Houston East (CAMS 1) monitoring site

AUGUST 26, 2011

EXCEPTIONAL EVENTS DEMONSTRATION PACKAGE

For the Houston-Galveston-Brazoria One-hour Ozone Nonattainment Area

TEXAS COMMISSION ON ENVIRONMENTAL QUALITY
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LIST OF ACRONYMS

AutoGC	Automatic Gas Chromatograph
AOD	Aerosol Optical Depth
AQI	Air Quality Index
AQS	Air Quality System
CALIOP	Cloud-Aerosol Lidar with Orthogonal Polarization
CALIPSO	Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation
CAMS	Continuous Air Monitoring Station
CASTNET	Clean Air Status and Trends Network
CFR	Code of Federal Regulations
CO	Carbon Monoxide
CST	Central Standard Time
EPA	Environmental Protection Agency
EDAS	Eta Data Assimilation System
EER	Exceptional Events Rule
F	Fahrenheit
FCAA	Federal Clean Air Act
GOES	Geostationary Operational Environmental Satellite
HGB	Houston-Galveston-Brazoria
HMS	Hazard Mapping System
HRM 3	Houston Regional Monitoring Site #3
HRVOC	Highly Reactive Volatile Organic Compounds
HYSPLIT	Hybrid Single Particle Lagrangian Integrated Trajectory
km	Kilometer
LDT	Local Daylight Time
LEADS	Leading Environmental Analysis and Display System
LIDAR	Light Detection and Ranging
LST	Local Standard Time
m	Meter
MODIS	Moderate Resolution Imaging Spectroradiometer
NAAQS	National Ambient Air Quality Standard
NASA	National Aeronautics and Space Administration
nm	Nanometer
NOAA	National Oceanic and Atmospheric Administration
NO_X	Oxides of Nitrogen
NO_Y	Total Reactive Nitrogen
NO_2	Nitrogen Dioxide
NWS	National Weather Service
OC	Organic Carbon
PAN	Peroxyacetyl Nitrate
PM	Particulate Matter
$PM_{2.5}$	Fine Particulate Matter less than or equal to 2.5 microns in diameter
PM_{10}	Particulate Matter less than or equal to 10 microns in diameter
ppb	parts per billion
ppbC	parts per billion by Carbon
ppm	parts per million
TCEQ	Texas Commission on Environmental Quality
TOMS	Total Ozone Mapping Spectrometer
U.S.	United States
UTC	Coordinated Universal Time

VOC	Volatile Organic Compounds
WFABBA	Wildfire Automated Biomass Burning Algorithm

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EXECUTIVE SUMMARY

On August 26, 2011, the Houston East (CAMS 1) monitoring site measured a daily maximum one-hour ozone concentration of 128 parts per billion (ppb) during the 1:00 p.m. to 2:00 p.m. monitoring hour. Large wildfire plumes from the Northwestern and Southeastern United States (U.S.) enhanced ozone levels beyond what it would otherwise have been and caused the measured value to exceed 125 ppb. This exceedance of the one-hour ozone National Ambient Air Quality Standard (NAAQS) created a violation of this standard. Without this exceedance, the Houston-Galveston-Brazoria (HGB) area, comprised of Brazoria, Chambers, Fort Bend, Galveston, Harris, Liberty, Montgomery, and Waller Counties, would be in attainment of the one-hour ozone NAAQS based on the 2010 through 2012 area design value. Based on its initial analysis, the Texas Commission on Environmental Quality (TCEQ) flagged this day at the Houston East (CAMS 1) monitoring site as an exceptional events day and notified the U.S. Environmental Protection Agency (EPA) as required by the Exceptional Events Rule (EER). The TCEQ submits this Exceptional Events Demonstration Package in support of the agency's claim that the HGB area experienced an exceptional event on August 26, 2011, which caused an exceedance of the one-hour ozone NAAQS. The TCEQ requests that the EPA concur with the technical demonstration contained in this document and enter an exceptional event concurrence flag into the appropriate Air Quality System (AQS) records for the Houston East (CAMS 1) monitoring site on August 26, 2011.

The TCEQ's claim is substantiated through the accumulated weight of evidence documented in this demonstration package. Chapter 1: *Introduction* outlines the event and complexities of ozone formation in the HGB area as well as an overview of the significant progress made in reducing ozone in the HGB area. Chapter 2: *Exceptional Event Rule Requirements for States* discusses the various requirements for satisfying the EER and how the TCEQ meets those requirements. Chapter 3: *Normal Historical Fluctuations at the Houston East (CAMS 1) Monitoring Site*, Chapter 4: *A Clear Causal Relationship Between Fire Emissions and Higher Ozone*, and Chapter 5: *No Exceedance but for the Exceptional Event* lay out the strong technical case that leads the TCEQ to conclude that this exceedance was an exceptional event as required in 40 Code of Federal Regulations (CFR) §50.14(a). The case is based on the following information.

- August 26, 2011 is clearly outside of the normal historical fluctuations for ozone at this site.

- Of the 19 HGB area ozone monitoring sites reporting data to the EPA's AQS database, 18 had daily maximum one-hour ozone measurements that were in the top 5% of 2009 through 2011 measurements. This establishes the unique nature of this event as it suggests an area wide event rather than local.

- High pressure off the coast of southeast Texas combined with subsiding air along and behind a weak frontal boundary passing over east Texas and the Lower Mississippi River Valley resulted in air masses passing over wildfires in the Lower Mississippi River Valley before entering the Houston area.

- An exhaustive analysis of Hybrid Single Particle Lagrangian Integrated Trajectory (HYSPLIT) trajectories shows that trajectories arriving at the Houston East (CAMS 1) monitoring site on August 26, 2011 passed over or near areas of concentrated wildfires outside of Texas on the way to the HGB area.

- A review of scientific literature shows a clear basis for the causal relationship between smoke emitted by wildfires and enhanced ozone production downwind.

- An analysis of satellite imagery shows that there were extensive areas of wildfires outside of Texas that affected air quality in the HGB area generally and at the Houston East (CAMS 1) monitoring site in particular.

- A surrogate day analysis concludes that, but for the smoke event, there would likely have been no ozone exceedance at the Houston East (CAMS 1) monitoring site on August 26, 2011.

The accumulated weight of evidence meets the requirements necessary for the EPA to concur with the TCEQ and flag August 26, 2011 as an exceptional event day for ozone at the Houston East (CAMS 1) monitoring site.

CHAPTER 1: INTRODUCTION

Extensive research and many regulatory activities have been conducted to address the ozone air quality of the Houston-Galveston-Brazoria (HGB) area, which is comprised of Brazoria, Chambers, Fort Bend, Galveston, Harris, Liberty, Montgomery, and Waller Counties. Ozone formation in the HGB area is complex, multi-faceted, and occurs under a variety of conditions. A population over 6.2 million, one of the largest concentrations of petrochemical refining and chemical production activities in the United States (U.S.), and plentiful biogenic emissions from large tracts of oak forests all provide a complex mix of sources that can contribute to exceedances of the ozone National Ambient Air Quality Standard (NAAQS) established under the Federal Clean Air Act (FCAA). Complex meteorological patterns common to Texas coastal areas add to the challenge of determining the contribution of local emissions sources. The HGB ozone picture becomes even more complex as transported ozone and ozone precursors play an increasingly important role in the area's ozone levels as local emissions decrease.

This introduction briefly examines a conceptual model of ozone formation in the HGB area, reviews HGB ozone and emissions trends over time, and introduces the exceptional event of August 26, 2011 that created the one-hour exceedance at the Houston East (CAMS 1) monitoring site.

1.1 A CONCEPTUAL MODEL OF OZONE FOR THE HGB AREA

Ozone formation in the HGB area peaks at the same time of year and for many of the same reasons as in other areas of Texas and the U.S. However, the ozone season in HGB lasts longer than in many other areas. The ozone season in HGB and other coastal areas in Texas is 12 months, whereas in more inland areas the ozone season is March through October. Elevated ozone levels usually form in the HGB area under the persistent hot, sunny, and relatively stagnant conditions associated with high pressure in the Gulf of Mexico during the summer, in the presence of emissions from the mobile, area, and industrial sources in the area.

Ozone production is generally associated with relatively clear skies, light winds, abundant sunshine, and warm temperatures. Typically, these meteorological conditions are associated with high pressure areas that migrate across the U.S. during the summer season. However, the persistent summertime high pressure area in the Gulf of Mexico and air mass flow reversals associated with the land/sea breeze phenomenon make the HGB area situation unusual, if not unique, among U.S. metro areas. High pressure areas have two characteristics that encourage ozone formation: light winds and subsidence inversions. Typically, winds circulating around a high pressure system are too weak to ventilate the urban area well, so local emissions tend to accumulate. Subsidence inversions hamper or limit vertical mixing and further aggravate the situation by concentrating local and transported pollutants in the boundary layer and near the surface. High pressure areas also create a clockwise rotation that transports ozone, particulate matter (PM), and ozone precursors into the HGB area from the northeast.

Ozone formation in the HGB area is also associated with the daytime/nighttime flow reversal of the land/sea breeze, which was identified as a cause during the 1993 Gulf of Mexico Air Quality Study and confirmed by several more recent studies by state and federal researchers. Land/sea breezes are common in coastal areas near 30 degrees (^{o}) north latitude and have been associated with ozone formation in other large metropolitan areas such as Athens, Greece and Barcelona, Spain in addition to the Houston area. Land/sea breeze flow reversal requires a light synoptic scale forcing associated with high pressure areas, thereby allowing local phenomena to dominate the local circulations. Light winds and the restricted vertical mixing allow high

concentrations of pollutants to accumulate during the night and morning hours, and the nocturnal land breeze carries the pollutants out over Galveston Bay and into the Gulf of Mexico. Then, during the afternoon, the sea breeze flow reversal carries the ozone and ozone precursors back into the city. In contrast, on low ozone days, precursor emissions are generally diluted and carried out of the area by stronger and more persistent winds.

Other area-specific factors also add to the complexity of ozone formation in the HGB area. For example, the large cluster of petrochemical industries and other sources in the Houston Ship Channel emit nitrogen oxides (NO_X) along with a variety of volatile organic compounds (VOC) precursors not typically found in other urban areas. Oak forests near the city emit large amounts of isoprene, which reacts strongly with the NO_X emitted from these industries and numerous other anthropogenic sources in the area. While local emissions sources routinely contribute to ozone levels in the HGB area, transport and exceptional events have become increasingly important as locally generated emissions and ozone decrease.

1.2 TRENDS IN HGB AREA EMISSIONS AND OZONE LEVELS

The HGB area is the fifth largest core-based metropolitan area in the U.S., home to nearly 6.2 million residents as of 2012 (U.S. Census Bureau, 2013). Houston itself is the fourth largest city in the nation as of 2012 (U.S. Census Bureau, 2013). The following figures highlight the tremendous strides the area has made to reduce ozone-forming emissions and ground level ozone.

Over time, the HGB area has made great strides in reducing emissions of ozone precursors. Figure 1-1: *HGB Area Point Source NOX Trends 1997 through 2012* shows that annual point source emissions of NO_X in the eight-county HGB area decreased approximately 85% over the 1997 through 2012 period. The HGB area has also made great strides in reducing overall and, in particular, point source NO_X emissions as shown in Figure 1-2: *2002 through 2011 NO_X Emissions Inventory Trend for the HGB Area*.

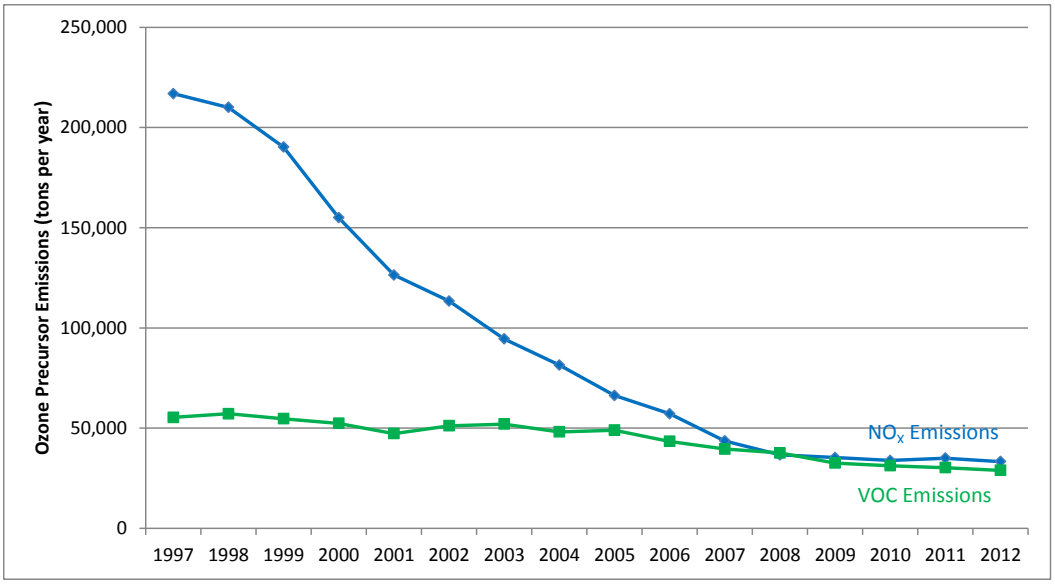


Figure 1-1: HGB Area Point Source VOC and NO_X Trends 1997 through 2012

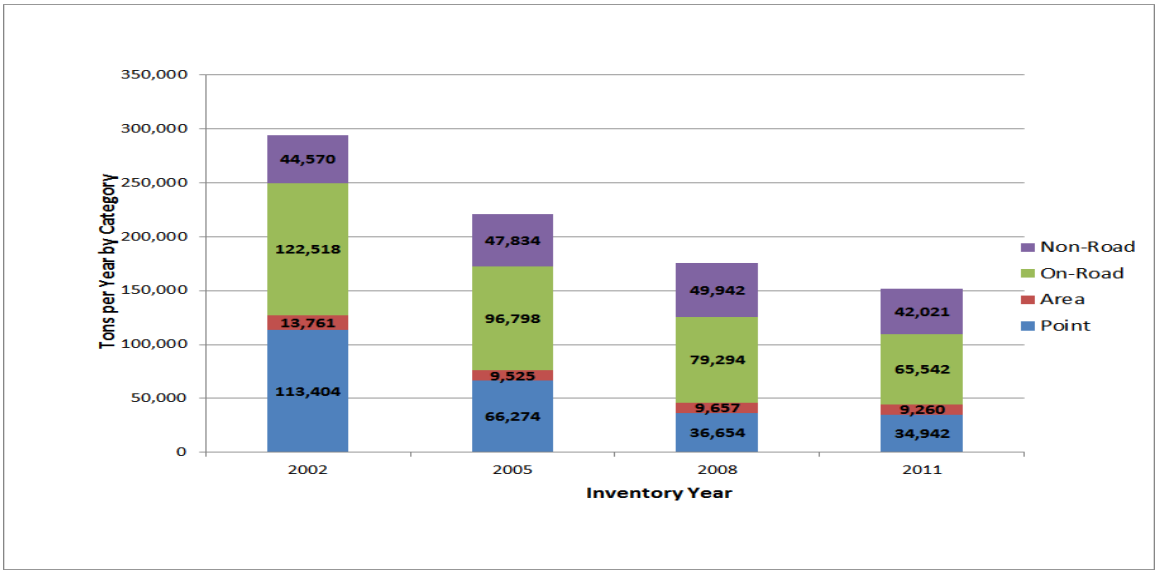


Figure 1-2: 2002 through 2011 NO_X Emissions Inventory Trend for the HGB Area

Even more significantly, one-hour and eight-hour ozone design values have sharply decreased while population has steadily increased. Figure 1-3: *HGB Area Ozone Design Value and Population Growth 1991 through 2013* shows that while population in the eight-county HGB nonattainment area has grown by almost 60%, the area's one-hour ozone design value has decreased by approximately 43% and the eight-hour ozone design value has decreased by approximately 26%.

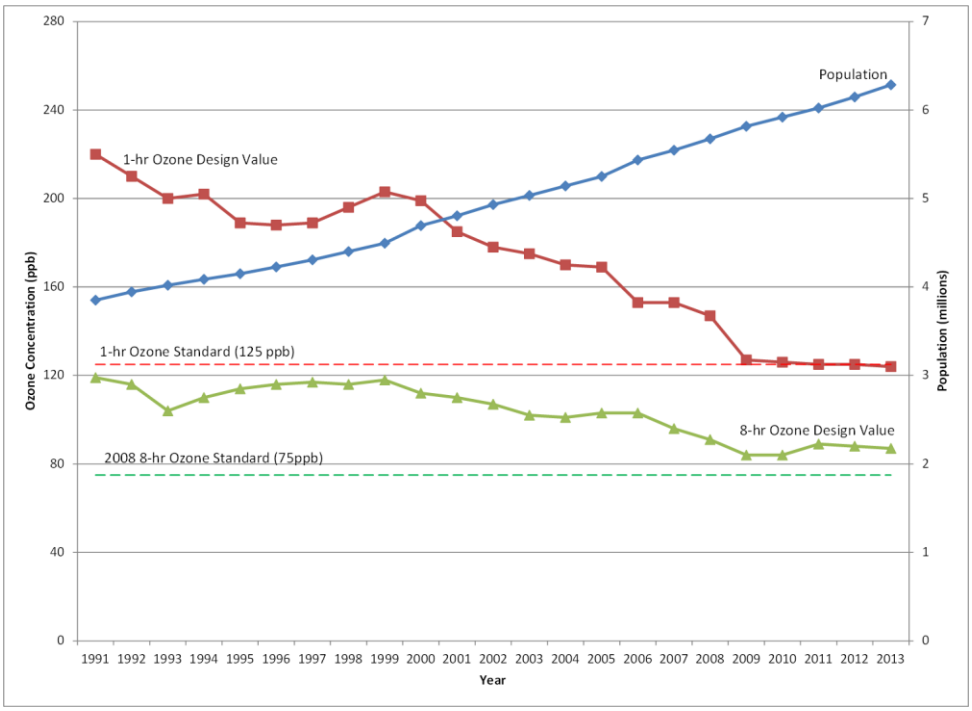


Figure 1-3: HGB Area Ozone Design Value and Population Growth 1991 through 2013

1.3 OZONE REDUCTION PROGRESS AT THE HOUSTON EAST (CAMS 1) MONITORING SITE

The Houston East (CAMS 1) monitoring site is located east of downtown Houston and near a major interstate highway, Interstate 610 loop and major industrial sources. (See Figure 1-4: *Houston East (CAMS 1) Location)*. Siting details of the monitor are provided in Table 1-1: *Siting Details of the Houston East (CAMS 1) Monitoring Site* .

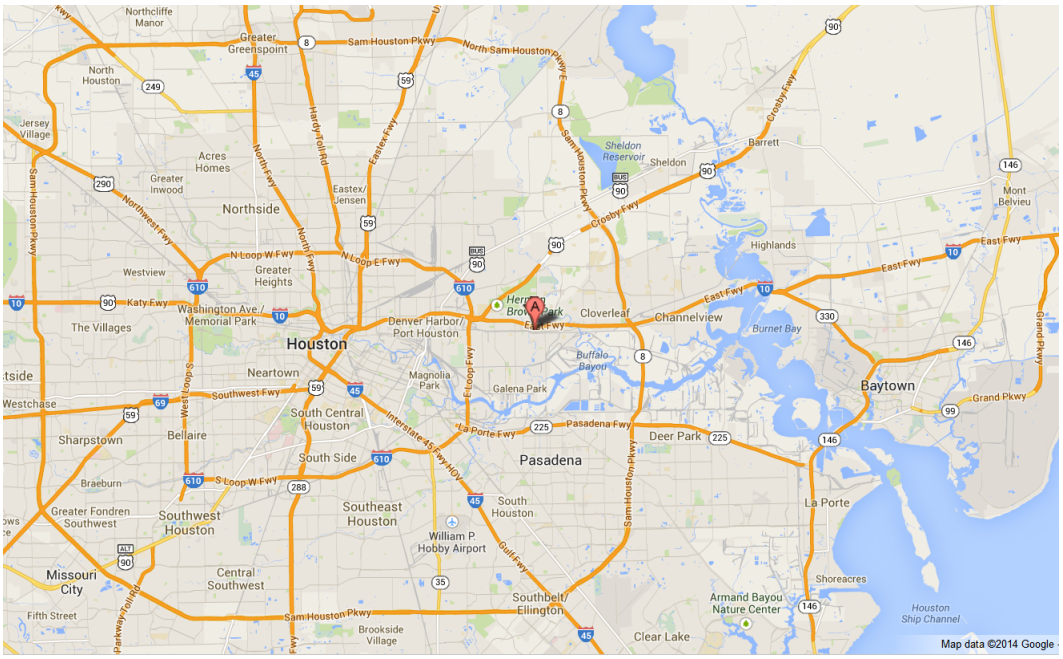


Figure 1-4: Houston East (CAMS 1) Location

Table 1-1: Siting Details of the Houston East (CAMS 1) Monitoring Site

EPA Site Number:	482011034
CAMS:	1
Activation Date:	January 1, 1973
Current Status:	Active
Address:	1262 ½ Mae Dr., Houston, Texas
County:	Harris
Latitude:	29° 46' 5" North (29.7679707°)
Longitude:	-95° 13' 14" West (-95.2205867°)

The Houston East (CAMS 1) monitoring site epitomizes the air quality improvements made in the HGB area. As shown by Figure 1-5: *Houston East (CAMS 1) Design Values 1990 through 2013* ***Error! Reference source not found.***, ozone design values for the Houston East

(CAMS 1) monitoring site have decreased significantly over the past 20 years. Since having a one-hour ozone design value of 210 parts per billion (ppb) in 1990, the Houston East (CAMS 1) monitoring site's one-hour ozone design value decreased over 40% to 121 ppb in 2013. The site's one-hour design value has not been above 125 ppb since 2006. The site's eight-hour ozone design value has decreased significantly as well. Starting from 110 ppb in 1990 the Houston East (CAMS 1) monitoring site's eight-hour design value decreased more than 25% to 80 ppb in 2013. The site has monitored attainment of the 1997 eight-hour ozone standard beginning since 2006. In Figure 1-5, the 1994 through 1996 design values for the eight-hour ozone NAAQS and the 1995 ozone design value for the one-hour ozone NAAQS are blank due to insufficient data return.

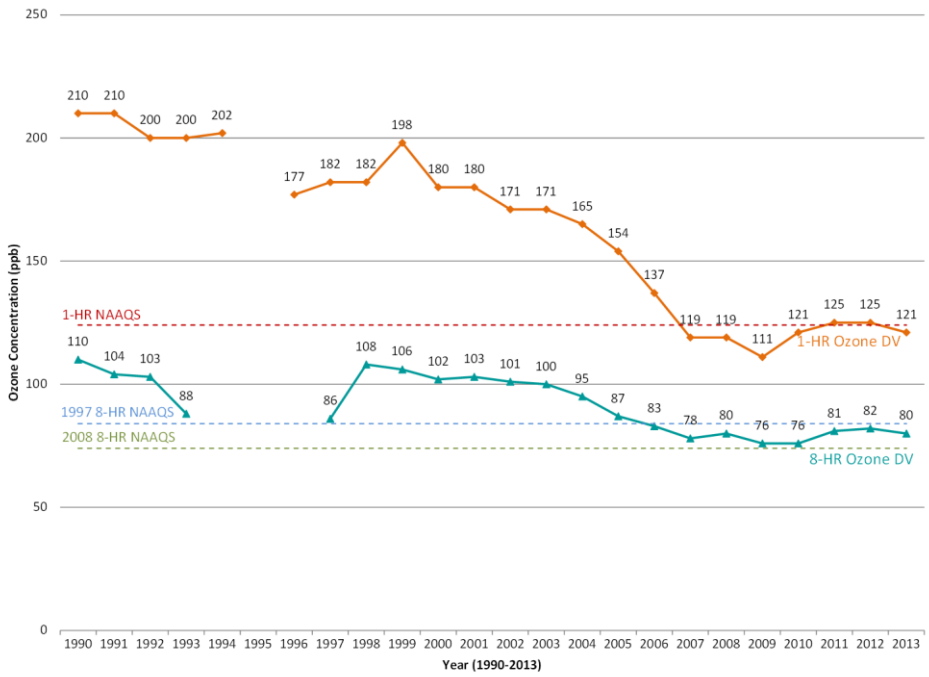


Figure 1-5: Houston East (CAMS 1) Design Values 1990 through 2013

1.4 THE EXCEPTIONAL EVENT OF AUGUST 26, 2011

As levels of ozone decrease across the entire HGB area, the contributions made by exceptional events and transport from regions outside the HGB area become more apparent. For years, the HGB area has received noticeable contributions of PM from fires in Central America, Mexico, Canada and several regions of the U.S. including Alaska (Morris et al. 2006; Wotawa and Trainer 2000; Forster et al. 2001). The HGB area also sees high levels of dust transported across the Atlantic Ocean, Caribbean Sea, and Gulf of Mexico from Northern Africa (Bozlaker 2013, TCEQ 2013). However, until recently, the focus has not been on ozone contributions from exceptional events unless those events were record events such as the Central American fires in April and May of 1998.

On August 26, 2011, during the 1:00 to 2:00 p.m. Central Standard Time (CST) hour, the Houston East (CAMS 1) monitoring site experienced a daily maximum ozone measurement of 128 ppb, which was an exceedance of the one-hour ozone NAAQS. The TCEQ believes that this one-hour exceedance was due to an exceptional event attributable to wildfires in the Pacific Northwest and in the Mississippi River Valley in Northeast Louisiana, Northwest Mississippi, and Southeast Arkansas that started during the last week of August 2011. Appendix A: Press

Releases/Media Reports provides Web-related news reports (links and PDFs) that document the occurrence of the fires. Background ozone on August 26, 2011 was unusually high, as demonstrated in Chapter 3: *Normal Historical Fluctuations at the Houston East (CAMS 1) Monitoring Site*, and Fine Particulate Matter less than or equal to 2.5 microns in diameter (PM2.5) and ozone measurements at the Houston East (CAMS 1) site peaked at the same time.

CHAPTER 2: EXCEPTIONAL EVENT RULE REQUIREMENTS FOR STATES

2.1 UNITED STATES ENVIRONMENTAL PROTECTION AGENCY REQUIREMENTS

On March 22, 2007, the United States (U.S.) Environmental Protection Agency (EPA) published the final Exceptional Events Rule (EER). The rule provided a process by which states could request that the EPA exclude monitoring data showing exceedances or violations of a criteria pollutant National Ambient Air Quality Standard (NAAQS) that were directly related to an exceptional event. When a state identifies a possible exceptional event, the state places a "flag" in the appropriate field of the data record in question for informational purposes in the Air Quality System (AQS) database. Prior to July 1 of the year following a state's placement of the informational flag, it must inform the EPA of the flag and provide some initial reason for its placement. From that point, a state has three years after the quarter in which the flagged data were reported to the EPA to submit (after notice and opportunity for public comment) a package to the EPA demonstrating the reasons that the event should be considered exceptional. If the EPA is satisfied with the state's demonstration package, it places a concurrence flag in the appropriate field and record in the AQS database.

