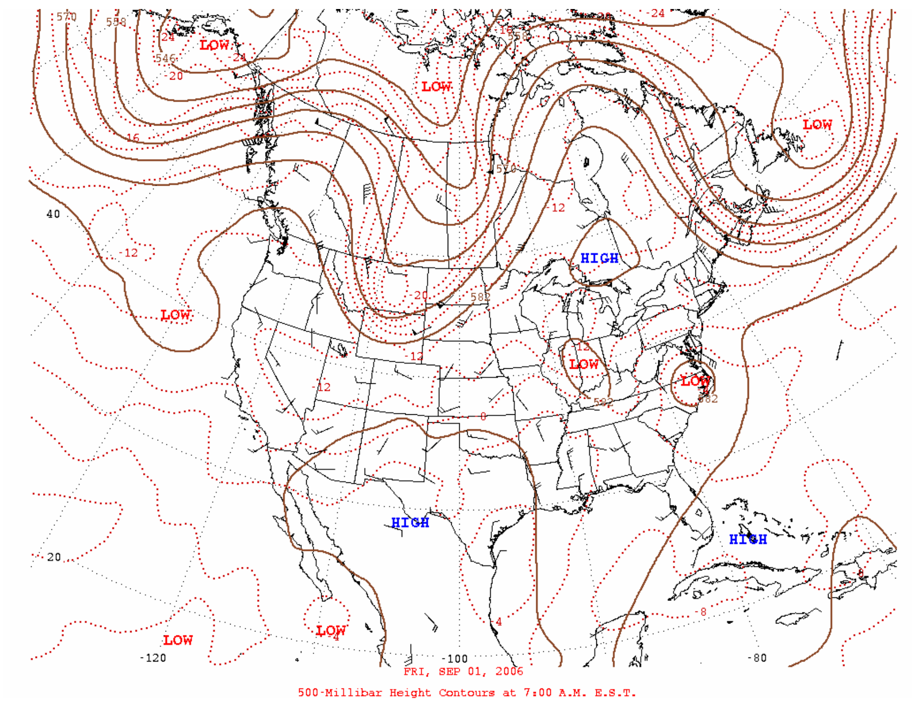


Figure 164. A map showing the height of the 500 mb pressure surface at 6:00 a.m. CST on September 1, 2006. A broad upper-level high-pressure system was located over Texas.

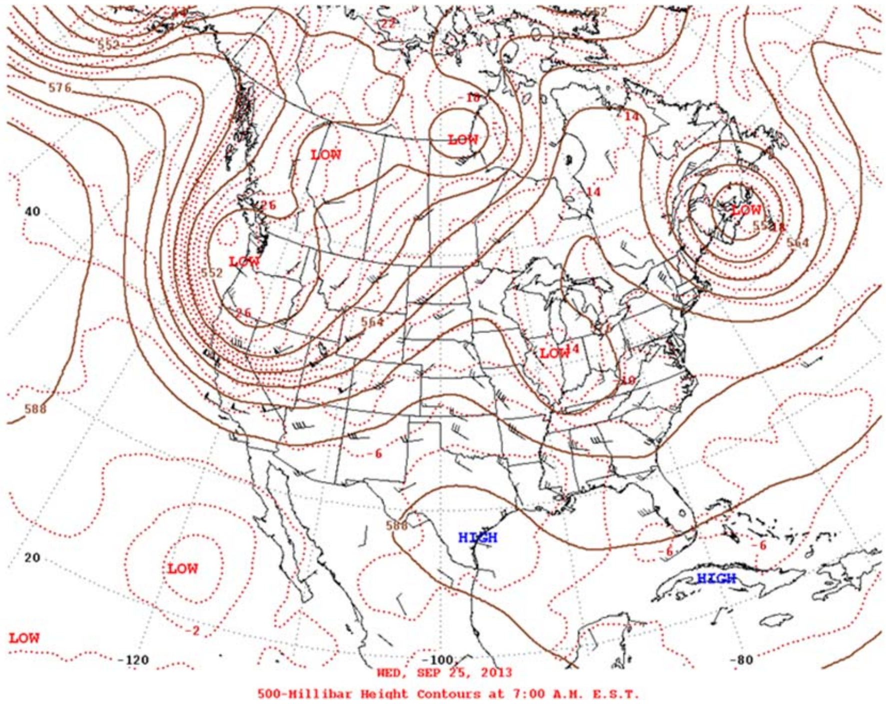


Figure 165. A map showing the height of the 500 mb pressure surface at 6:00 a.m. CST on September 25, 2013. An upper-level high-pressure system was located over Texas.