The EER specifies at 40 Code of Federal Regulations (CFR) §50.14(c)(3)(iv) that states proposing to exclude monitoring data from consideration based on exceptional events must provide evidence that:

- the event satisfies criteria set out in the definition of exceptional event (40 CFR §50.1(j));
- there is a clear causal relationship between the measurement under consideration and the event;
- the event is related to a measured concentration in excess of normal historical fluctuations;
- there would have been no exceedance but for the event; and
- the public comment process was followed.

The EPA defines "exceptional event" in the EER (40 CFR §50.1(j)) as an event that:

- affects air quality;
- is not reasonably controllable or preventable; and
- is an event caused by human activity that is unlikely to recur at a particular location or a natural event, and is determined by the Administrator to be an exceptional event.

Additionally, the EER (40 CFR §51.930) requires that a state requesting a concurrence on an exceptional event day must take "appropriate and reasonable actions to protect public health from exceedances or violations of the national ambient air quality standards." A state, at a minimum, must provide for:

- prompt public notification when air quality concentrations are expected to exceed a criteria NAAQS;

- public education regarding actions that individuals may take to reduce exposure to unhealthy levels of the pollutant during and following an event; and

- implementation of appropriate measures to protect health from exceedances of criteria NAAQS caused by exceptional events.

The EPA has released three packages of interim guidance information to provide direction on how states are to meet these requirements and to consolidate documents and memos relating to high wind events and wildfires. The latest of these guidance packages, issued May 10, 2013, remains primarily focused on high wind events and other particulate matter (PM)-related events. The EPA expects to publish additional guidance more focused on ozone exceptional events related to fires later this year. Texas appreciates the EPA's commitment to provide this guidance.

2.2 RESPONSES TO EXCEPTIONAL EVENT RULE REQUIREMENTS

The following section summarizes the Texas Commission on Environmental Quality's (TCEQ) adherence to the EER guidance and presents the necessary evidence and circumstantial information to support marking ozone data at the Houston East (CAMS 1) monitoring site as impacted by an exceptional event on August 26, 2011. Consistent with the guidance (page 2; EPA 2013), the TCEQ relies on a weight of evidence approach for its demonstration. As the EPA notes in the guidance (page 2; EPA 2013), the different requirements are inter-related, and thus, sections of this demonstration may support more than requirements and may refer to other sections of the demonstration package. Chapter 3: *Normal Historical Fluctuations at the Houston East (CAMS 1) Monitoring Site*, Chapter 4: *A Clear Causal Relationship between Fire Emissions and Higher Ozone*, and Chapter 5: *No Exceedance but for the Exceptional Event* provide a more detailed demonstration of how data from August 26, 2011 meet the rule requirements that:

- the event is related to a measured concentration in excess of normal historical fluctuations;

- there is a clear causal relationship between the measurement under consideration and the event; and

- there would have been no exceedance but for the event.

2.2.1 The Event Affected Air Quality

The event under consideration is the wildfire-induced exceedance of the one-hour ozone NAAQS measured at the Houston East (CAMS 1) monitoring site on August 26, 2011. Although the one-hour ozone NAAQS (0.12 parts per million) has been revoked and replaced with the eight-hour NAAQS of 1997 and 2008, states are still required to adhere to specific requirements based on attainment or nonattainment of the one-hour ozone NAAQS. Consequently, the TCEQ is submitting this event as an exceptional event under the one-hour ozone NAAQS.

When the EPA published the final version of the EER on March 22, 2007 (U.S. National Archives and Records Administration 2007, 13569) it noted in the preamble that:

> "The final rule permits a case-by-case evaluation, without prescribed threshold criteria, to demonstrate that an event affected air quality. The demonstration would be based on the weight of available evidence, but must consider the historical frequency of such measured

concentrations. While a State may determine the specific approach to use for such analysis, it must compare contemporary concentrations with the distribution of all measured data during the past several years."

The August 26, 2011 event did affect air quality as evidenced by the following reasons. First, the event occurring on this day was well outside the normal historical fluctuations of recent monitored values (see Sections 3.1: *An Analysis of Historic Seasonal Fluctuation of Maximum Daily Ozone Values at the Houston East (CAMS 1) Monitoring Site* through 3.4: *Short-Term Analysis of the Houston East (CAMS 1) Monitoring Site Daily Maximum Ozone Measurements*). The maximum one-hour measurement at the Houston East (CAMS 1) monitoring site on this day was 128 parts per billion (ppb). This maximum ranks above the 99th percentile when considering the population of daily maximum one-hour measurements for a contemporary period of 2009 through 2011, which contains over 700 days at this monitoring site (see Section 3.1). Wildfires across the northwestern and southeastern U.S. produced significant amounts of ozone precursors. Winds transported these emissions to the Houston-Galveston-Brazoria (HGB) area and this fire-induced event caused ozone levels that were well outside the normal historical fluctuation of ozone values at the Houston East (CAMS 1) monitoring site. Second, the fire-induced event caused the day's maximum hourly ozone value for August 26, 2011 to climb above the one-hour ozone NAAQS and exceed the standard. Through a weight of evidence approach, the TCEQ demonstrates the causal relationship between these fires and the measured ozone concentrations at the Houston East (CAMS 1) monitoring site and how this event affected air quality by causing an exceedance of the one-hour ozone NAAQS and higher ozone concentrations than would have been experienced without the transported wildfire emissions.

2.2.2 The Event is not Reasonably Controllable or Preventable

The fires causing elevated ozone measurements at the Houston East (CAMS 1) monitoring site on August 26, 2011 occurred outside of Texas (see Section 4.3.2: *Trajectory Analysis 2 – HYSPLIT Matrix Forward Trajectories from Areas with Clusters of Fires* for a list of active fires outside of Texas that may have contributed to the ozone exceedance of August 26, 2011). The State of Texas could not have taken any action to prevent or control the fires.

2.2.3 The Event is not Likely to Recur or is Natural

Of the active fires that might have contributed to this exceptional event, human activity initiated some and others started naturally. Once an area has been burned out, the likelihood of that area burning again declines for an extended period (assuming that the fire was completely extinguished), and the biomass available to burn is significantly reduced such that a fire in the same area in the next several years would likely yield significantly fewer emissions. Any of the fires attributable to human causes that occur outside of Texas are not controllable or preventable by the State of Texas.

2.2.4 The State Follows the Public Comment Process

The details of the public comment process followed by the TCEQ appear in Chapter 6: *Documentation of the Public Comment Process* of this demonstration package, and the public comments received will be included - prior to submittal of this demonstration package to EPA Region 6.

2.2.5 Mitigation Requirements of 40 CFR §51.930

Section 51.930 of the EER requires that "a State requesting to exclude air quality data due to exceptional events must take appropriate and reasonable actions to protect public health from

exceedances or violations of the national ambient air quality standards." The TCEQ addresses each of the specific requirements individually below.

2.2.5.1 Prompt Public Notification

The first mitigation requirement is to "provide for prompt public notification whenever air quality concentrations exceed or are expected to exceed an applicable ambient air quality standard." The TCEQ provided (and continues to provide) ozone, Fine Particulate Matter less than or equal to 2.5 microns in diameter ($PM_{2.5}$), and Particulate Matter less than or equal to 10 microns in diameter (PM_{10}) Air Quality Index (AQI) forecasts for the current day and the next three days for 14 areas in Texas including the HGB area. These forecasts are available to the public on the Today's Texas Air Quality Forecast Web page of the TCEQ website (http://www.tceq.texas.gov/airquality/monops/forecast_today.html), and on the EPA's AIRNOW website (http://airnow.gov/). The TCEQ provides near real-time hourly ozone measurements from monitors across the state, including the HGB area, which the public may access on the Current Ozone Levels page of the TCEQ website (http://www.tceq.texas.gov/cgi-bin/compliance/monops/select_curlev.pl). The TCEQ also publishes an AQI Report for a number of Texas metropolitan areas including the HGB area on the Air Quality Index page of the TCEQ website (http://www.tceq.state.tx.us/cgi-bin/compliance/monops/aqi_rpt.pl), which displays current and historical daily AQI measurements. Finally, the TCEQ publishes daily updates to its air quality forecast to interested parties through electronic mail . Any person wishing to receive these updates may register on the TCEQ website (http://www.tceq.texas.gov/airquality/monops/ozone_email.html). These measures provide daily and near real-time notification to the public of current, expected, and changing air quality conditions.

2.2.5.2 Public Education

The second mitigation requirement is to "provide for public education concerning actions that individuals may take to reduce exposures to unhealthy levels of air quality during and following an exceptional event." Through its website, the TCEQ provides the public with technical, health, personal activity, planning, and legal information and resources concerning ozone pollution.

The TCEQ maintains an ozone fact sheet (http://www.tceq.texas.gov/airquality/monops/ozonefacts.html), which provides important information regarding the health effects of ozone, steps that individuals can take to limit ozone formation, and actions they may wish to take to reduce their exposure to higher levels of ozone. A hyperlink to this fact sheet is located on the TCEQ daily air quality forecast page. The fact sheet points individuals towards additional health-related information from the Centers for Disease Control, the Texas Department of State Health Services, and the EPA.

The TCEQ's main Web page for air (http://www.tceq.texas.gov/agency/air_main.html) provides air quality information on topics such as advisory groups, emissions inventories, air quality modeling and data analysis, scientific field studies, state implementation plans (SIP), air permits, rules, air monitoring data, and how to file complaints.

The TCEQ provides a specific "Air Pollution from Ozone" Web page (http://www.tceq.texas.gov/airquality/sip/criteria-pollutants/sip-ozone), which provides the latest information on air quality planning activities by both the TCEQ and the EPA.

The TCEQ's website provides a hyperlink to the Texas "AirNow" website operated by the EPA (http://www.airnow.gov/index.cfm?action=airnow.local_state&stateid=45&tab=0). This website links the public to additional information regarding health effects of ozone,

strategies for reducing one's exposure to ozone, and actions that individuals can take to reduce pollution levels.

The Texas Department of Transportation sponsors the public education and awareness campaign, "Drive Clean Across Texas" (http://www.drivecleanacrosstexas.org). The campaign raises awareness about the impact of vehicle emissions on air quality and motivates drivers to take steps to reduce air pollution. The campaign's activities are concentrated during the summer months when ozone levels rise.

The TCEQ sponsors the "Take Care of Texas" program (http://takecareoftexas.org/air-quality), which addresses air quality and provides the public with proactive steps to reduce air pollution particularly on days when air quality forecasts are issued predicting greater potential for ozone formation.

2.2.5.3 Implementation of Measures to Protect Public Health

When dealing with exceptional events originating from outside Texas (e.g., the case of August 26, 2011), there is very little that the TCEQ can do to mitigate the impact of additional ozone created by the exceptional event. Because the HGB area is an ozone nonattainment area classified as "Severe" for the one-hour standard, the TCEQ has implemented an extensive set of creative and innovative control strategies designed to reduce emissions of ozone precursors such as volatile organic compounds (VOC) and nitrogen oxides (NO_X). Texas Attainment Demonstration SIP revisions for the HGB area include both Reasonably Available Control Measures and Reasonably Available Control Technologies analyses conducted by the TCEQ and have been approved by the EPA for the one-hour and the 1997 eight-hour ozone NAAQS. These steps in conjunction with the ozone forecasts and notifications for the public strongly support the conclusion that Texas has taken every reasonable step to protect its citizens from exceedances of the ozone NAAQS. Sections 1.2: *Trends in HGB Emissions and Ozone Levels* and 1.3: *Ozone Reduction Progress at the Houston East (CAMS 1) Monitoring Site* of this demonstration package show that Texas' strategies have been remarkably successful at reducing both precursor emissions and ozone levels across the HGB area and at the Houston East (CAMS 1) monitoring site. More detailed information about the state's ozone reduction strategies can be found on the following Web pages:

Control Strategies for Stationary Sources: http://www.tceq.texas.gov/airquality/stationary-rules/ozone

Control Strategies for On-Road Mobile Sources: http://www.tceq.texas.gov/airquality/mobilesource/mobile_source.html

Air Permitting: http://www.tceq.texas.gov/permitting/air

Texas Emissions Reduction Plan Program: http://www.tceq.texas.gov/airquality/terp/erig.html

2.2.6 A Clear Causal Relationship Exists

Scientific consensus exists that emissions from fires can increase ozone levels downwind of the fire area. In Chapter 4: *A Clear Causal Relationship Between Fire Emissions and Higher Ozone*, the TCEQ provides scientific evidence of a causal relationship with a review of the current technical literature regarding wildfires and ozone formation. Following the review, this demonstration package uses a variety of corroborative information to conclude that the ozone exceedance on August 26, 2011 was caused by fire emissions transported into the HGB area

from outside Texas. The TCEQ presents analyses of ambient monitoring data at the Houston East (CAMS1) and other nearby monitoring sites, trajectory modeling, aerosol modeling, synoptic meteorological conditions, satellite imagery, and a surrogate day analysis. These analyses show through a weight of evidence approach that fires in the Pacific Northwest and in the Mississippi River Valley in Northeast Louisiana, Northwest Mississippi, and Southeast Arkansas caused ozone levels measured at the Houston East (CAMS 1) monitoring site on August 26, 2011 to exceed the one-hour ozone standard.

2.2.7 In Excess of Normal Historical Fluctuations

Although the EPA has not precisely defined when a measured concentration is "in excess of normal historical fluctuations," the 128 ppb ozone measurement observed at the Houston East (CAMS 1) monitoring site on August 26, 2011 is clearly in excess of normal fluctuations. The daily maximum one-hour ozone value measured at the Houston East (CAMS 1) monitoring site on August 26, 2011 exceeds the 99th percentile of data from the 12 months of seasonal daily maximum ozone concentrations over a three-year period. The same day's maximum one-hour ozone measurement also exceeds the 99th percentile of data from the annual daily maximum ozone concentrations for 2009 through 2011. In Chapter 3: *Normal Historical Fluctuations at the Houston East (CAMS 1) Monitoring Site*, the TCEQ analyzes monitoring data from the Houston East (CAMS 1) monitoring site from four different perspectives and shows the unique nature of this day.

2.2.8 There Would Have Been no Exceedance but for the Event

In Chapter 5: *No Exceedance but for the Exceptional Event*, the TCEQ uses an analysis of a surrogate day to demonstrate that without the transported emissions of fires in other states, the exceedance of August 26, 2011 would not have occurred. The surrogate day analysis compares August 27, 2009 to August 26, 2011. These two days are very similar except for the presence of significant transported fire emissions on August 26, 2011, based on satellite imagery and HYSPLIT trajectories. Ozone levels measured on this surrogate day are below the one-hour ozone NAAQS. The lack of an exceedance on a day that is very similar to August 26, 2011 in terms of meteorology and local emissions provides powerful evidence that without emissions from the fires present immediately before the exceptional event, an ozone exceedance would not have occurred.

CHAPTER 3: NORMAL HISTORICAL FLUCTUATIONS AT THE HOUSTON EAST (CAMS 1) MONITORING SITE

The United States (U.S.) Environmental Protection Agency (EPA), in Attachment 1 (*"Interim Exceptional Events Rule Frequently Asked Questions"*) of its most recent interim guidance for the Exceptional Events Rule (EER) (pages 5-6; EPA 2013, Att. 1), suggests that states use more than one approach to establish that a claimed event day is outside of normal historical fluctuations in monitored measurements at the site. The EPA also suggests that, in most cases, analyses involve data over a three to five-year period and contain at least 300 observations (pages 5-6; EPA 2013, Att. 1). The Texas Commission on Environmental Quality (TCEQ) chose four different analyses to demonstrate the uniqueness of August 26, 2011:

- a historic comparison of seasonal one-hour daily maximum ozone measurements at the Houston East (CAMS 1) monitoring site;
- a historic comparison of annual one-hour daily maximum ozone measurements at the Houston East (CAMS 1) monitoring site;
- an analysis of the historic diurnal profile at the Houston East (CAMS 1) monitoring site for the month of August; and
- a 15-day time series comparison of one-hour ozone daily maximum ozone measurements from neighboring days in the years 2009, 2010, and 2011 at the Houston East (CAMS 1) monitoring site.

3.1 AN ANALYSIS OF HISTORIC SEASONAL FLUCTUATION OF MAXIMUM DAILY OZONE VALUES AT THE HOUSTON EAST (CAMS 1) MONITORING SITE

On August 26, 2011 the Houston East (CAMS 1) monitoring site observed a daily maximum one-hour ozone concentration of 128 parts per billion (ppb), which exceeded the one-hour ozone National Ambient Air Quality Standard (NAAQS). The TCEQ's analysis of ozone measurements at the Houston East (CAMS 1) monitoring site during the years 2009 through 2011 shows that this event is clearly outside of the normal historical fluctuations of seasonal ozone measurements at the site. The daily maximum ozone concentration from August 26, 2011 was compared to seasonal daily maximum ozone concentrations measured during those years.

For a seasonal analysis of historical one-hour ozone measurement fluctuations, the TCEQ chose the months of March through October and the years 2009 through 2011. The EPA has declared as a matter of rule that ozone season in the HGB area is year-round. The TCEQ has found that, historically, the months of March through October tend to measure higher ozone concentrations and exhibit a higher frequency of ozone exceedances than the other four months (TCEQ, 2010), thus the TCEQ review focused on these months to ensure a conservative review. The TCEQ used data from its Leading Environmental Analysis and Display System (LEADS). The data set used in this analysis contained data collected over a three-year period with 705 individual data points. Of these data points, August 26, 2011 is in the top 1% of observations, which indicates that it is well outside the historical norm. The result of this analysis is displayed in Figure 3-1: *Percentile Rankings of Seasonal Daily Maximum One-Hour Ozone Concentrations at the Houston East (CAMS 1) Monitoring Site from 2009 through 2011*. The only two days measuring higher than August 26, 2011 were August 29, 2011 at 136 ppb and July 16, 2010 at 129 ppb. August 29, 2011 was also likely influenced by the fire emissions described in this demonstration.

Given daily maximum one-hour ozone measurements from 705 ozone season days, the measurement of 128 ppb ozone occurs rarely – less than 0.5% of the time.

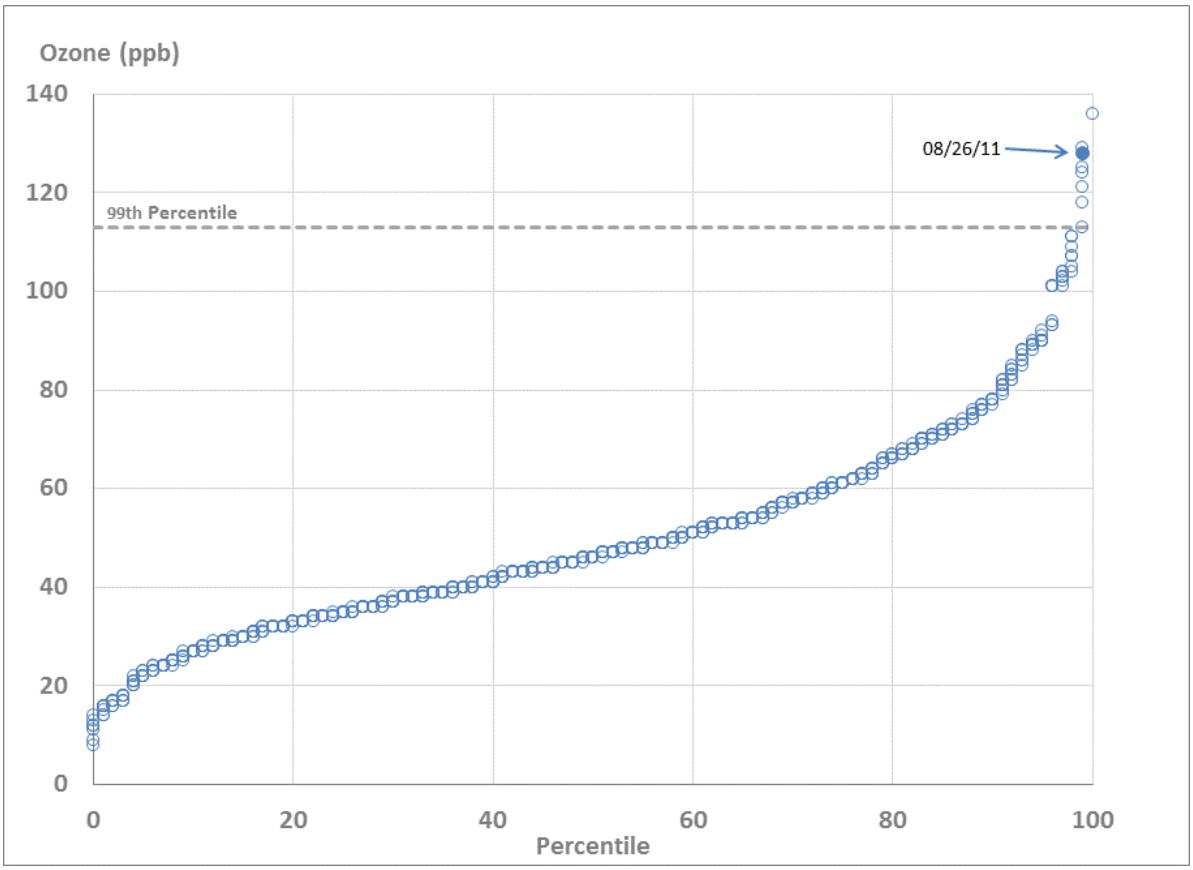


Figure 3-1: Percentile Rankings of Seasonal Daily Maximum One-Hour Ozone Concentrations at the Houston East (CAMS 1) Monitoring Site from 2009 through 2011

3.2 AN ANALYSIS OF ANNUAL DAILY MAXIMUM ONE-HOUR OZONE MEASUREMENTS AT THE HOUSTON EAST (CAMS 1) MONITORING SITE

As discussed in this chapter, the TCEQ's analysis of seasonal daily maximum one-hour ozone measurements provides strong evidence that the observed daily one-hour maximum on August 26, 2011 was outside of normal historical fluctuations. The TCEQ also compared the August 26, 2011 maximum one-hour ozone measurement to annual hourly ozone collected at Houston East over the years 2009 through 2011. The TCEQ used data from its LEADS. The data set used in this analysis contained data over a three-year period with 1,054 individual data points. Of these, the measurement on August 26, 2011 is in the top 1% of observations which again is well outside the historical norm observed values. The result appears in Figure 3-2: *Percentile Rankings of Annual Daily Maximum One-Hour Ozone Concentrations at the Houston East (CAMS 1) Monitoring Site from 2009 through 2011*. The only two days measuring higher than August 26, 2011 were August 29, 2011 at 136 ppb and July 16, 2010 at 129 ppb. August 29, 2011 was also influenced by the fire emissions described in this demonstration. Given the daily maximum one-hour ozone concentrations from these 1,054 individual data points, the measurement of 128 ppb ozone occurs very rarely – less than 0.5% of the time.

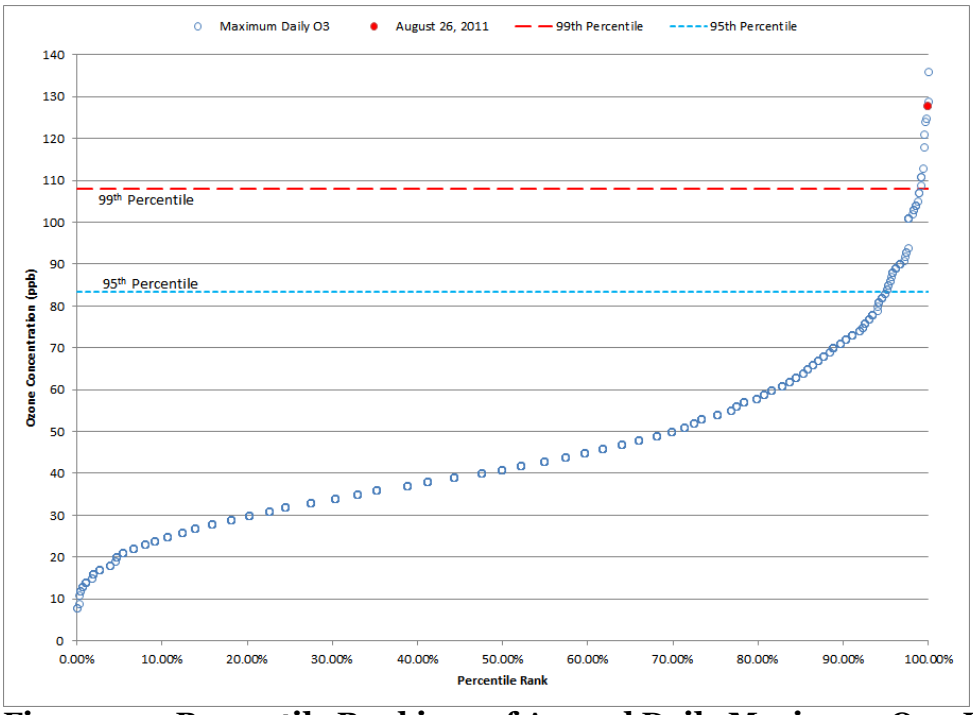


Figure 3-2: Percentile Rankings of Annual Daily Maximum One-Hour Ozone Concentrations at the Houston East (CAMS 1) Monitoring Site from 2009 through 2011

3.3 AN ANALYSIS OF DIURNAL PROFILES AT THE HOUSTON EAST (CAMS 1) MONITORING SITE

In addition to analysis of daily maximum ozone measurements to view the historical fluctuation of ozone values, diurnal profiles of ozone may also be examined. This section examines diurnal profiles to provide further evidence that August 26, 2011 was clearly outside of normal historical fluctuations for ozone measurements at the Houston East (CAMS 1) monitoring site.

The TCEQ constructed a diurnal profile of ozone data collected at the Houston East (CAMS 1) monitoring site. Hourly ozone data from the month of August for 2008 through 2012 were obtained from the EPA's Air Data website (http://www.epa.gov/airdata). August was chosen because the period contained August 26, 2011. A diurnal profile for the month of August provides a representative basis on which to compare hour-by-hour data from August 26, 2011. The years 2008 through 2012 were chosen to enlarge the time period analyzed, while allowing comparison of representative emission activity and meteorological conditions. The TCEQ arranged the data to generate a table with dates comprising the rows and hours of the day comprising the columns. Five invalid sampling days were removed due to lack of data, leaving a possible 150 observations for each hour of the day. The TCEQ calculated percentiles for each hour of the day. The analysis used 3,561 hourly observations out of a total 3,600 possible hourly observations because approximately 49 observations did not contain a sample measurment. The diurnal ozone profile at the Houston East (CAMS 1) monitoring site for August 26, 2011 was then compared to the standard fifth, 25th, Median, 75th, 95th, and 99th percentile values on an hour-by-hour basis. These percentile levels were used because they provide information regarding the central tendency and variability of the distribution at each hour of the day.

The results are shown in Figure 3-3: *August Diurnal Profile Analysis for Ozone at the Houston East (CAMS 1) Monitoring Site during 2008 through 2012*. Figure 3-3 clearly shows that the

day's maximum ozone measurement of 128 ppb, occurring at the 13:00 hour Central Standard Time (CST) and based on a percentile calculation using 149 observations, is in the top 1% of values for this hour of the day. Further, the figure shows that hourly ozone measurements "follow" the 99th percentile curve beginning in the 12:00 hour CST and continuing for the rest of the day. Clearly, the ozone measurements observed at the Houston East (CAMS 1) monitoring site were outside of historical fluctuations on an hourly basis as well as a daily basis. This evidence makes an even stronger case for August 26, 2011 having met the requirement for ozone being outside of normal historical fluctuations. Figure 3-4: *Hour-by-Hour Percent Rank for Ozone Measurements at the Houston East (CAMS 1) Monitoring Site on August 26, 2011*shows that after the 11:00 hour CST, hourly ozone values "following" the 99th percentile curve never drop below the 97th percentile. This is additional evidence that a large portion of hourly ozone measurements at the Houston East (CAMS 1) monitoring site on August 26, 2011 were outside the normal historical fluctuation of ozone values on an hour-by-hour basis.

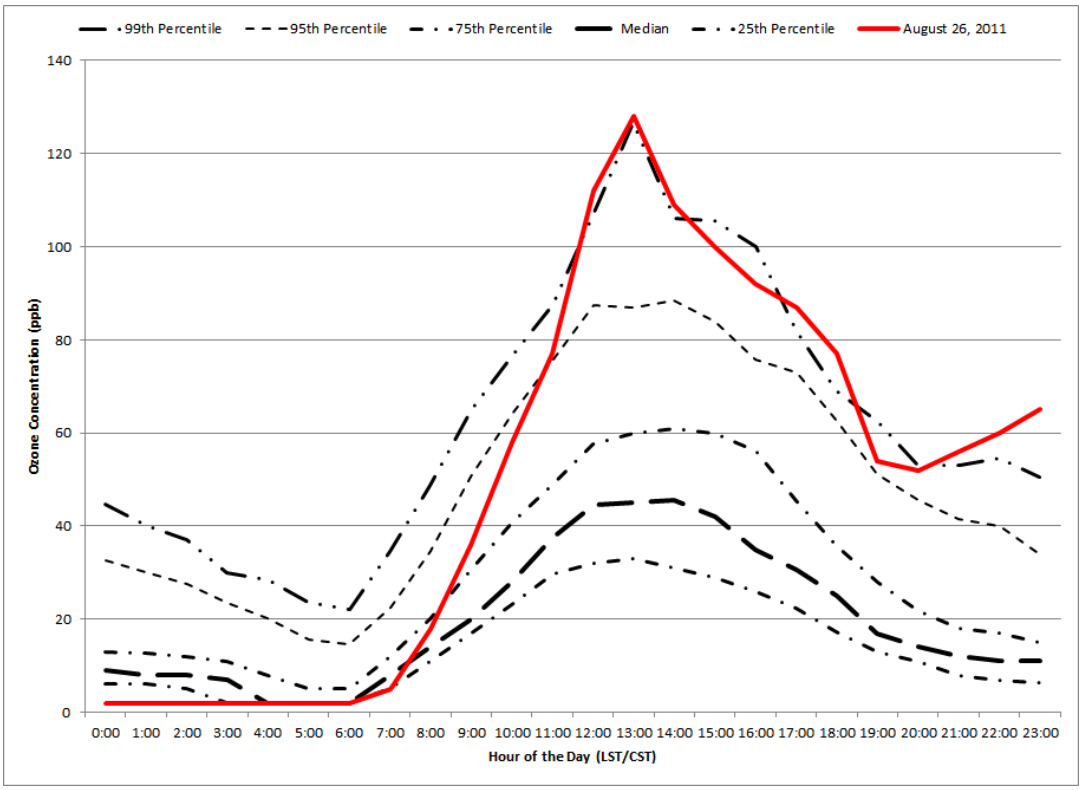


Figure 3-3: August Diurnal Profile Analysis for Ozone at the Houston East (CAMS 1) Monitoring Site during 2008 through 2012

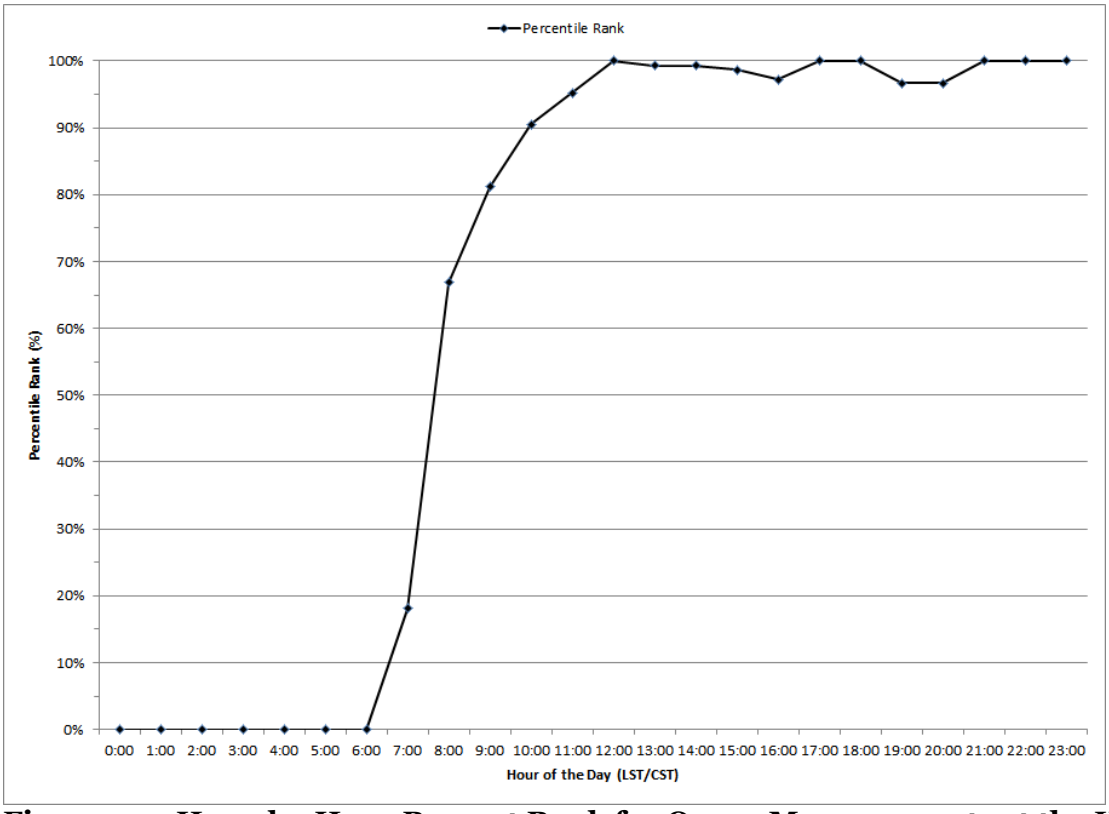


Figure 3-4: Hour-by-Hour Percent Rank for Ozone Measurements at the Houston East (CAMS 1) Monitoring Site on August 26, 2011

3.4 SHORT-TERM ANALYSIS OF THE HOUSTON EAST (CAMS 1) MONITORING SITE DAILY MAXIMUM OZONE MEASUREMENTS

Although its interim EER guidance calls for at least three to five years of data and a minimum of 300 observations for analysis of historical fluctuations, the EPA also notes that states could choose to analyze shorter time periods containing less data as an additional piece of evidence to substantiate a claim that the day in question is outside of normal historical fluctuations at the site (page 6; EPA 2013, Att. 1). In addition to evaluating a large historical data set as shown in the previous sections of this chapter, the TCEQ prepared a time series of 15 days so that the daily maximum one-hour ozone measurement for August 26, 2011 could be compared to calendar days immediately surrounding it in 2011. The time series began on August 19, 2011 and concluded on September 2, 2011. The 15 day period contained August 26, and seven days on both sides. The TCEQ also prepared similar time series for the corresponding calendar days 2009 and 2010 so that a comparison to 2011 might be made.

The resulting time series evaluations appear in Figure 3-5: *A Comparison of August 26, 2011 to its Neighboring Days in 2011 and a Comparison of 2011 to the Years 2009 and 2010*. This figure reveals another candidate exceptional event day in 2011. On August 29, 2011, the Houston East (CAMS 1) monitoring site experienced an exceedance of the one-hour ozone NAAQS that measured 136 ppb – 8 ppb higher than the exceptional event on August 26, 2011. This day experienced meteorological conditions similar to August 26, 2011 and had smoke and emissions emitted from wildfires in the northwestern and southeastern U.S. present in the HGB area. Although the TCEQ could submit a demonstration package in support of excluding August 29, 2011, it has not done so for the time being. The EPA requests that states only submit packages for exceptional event days that are of regulatory significance (page 5; EPA 2013). Since exclusion

of either day would bring the HGB area into attainment of the one-hour ozone NAAQS, only one of the days is of regulatory significance, and the TCEQ has chosen at this time to submit a request for exclusion for August 26, 2011.

Figure 3-5: *A Comparison of August 26, 2011 to its Neighboring Days in 2011 and a Comparison of 2011 to the Years 2009 and 2010* shows that, with the exception of August 29, 2011, the daily maximum ozone concentration for August 26, 2011 is much higher than any neighboring days. The next highest day after August 26 in 2011 is August 28, 2011 with a daily maximum of 104 ppb – a difference of 24 ppb. Averaging across all of its 14 neighboring days in 2011 (including August 29) the daily maximum for August 26 is 49.6 ppb higher than the neighboring days. As a whole, the 15 days in 2011 are higher than their corresponding days in 2010 by 40.3 ppb and in 2009 by 16.9 ppb. When one compares August 26, 2011 to each of the other 44 days in this three-year window, August 26, 2011 is higher than the other days by 66.8 ppb on average. While this comparison of immediate neighboring days lacks the preferred number of observations, it offers a striking illustration of just how unique August 26, 2011 is for this period both in 2011 and compared to other recent years.

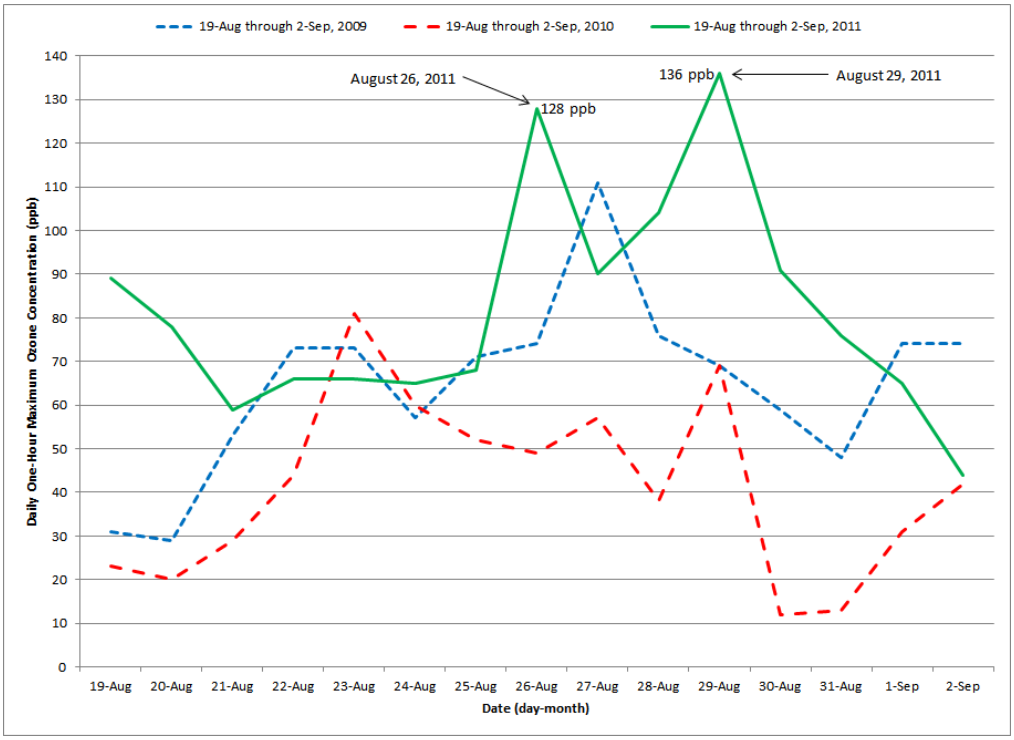


Figure 3-5: A Comparison of August 26, 2011 to its Neighboring Days in 2011 and a Comparison of 2011 to the Years 2009 and 2010

3.5 COMPARISONS BETWEEN NITROGEN OXIDES (NO_X) AND OZONE DATA COLLECTED AT THE HOUSTON EAST (CAMS 1) AND NEARBY MONITORING SITES

Biomass burning is known to produce elevated concentrations of NO_X, an important precursor of ozone, which can be transported far downwind (Morris, 2006; Val Martin, 2008). The TCEQ compared daily maximum hourly concentrations of NO_X from August 26, 2011 at the Houston

East (CAMS 1) monitoring site to seasonal daily maximum NO_X concentrations for 2009 through 2011 because of the important relationship between NO_X and ozone formation.

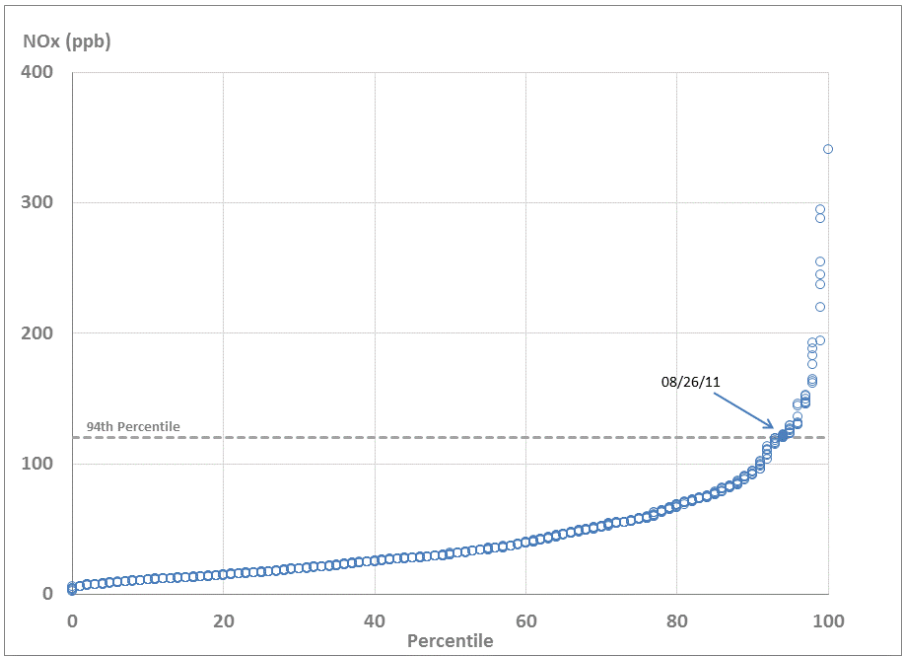


Figure 3-6: Seasonal Percent Rankings of Daily Maximum One-Hour NO_X Concentrations at the Houston East (CAMS 1) Monitoring Site from 2009 through 2011

Figure 3-6: *Seasonal Percent Rankings of Daily Maximum One-Hour NOX Concentrations at the Houston East (CAMS 1) Monitoring Site from 2009 through 2011* plots three years of ozone season daily maximum one-hour NO_X concentrations in rank order. The data set used by the TCEQ consists of 690 observations. The value for August 26, 2011, 122.42 ppb, ranks in the 94th percentile of the distribution, i.e., 94% of observed daily maximum NO_X concentrations fell at or below this level. This value should be considered anomalous for the series, or outside normal historical fluctuation. This is not a surprising result since NO_X is emitted from wildfires and is a precursor to ozone, and ozone concentrations were elevated at multiple HGB area monitors on August 26, 2011.

Because the fires that affected the Houston East (CAMS 1) monitoring site were quite distant from the region and required from several hours up to several days to reach the HGB area, the plume of emissions from the fires, including NO_X, would likely have been dispersed over a wide area. Additional monitors near the Houston East (CAMS 1) monitoring site were also selected for similar analysis, to determine whether the patterns observed for ozone and NO_X at the Houston East (CAMS 1) monitoring site were observed elsewhere, suggesting a regional phenomenon. If events at the Houston East (CAMS 1) monitoring site were isolated and not observed elsewhere, it would suggest a more localized emissions event likely influenced the Houston East (CAMS 1) measurements. Nearby monitors selected for analysis include Houston Aldine (CAMS 8), Channelview (CAMS 15), Clinton (CAMS 403), and Houston Deer Park (CAMS 35). These monitors were chosen because they all measure ozone and NO_X, they are in close geographic proximity to Houston East (CAMS 1) monitoring site and share similar meteorology patterns. The monitors are shown on Figure 3 7: *Map of Monitors in Close Proximity to the Houston East (CAMS 1) Monitoring Site.*

Figure 3-7: Map of Monitors in Close Proximity to the Houston East (CAMS 1) Monitoring Site

Statistics from the distributions of daily maximum one-hour ozone concentrations at each of the monitors were computed over 2009 through 2011 and are presented in Table 3-1: *Seasonal Daily Maximum One-Hour Ozone for the Houston East (CAMS 1) and Nearby Monitors, 2009 through 2011*. The table includes the maximum one-hour ozone on August 26, 2011 and the percentile of that peak compared to the three ozone seasons of observations. The distributions of daily maximum one-hour ozone concentrations are remarkably similar across the five monitors. Ozone concentrations on August 26, 2011 were unusually high with respect to the three ozone seasons under consideration at all of these monitors. The data suggest that a more widely dispersed emission event from outside the HGB area impacted numerous monitors, and it was not a local source affecting only the Houston East (CAMS 1) monitoring site on August 26, 2011.

Table 3-1: Seasonal Daily Maximum One-Hour Ozone for the Houston East (CAMS 1) and Nearby Monitors, 2009 through 2011

Statistic	Houston East (CAMS 1) (ppb)	Channelview (CAMS 15) (ppb)	Clinton (CAMS 403) (ppb)	Houston Aldine (CAMS 8) (ppb)	Houston Deer Park (CAMS 35) (ppb)
Minimum	8	14	10	12	11
25th Percentile	35	37	32	39	35
Median	46	48	43	49	47
75th Percentile	61	61	57	63	61
90th Percentile	77	79	71	79	76
Maximum	136	126	125	129	139
Maximum on 8/26/2011	128	97	114	129	104
8/26/2011 Percentile	99%	97%	99%	99%	98%

Statistics from the distributions of the daily maximum one-hour NO_X concentrations at each of the monitors computed for the 2009 through 2011 ozone seasons are presented in Table 3-2: *Seasonal Daily One-Hour NO_X Statistics for the Houston East (CAMS 1) and Nearby Monitors During 2009 through 2011 and Comparison with August 26, 2011* along with the daily peak one-hour NO_X concentration on August 26, 2011 and the percentile of that peak compared to the three ozone seasons of observations. The distributions are somewhat similar across monitors, although there is a great deal of variability in the maximum concentrations. Daily maximum one-hour concentrations measured at Channelview (CAMS 15), Clinton (CAMS 403), Houston Aldine (CAMS 8), and Houston Deer Park (CAMS 35) on August 26, 2011 were all higher than normal and ranged between the 79th and 95th percentiles. The daily maximum NO_x one-hour concentrations on August 26, 2011 for Channelview (CAMS 15), Clinton (CAMS 403), Houston Aldine (CAMS 8), and Houston Deer Park (CAMS 39) exceeded their median values by 39 ppb, 67 ppb, 29 ppb, and 46 ppb, respectively. The complexity of NO_X behavior in the atmosphere, the large variability of these measurements due to local sources, and transport complicate determination of whether these monitors are experiencing a regional or local event based solely on the NO_X data. It is evident however that some event is influencing the area and values are higher than normal across a wide geographic area encompassing large parts of east Texas, Louisiana, Arkansas and Mississippi.

Table 3-2: Seasonal Daily One-Hour NO_X Statistics for the Houston East (CAMS 1) and Nearby Monitors During 2009 through 2011 and Comparison with August 26, 2011

Statistic	Houston East (CAMS 1) (ppb)	Channelview (CAMS 15) (ppb)	Clinton (CAMS 403) (ppb)	Houston Aldine (CAMS 8) (ppb)	Houston Deer Park (CAMS 35) (ppb)
Minimum	2	4	4	0	0
25th Percentile	17	15	26	13	9
Median	30	23	40	23	15
75th Percentile	58	42	58	38	25
90th Percentile	91	85	90	63	43
Maximum	341	400	265	160	133
Maximum on 8/26/2011	122	62	107	52	64
8/26/2011 Percentile	94%	85%	95%	79%	86%

For August 26, 2011, the Houston East (CAMS 1) monitoring site observed high hourly ozone values above recent historical fluctuation. The surrounding monitors, Houston Aldine (CAMS 8), Channelview (CAMS 15), Clinton (CAMS 403), and Houston Deer Park (CAMS 39), exhibited exceptionally high hourly ozone concentrations. With the other area monitors and Houston East (CAMS 1) measuring historically high hourly ozone, this ozone event is above historical fluctuation and qualifies as an exceptional event.

3.6 SOUTHEAST TEXAS MONITORING SITES

To get a better understanding of where August 26, 2011 stood with respect to other days and other monitors, the TCEQ compared the daily maximum one-hour ozone measurements for all ozone season days in the years 2009 through 2011 across a larger area. Such an evaluation can reveal patterns that suggest either local or regional influences, as well as temporal anomalies. For this period of time, there were 21 monitoring sites in the HGB area, nine monitoring sites in the Beaumont/Port Arthur area, and one Clean Air Status and Trends Network (CASTNET) site at the Alabama-Coushatta Tribal Reservation in Polk County that regularly submitted data to the EPA Air Quality System, These monitoring sites are the entire complement of federally registered ozone monitoring sites in Southeast Texas. The TCEQ examined the daily maximum one-hour ozone measurements on August 26, 2011 as well as the percent rank of these measurements at each of the 31 monitoring sites over the 2009 through 2011 ozone seasons.

The detailed results are in Table 3-3: *Daily Maximum Values and Percentile Rankings of August 26, 2011 at Monitors in Southeast Texas*. Of the 31 sites, two did not collect sufficient measurements to have what EPA considers a valid monitoring day according to the one-hour ozone NAAQS, two monitoring sites exceeded the one-hour ozone NAAQS, four of the

monitoring sites ranked below their 95th percentile, and 25 monitoring sites exceeded their 95th percentile on August 26, 2011. These results are especially compelling when one notes that 18 of 19 sites in the HGB area had measurements that exceeded their site's 95th percentile, regardless of geographical location.

On a typical high ozone day in the HGB area, high one-hour ozone values are more likely to occur in only one part of the HGB area (for example near the Ship Channel, on the eastern side of Harris County, or in the southern part of Harris County) on a single day (TCEQ, 2010). The fact that so many unusually high ozone values (greater than the 95th percentile) occurred on the same day and were spread throughout the entire HGB area leads to a conclusions that a highly unusual factor was at work. As shown in Section 5.1: *Analysis of a Surrogate Day*, meteorology and emissions in the HGB area on August 26, 2011 were typical in many ways. The only apparent factor that most likely explains the breadth of high ozone measurements in southeastern Texas on August 26, 2011 is the transport of fire-related ozone and ozone precursors into the HGB area and mixing down where they could cause unusually high ozone values in the HGB area on this day.

Table 3-3: Daily Maximum Values and Percentile Rankings of August 26, 2011 at Monitors in Southeast Texas

Site*	Daily Maximum (ppb)	Percentile (%)
Houston East (CAMS 1)	128	99.7%
Northwest Harris County (CAMS 26)	MISSING	N/A
Houston Westhollow (CAMS 410)	94	99.4%
Bunker Hill Village (CAMS 562)	91	98.3%
Houston Bayland Park (CAMS 53)	102	98.6%
Houston Lang (CAMS 408)	110	99.0%
Houston Croquet (CAMS 409)	98	98.7%
Lake Jackson (CAMS 1016)	80	97.8%
Conroe Relocated (CAMS 78)	90	98.3%
Manvel Croix Park (CAMS 84)	117	99.1%
Houston Texas Avenue (CAMS 411)	106	99.0%
Houston Aldine (CAMS 8)	129	100.0%
Houston Regional Office (CAMS 81)	120	99.5%

Site*	Daily Maximum (ppb)	Percentile (%)
Houston Park Place (CAMS 416)	104	98.5%
Houston North Wayside (CAMS 405)	131	100.0%
Houston Clinton (CAMS 403)	114	99.0%
Deer Park (CAMS 35)	104	98.5%
Channelview (CAMS 15)	97	97.2%
Lynchburg Ferry (CAMS 1015)	88	95.3%
Seabrook Friendship Park (CAMS 45)	70	89.8%
Galveston 99th Street (CAMS 1034)	MISSING	N/A
Alabama-Coushatta Reservation (CASTNET)	71	82.7%
Hamshire (CAMS 64)	70	91.5%
Beaumont Downtown (CAMS 2)	88	98.0%
Nederland High School (CAMS 1035)	92	99.3%
SETRPC Jefferson Co Airport (CAMS 643)	92	99.4%
Port Arthur West (CAMS 28)	88	98.0%
SETRPC Port Arthur (CAMS 628)	76	96.6%
SETRPC Sabine Pass (CAMS 640)	78	93.1%
SETRPC Mauriceville (CAMS 642)	97	100.0%
West Orange (CAMS 9)	81	95.9%

*Except for Houston East (CAMS 1), the monitoring sites are listed in order of increasing longitude (from West to East).

CHAPTER 4: A CLEAR CAUSAL RELATIONSHIP BETWEEN FIRE EMISSIONS AND HIGHER OZONE

4.1 LITERATURE REVIEW

In this section, the Texas Commission on Environmental Quality (TCEQ) reviews the scientific literature on fire emissions and ozone in order to answer the following questions about ozone and wildfires; Can wildfire emissions produce ozone or ozone precursors? Can the ozone and ozone precursors produced by wildfires be transported long distances? Have ozone and precursors produced by wildfire transported over long distances and affected surface ozone in Texas?

Jaffe (2012) provides an excellent overview and summary of research on characterization, transport and fate of emissions from wildfires, and their effects on air quality including contributions to exceedances of the ozone National Ambient Air Quality Standard (NAAQS). The peer-reviewed studies agree that wildfires can be a source not only of smoke, particulate matter, and carbon dioxide but also of the ozone precursors non-methane organic gases and nitrogen oxides (NO_X). Ozone can be enhanced above background concentrations far downwind of fires due to transport of ozone in photochemically active or photochemically dormant plumes. In fact, ozone may not be formed immediately downwind of a fire but may form much further downwind when the chemical atmosphere of the fire plume becomes more conducive to ozone formation (Andreae, et al. 1994). Under suitable chemical conditions, emissions from fires can remain in the atmosphere for many days and can be tracked and detected thousands of kilometers (km) downwind. The discussion below presents more details about the large body of work related to wildfire-generated ozone.