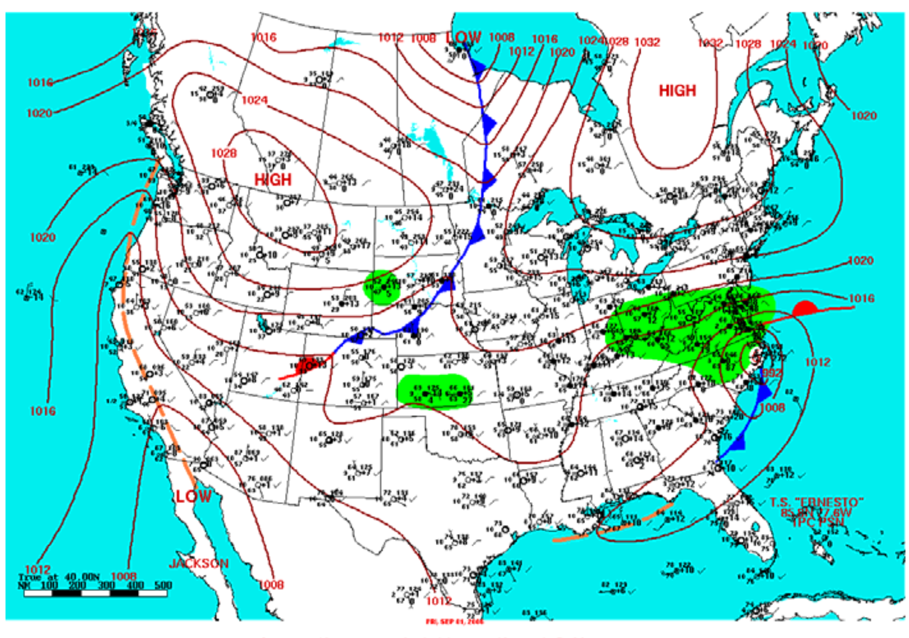


Figure 166. Surface pressure map at 6:00 a.m. CST on September 1, 2006. A surface high-pressure system extended from the Great Lakes southwestward to the southern Plains, and a weak trough of low pressure was located east of Houston, resulting in a weak offshore large-scale pressure gradient in the Houston area.

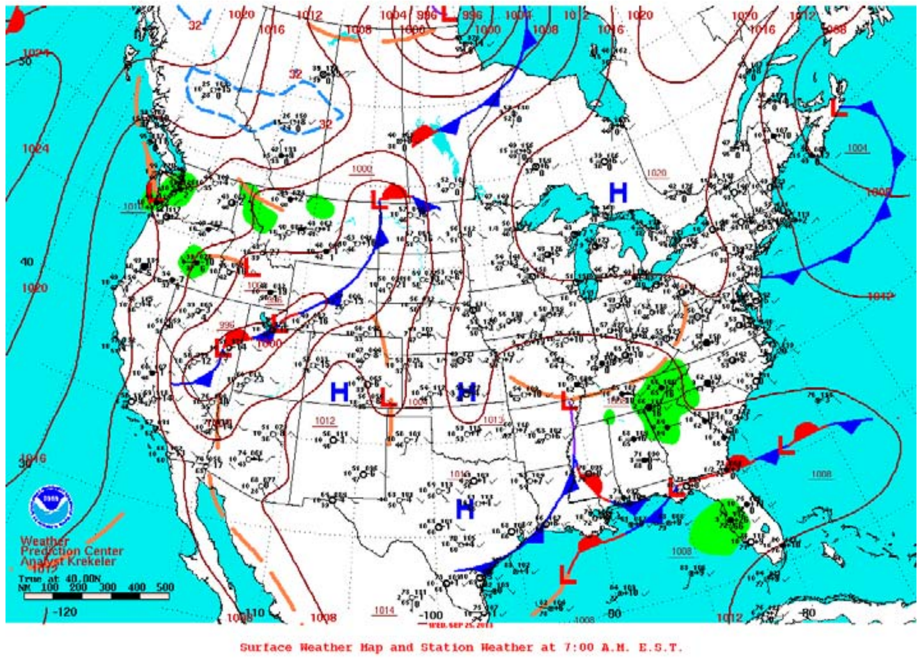


Figure 167. Surface pressure map at 6:00 a.m. CST on September 25, 2013. A surface high-pressure system was located over the southern Plains and a cold front was located southeast of Houston, resulting in a weak offshore large-scale pressure gradient in the Houston area.