Wildfire emissions can produce ozone and ozone precursors as well as smoke aerosols.

Some of the earliest work published on the topic of wildfire emissions reported ozone concentrations at 40 to 50 parts per billion (ppb) (Westberg, 1981) and 44 ppb (Stith, 1981) above ambient levels in regions downwind or near biomass fires. Ozone is enhanced due to the substantial quantities of ozone precursors emitted by wildfires and other biomass burning. Pickering (1996) reported that biomass burning significantly increased NO_X and hydrocarbons downwind resulting in ozone formation rates of 7 to 8 ppb per day. Mauzerall (1998) determined that ozone production in fire plumes was limited by available NO_X but that ozone continued to be produced as a plume aged. Cheng (1998) observed 50 to 150% enhancements in nitrogen dioxide (NO_2) and ozone downwind from fires and that forest fires had a noticeable influence on air quality in urban areas even though local emissions were much higher. Jonquieres (1998) reported ozone production of 15 to 35 ppb per day in plumes from 1987 African fires as well as circulation patterns that contributed to long-range transport.

Fires have affected ozone concentrations throughout the world. Large fires in Alaska, Canada, California, Colorado, Indonesia, Central America, Africa, and Siberia have all affected ozone concentrations in areas downwind. Goode (2000) found an ozone production rate of about 50 ppb per hour in smoke plumes from four Alaskan fires in 1997. Jaffe (2008) reported that inter-annual variation in ozone was related to the size of the area burned and the types of biomass consumed by wildfires in the western United States (U.S.). Large fire years exhibited widespread enhanced ozone with mean regional ozone elevated by 2 ppb and 8.8 ppb in maximum fire years. The presence of fires was a more important predictor of ozone than temperature. Pfister (2008) modeled increases of about 10 ppb in eight-hour averages of surface ozone from fires in California in 2007.

Fujiwara (1999) used ozonesondes to study emissions from Indonesian fires in 1994 and 1997 and reported that ozone exceeded 80-100 ppb within different layers of the troposphere, due to photochemical production of ozone from precursors emitted by the fires. Hauglustaine (1999) reported 20 to 25 ppb enhancements to tropospheric ozone from 1997 Indonesian fires. Kita (2000) observed significant increases in ozone from 1994 and 1997 fires in Indonesia and noted the importance of horizontal advection in the lower troposphere and vertical transport. Verma (2009) reported ozone was enhanced by up to 90 ppb in locations close by and distant from Siberian fires in areas where sunlight and NO_X are abundant and lower ozone in the free troposphere where thick aerosol plumes occur. Kaufman (1992) found a strong relationship between spatial distribution of fires and ozone concentrations for 1989 fires in South America. Chandra (2009) estimated that El Nino-related drought and resultant fires in 2006 contributed 2 to 3% of the global ozone.

Ozone production from wildfires is influenced by factors including availability and types of precursors, weather patterns, fuel type, combustion characteristics, extent of burn area, photochemistry, proximity of urban areas, and other factors (Jaffe, 2012). Ozone can form rapidly after precursors are emitted from fires. Trentmann (2003) noted elevated ozone of 70 ppb in a young biomass burning plume. Models were used to simulate behavior of smoke plumes as they were transported at high altitudes and later mixed to the surface. Yokelson (2009) found within fire plumes ozone concentrations increased by about 15% in less than one hour, which is faster and at finer spatial scales than some models can simulate.

Ozone can also be formed from wildfire-generated precursors far downwind from the original source. Val Martin (2006) studied impacts of boreal wildfire emissions six to 15 days downwind at a high altitude site in the Azores including long-range transport, large enhancements of total reactive nitrogen (NO_Y) and NO_X, and decomposition of peroxyacetyl nitrate (PAN) to NO_X leading to continuing ozone formation reaching 75 ppb in well-aged plumes.

The scientific literature clearly indicates that wildfires and other types of biomass burning can generate ozone precursors in large quantities, and these precursors can form ozone near the original fire source and can continue ozone formation far downwind.

Ozone, ozone precursors, and smoke generated by wildfires can be transported thousands of km from the fires and can influence ozone concentrations far downwind and over a large area.

Thompson (1996) found elevated ozone over the Atlantic Ocean, up to 90 ppb, in layers all the way up to the tropopause, from African biomass burning. Ozone formation rates of up to 15 ppb per day were observed within the lowest 4 km of the troposphere. The ozone maximum was attributed to abundant precursors from fires, long residence time in stable air, and convective transport with additional NO_X from lightning and biogenic sources.

Singh (2000) found maximum PAN and ozone over the Pacific Ocean in very dry air from 5 to 7 km altitude and traced these to biomass burning in South Africa with large perturbations in ozone and precursors due to long-distance transport and subsiding trajectories.

Phadnis (2000) compared ozone with and without influences from 1987 fire emissions in China and found increases of 5 to 10 ppb with an increase in the monthly average of about 30% in the boundary layer close to the fire.

Forster (2001) found that large-scale haze over Europe in 1998 was caused by emissions from Canadian fires transported over thousands of km at altitudes from 3 to 6 km.

Jaffe (2001) observed significantly higher carbon monoxide (CO), ozone, NO_X, PAN, and non-methane hydrocarbons at an ostensibly "clean" site on the coast of Washington (state) attributable to unusually large areas of biomass burning in Asia in 1997 and 1998.

McKeen (2002) reported enhancements of 10 to 30 ppb of ozone in transported air, found that most of the increase in ozone from fires in Canada was attributable to NO_X emitted by the fires, and that urban receptor areas are more sensitive to influences from long-range transport from fires because of the many local precursor sources.

Staudt (2002) identified a considerable influence of biomass burning on ozone up to 12 km in altitude with long-range transport from Africa and South America. Biomass burning, with decomposition of PAN, was the predominant source of NO_X in the lower troposphereand lightning was the predominant source of NO_X in the upper troposphere with subsidence of NO_X from the uppermost troposphere.

Duncan (2003) reported on emissions from 1997 Indonesian wildfires enhancing ozone concentrations 10%, and CO by 50%.

Sinha (2003) observed transport of smoke plumes from southern Africa westward over the Atlantic Ocean to South America and the southern Pacific Ocean in 2000, with ozone of 76 ppb aloft and thin, relatively clean layers between thick layers of pollution at about 3 km aloft.

Honrath (2004) traced an enhancement of ozone at a tropospheric site in the Azores backward to North American fire emissions due to long-range transport.

Jaffe (2004) modeled transport of smoke from Siberian fires to North America and found ozone enhancements of 5 to 9 ppb linked to these global processes and that this elevated background contributed to exceedances in the U.S. Pacific northwest.

Konda (2004) reported that 70% of ozone from Asian fires was transported to the western Pacific, PAN was conserved during transport, and NO_X decreased with altitude.

Bertschi (2004, 2005) found well-defined layers of enhanced ozone and other emissions from fires from 0 to 6 km altitude with ozone exceeding 100 ppb in some cases. These layers were found to be efficient in transporting fire emissions from Asia to North America. These researchers traced these layers back to Siberia using the HYSPLIT trajectory model and found that under certain conditions this Siberian smoke was transported down to the surface.

DeBell (2004) studied the largest Canadian fire plume to impact the U.S. in a decade and found elevated ozone and Total Reactive Nitrogen (NO_Y), as well as nitrate, ammonium, and sulfate ions that varied with elevation and latitude attributable to transport and surface deposition.

Lapina (2006) found significant impact of boreal wildfires on ozone in the lower free troposphere.

Pfister (2006) estimated an increase of 7 to 9% in ozone in the Azores from well-aged boreal forest fire plumes.

Real (2007) observed long-range transport of chemically active plumes from 2004 Alaskan fires. A plume was tracked by aircraft over North America, the North Atlantic Ocean and Europe. Ozone was observed to increase by 17 ppb over five days, while enhanced concentrations of CO,

VOC, and NO_y were also measured. Ozone production was determined to be dependent on temperature during transport and water vapor in the lower troposphere.

Yokelson (2007a) reported smoke from African fires was transported over 2,000 km with elevated ozone, NO_2, and other reactive species.

Tanimoto (2008) reported ozone enhancements in Japan from biomass burning in Siberia ranged from slightly negative to up to 40%.

Val Martin (2008) found year-round potential for substantial ozone formation in the Azores downwind of North American fire sources due to transport and decomposition of PAN.

Nassar (2009) examined the contribution of Indonesian fires to ozone enhancements and found a range of 10 to 75% depending on season.

Oltmans (2010) observed unusually high ozone over 35 continuous hours in Alaska related to enhanced lower troposphere ozone enhancements likely from biomass burning in Russia.

Singh (2010) found widespread influences in the Arctic from 2008 biomass burning in Europe and Asia with PAN-dominant plumes transported in the mid to upper troposphere.

Jaffe (2011) found that ozone generated by biomass burning in the western U.S. strongly influenced both surface and free troposphere ozone concentrations, with mixing ratios frequently exceeding 65 ppb between 3 to 6 km above ground level. Further, Jaffe (2011) determined that "wildfires significantly increase the number of exceedance days across the western US." This extensive body of evidence supports the supposition that elevated concentrations of ozone can be found at locations far distant from the sources of precursors.

Widger et al. (2013) analyzed 32 wildfire events between 2004 through 2011 that may have influenced ozone concentrations observed at the Mount Bachelor observatory in Oregon.Two events were linked to wildfire emissions that had been transported long distances (from Montana and British Columbia), and both of these had enhanced ozone. They found an apparent link between higher ozone production in biomass burning plumes and the interaction of the plumes with urban emissions.

In conclusion, the scientific literature clearly shows that ozone generated from fires can be transported thousands of km across oceans and continents to affect air quality in places distant from the original fire sources.

Wildfire-produced ozone and precursors have been transported long distances to affect surface ozone in Texas.

In the recent scientific literature, three examples of long-distance transport of fire-generated smoke, ozone, and/or ozone precursors into eastern Texas have been documented, as discussed below:

- May 1998 Central American fires;
- July 19-20, 2004 Alaskan and western Canadian wildfires; and
- September 25-26, 2006 Southern California wildfires.

The largest event in recent history occurred in May 1998 when the springtime agricultural fires that are set annually in Mexico and Central America to clear the fields went out of control and burned large areas. The smoke from these fires was transported thousands of km into Texas and the central U.S., and the ozone resulting from the emissions affected many cities. Peppler et al. (2000) documented smoke in Oklahoma at the Atmospheric Radiation Measurement field station as the smoke and associated emissions were transported through Texas. They observed smoke aerosols with several different remote sensing tools and with standard surface particulate matter monitors. In addition, high ozone was observed coincidently with the smoke at sites in central Oklahoma and Dallas-Fort Worth with the highest concentrations observed on May 11, 1998. Rogers and Bowman (2001) observed high aerosol concentrations during May 1998 by satellite with the Total Ozone Mapping Spectrometer (TOMS) and tracked the observed aerosol back to the source regions in Central America with trajectory modeling. Cheng and Lin (2001) also used back trajectories to track smoke to the sources but used the Potential Source Contribution Function technique. In et al. (2007) modeled the smoke episode using the Community Multi-scale Air Quality chemical transport model. During May 1998, the TCEQ documented strong enhancements of background ozone resulting in eight-hour ozone exceedances in cities that rarely, if ever, observe ozone exceedances, e.g., Brownsville.

Another event occurred in July 2004. Morris et al. (2006) reported observations by satellite, ozone sounding balloons, surface monitoring, and back trajectories that were consistent with an enhancement of background ozone concentrations by wildfire emissions. Ozonesonde measurements on July 19-20, 2004 showed a layer of enhanced ozone that could be traced with trajectories back to a region where large wildfires had been occurring in Alaska and western Canada, a distance of over 4,000 km.

During the Texas Air Quality Study field campaign conducted in 2005 and 2006, two research groups observed smoke aerosols, CO, and ozone in a layer of the lower troposphere that may have been able to mix down to the surface (Schwarz et al., 2008; Brioude et al. 2007). On September 25-26, 2006, the two groups intercepted smoke plumes aloft in eastern Texas. Brioude et al. presented satellite images of smoke plumes apparently traveling from the southwest U.S. into Texas. Back trajectory analyses linked the smoke plumes to wildfires that were occurring at the time in southern California.

Based upon these and related studies, emissions from distant fires have been shown to strongly influence the air quality in Texas including enhancing surface ozone concentrations. The studies listed above identified three different source regions for fire emissions affecting Texas cities indicating that a variety of transport patterns are capable of carrying fire emissions and ozone for long distances into Texas.

4.2 WILDFIRES OF 2011

Figure 4-1: *Locations of Wildfires and Prescribed Burns Identified by NOAA,* shows locations of wildfires and prescribed burns identified by the National Oceanic and Atmospheric Administration (NOAA) using satellite measurements and the Wildfire Automated Biomass Burning Algorithm (WFABBA) during the week preceding the proposed exceptional event on August 26, 2011. Fires were detected in almost every state, as well as Canada and Mexico, but were concentrated in the Pacific Northwest, Central Plains, and Southeastern U.S.

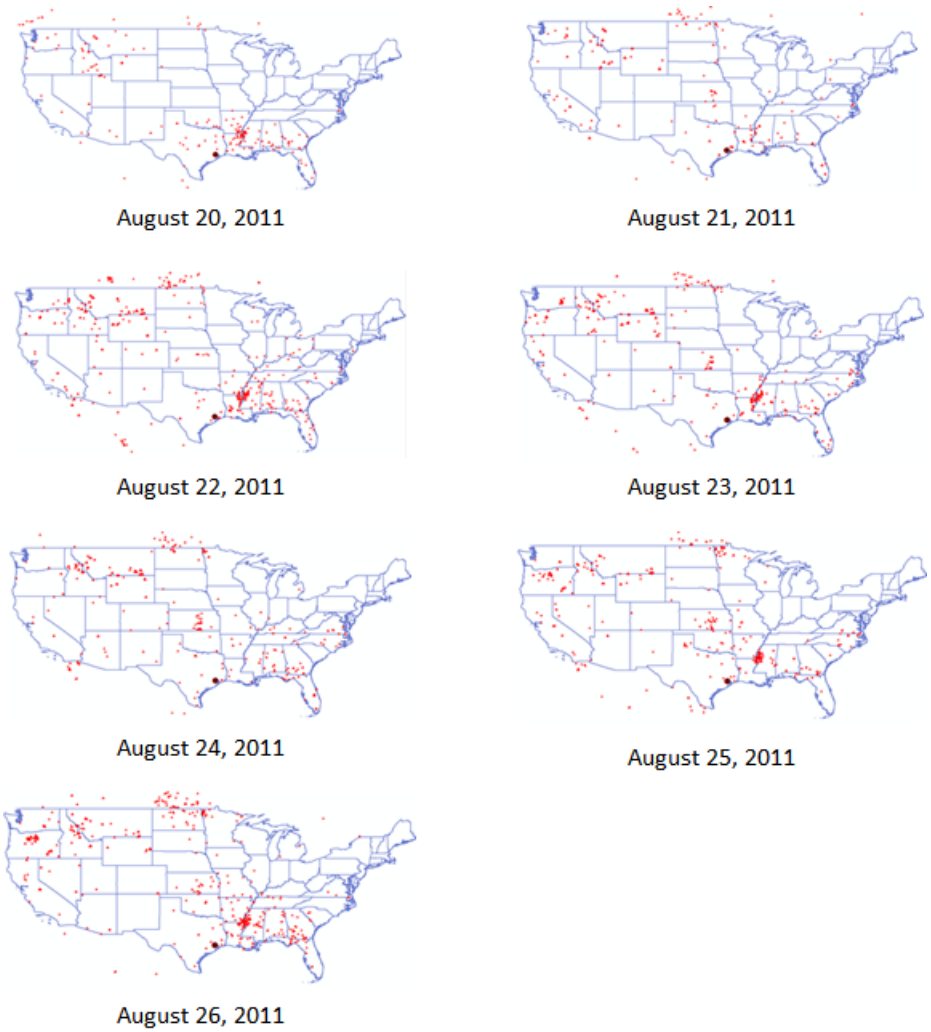


Figure 4-1: Locations of Wildfires and Prescribed Burns Identified by NOAA

Because the exceptional event at the Houston East (CAMS 1) monitoring site on August 26, 2011 was the result of transport of ozone and ozone precursors from fires burning upwind, it is informative to examine the size and intensity of the fires in the latter half of August 2011. Numerous federal and state agencies identify, monitor, and combat wildfires and prescribed burns in the U.S. and North America, including the U.S. Forest Service, the National Park Service, the Bureau of Land Management, the U.S. Fish and Wildlife Service and the Federal Emergency Management Administration. These and other agencies participate in the National Interagency Coordination Center. Some fires are reported by monitoring agencies, while others are only identified from satellite measurements using computer algorithms and manual inspection.

The NOAA uses the WFABBA (http://wfabba.ssec.wisc.edu/algorithm.html) to identify likely fires for each day using satellite measurements and imagery, computer algorithms, and manual error correction. These fires could be wildfires or prescribed burns and could be as small as two acres depending on conditions (personal communication, 2013). Some fires might not be detected due to cloud cover or poor timing of satellite overpass. The algorithm can also incorrectly identify as fires thermal anomalies that are actually reflection of solar radiation off reflective surfaces, such as clouds, sand, water, or even solar panels. As many of these fire

anomalies as possible are removed from the database by NOAA analysts using a manual correction technique. Exact locations of fires are difficult to determine because many fires are smaller than a single satellite image pixel, fire fronts are mobile, the Geostationary Operational Environmental Satellites (GOES) platform provides two measurements per day, and different satellites, due to different viewing angles (azimuths), might detect fires in slightly different locations. However, though locations of fires are only estimates, most are believed to be actual fires and to be within about 2 km of the estimated location. Larger fires, which emit more ozone precursors, are more likely to be correctly identified with the algorithm because they provide a clearer thermal anomaly when compared to surrounding thermal conditions. The number of fires identified in each state and the countries of Canada and Mexico are reported in Table 4-1: *Number of Fires Identified by NOAA, by Day, August 20 through 26, 2011.*

Table 4-1: Number of Fires Identified by NOAA, by Day, August 20 through 26, 2011

Region/State	Aug. 20	Aug. 21	Aug. 22	Aug. 23	Aug. 24	Aug. 25	Aug. 26
Lower Mississippi River Valley							
Arkansas	16	3	21	11	5	13	24
Louisiana	24	27	40	48	3	24	43
Mississippi	22	11	57	57	10	56	61
Upper Mississippi River Valley							
Illinois	0	1	3	0	4	0	2
Iowa	0	0	0	0	1	1	1
Minnesota	1	9	3	9	9	32	22
Missouri	1	0	0	1	4	6	8
Wisconsin	0	0	4	0	0	3	1
Southeastern US							
Alabama	11	5	23	6	21	17	19
Florida	10	23	20	15	43	9	15
Georgia	11	15	20	25	35	32	33
North Carolina	1	5	6	11	7	18	0
South Carolina	0	0	2	2	0	1	4
Tennessee	0	1	6	4	9	1	4
South Central Plains							
Kansas	0	11	9	27	25	26	15
Oklahoma	7	3	1	2	3	9	7
Texas	23	25	21	15	19	25	15
North Central Plains							

Region/State	Aug. 20	Aug. 21	Aug. 22	Aug. 23	Aug. 24	Aug. 25	Aug. 26
Nebraska	0	1	1	0	1	2	1
North Dakota	1	7	5	4	11	3	24
South Dakota	1	5	1	4	1	1	1
Southern Rocky Mountains/Pacific Southwest							
Arizona	2	3	2	2	2	1	0
California	4	32	27	19	5	17	25
New Mexico	6	1	2	2	2	1	0
Nevada	3	0	0	0	3	6	13
Utah	15	0	14	1	1	1	2
Northern Rocky Mountains/Pacific Northwest							
Alaska	0	1	0	0	0	0	1
Idaho	23	78	99	63	73	40	79
Montana	16	28	194	254	166	57	105
Oregon	1	6	32	31	8	89	251
Washington	9	8	4	20	4	4	11
Wyoming	6	37	114	137	45	13	31
Eastern/Midwest US							
Indiana	0	0	0	0	1	0	0
Kentucky	0	1	4	1	3	0	3
Michigan	0	0	0	0	1	0	2
New Jersey	0	0	2	0	0	0	0
Ohio	0	0	5	0	0	0	0
Pennsylvania	0	2	0	0	0	0	0
Virginia	1	11	7	7	18	19	11
West Virginia	0	2	1	0	0	0	0
International							
Canada	18	41	109	48	46	17	92
Mexico	4	22	73	64	72	48	15

Note: Locations of fires identified by WFABBA and expert review were supplied by NOAA.

The number of fires identified varied greatly from day to day. Some fires could be prescribed burns that are often agricultural in nature. Others could be smaller wildfires that ended quickly. A few were larger fires that persisted across many days and consumed larger areas of biomass. Though fires were scattered throughout nearly every state in the U.S., fires were mostly clustered in the central and western states. These areas included the Mississippi Delta in

Mississippi, Louisiana, and Arkansas, the central plains of Kansas and Oklahoma, the northern plains of North Dakota plus Manitoba and Saskatchewan provinces in Canada, and in the Pacific Northwest in Idaho, Montana, and Oregon.

Figure 4-2: *Annual Number of Wildfires in the U.S.,* shows that the number of wildfires recorded from 1960 through 2013 was also variable, with an upward trend peaking in 1983 bounded between 50,000 and 100,000 ever since. The total number of wildfires in 2011 (65,500) was not unusually large. However, as shown in Figure 4-3: *Annual Acreage Burned in the U.S.,* the acreage burned by wildfires in 2011 (6.6 million acres) is one of the highest on record.

Figure 4-2: Annual Number of Wildfires in the U.S.

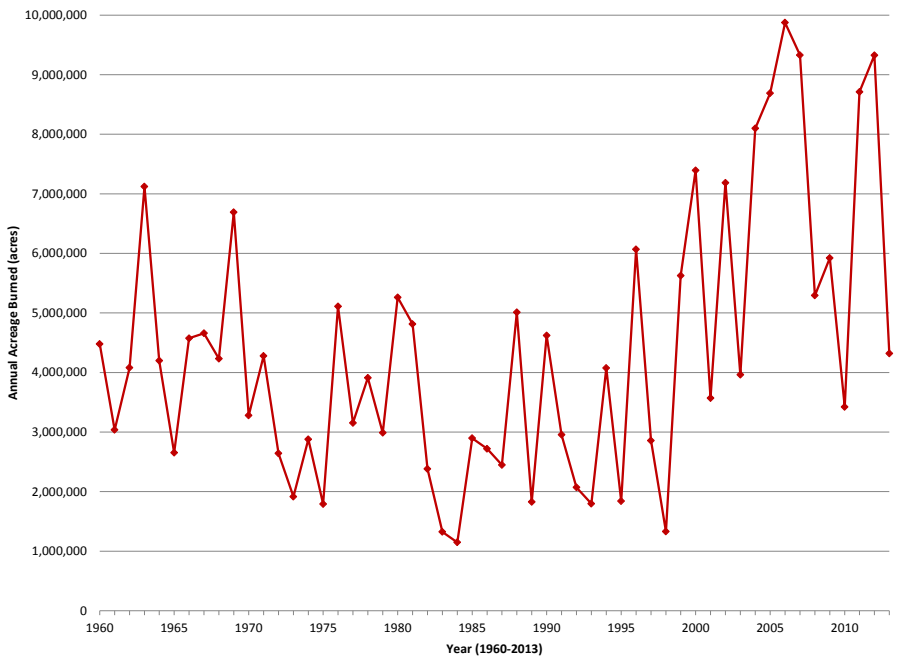


Figure 4-3: Annual Acreage Burned in the U.S.

The trajectory analyses presented in Section 4.4: *Trajectory Analyses* show that fires burning in several states along the Mississippi River (Arkansas, Louisiana, and Mississippi) could have contributed ozone and ozone precursors to the Houston-Galveston-Brazoria (HGB) area during the days and hours preceding the ozone exceedance on August 26, 2011. These analyses also determined that emissions from wildfires burning in the northern Rocky Mountains region and the Pacific Northwest during the week preceding the elevated ozone event, were delivered to the HGB area by August 26, 2011.

The U.S. EPA's guidance on preparation of exceptional events demonstrations suggests that states include news reports, special weather statements, advisories, and related information on fires, dust storms, or other phenomena published at the time of the event that help establish the occurrence and geographic extent of an event in support of exceptional events evidence. Not all fires identified through remote sensing will be covered by the news media. TCEQ provides a sampling of news reports below. These news reports give an idea of how quickly wildfires can grow and start.

On August 20, 2011, the *Missoulian,* the newspaper in Missoula Montana, (Florion 2011) reported on three fires that had burned a combined 4760 acres in the Flathead National Forest (northwestern Montana). One of the fires had grown from 2000 to 2600 acres just that day and two of the fires were not actually being suppressed because they were in a wilderness area.

Two days later, on August 22, 2011, the *Missoulian* (Scott 2011) was reporting that the two wilderness area fires had grown from 3,850 acres to 4,100 acres and were expected to burn for weeks. The third fire which had grown from 910 acres to 1215 acres, was not being actively suppressed. This fire, too, was expected to burn for a number of weeks.

That same day, the *Missoulian* ran three other articles on wildfires in Montana and neighboring Idaho. A local wildfire had just started and already burned 1,000 to 2,000 acres (Nickell 2011).

A second article covered the beginning of a new fire on the Montana-Wyoming border (Associated Press August 24, 2011). The third article (Erickson 2011) reported on the Saddle Complex fire which had burned about 1,045 acres near the Idaho-Montana border. In the case of the Saddle Complex fire, the paper noted that "The Saddle Complex fire burning in a remote portion of Idaho's Frank Church-River of No Return Wilderness moved onto the Bitterroot National Forest on Sunday afternoon and grew to 1,018 acres during the day Monday. The complex is comprised of two wildfires burning near the Montana-Idaho border about 20 miles southwest of Painted Rocks State Park - the Saddle fire on the Idaho side and the 27-acre Stud fire on the Montana side of the border. According to Salmon-Challis National Forests public information officer Jesse Bender, both fires are burning in an area that has not been impacted by fire in more than 100 years. The Saddle fire is being managed for resource benefits, meaning it is not actively being suppressed."

On August 24, 2011, the *Missoulian* was reporting on additional fires in southeastern Montana that had burned over 14,000 acres (Associated Press August 24, 2011). The previously mentioned fire in the Frank Church-River of No Return Wilderness had grown to 18,275 acres and crossed into Montana (Associated Press August 24, 2011). The *Missoulian* published an additional five articles on August 24, including a report that smoke plumes were visible in Missoula from a prescribed burns set on August 12 and 15, 2011 in the Nez Perce National Forest (Idaho) (Missoulian August 24, 2011).

The local CBS television affiliate in Sacramento, California, reported on August 26, 2011 that "The main highway into Yosemite National Park remains closed as firefighters continue to battle a wildfire outside of the park. A U.S. Forest Service officials [sic] says the blaze has consumed more than 1,000 acres since it was reportedly sparked Thursday when a motor home caught fire (CBS Sacramento 2011)." Another CBS affiliate in San Francisco reported that "Officials say the blaze has consumed about 400 acres along Highway 140 since it was first reported a little before 1 p.m. Thursday."

4.3 TIMING OF HOURLY FINE PARTICULATE MATTER LESS THAN OR EQUAL TO 2.5 MICRONS IN DIAMETER ($PM_{2.5}$) AND OZONE MEASUREMENTS ON AUGUST 26, 2011

Hourly $PM_{2.5}$ and ozone measurements at the Houston East (CAMS 1) monitoring site provide good evidence that the measured ozone exceedance is related to smoke from wildfires in the northwestern and southeastern U.S. Figure 4-4: *Ozone and PM2.5 Diurnal Profiles Measured at the Houston East (CAMS 1) Monitoring Site on August 26, 2011* shows that ozone and $PM_{2.5}$ reach their daily maximum during the same hour. The $PM_{2.5}$ data for this figure relies on five data points from 11:00 AM (Local Standard Time (LST)/ Central Standard Time (CST)) through 3:00 PM (LST/CST) that were used for the purposes of the EPA's Air Now website, but were subsequently determined to be invalid because the internal station temperature rose above 87° Fahrenheit (F). TCEQ monitoring staff do not believe that the increased internal temperature, which did not rise above 89.7° F, would significantly impact to the quality of the data collected during those hours. In fact, the TCEQ believes that higher temperatures may have caused some semi-volatile particles to evaporate, thereby underestimating the actual $PM_{2.5}$ values. Because the internal station temperature is unlikely to have seriously altered $PM_{2.5}$ measurements, the TCEQ presents the results for consideration with the appropriate caveats. Regardless of the absolute accuracy of the $PM_{2.5}$ data, Figure 4-4 shows the rising and peaking of $PM_{2.5}$ values at the same time that ozone rises and peaks.

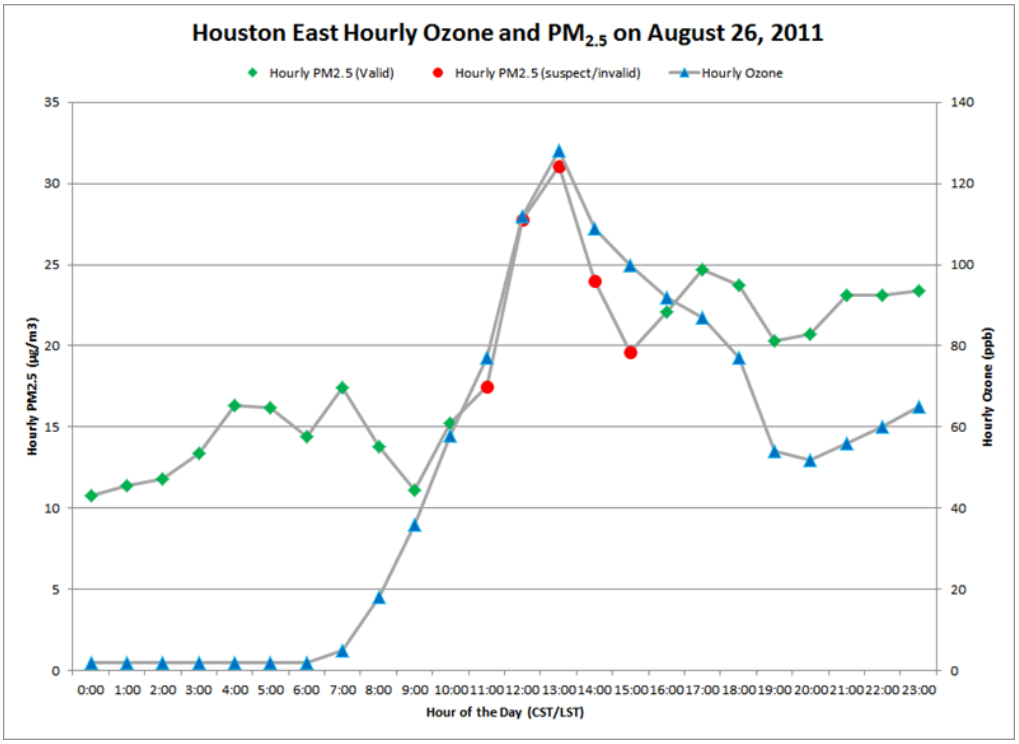


Figure 4-4: Ozone and PM2.5 Diurnal Profiles Measured at the Houston East (CAMS 1) Monitoring Site on August 26, 2011

4.4 TRAJECTORY ANALYSES

The TCEQ performed numerous analyses of trajectories to determine whether emissions from wildfires and prescribed burns (i.e., unspecified fires) could have contributed to the one-hour ozone exceedance observed at the Houston East (CAMS 1) monitoring site on August 26, 2011. The four approaches employed the NOAA Hybrid Single Particle Lagrangian Integrated Trajectory (HYSPLIT) trajectory and dispersion model (Draxler and Rolph, 2014) to trace possible trajectories that could have transported biomass-burning emissions from fires to the HGB area and the Houston East (CAMS 1) monitoring site. The first method initialized backward trajectories at varying altitudes from the Houston East (CAMS 1) monitoring site at the time of the one-hour ozone exceedance event to estimate their likely paths backward in time to their origins. These trajectories were compared to locations of known or likely fires identified by NOAA. The second method estimated forward trajectories from areas throughout the U.S. where extensive fire activity was detected during the week prior to the one-hour exceedance event using the HYSPLIT matrix option to determine whether emissions from these areas could have been transported to the HGB area. Third, a small-scale matrix was defined over the HGB area, and HYSPLIT backward trajectories were estimated to explore local-scale atmospheric behavior during the week prior to the event. Finally, forward trajectories were initialized from locations of fires identified by NOAA for each day of the week prior to the event and evaluated to determine if emissions from those fires were delivered to the HGB area and the Houston East (CAMS 1) monitoring site.

The first method revealed many backward trajectories that traveled over or near areas with substantial wildfire activity the week prior to the one-hour exceedance event before arriving at the location of the Houston East (CAMS 1) monitoring site. The trajectory analysis indicates that emissions of ozone or precursors from these fires were carried by prevailing winds to the HGB area. The second method identified two matrices of five that were tested where fire activity was

extensive, which could have provided ozone or precursors that were delivered to the HGB area. The third method identified a strong subsidence event over the HGB area beginning late August 24 or early August 25 and continuing through August 26, 2011 that transported air parcels from the upper troposphere, where long distance transport occurs, down into the mixing layer and near the surface at the Houston East monitor. The fourth method tracked forward trajectories from every detected fire in North America during the week prior to the exceedance event and found that many trajectories approached the HGB area and the Houston East (CAMS 1) monitor. The combination of these multiple approaches provides strong evidence that emissions from fires burning throughout the continent were transported to the HGB area at altitudes low enough to mix with local emissions and background ozone precursors in the ambient air and be detected by the surface monitoring network.

4.4.1 Trajectory Analysis 1 – Backward Trajectories from the Houston East (CAMS 1) Monitoring Site

The first trajectory analysis computed 168-hour, or seven-day, backward trajectories from the Houston East (CAMS 1) monitoring site on August 26, 2011 using the HYSPLIT model (Draxler and Rolph, 2013) available on-line from NOAA. Twenty trajectories were estimated using starting altitudes from 50 meters (m) to 4,500 m above ground level, including 50 m, 100 m, and 250 m to 4,500 m at 250 m increments. Output from HYSPLIT includes maps and coordinates of the vertices of the estimated trajectories at one-hour increments, as well as estimates of the altitude of the boundary layer, also called the mixing layer, at each vertex and other measures including altitude of the terrain, relative humidity, and solar radiation.

Vertices of estimated HYSPLIT backward trajectories are plotted in Figure 4-5: *Twenty HYSPLIT Backward Trajectories Originating at the Houston East (CAMS 1) Monitoring Site, August 26, 2011 at 17:00 UTC*. NOAA-detected fires for August 20 through 26, 2011 are shown as red triangles. Twenty trajectories were initialized at 50 m, 100 m, and then at 250 m increments (250 m through 4,500 m altitude) and run backward 168 hours (7 days), terminating on August 19, 2011 at 17:00. Dark blue circles indicate vertices that were within the mixing layer and below 1 km altitude; light blue circles are vertices within the mixing layer but above 1 km; grey circles are vertices below 1 km but above the mixing layer; and open (unshaded) circles are vertices above 1 km and above the mixing layer. Many of the trajectories, particularly those at high altitudes, originated over the Pacific Ocean on Saturday, August 20, 2011, traveled northeast over the Rocky Mountains region the next day (August 21, 2011), and began traveling east-southeast over the northern Great Plains the day after that (August 22,2011). The trajectories continued southeasterly over the central Mississippi Valley on August 23, 2011, though some began that day in the Pacific Northwest, encountered very high wind speeds, and were transported near the Mississippi Valley the same day. On August 24, 2011, most of these trajectories reversed direction and began heading southwest over the lower Mississippi Delta region, continued in a west-southwest or southwesterly direction across that region on August 25, 2011, and then terminated at the Houston East (CAMS 1) monitoring site on August 26, 2011. Other trajectories, notably those at much lower altitudes, originated in the Gulf of Mexico or over land in the southeastern U.S. These trajectories traveled much more slowly in a westerly direction before arriving at the Houston East (CAMS 1) monitoring site at 17:00 UTC on August 26, 2011.

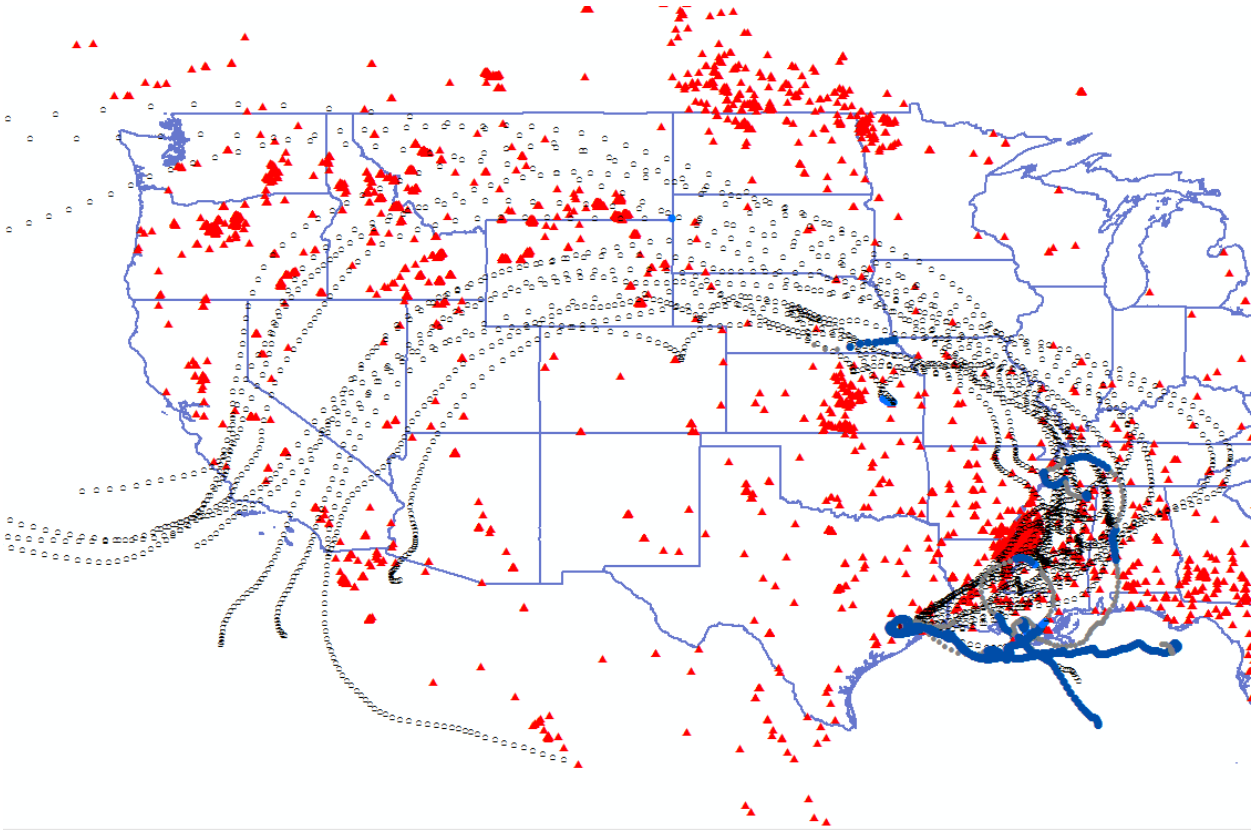
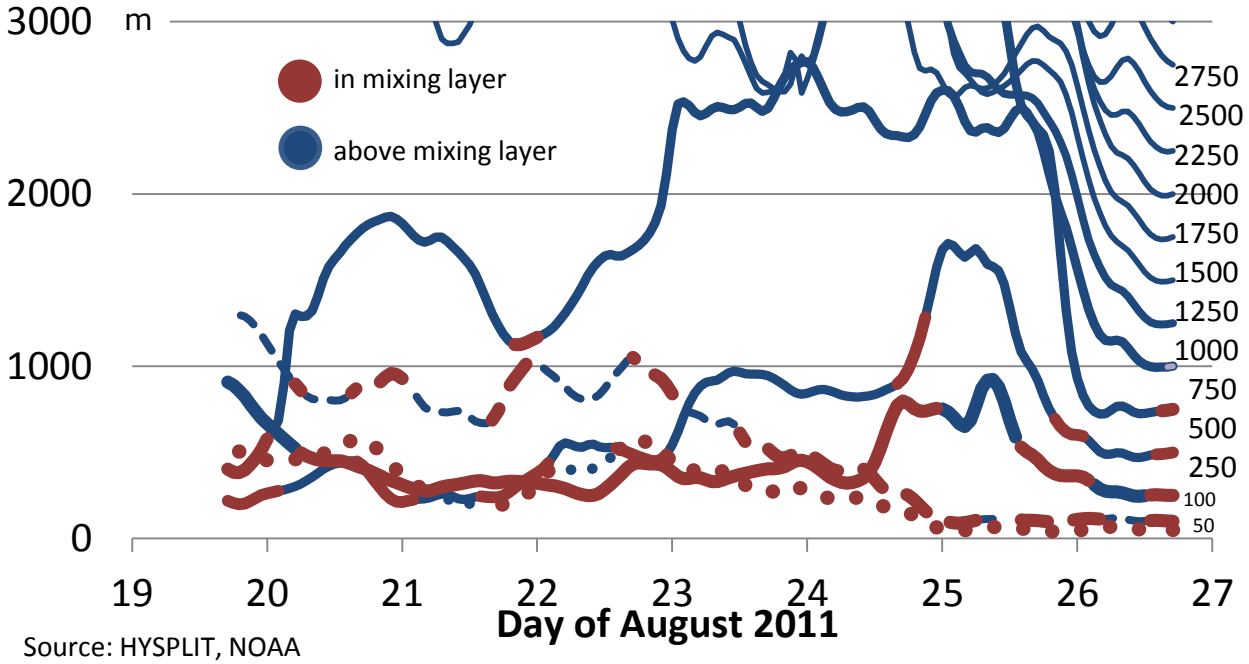


Figure 4-5: Twenty HYSPLIT Backward Trajectories Originating at the Houston East (CAMS 1) Monitoring Site, August 26, 2011 at 17:00 UTC

Figure 4-6: *Altitudes of HYSPLIT Backward Trajectories Originating at the Houston East (CAMS 1) Monitoring Site on August 26, 2011 at 17:00 UTC* shows altitudes of the 20 trajectories hour by hour, starting at the left where they began at 17:00 UTC on August 19, 2011 and following their altitudes until they arrived at the Houston East (CAMS 1) Monitoring Site at 17:00 UTC on August 26, 2011. From Figure 4-7: *Altitudes of HYSPLIT Backward Trajectories Originating at the Houston East (CAMS 1) Monitoring Site on August 26, 2011 at 17:00 UTC Shown on a Logarithmic Scale*, it can be noted that trajectories that terminated at the Houston East (CAMS 1) monitoring site at higher elevations generally also began seven days earlier at higher altitudes and did not descend below the boundary layer. However, several trajectories that terminated at the Houston East (CAMS 1) monitoring site at elevations below 2 km began seven days earlier at similar elevations below 2 km, as well, and passed into and out of the mixing layer at various points along the journey. Generally, these trajectories entered the mixing layer during the day, as the mixing layer expanded, then exited at night as it contracted. These trajectory paths suggest that it was possible that fire emissions could have been carried aloft from locations of fires to the HGB area and the Houston East (CAMS 1) monitoring site.

Note that estimated trajectories terminating at the Houston East (CAMS 1) monitoring site at 17:00 UTC at heights of 1 km and below (six total trajectories) all entered and exited the mixing layer numerous times during transit, except for the 50 m termination height trajectory, which resided entirely within the mixing layer during transit. All estimated trajectories up to 1 km terminated within the mixing layer when they reached the Houston East (CAMS 1) monitoring site. A sharp subsidence event late in the evening of August 25, 2011 brought air parcels from

altitudes above 2 km down below 1 km over the course of only 3 or 4 hours on the morning of August 26 and into the mixing layer only hours before the exceedance event at Houston East (CAMS 1). Many trajectories that were transported at altitudes above 3 km descended very sharply as well to altitudes below 2 km. All estimated trajectories that terminated at Houston East (CAMS 1) at 750 m and below (50 m, 100 m, 250 m, 500 m, and 750 m) originated at altitudes below the mixing layer several days previously, were lofted above the mixing layer, as high as 2,500 m in some cases, over August 23, 2011 through August 25,2011 and then descended into the mixing layer late on August 25, 2011.This result suggests that these trajectories rose and fell at many points while in transit offering numerous opportunities to entrain ozone and precursors from fires while in transit to the Houston East (CAMS 1) monitoring site.



Source: HYSPLIT, NOAA

Figure 4-6: Altitudes of HYSPLIT Backward Trajectories Originating at the Houston East (CAMS 1) Monitoring Site on August 26, 2011 at 17:00 UTC

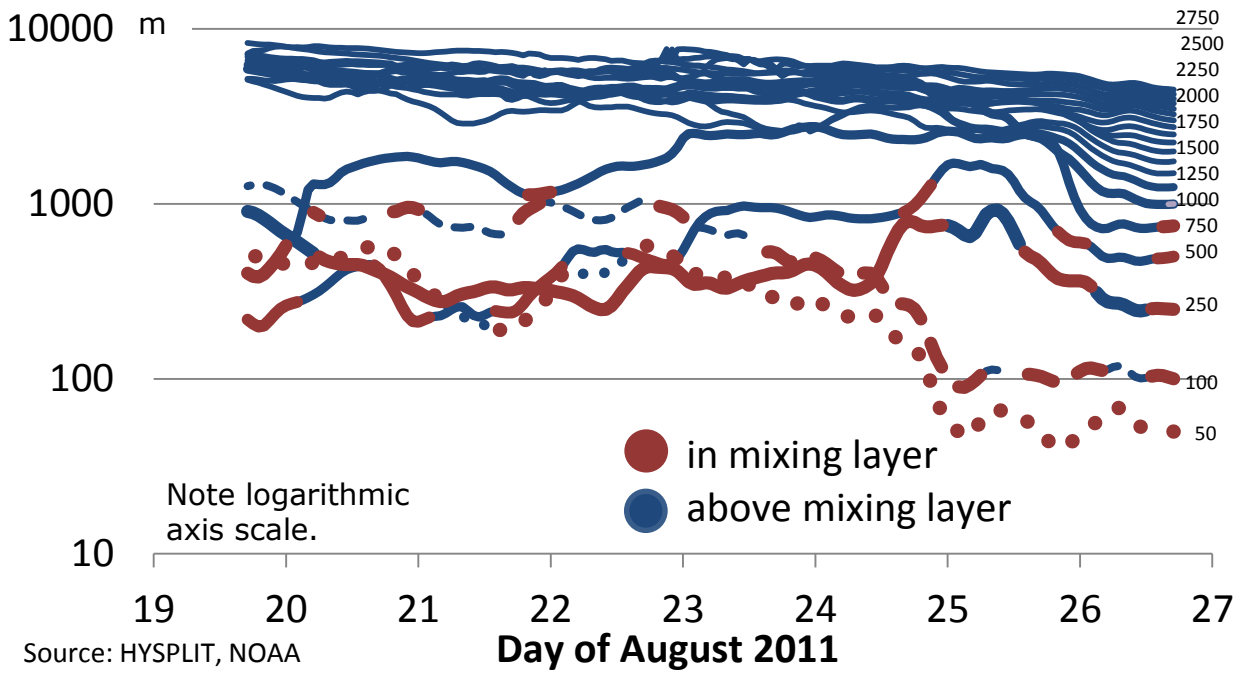


Figure 4-7: Altitudes of HYSPLIT Backward Trajectories Originating at the Houston East (CAMS 1) Monitoring Site on August 26, 2011 at 17:00 UTC Shown on a Logarithmic Scale

4.4.2 Trajectory Analysis 2 – HYSPLIT Matrix Forward Trajectories from Areas with Clusters of Fires

The HYSPLIT model offers a powerful option for performing trajectory analysis using a matrix or grid of starting locations. To assess the possibility that emissions from areas with active fires could have been transported to the HGB area, forward trajectories were computed using the matrix option in HYSPLIT. This option enables the user to compute trajectories for starting points arrayed in a grid with coordinates supplied by the user. In this way, a large number of trajectories can be computed simultaneously for an area of a specified size to determine whether trajectories originating from that area could have traveled to a specific location downwind.

Five matrices were defined for five source regions with large numbers of identified fires. These matrices are detailed in Table 4-2: *HYSPLIT Matrices Defined for Forward Trajectory Computations* and shown in Figure 4-8: *Map of Matrices Defined for Computing Forward Trajectories Using the HYSPLIT Matrix Option* . Matrix 1 covered Kansas, Oklahoma, and the northern part of Texas. Matrix 2 covered the Mississippi Delta region of Arkansas, Louisiana, Mississippi, and Tennessee, plus Alabama and parts of Georgia and other southeastern states. Matrix 3 covered the northern plains states of Minnesota, North Dakota, South Dakota, and parts of Iowa, Wisconsin, and Nebraska. Matrix 4 covered the northern Rocky Mountains states of Idaho, Montana, Wyoming, and parts of Nevada and Utah. Matrix 5 covered the Pacific Northwest including Oregon, Washington, and parts of California and Idaho.

The 84 hour forward trajectories, the maximum duration permitted by the HYSPLIT matrix option, were computed starting on August 23, 2011 at 5:00 UTC. Matrix number 2 was also run over 48 hours since it is much closer to the HGB area and emissions could have easily reached the Houston East (CAMS 1) monitoring site much sooner than 84 hours. Computed trajectories were then evaluated to determine if any (1) entered the mixing layer near a fire, and (2) passed

close enough to the Houston East (CAMS 1) monitoring site to have carried fire emissions to the monitor.

Table 4-2: HYSPLIT Matrices Defined for Forward Trajectory Computations

Matrix	Description	Duration (hrs)	Southwest Corner of Matrix		Northeast Corner of Matrix		Total Trajectories in Grid
			Lat (deg)	Lon (deg)	Lat (deg)	Lon (deg)	
1	OK/KS/TX	84	33º	-103º	40º	-94º	80
2	AR/LA/MS/AL/TN	84	28º	-95º	37º	-84º	120
2b	AR/LA/MS/AL/TN	48	28º	-95º	37º	-84º	120
3	MN/ND/SD/IA/WI	84	43º	-105º	50º	-91º	120
4	ID/MT/WY/NV/UT	84	41º	-118º	49º	-104º	135
5	OR/WA/CA/NV	84	41º	-125º	49º	-117º	81

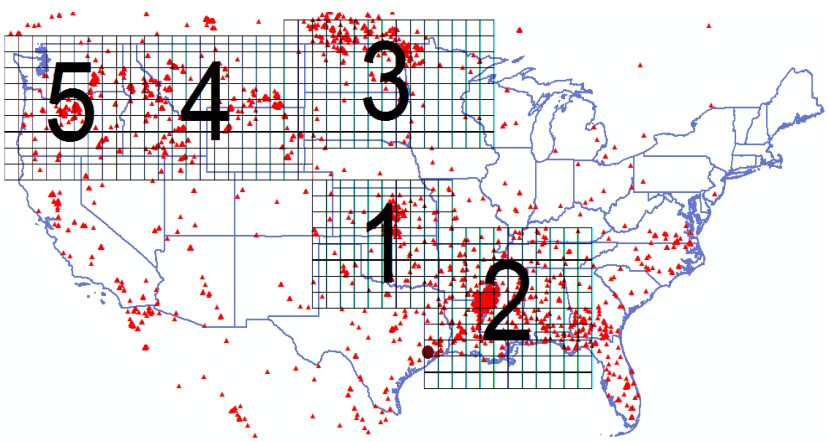


Figure 4-8: Map of Matrices Defined for Computing Forward Trajectories Using the HYSPLIT Matrix Option

Examination of forward trajectories computed for these matrices determined that fire emissions, which were not distinguished by type, originating in Matrices 3 and 4 likely did not travel to the HGB area. A couple of trajectories originating from Matrix 1 entered Texas and approached the HGB area while several trajectories originating from Matrices 2 and 5 approached the HGB area and the Houston East (CAMS 1) monitoring site on August 25 and August 26, 2011.

Trajectories originating from Matrix 1 at lower altitudes, e.g. 50 m and 100 m, were impacted by a clockwise rotation that carried them north then east then south. For other starting altitudes, most of the trajectories traveled northeast or east. Several started east then reversed direction and traveled southwest into Texas and other southeastern states. Two trajectories were seen to travel near the HGB area, and these originated in western Kansas and southeastern Colorado. The latter originated at an altitude of 1 km, dropped into the mixing layer in central Kansas, and passed through a cluster of fires in Kansas near several more fires in Arkansas and Louisiana before traveling within about 20 miles of the Houston East (CAMS 1) monitoring site. However, the ones that entered Texas did so on August 25, 2011, a day in advance of the exceedance event. Remnants of fire emissions in these air parcels could have lingered in the atmosphere another day and contributed to the exceedance event.

As shown inFigure 4-9: *84-Hour HYSPLIT Forward Trajectories from Matrix 2 at Selected Starting Altitudes Originating on August 23, 2011 at 5:00 UTC,* many trajectories originating from Matrix 2 were affected by a clockwise rotation pattern suggesting a synoptic weather pattern impacting the entire central plains region that week. Trajectories originating from the northern part of Matrix 2 continued to the northeast, and those to the south curved southwest into the Gulf of Mexico and Texas. Winds in the center of this matrix were variable. Several trajectories traveled into the HGB area and near the Houston East (CAMS 1) monitoring site, one at the 750 m starting height and one at 1 km.