2.2 General Comparison of Meteorological Conditions During DISCOVER-AQ to Conditions in the Past Ten Years

This analysis puts the DISCOVER-AQ ozone profiles and general meteorological conditions in context by

- Comparing profiles during DISCOVER-AQ to the September average profiles over the last 10 years
- Examining the general meteorological variability over that 10-yr period.

To compare the vertical ozone structure observed during the DISCOVER-AQ period to that of other recent Septembers, ozonesonde data for September from 2004 to 2012 were averaged and plotted to create a September average ozone profile. Figure 168 shows the September average ozone profiles for 2013, 2014, and the 2004-2012 average. The gray shaded region denotes the 2004-2012 average plus or minus one standard deviation, and the parentheses show the number of individual profiles included in the average. Of particular note is that in 2013 (the DISCOVER-AQ study year), there was a much stronger vertical gradient in ozone (ozone increases with height) compared to previous years. This strong vertical gradient in ozone indicates less mixing of ozone vertically through the troposphere. A strong vertical gradient in ozone is common during the mid-summer months in Houston, but by late summer and early fall, cold frontal passages typically enhance the mixing of ozone through the troposphere and result in a more-uniform ozone profile. In 2013, however, the first significant cold frontal passage did not occur until September 20.

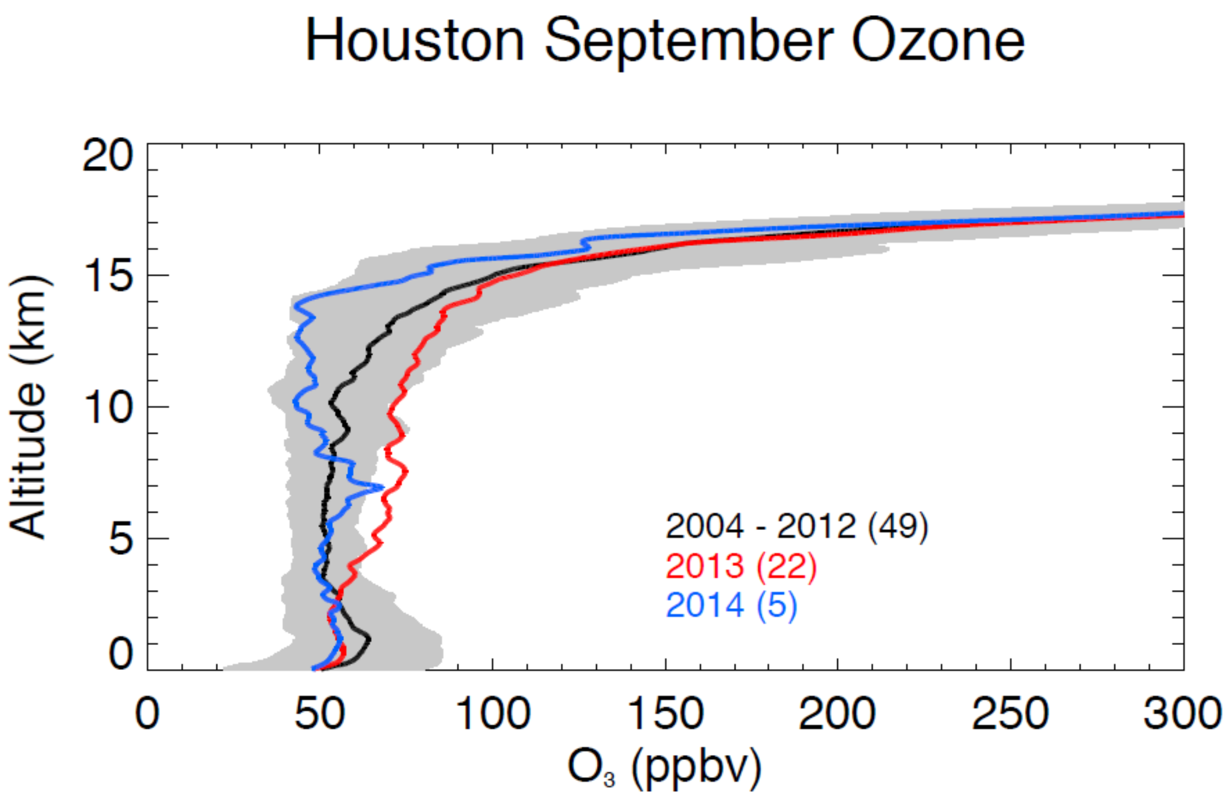


Figure 168. September average ozone profiles for 2013, 2014, and 2014-2012. The profile for 2013 showed a much stronger vertical gradient in ozone compared to the 2014-2012 average.

To better assess the change in tropospheric ozone profiles from summer to fall, 2004-2012 average ozone profiles and the 2013 ozone profile were averaged by week for August and September (Figure 169). The profiles with black outlines are the 2004-2012 averages, and the profiles without an outline are from 2013. In the 2004-2012 average profiles, a much stronger vertical gradient was evident in August, followed by a transition to a more-uniform ozone profile in late August to early September. This transition typically occurs with the arrival of the first mid-latitude cold fronts of the season. In 2013, the profiles continued to show a strong vertical gradient in ozone through mid-September. Thus, is can be concluded that tropospheric ozone conditions in 2013 were abnormal compared to the 2004-2012 average, largely due to the lack of frontal passages and the associated tropospheric mixing.