For both Figure 4-9 and Figure 4-10: *84-Hour HYSPLIT Forward Trajectories from Matrix 2b at Selected Starting Altitudes Originating on August 24, 2011 at 17:00 UTC*, dark blue circles are coordinates that are below 1 km and in the mixing layer; light blue are above 1 km but in the mixing layer; grey are below 1 km but above the mixing layer; and open (unshaded) circles are above 1 km and above the mixing layer. Houston East is represented by the brown circle.

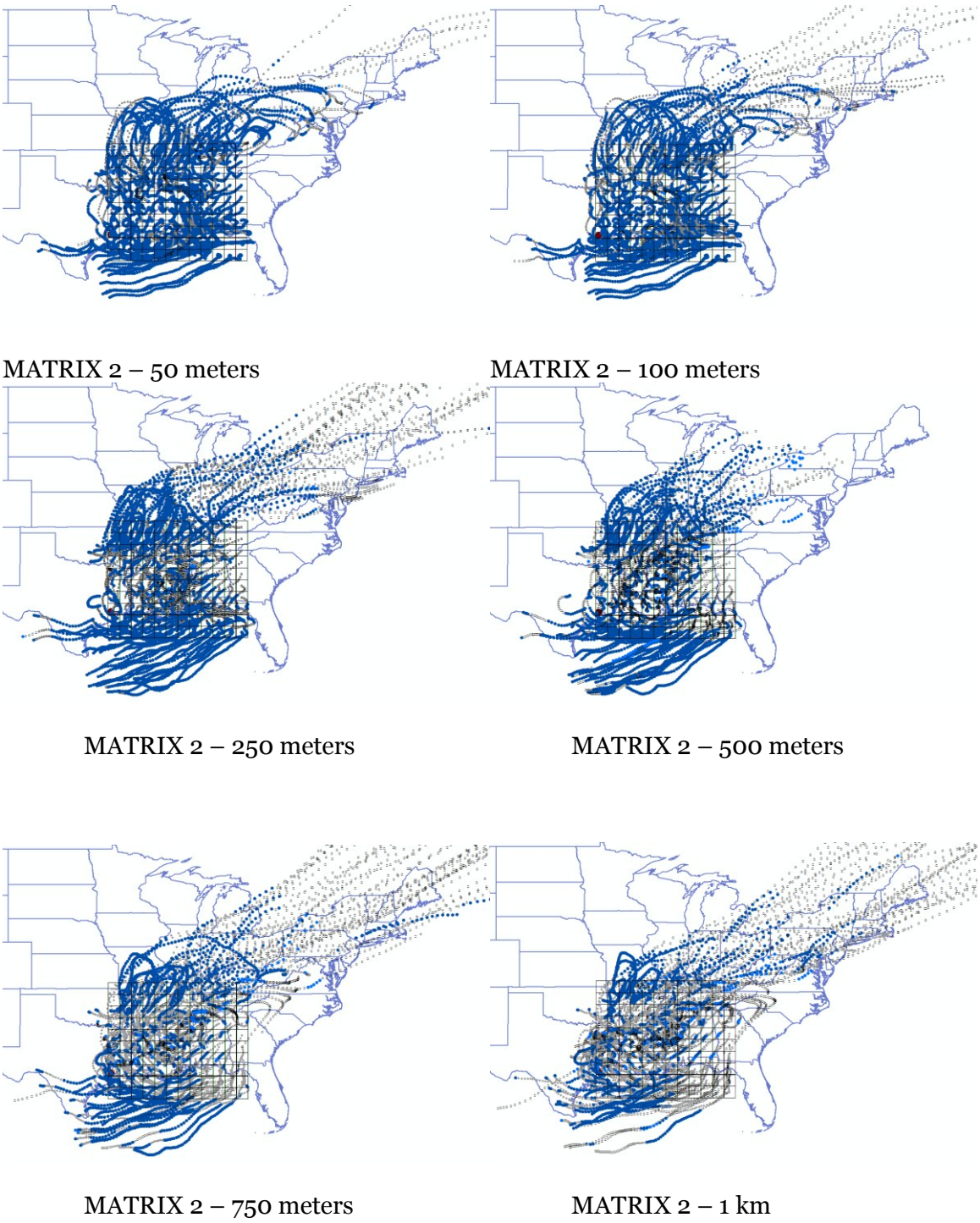
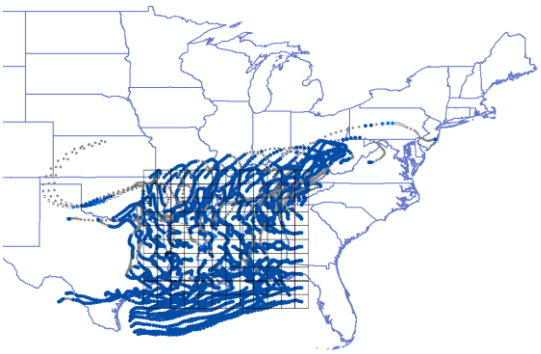


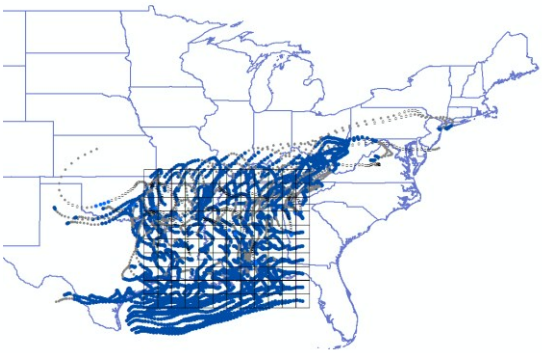
Figure 4-9: 84-Hour HYSPLIT Forward Trajectories from Matrix 2 at Selected Starting Altitudes Originating on August 23, 2011 at 5:00 UTC

Because Matrix 2 is in close proximity to the HGB area, HYSPLIT models for Matrix 2 were re-run with a shorter duration of 48 hours. Results of these models are presented as Matrix 2b. As shown in Figure 4-10, many trajectories originating from Matrix 2b (identical to Matrix 2 only of shorter duration) traveled to the HGB area and approached the Houston East (CAMS 1)

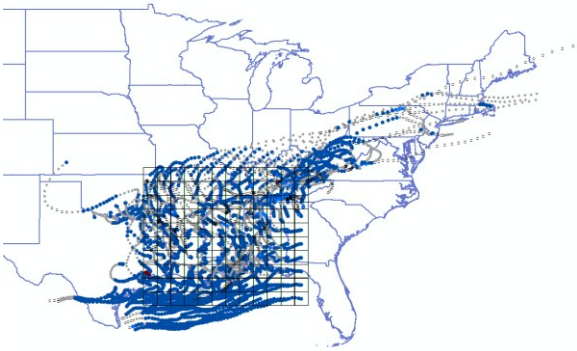
monitoring site, including seven at 250 m starting altitude, four at 750 m, and six at 1 km. Emissions from fires burning in this region on August 24 and August 25 were likely transported to the HGB area over the next 48 hours and contributed to the exceedance event at the Houston East (CAMS 1) monitoring site on August 26, 2011.



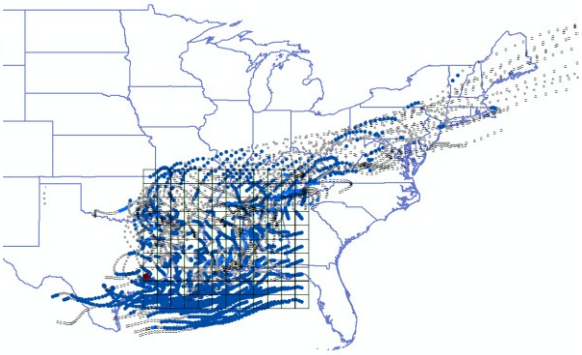
MATRIX 2b – 50 meters



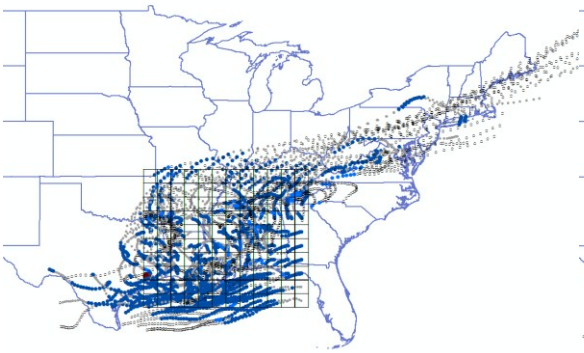
MATRIX 2b – 100 meters



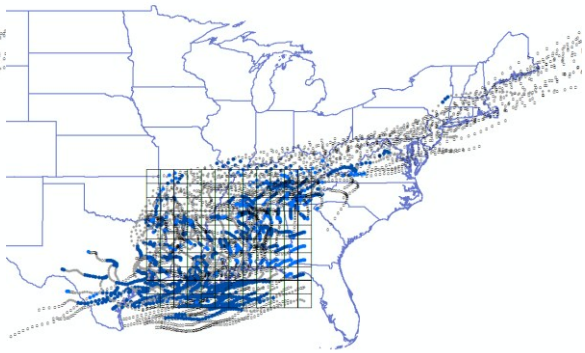
MATRIX 2b – 250 meters



MATRIX 2b – 500 meters



MATRIX 2b – 750 meters



MATRIX 2b – 1 km

Figure 4-10: 84-Hour HYSPLIT Forward Trajectories from Matrix 2b at Selected Starting Altitudes Originating on August 24, 2011 at 17:00 UTC

Most trajectories originating from Matrix 5 traveled northeast or south. None of the 84-hour trajectories reached Texas. However, because the HYSPLIT matrix option is limited to trajectories of 84 hours duration or less, this matrix analysis was limited. Analyses of forward trajectories from the locations of NOAA-detected fires presented below indicate that over longer durations, trajectories originating from the area of Matrix 5 do reach the HGB area and could have affected the Houston East (CAMS 1) monitoring site.

Details of specific trajectories from Matrix 1 and Matrix 2b that approached the HGB area and the Houston East (CAMS 1) monitoring site are presented in Figure 4-11: *Locations (Left Panels) and Altitudes (Right Panels) of HYSPLIT Forward Trajectories Passing Near the Houston East (CAMS 1) Monitoring Site on August 26, 2011*. Left panels in this figure are maps of Texas and/or the coast of the Gulf of Mexico. The dark red circle is the location of the Houston East (CAMS 1) monitoring site. Black squares are the grids defined for the HYSPLIT Matrix noted. Dark blue circles are trajectory vertices within the mixing layer below 1 km altitude; light blue circles are within the mixing layer above 1 km; grey circles are above the mixing layer but below 1 km; open (unshaded) circles are above the mixing layer and above 1 km. Right panels show altitude by day: red circles are trajectory vertices within the mixing layer; and grey squares are above the mixing layer. These trajectories are presented alongside their vertical profiles to show that they entered and exited the mixing layer at various points along their paths during which time they could have encountered fire emissions. Several trajectories terminated on August 26, 2011 within the mixing layer, which suggests an influence on surface ambient air quality. Trajectories arriving from the Gulf of Mexico experienced over night mixing heights under 2 km, whereas trajectories arriving from the east and northeast over Louisiana and Mississippi saw over night mixing heights up to 4 km. Along several trajectories terminating at Houston East (CAMS 1), HYSPLIT reports mixing heights as low as 10 m during night time hours on August 23 and 24, 2011 and as low as 50 m during night time hours on August 25 and 26, 2011.

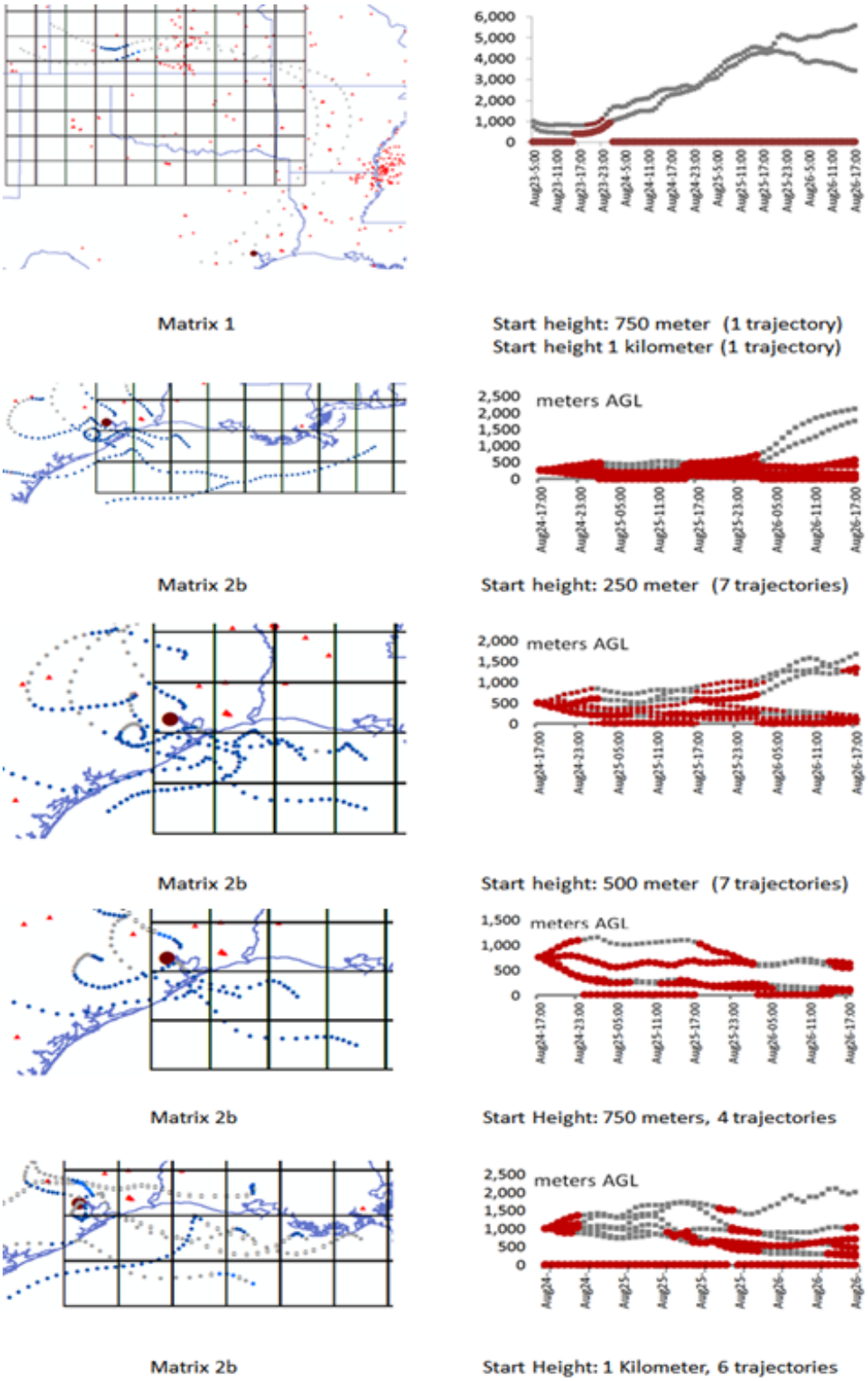


Figure 4-11: Locations (Left Panels) and Altitudes (Right Panels) of HYSPLIT Forward Trajectories Passing Near the Houston East (CAMS 1) Monitoring Site on August 26, 2011

4.4.3 Trajectory Analysis 3 – HYSPLIT Matrix 6

Previously, in Figure 4-6: *Altitudes of HYSPLIT Backward Trajectories Originating at the Houston East (CAMS 1) Monitoring Site on August 26, 2011 at 17:00 UTC*, an extreme subsidence event is evident during the later hours of August 25, 2011 and the morning hours of August 26, 2011. In meteorological terms, subsidence occurs when an air mass sinks or loses altitude, usually over a broad area. From the course of the HYSPLIT trajectories shown, it appears the event occurred over many meters of altitude in the atmosphere above 500 m, up to at least 3 km, with the sharpest downward motion occurring near 750 m altitude. This event could have brought transported emissions from active fires burning elsewhere in North America down to the surface where they contributed to ozone formation and the subsequent exceedance of the one-hour ozone NAAQS on August 26, 2011 as explained in Section 4.4.4: *Ozonesonde Anlaysis*.

From Figure 4-6, it appears the event began at lower altitudes in the afternoon hours of August 25, 2011 where the vertical slopes of the trajectories began their descent to lower altitudes. Later, in the late hours of August 25, 2011 and the early hours of August 26, 2011, higher altitude trajectories exhibit a sharp descent over a very brief period of only a few hours. The trajectory that terminates at the Houston East (CAMS 1) monitoring site at 750 m on August 26, 2011 began the day at nearly 2.5 km altitude and shows the steepest descent.

To investigate this phenomenon further, 84-hour HYSPLIT backward trajectories for termination heights from 50 m to 1,250 m were estimated using the matrix option for a set of matrix points in close proximity to the Houston East (CAMS 1) monitoring site. The definition of this matrix, termed Matrix 6, is presented in Table 4-3: *The Definition of HYSPLIT Matrix 6*, yielded 110 grid cells. Matrix 6 is defined over an area that is large enough to facilitate examination of the event over an area that covers a large portion of the urban area but uses a grid spacing that is small enough to observe smaller scale distinctions in the behavior and extent of the event. A map of the grid overlaid onto the HGB area is displayed in Figure 4-12: *Map of HYSPLIT Matrix 6 Overlaid on the HGB Area*.

Table 4-3: The Definition of HYSPLIT Matrix 6

Attribute	Latitude	Longitude
Southwest Corner	29.50º	-95.50º
Northwest Corner	30.00º	-95.00º
Grid Spacing	0.05º	0.05º
Houston East	29.7679707º	-95.2205867º

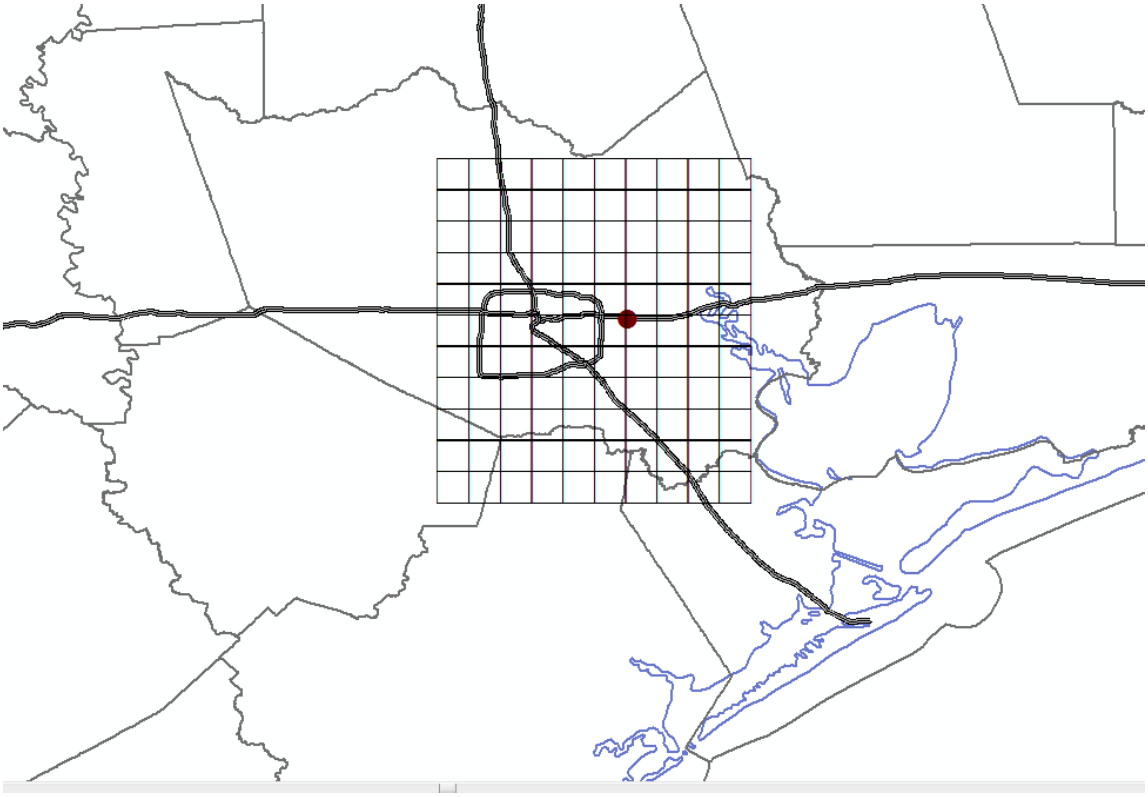


Figure 4-12: Map of HYSPLIT Matrix 6 Overlaid on the HGB Area

HYSPLIT backward trajectories estimated from Matrix 6 are presented in the following seven figures. Trajectory coordinates that were resident in the mixing layer are colored blue and those above the mixing layer are colored red. Trajectory coordinates for trajectories terminating at the four matrix cells closest to the Houston East (CAMS 1) monitoring site are colored green. For Matrix 6 termination heights of 50 m and 100 m, shown in Figure 4-13: *Altitudes of Estimated HYSPLIT Backward Trajectories for Matrix 6 Terminating at 50 m at Houston East on August 26, 2011 at 17:00 UTC* and Figure 4-14: *Altitudes of Estimated HYSPLIT Backward Trajectories for Matrix 6 Terminating at 100 m at Houston East on August 26, 2011 at 17:00 UTC,* no subsidence is apparent over August 25, 2011 and August 26, 2011 as these trajectories traverse a relatively stable altitude over those two days. However, prior to August 25, 2011 both sets of trajectories descended from much higher altitudes beginning on August 23, 2011 and continuing on August 24, 2011. For these two figures and the following five, trajectory coordinates resident in the mixing layer are blue, while those above the mixing layer are red. Trajectories for the four matrix points nearest the Houston East (CAMS 1) monitoring site are green.

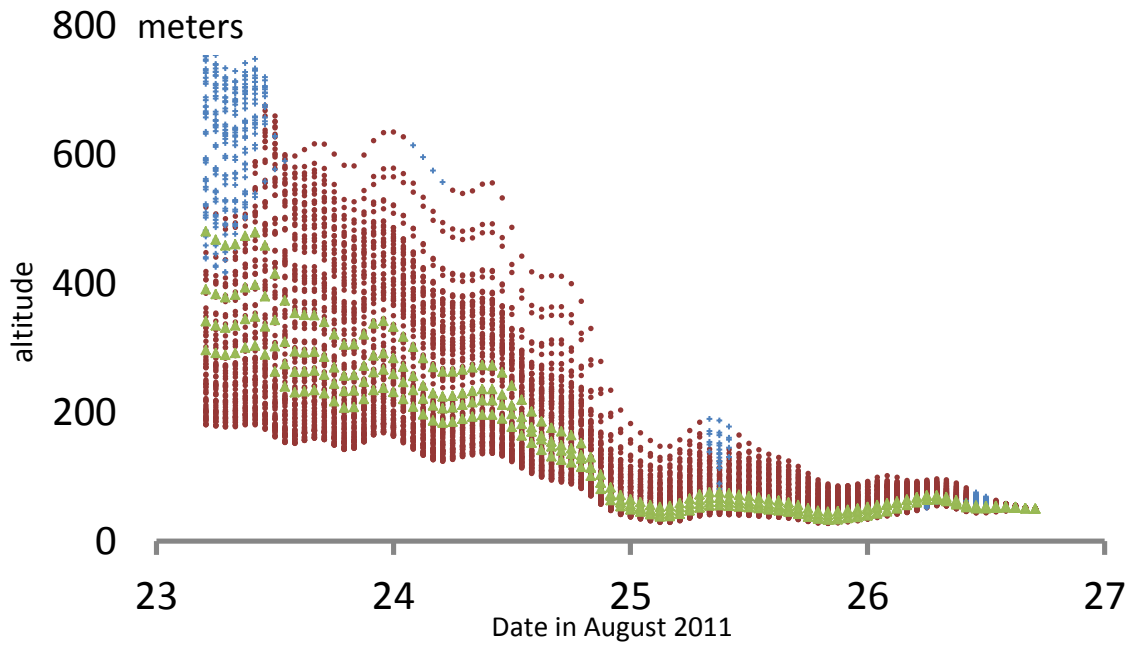


Figure 4-13: Altitudes of Estimated HYSPLIT Backward Trajectories for Matrix 6 Terminating at 50 m at Houston East on August 26, 2011 at 17:00 UTC

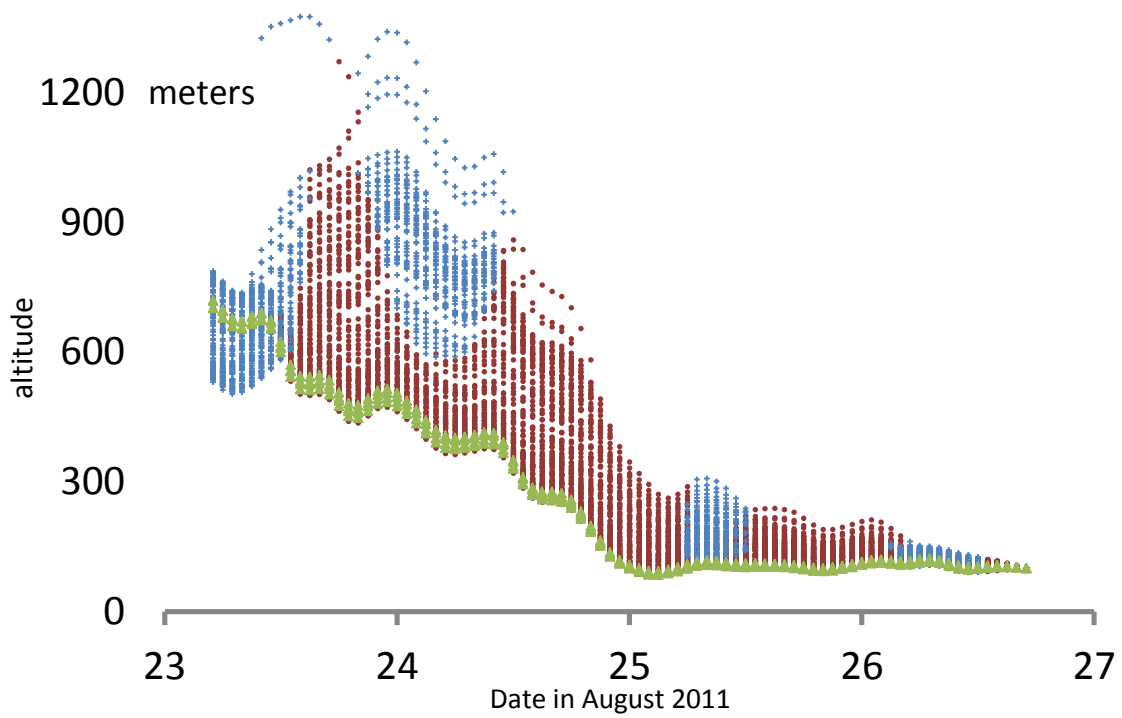


Figure 4-14: Altitudes of Estimated HYSPLIT Backward Trajectories for Matrix 6 Terminating at 100 m at Houston East on August 26, 2011 at 17:00 UTC

For the Matrix 6 termination height of 250 m, shown in Figure 4-15: *Altitudes of Estimated HYSPLIT Backward Trajectories for Matrix 6 Terminating at 250 m at the Houston East (CAMS 1) Monitoring Site on August 26, 2011 at 17:00 UTC*, the extreme subsidence event beginning on August 25, 2011 becomes apparent. Most of these trajectories began at lower altitudes on August 23, 2011 within the mixing layer, and then ascended above the mixing layer throughout August 24, 2011 and early August 25, 2011. Beginning about mid-day on August 25, 2011, these trajectories all began a sharp descent, which stabilized early on August 26, 2011. This finding indicates that air parcels over the HGB area just one or two days prior to the exceedance event were transported down near the surface. Air containing fire emissions transported to the HGB area by the long-range trajectories shown earlier would have been subject to this vertical transport upon arrival in the HGB area the day before and early on the day of the exceedance event.

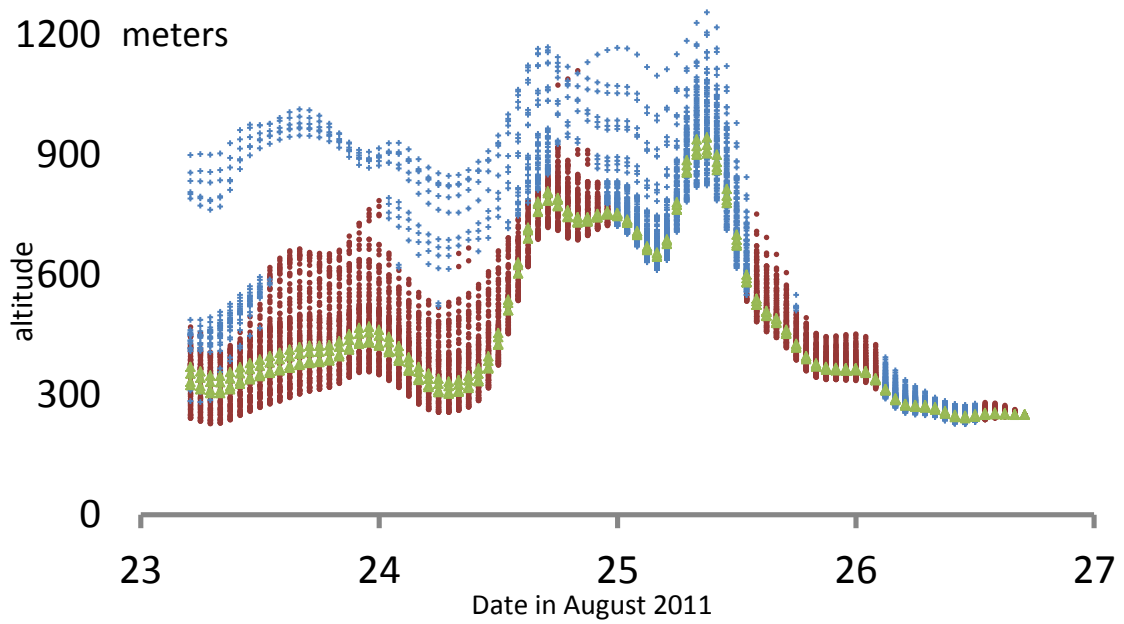


Figure 4-15: Altitudes of Estimated HYSPLIT Backward Trajectories for Matrix 6 Terminating at 250 m at the Houston East (CAMS 1) Monitoring Site on August 26, 2011 at 17:00 UTC

For the Matrix 6 termination height of 500 m, shown in Figure 4-16: *Altitudes of Estimated HYSPLIT Backward Trajectories for Matrix 6 Terminating at 500 m at the Houston East (CAMS 1) Monitoring Site on August 26, 2011 at 17:00 UTC,* the trajectories began on August 23, 2011 from altitudes ranging from 400 m to above 2 km. Most of these trajectories remained above the mixing layer throughout August 23, 24, and 25, 2011. Beginning very early on August 25, 2011, these trajectories began a sharp descent that continued throughout the day. Many of these trajectories entered the mixing layer late on August 25, 2011. By the early hours of August 26, 2011, these trajectories stabilized at around 400 m to 500 m, rising above the mixing layer in the early hours of that day and then returning to the mixing layer just a few hours before the exceedance event occurred.

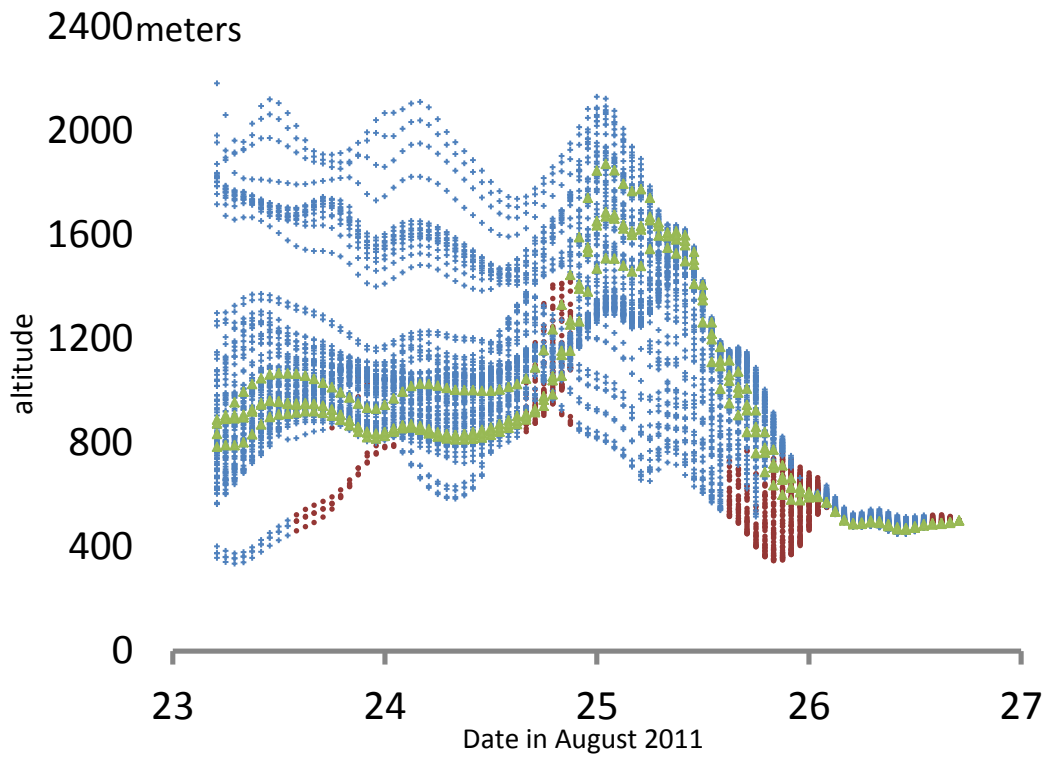


Figure 4-16: Altitudes of Estimated HYSPLIT Backward Trajectories for Matrix 6 Terminating at 500 m at the Houston East (CAMS 1) Monitoring Site on August 26, 2011 at 17:00 UTC

The altitude changes revealed for the Matrix 6 termination heights of 750 m, shown in Figure 4-17: *Altitudes of Estimated HYSPLIT Backward Trajectories for Matrix 6 Terminating at 750 m at the Houston East (CAMS 1) Monitoring Site on August 26, 2011 at 17:00 UTC,* are very informative. These trajectories began on August 23, 2011 at a very wide range of altitudes, from about 140 m to over 5 km, though all were above the mixed layer. Over the next two days, lower altitude trajectories ascended in the atmosphere passing into and out of the mixing layer. Higher altitude trajectories descended somewhat. All trajectories began a rapid descent late in the evening of August 25, 2011, some into the mixing layer, and converged by early August 26, 2011 to end at 750 m, within the mixing layer. Therefore, emissions transported into the area aloft (up to 3 km) were brought down into the layer that could mix ozone and ozone precursors with air measured by the monitor at the time the exceedance was monitored.

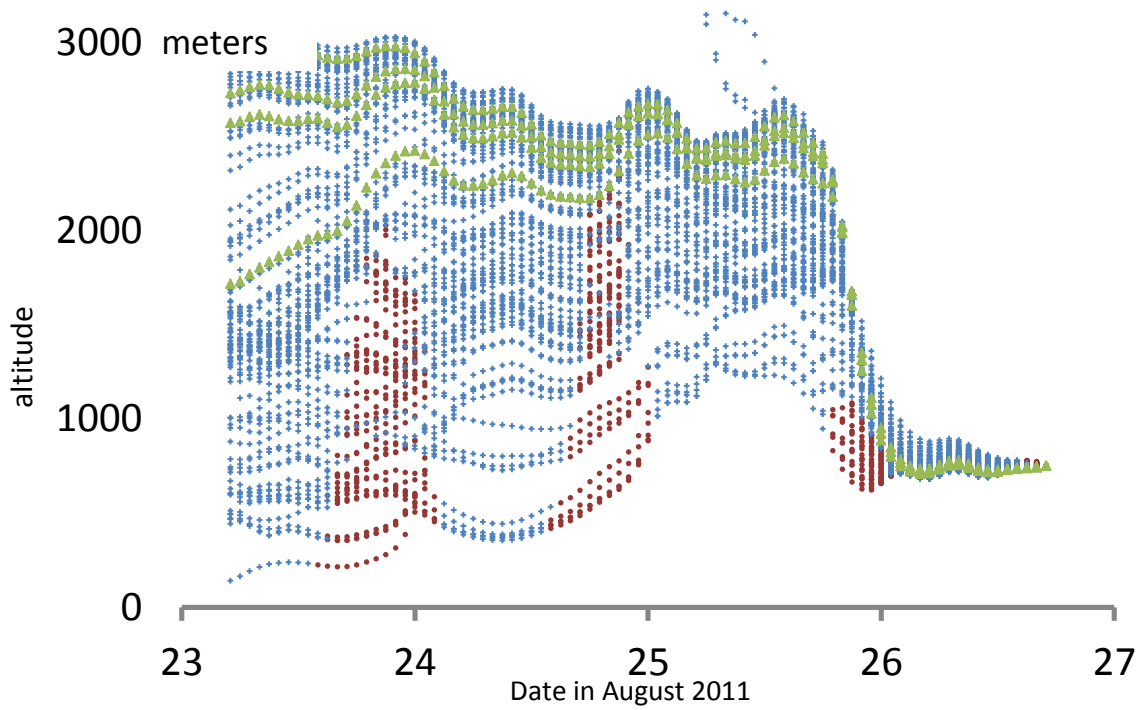


Figure 4-17: Altitudes of Estimated HYSPLIT Backward Trajectories for Matrix 6 Terminating at 750 m at the Houston East (CAMS 1) Monitoring Site on August 26, 2011 at 17:00 UTC

4.4.4 Ozonesonde Analysis

Weather balloons with ozone-measuring instruments are periodically launched in the HGB area and elsewhere around Texas. These balloons, termed "ozonesondes," "radiosondes," or just "sondes," sample the atmosphere and radio these measurements to ground-based receivers providing nearly continuous measurement of characteristics of the atmosphere, including ozone concentrations, at different altitudes as the balloons ascend. These measurements provide details of the meteorology of the upper atmosphere, which are not obtainable with ground-based sensors, as well as showing the presence of atmospheric layers containing greater or lesser concentrations of ozone. Launches conducted for the TCEQ are intended to sample when

meteorological conditions suggest imminent arrival of synoptic weather systems that could be transporting elevated concentrations of ozone or precursors in the upper atmosphere.

Information derived from these launches provides additional weight of evidence to support there was transport of elevated ozone and precursors from long distances during August 2011. While no launch was performed on August 26, 2011, launches were conducted on August 19, 2011, August 27, 2011, and August 29, 2011. Radiosondes containing ozone instruments were released from the campus of the University of Houston, located about nine miles west of the Houston East (CAMS 1) monitoring site. These launch dates were selected in order to sample synoptic, or large scale, weather systems potentially delivering air parcels containing elevated concentrations of ozone and precursors into the HGB area. Decisions to launch on these days were made independent of the observation of elevated ozone at the Houston East (CAMS 1) monitoring site but were made based on forecasts of synoptic weather patterns over North America, southeast Texas, and the HGB area. Ozone concentrations measured at the surface of the location of the launch ranged from 57 ppb to 136 ppb on the three days. Ozone concentrations at upper elevations were higher, substantially higher in two cases, indicating air parcels in the upper atmosphere contained high concentrations of ozone. In particular, August 29, 2011 was impacted by the same fires and weather pattern as August 26, 2011 and has ozone measurements aloft of 153 ppb. This coupled with the back trajectory evidence showing that there was some mixing between altitudes of up to 3 km and the boundary layer on or just prior to the August 26, 2011 exceptional event is supportive of long range transport of elevated ozone. Table 4-4: *Ozone Concentrations (ppb) at the Surface and Peak Ozone Concentrations (ppb) in the Lower Troposphere (Measured by Ozonesondes)* provides these measurements.

Table 4-4: Ozone Concentrations (ppb) at the Surface and Peak Ozone Concentrations (ppb) in the Lower Troposphere (Measured by Ozonesondes)

Date	Ozone at Surface (ppb)	Peak Ozone in Troposphere (ppb)	Altitude of Peak Ozone (km)
August 19, 2011	57	84	1.887
August 27, 2011	89	95	0.927
August 29, 2011	136	153	2.600

Figure 4-18: *Ozone Concentrations Measured by Ozonesondes Launched from University of Houston Campus, August 19, August 27, and August 29, 2011, Below 20 km Altitude* shows ozone concentrations as the balloons rose through the atmosphere from ground level (0.1 km altitude) to 20 km altitude. Figure 4-19: *Ozone Concentrations Measured by Ozonesondes Launched from University of Houston Campus, August 19, August 27, and August 29, 2011, Below 4 km Altitude* shows the same information for measurements below 4 km to facilitate closer inspection of the lower ozone concentrations observed in the lower atmosphere. Above about 15 km altitude, ozonesondes encounter the lower boundary of the stratospheric ozone layer, which contains exceptionally high concentrations of ozone compared to surface concentrations. While ozone from this layer can be transported downward and impact ozone concentrations at lower altitudes (Jacob, 1992), this section is focused on ozone transported in atmospheric layers at lower altitudes, that is, those below 15 km.

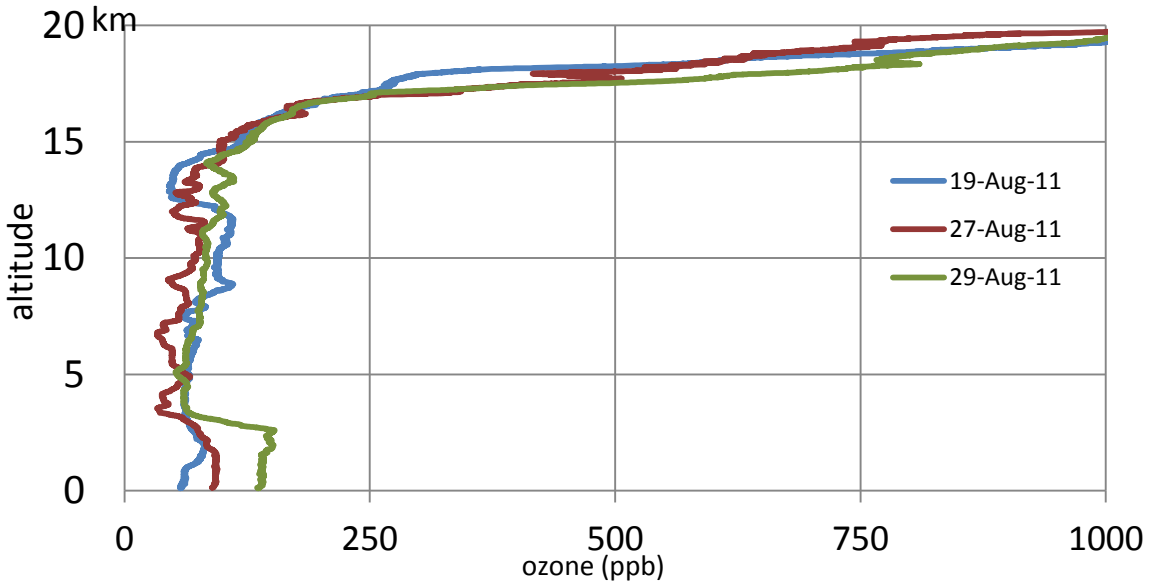


Figure 4-18: Ozone Concentrations Measured by Ozonesondes Launched from University of Houston Campus, August 19, August 27, and August 29, 2011, Below 20 km Altitude

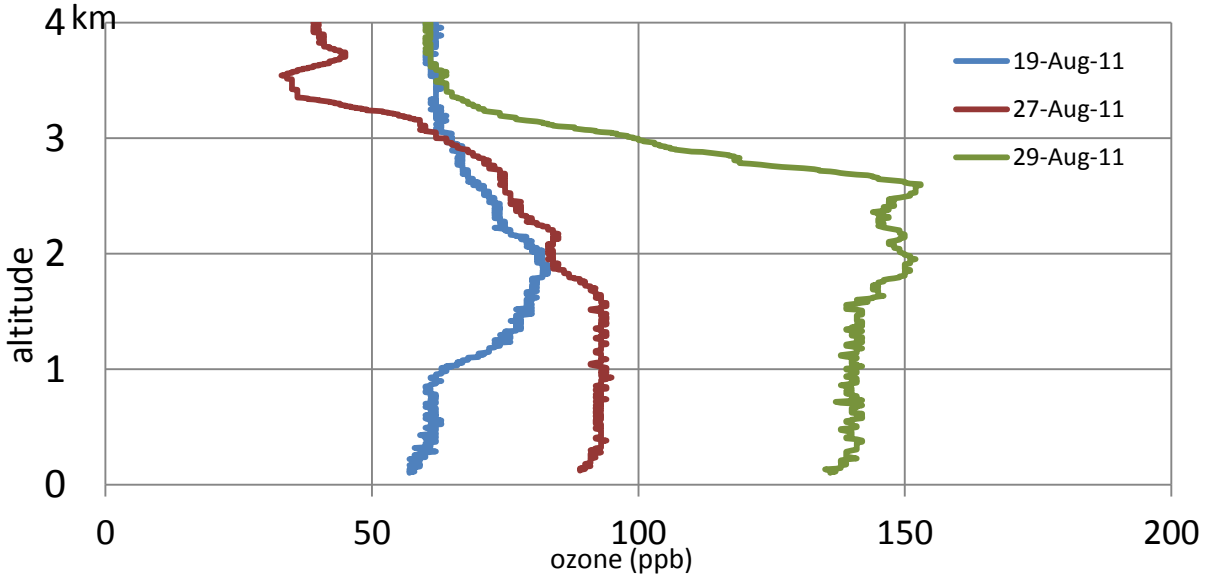


Figure 4-19: Ozone Concentrations Measured by Ozonesondes Launched from University of Houston Campus, August 19, August 27, and August 29, 2011, Below 4 km Altitude

Figures 4-18 and 4-19 show that ozone concentrations at the surface are slightly lower than ozone concentrations only a few hundred meters aloft. Above that, up to about 1 to 1.5 km, ozone concentrations are roughly constant. On August 19, 2011, ozone concentrations began increasing sharply at a point just below 1 km altitude, from about 60 ppb up to 84 ppb at about 1.9 km. On both August 27, 2011 and August 29, 2011, ozone concentrations were nearly constant from ground level up to roughly 1.5 km altitude, at about 90 ppb and 140 ppb, respectively. On August

27, 2011, ozone concentrations decreased from about 90 ppb with increasing altitude above 1.5 km, falling to around 30 ppb at 3.5 km altitude. On August 29, 2011, ozone concentrations increased up to about 2 km altitude by 10 ppb, varied or fell up to about 2.5 km altitude, then began falling to about 60 ppb by about 3.5 km altitude. On both the later dates, ozone concentrations fell by about 40 ppb on August 27, 2011 and about 90 ppb on August 29, 2011 in atmospheric layers above about 2.5 km altitude. On August 19, 2011, however, a 2 km thick layer of elevated ozone with concentrations reaching up to 84 ppb is evident between 1 and 3 km altitude. In all cases, ozone concentrations above about 3 km altitude were much lower than ozone concentrations between about 1 and 3 km altitude.

These findings suggest that there are layers of air in the upper atmosphere that contain elevated concentrations of ozone, in some cases substantially elevated, compared to ozone measured at the surface. Elevated concentrations of ozone reside in layers just above the surface layer. In two cases, August 19, 2011 and August 29, 2011, other layers at higher altitudes contained parcels with even higher ozone concentrations exceeding 150 ppb on August 29, 2011. These layers of elevated ozone are a possible mechanism by which parcels of air containing elevated ozone, and possibly ozone precursors, are transported from distant sources (EPA, 1998; Brock et al., 2004; Chin et al., 2007; Lin et al., 2012). These parcels were observed above the HGB area one week prior to the August 26, 2011 one-hour ozone exceedance event and one and three days after.

The pattern of elevated ozone aloft corresponding with arrival of synoptic weather systems is observed at every launch location in the state. Currently, ozonesonde launches are conducted periodically from Houston, Beaumont, and Idabell, Oklahoma, at a location just north of the Red River in southeastern Oklahoma. In prior years, launches have been conducted from other locations around the HGB area. Figure 4-20*: Average Ozone Concentrations (ppb) in 1 km Layers of the Atmosphere* shows average ozone concentrations across all launches at a location in 1 km layers, up to 10 km altitude, measured at various locations. In the majority of cases, it is clear that ozone concentrations aloft are elevated above those at or near ground level. The plots for each location show higher ozone concentrations aloft with noticeable notches where ozone is particularly elevated in certain layers. Whereas ozone concentrations in the lowest layer range from 42 to 65 ppb, on average depending on launch location, from 9 to 10 km altitude ozone concentrations range from 59 to 77 ppb, on average. Ozonesonde analysis supports the finding that ozone concentrations can be much higher at higher altitude than at the surface, that this ozone can be transported in air parcels by synoptic weather systems, and that under the appropriate conditions, such as a subsidence event, this ozone can be brought down to the lower atmosphere to affect ozone concentrations measured by the surface monitoring network.

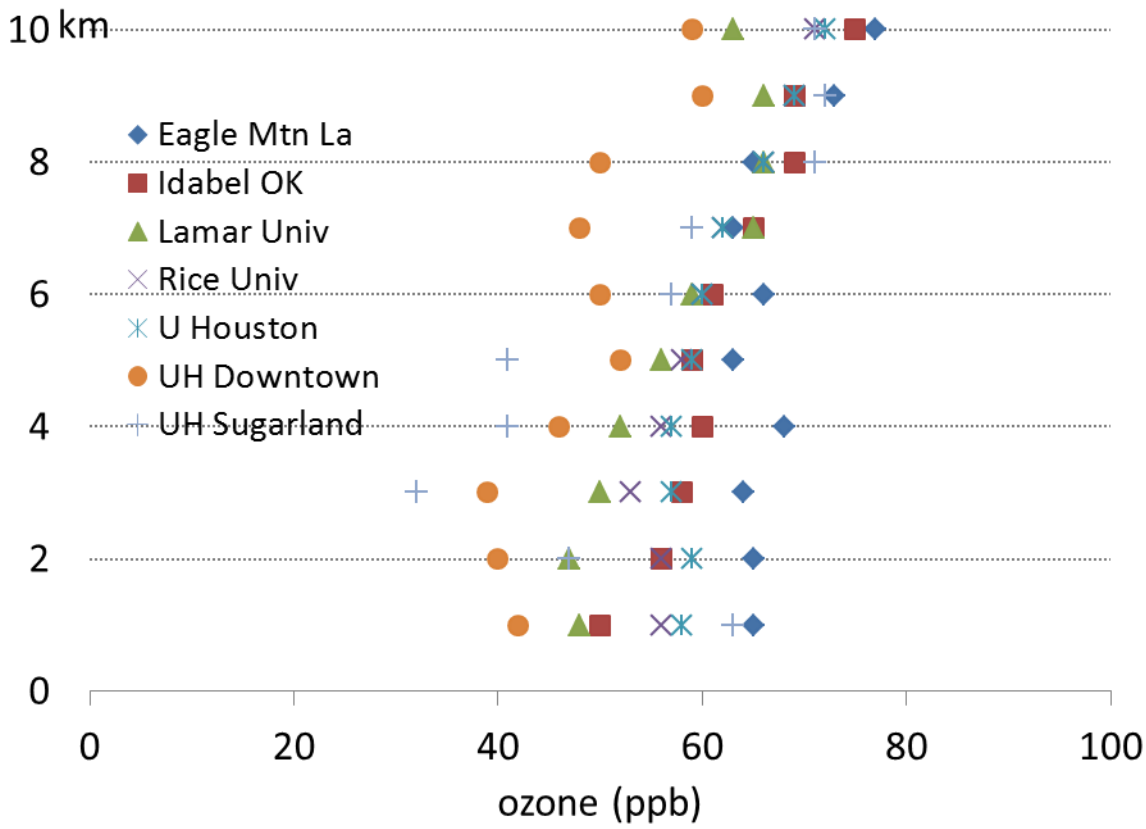


Figure 4-20: Average Ozone Concentrations (ppb) in 1 km Layers of the Atmosphere

4.4.5 Uncertainties

Although locations of identified fires and HYSPLIT model inputs and outputs are reported to very high precision, there are still a number of uncertainties in the computations and results obtained from the methods presented above. Some of these uncertainties are briefly discussed below. The HYSPLIT model estimates trajectory pathways and reports coordinates of these trajectories at one-hour increments. However, the HYSPLIT model does not report confidence bounds or standard errors on these coordinate estimates. Because HYSPLIT uses the 40 km Eta Data Assimilation System (EDAS) there may be errors in the estimates of the hourly coordinates. Further, these errors could be compounded by the longer the duration of a trajectory.

HYSPLIT documentation available at: http://ready.arl.noaa.gov/edas40.php, notes that to create the input EDAS data set "48 km data are interpolated to a 40 km, Lambert Conformal Grid, covering the continental United States." This interpolation could introduce a source of uncertainty of unknown magnitude due to averaging and smoothing inherent in an interpolation procedure.

Uncertainties also could arise in conversion among projection systems in geographic information systems used to analyze and interpret model results. Different geographic projections handle different aspects of conversion with greater or less precision, depending on the intended purpose of the system. The HYSPLIT model and the WFABBA fire detection and

identification system may use different coordinate projection systems when computing and reporting latitudes and longitudes.

Finally, the HYSPLIT model provides estimates of the mixing layer height to an unknown level of accuracy. The true boundary layer could be higher or lower than these estimates, which could affect determinations of whether or not fire emissions were mixed or lofted above the boundary layer and transported.

Even with the uncertainties, the tools and procedures used in this analysis are quite sophisticated and provide substantial evidence suggestive of the impact of fire emissions on ozone concentrations in the HGB area.

4.5 GOES SATELLITE IMAGERY

In addition to monitoring data, the TCEQ has made extensive use of satellite imagery in its analysis. The NOAA satellite program includes a number of different satellite platforms. One of the most useful satellite series is the GOES satellite program that provides nearly continuous monitoring and imagery of the western hemisphere. In addition to the many meteorological parameters they measure, GOES satellites also detect several airborne pollutants such as smoke and dust.