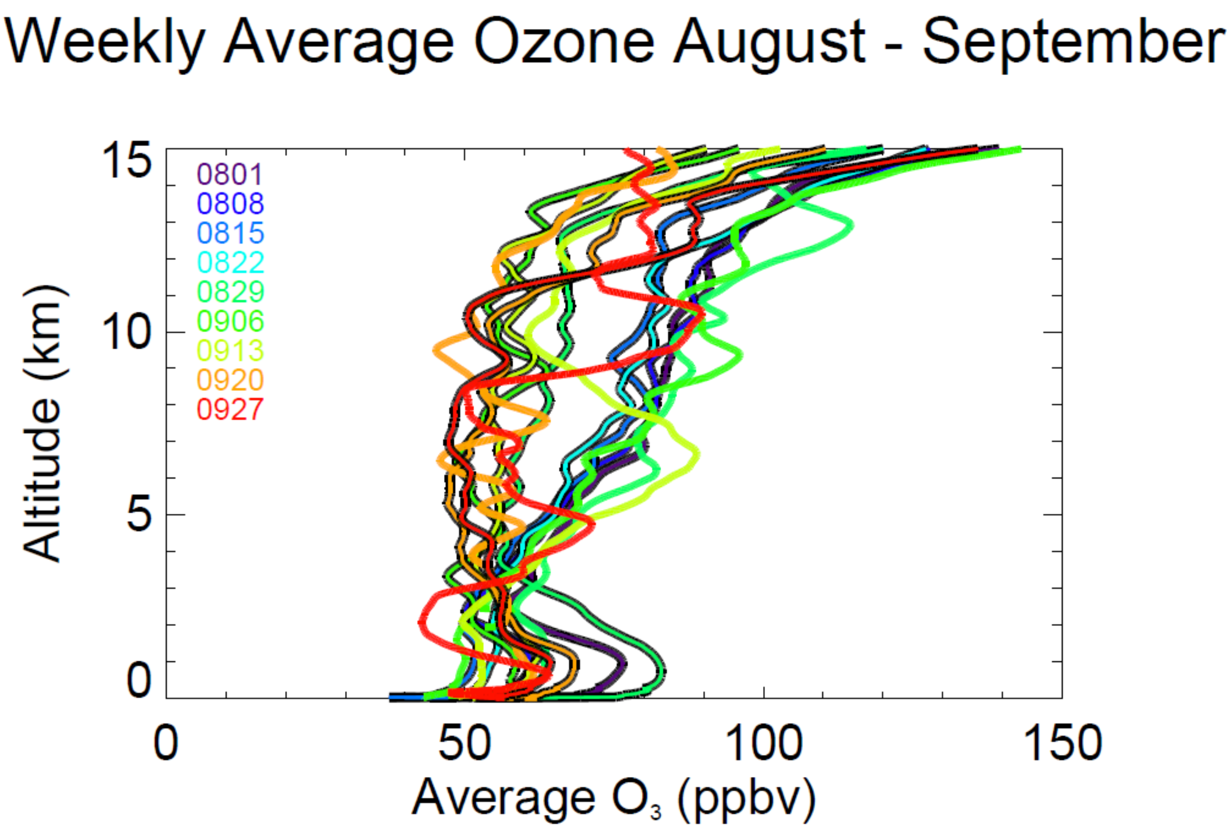


Figure 169. August and September weekly average ozone profiles for 2013 and 2004-2012.

Surface meteorological data from Houston Hobby Airport were used to examine general meteorological variability over the 10-yr (2004-2013) period. In addition, daily surface meteorological maps were reviewed to estimate the number of August and September cold frontal passages each year. Surface ozone concentrations are typically highest in Houston following passage of late-summer cold fronts.

Figure 170 shows averages of daily maximum temperature and daily maximum 1-hr ozone at Houston-area air quality monitors, total rainfall accumulation, number of late-summer frontal passages, and number of days with dew point temperatures of less than 65°F (hereby referred to as "low dew point days"), which are indicators of frequency of post-frontal, continental air masses for each September from 2004-2013, and the average of these metrics over the full 10-yr period. The corresponding data values are also shown in Table 15. Ozone data used in this analysis are from the Houston Texas Avenue ozone monitor (CAMS 411) except in 2008, when data from the TCEQ Houston Regional Office (CAMS 81) were used. Meteorological data are from Houston Hobby Airport.

September 2013 (DISCOVER-AQ) was slightly warmer, much wetter, had fewer low dew point days, and had lower ozone concentrations compared to the 10-yr averages. General meteorological conditions in September 2013 were similar to those observed in September 2009 and 2010, which also had lower ozone levels. Observations from this analysis contextualizing meteorological and air quality conditions during DISCOVER-AQ and the full 10-yr period include:

- Ozone concentrations were generally lower in Septembers with infrequent low dew point days, such as September 2007, 2009, 2010, and 2013 (DISCOVER-AQ). This suggests more-persistent onshore winds in these years, which transport cleaner, maritime air into the Houston area.
- Ozone concentrations were lower in Septembers with much above-normal rainfall, such as September 2009, 2010, and 2013 (DISCOVER-AQ). Such a result is not surprising given that cloudy, rainy days reduce ozone production and depress monthly ozone metrics.
- Ozone concentrations were usually, but not always, lower when there were fewer late-summer frontal passages. A notable exception is 2009, which had lower ozone concentrations but six frontal passages.
- There was little, if any, relationship between September daily maximum temperatures and ozone concentrations.
- While temperatures, rainfall, and humidity levels showed annual variability but little evidence of any trends over the past 10 years, ozone concentrations have steadily decreased over this period.

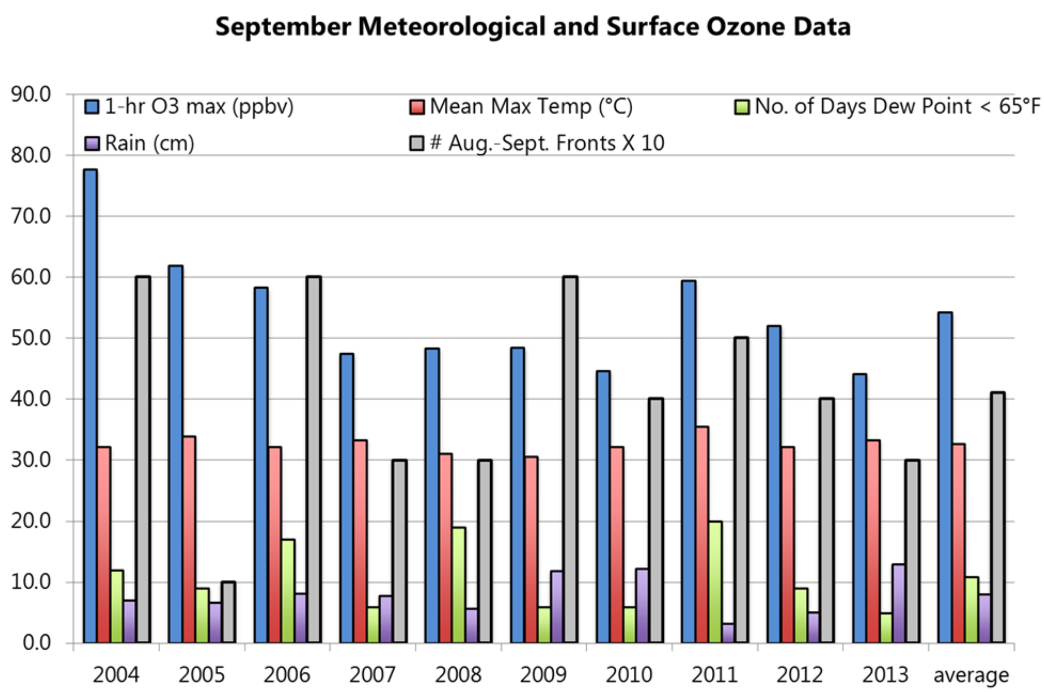


Figure 170. General meteorological conditions and ozone concentrations observed in Houston in September 2004-2013.

Table 15. General meteorological conditions and ozone concentrations observed in Houston in September 2004-2013.

Year	Avg. Daily Max. 1-hr Ozone (ppb)	Avg. Daily High Temp. (°C)	Rainfall (in.)	Number of Late-Summer Frontal Passages	Number of Low Dew Point Days
2004	77.6	32.2	7.01	6	18
2005	61.8	33.9	6.68	1	12
2006	58.2	32.2	8.18	6	21
2007	47.4	33.3	7.75	3	7
2008	53.6	31.1	5.77	3	24
2009	48.4	30.6	11.89	6	6
2010	44.6	32.2	12.22	4	1
2011	59.3	35.6	3.25	5	27
2012	52.0	32.2	5.13	4	14
2013	44.1	33.3	12.93	3	5
2004-2013 Average	55.9	32.7	8.1	4.1	13.5

2.3 Conclusion

The comparisons of meteorological conditions observed during DISCOVER-AQ to those observed during TexAQS-II, and more generally over the past ten years, illustrate two main points:

1. In general, peak ozone concentrations in the Houston area have decreased, despite the recurrence of similar meteorological conditions that are conducive to ozone formation. This suggests that the reduction in ozone is at least partially attributable to reductions in pollution emissions.

2. Meteorological conditions during the DISCOVER-AQ period in 2013 were abnormal compared to average September conditions in Houston, with fewer frontal passages, fewer low-humidity days, and more rainfall occurring in September 2013. These conditions limit ozone formation in the Houston area.

With this analysis complete, we suggest the following as possible future investigations:

- Performing a detailed comparison of boundary layer conditions simulated by meteorological models to the boundary layer observations summarized in this report.
- Assessing the benefits of ingesting observational boundary layer data into meteorological models.
- Determining the sources of aloft ozone layers that were identified in the ozonesonde data and assessing the impact of these aloft ozone layers on surface ozone concentrations.
- Performing a network assessment to assess the number of radar wind profilers and other upper-air meteorology instruments that are needed to adequately characterize the spatial and temporal changes in boundary layer conditions in the Houston area.

3. Links

Links to meteorological data used in this analysis are listed below.

- Surface and upper-level weather maps: http://www.wpc.ncep.noaa.gov/dwm/dwm.shtml
- Archived weather satellite and radar imagery: http://www2.mmm.ucar.edu/imagearchive/
- Ozonesonde data: http://physics.valpo.edu/ozone/
- Surface meteorological data: http://www.weatherunderground.com
- Surface ozone data: http://www.tceq.state.tx.us/cgi-bin/compliance/monops/select_summary.pl?region12.gif
- NASA DISCOVER-AQ data archive: http://www-air.larc.nasa.gov/missions/discover-aq/discover-aq.html

4. References

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