In this demonstration, the TCEQ analyzed GOES imagery for August 24, 2011 through August 26, 2011 supplemented by written descriptions of GOES imagery published by NOAA. The narrative and imagery published by NOAA provides independent evidence that smoke from the northwestern and southeastern U.S. was transported to the Texas Gulf Coast. On August 24, 2011, the afternoon narrative issued by NOAA at 18:14 UTC read in part:

> "...Montana/Wyoming through Northern/Central Plains to Midwest/Great Lakes region: An expansive area of aerosol composed of a mixture of remnant smoke and elevated dust particles from eastern Montana covered much of the northern U.S. this morning. The mixture stretched from Montana/Wyoming southeastward as far as Oklahoma/northeast Texas/Arkansas and as far east as the western Great Lakes, Ohio, and Kentucky. The remnant smoke that makes up a large part of this aerosol mixture has mostly originated from wildfires burning in the Northwestern U.S.; with fires in Montana, Wyoming, and Idaho contributing the most.
>
> Gulf Coast:
> Aerosol seen this morning along the Gulf is believed to be a mixture of light smoke, haze, and possibly other unknown aerosols. Fires along the Lower Mississippi River Valley and in the rest of the Southeast U.S., including a large smoke producing fire in southern Georgia, are the likely source points for this light smoke..." (Dept. of Commerce, NOAA, August 24, 2011 18:14 UTC)

Figure 4-21: *GOES Imagery on August 24, 2011 (22:08 UTC)* shows a GOES image focused on East Texas and the southern U.S. taken later that same afternoon. The image clearly shows (in the circled areas) the smoke from the northwestern and southeastern U.S. described by NOAA.

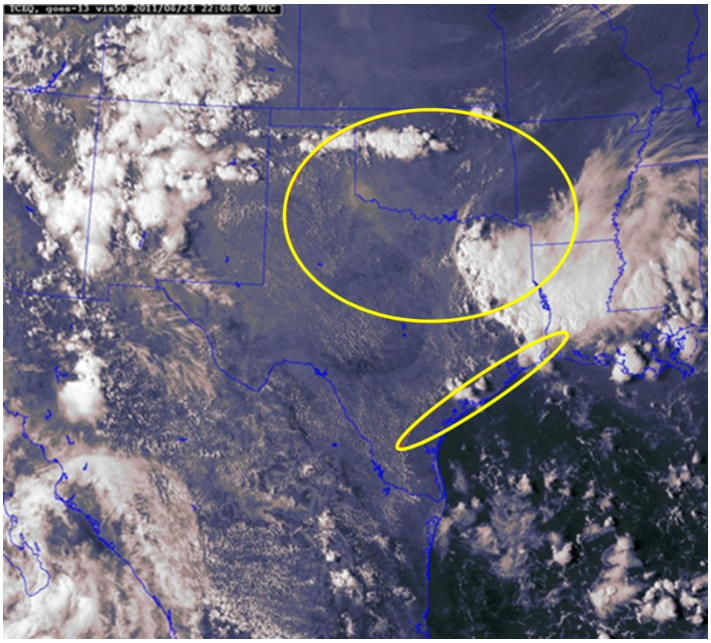


Figure 4-21: GOES Imagery on August 24, 2011 (22:08 UTC)

Figure 4-22: *GOES Imagery on August 25, 2011 (22:08 UTC)* shows more convincing evidence of smoke in Texas. The NOAA narrative for August 25, 2011 at 15:22 UTC paints a similar picture:

> "…Montana/Wyoming through Northern/Central Plains to Midwest region:
> Large area of remnant smoke plume extends from southeastern Saskatchewan southward into southwest Texas and portions of northeastern Mexico. Plume is seen extending as far east to central Kentucky, western Tennessee and northern Mississippi. However since GOES WEST satellite does not allow for viewing any further east and sun angle is not ideal for thin smoke detection using GOES East it is likely that light smoke extends across portions of southeast U.S. but cannot be seen in morning satellite imagery. Source of smoke plume is mostly from several wildfires that have been burning for days across Montana, Idaho, and Wyoming…"

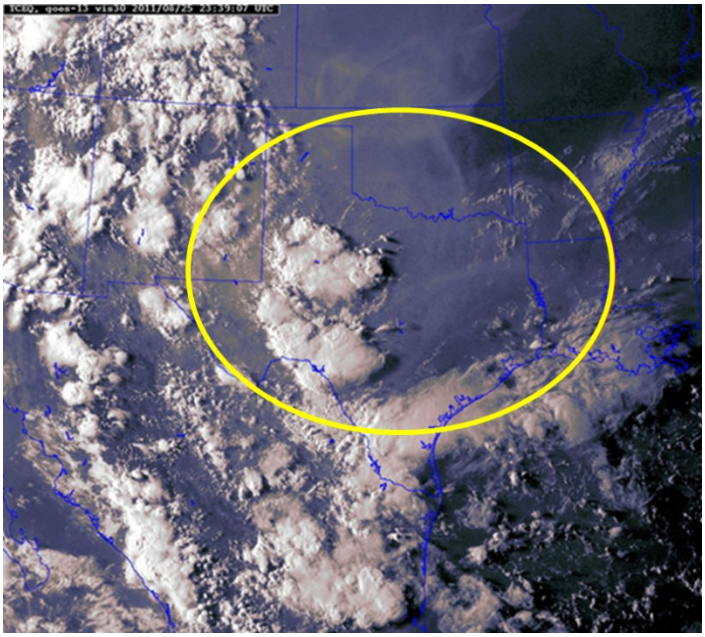


Figure 4-22: GOES Imagery on August 25, 2011 (22:08 UTC)

On August 26, 2011, NOAA issued a narrative at 15:15 UTC and made note of the heightened levels of smoke blanketing Texas and the southern plains:

> "… Southcentral U.S.:
> A ridge of high pressure over NE TX continues to hold smoke from emissions earlier this week from the fires in ID/MT and WY. This smoke is thin with small linear shaped pockets/strands of moderate smoke covering all of KS, OK, TX, LA and NM with portions of smoke affecting SW AR, and SW MS and the coastal Gulf of Mexico from Brownsville, TX over to Mobile, AL. Smoke over SE KS/E OK/SW AR and LA is moving SEward into the Gulf, while influence from the upper level ridge is moving smoke in TX, W OK, W KS due south into Old Mexico and southwestward across NM starting to move into SE AZ…"

Figure 4-23: *GOES Imagery on August 26, 2011 (21:08 UTC)* shows these heightened smoke levels over Texas and the HGB area.

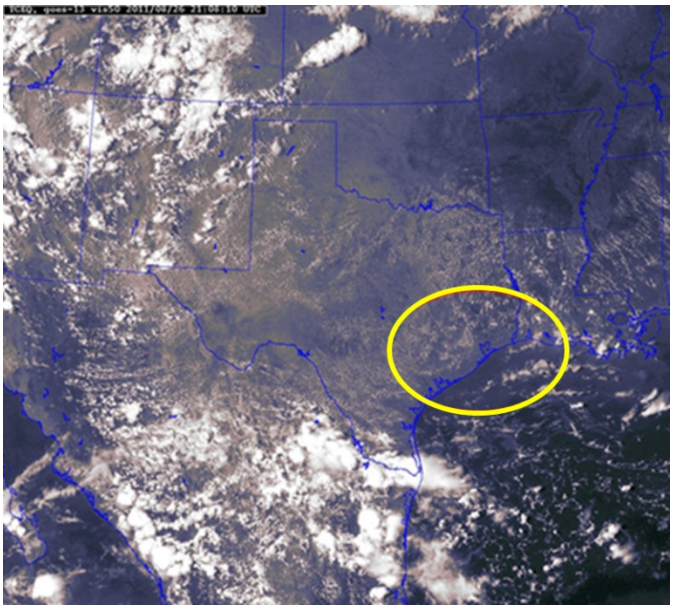


Figure 4-23: GOES Imagery on August 26, 2011 (21:08 UTC)

4.6 SATELLITE AEROSOL OPTICAL DEPTH IMAGES WITH HYSPLIT BACKWARD TRAJECTORIES

Wildfires produce aerosols, which are solid particles or droplets of liquid suspended in the air. Common aerosols include smoke, dust, and clouds. These aerosols can be detected by satellites and analyzed using satellite imagery. The MODIS (Moderate Resolution Imaging Spectroradiometer) Aqua satellite (modis.gsfc.nasa.gov), launched and monitored by the National Aeronautics and Space Administration (NASA), is equipped with instruments to measure aerosol optical depth (AOD), a measure of visibility within a column of atmosphere based on light extinction. Measures of AOD can be used to track emissions from fires that release aerosols or smoke into the air. Aerosol satellite imagery can be paired with NOAA HYSPLIT model (Draxler and Rolf, 2013) backward trajectories to show that air parcels passed through fire-generated aerosol plumes in transit to a particular area or that aerosol plumes from wildfires moved into an area over time.

The HYSPLIT trajectory model was used to estimate backward trajectories for three days prior to August 26, 2011. Trajectory durations were chosen to correspond to the length of time necessary for the trajectory to reach the Houston East (CAMS 1) monitoring site on August 26, 2011 at 13:00 LST, the hour of the one-hour ozone exceedance. Therefore, for August 23, 2011 a 72-hour trajectory was estimated; for August 24, 2011 a 48-hour trajectory was estimated; and for August 25, 2011 a 24-hour trajectory was estimated. Three termination heights were used for each day: 1 km, 1.5 km, and 2 km. These are shown as red, blue, and green trajectories, respectively, in the following figures. The three trajectories for each day were overlaid on images of AOD obtained from the MODIS Aqua satellite.

On August 23, 2011, two of the 72-hour HYSPLIT backward trajectories originate from Illinois and Indiana, as shown in Figure 4-24: *HYSPLIT 72-Hour Backward Trajectories Overlaid on AOD Imagery from MODIS Aqua Satellite, August 23, 2011*. One trajectory, the 1.5 km termination height, originated somewhere over the southeast in Alabama or Tennessee. Aerosols are shown on the following maps with red representing the thickest AOD, meaning more aerosols that block light reflectance, and therefore, likely more smoke, while blue represents the thinnest AOD. The red trajectory represents 1 km starting height, blue represents 1.5 km starting

height, and green represents 2 km starting height. The MODIS instrument detected a large aerosol plume, likely from fires, in the northern plains over South Dakota and parts of Nebraska, Iowa, and Minnesota. While the detected aerosol plume is beyond the trajectory path for August 23, 2011, it is in the proper direction. Based on other trajectories presented in this report that showed prevailing winds from the northwest U.S. passing over the northern plains at very high speeds, it is likely the aerosol smoke from fires in this area could have been transported to the HGB area by August 26, 2011.

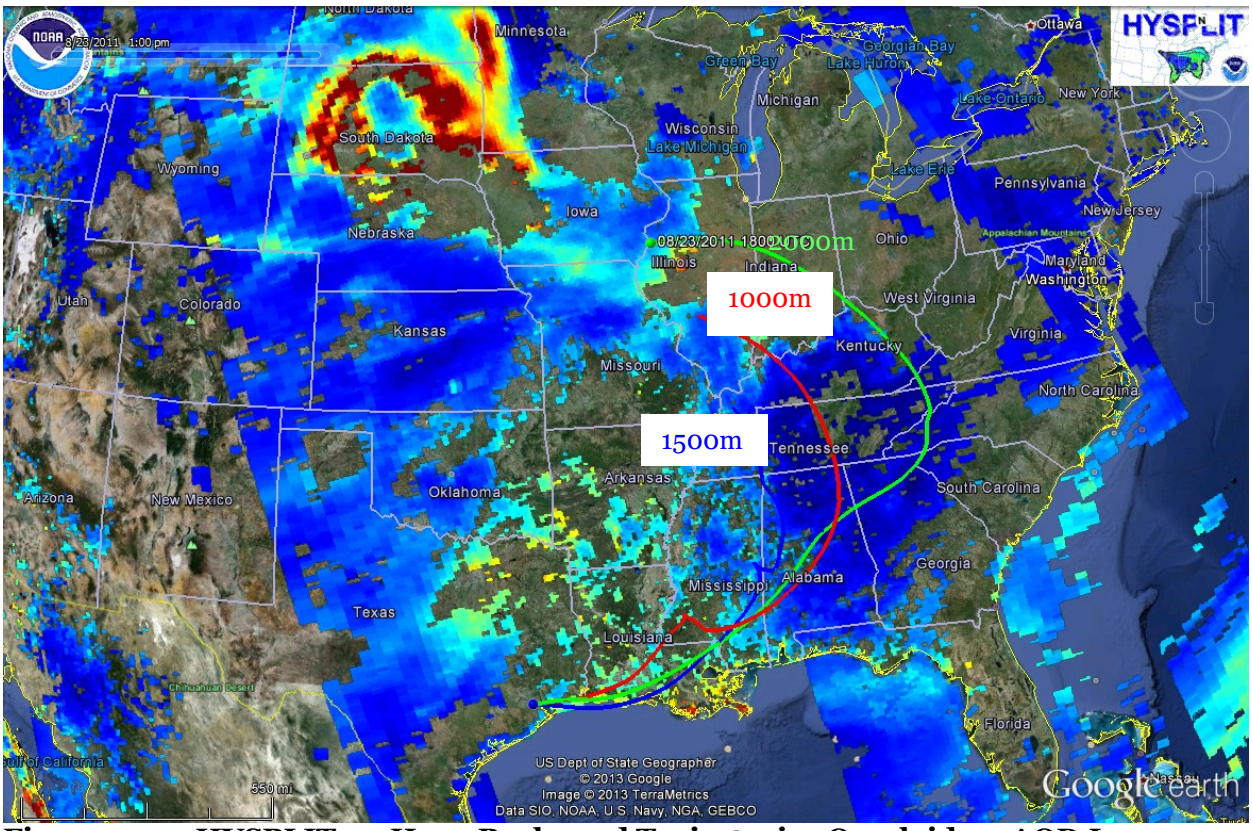


Figure 4-24: HYSPLIT 72-Hour Backward Trajectories Overlaid on AOD Imagery from MODIS Aqua Satellite, August 23, 2011

Forty-eight hour HYSPLIT backward trajectories, shown in Figure 4-25: *HYSPLIT 48-Hour Backward Trajectories Overlaid on AOD Imagery from MODIS Aqua Satellite, August 24, 2011* originated from the southeastern U. S. over Alabama and Tennessee on August 24, 2011. By this day, the aerosol plume was detected over a wide area of the midwestern U.S. centered over Illinois, Indiana, and Kentucky and including portions of Ohio, Tennessee, West Virginia, Virginia, and Missouri. The 2 km trajectory appears to originate within this plume area suggesting the likelihood of aerosol transport into the HGB area. In the top left of the satellite image, there is another aerosol plume detected over southwest South Dakota and western Nebraska.

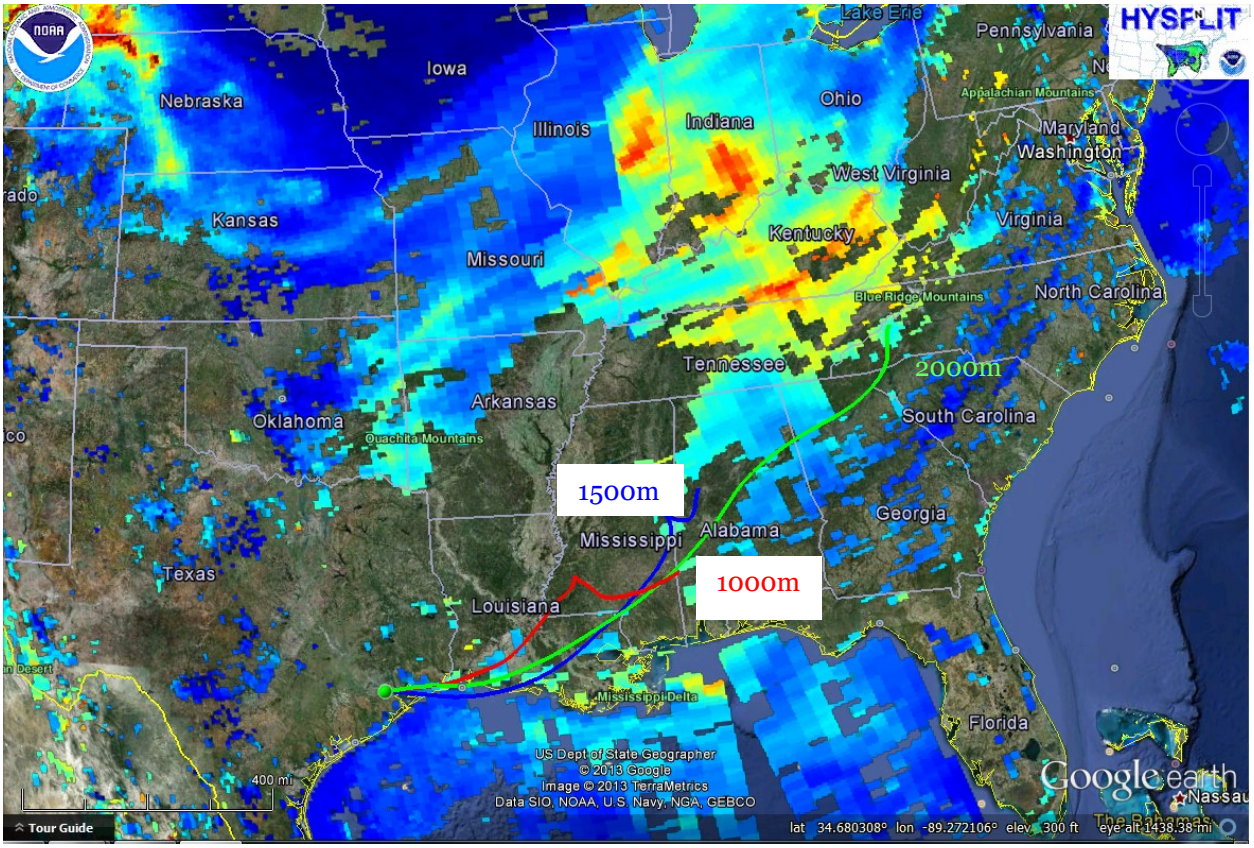


Figure 4-25: HYSPLIT 48-Hour Backward Trajectories Overlaid on AOD Imagery from MODIS Aqua Satellite, August 24, 2011

The 24-hour HYSPLIT backward trajectories, shown in Figure 4-26: *HYSPLIT 24-Hour Backward Trajectories Overlaid on AOD Imagery from MODIS Aqua Satellite, August 25, 2011* originated from the southeastern U. S. over Louisiana, Mississippi, and Alabama. The satellite AOD image shows moderate to high concentrations of aerosols over these states. Each of the three trajectories passes through the aerosol plume indicating that aerosols from fires in the northern plains or Midwest were likely to be transported to the HGB area. The satellite AOD image shows that there may be some aerosols from these northwest wildfires arriving in Houston.

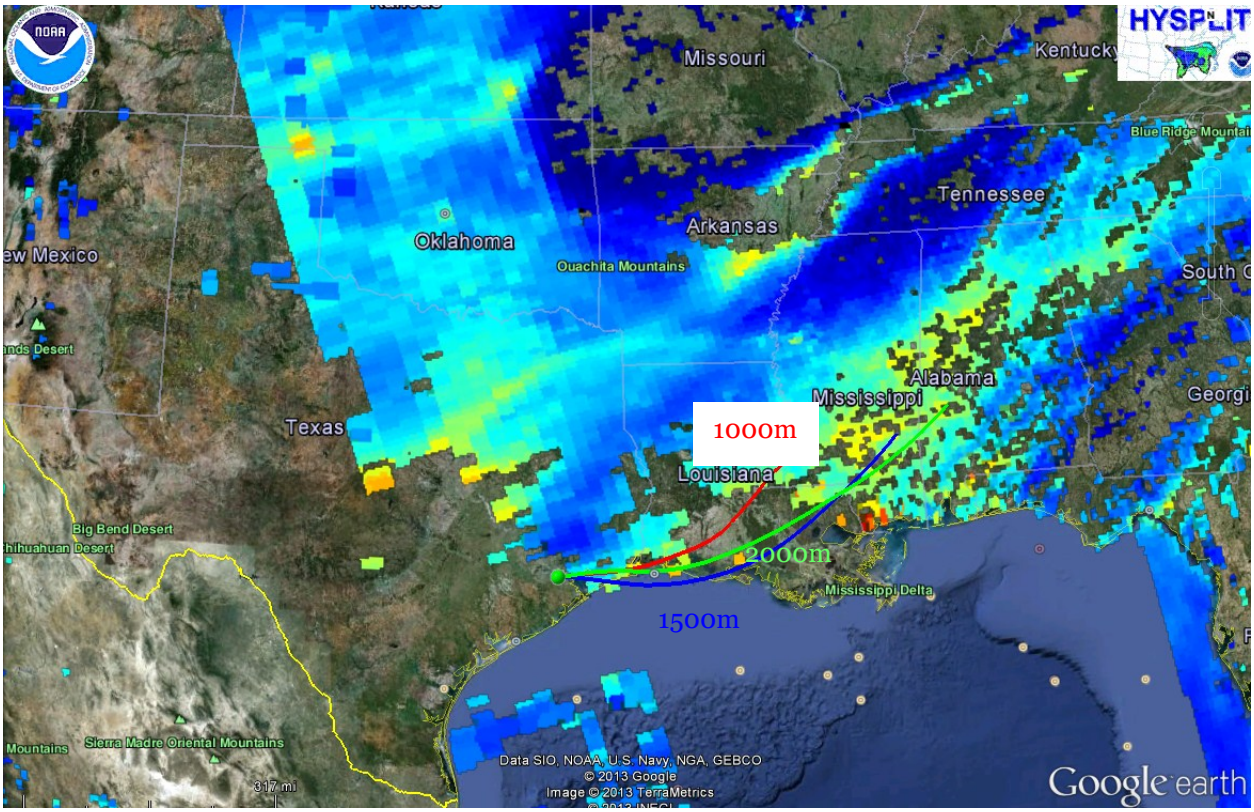


Figure 4-26: HYSPLIT 24-Hour Backward Trajectories Overlaid on AOD Imagery from MODIS Aqua Satellite, August 25, 2011

Figure 4-27: *AOD Imagery from MODIS Aqua Satellite, August 26, 2011* shows MODIS Aqua AOD satellite imagery on August 26, 2011. The thickest concentrations of aerosols were detected east of Houston in Louisiana and over Terrell, Pecos, and Brewster Counties in southwest Texas.

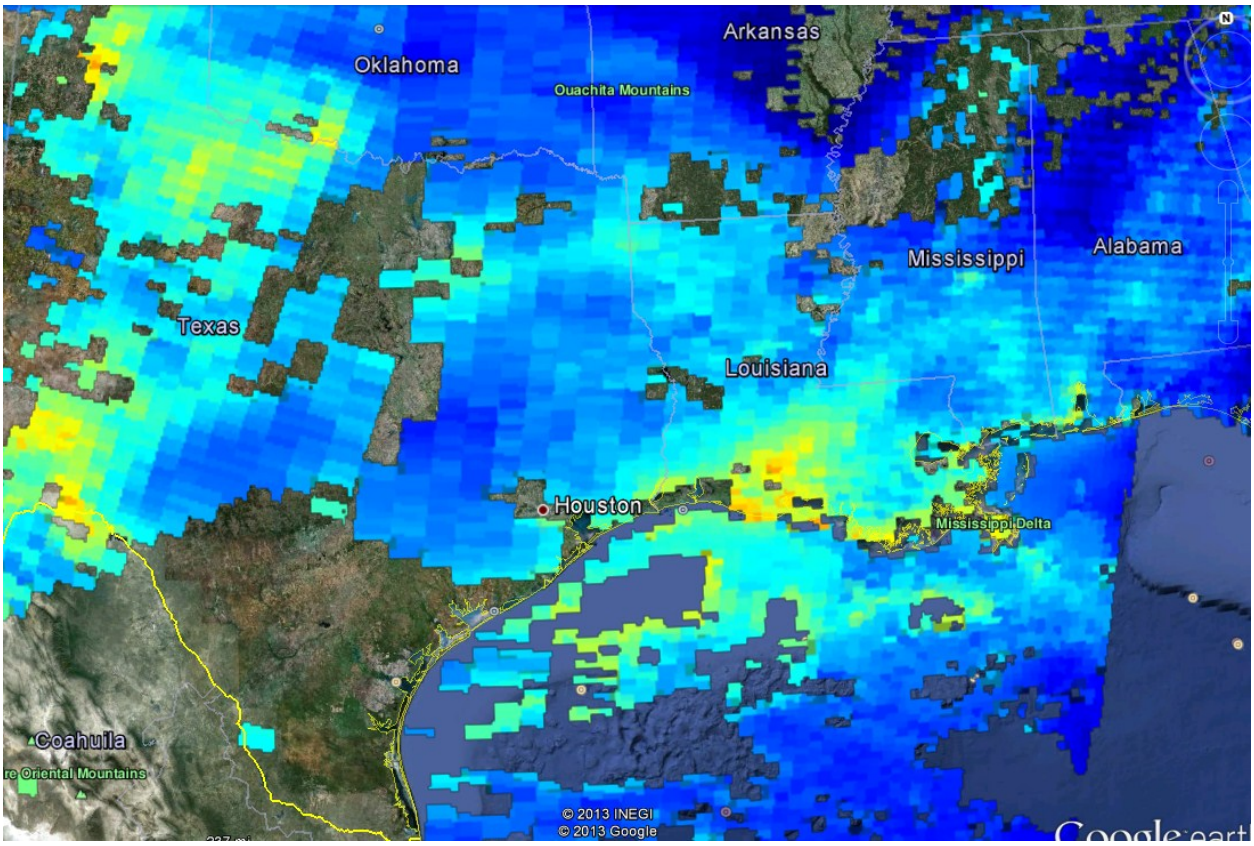


Figure 4-27: AOD Imagery from MODIS Aqua Satellite, August 26, 2011

NOAA's Hazard Mapping System (HMS) combines data from nine satellites, computer algorithms, and expert analysis to identify and map locations of fires in North America year-round. Automated fire detection algorithms are applied to satellite measurements to detect surface heat anomalies. Expert evaluations determine whether these anomalies were the result of fires or other sources of heat (e.g., solar reflectance from clouds or sandy soils) and also add known fires not detected by satellites due to interference or gaps in orbital coverage. Figure 4-28: *HMS Smoke and HYSPLIT 72-Hour Back Trajectories from AirNowTech.org on August 26, 2011* shows that the trajectories pass through the modeled smoke agreeing with the MODIS AOD with HYSPLIT trajectory maps. There is heavy smoke modeled on August 26, 2011 agreeing with the AOD MODIS satellite data from August 26, 2011. The red trajectory represents 1 km starting height, blue represents 1.5 km starting height, and green represents 2 km starting height. The red triangles represent a detected fire and the shaded gray areas are smoke modeled by HMS.

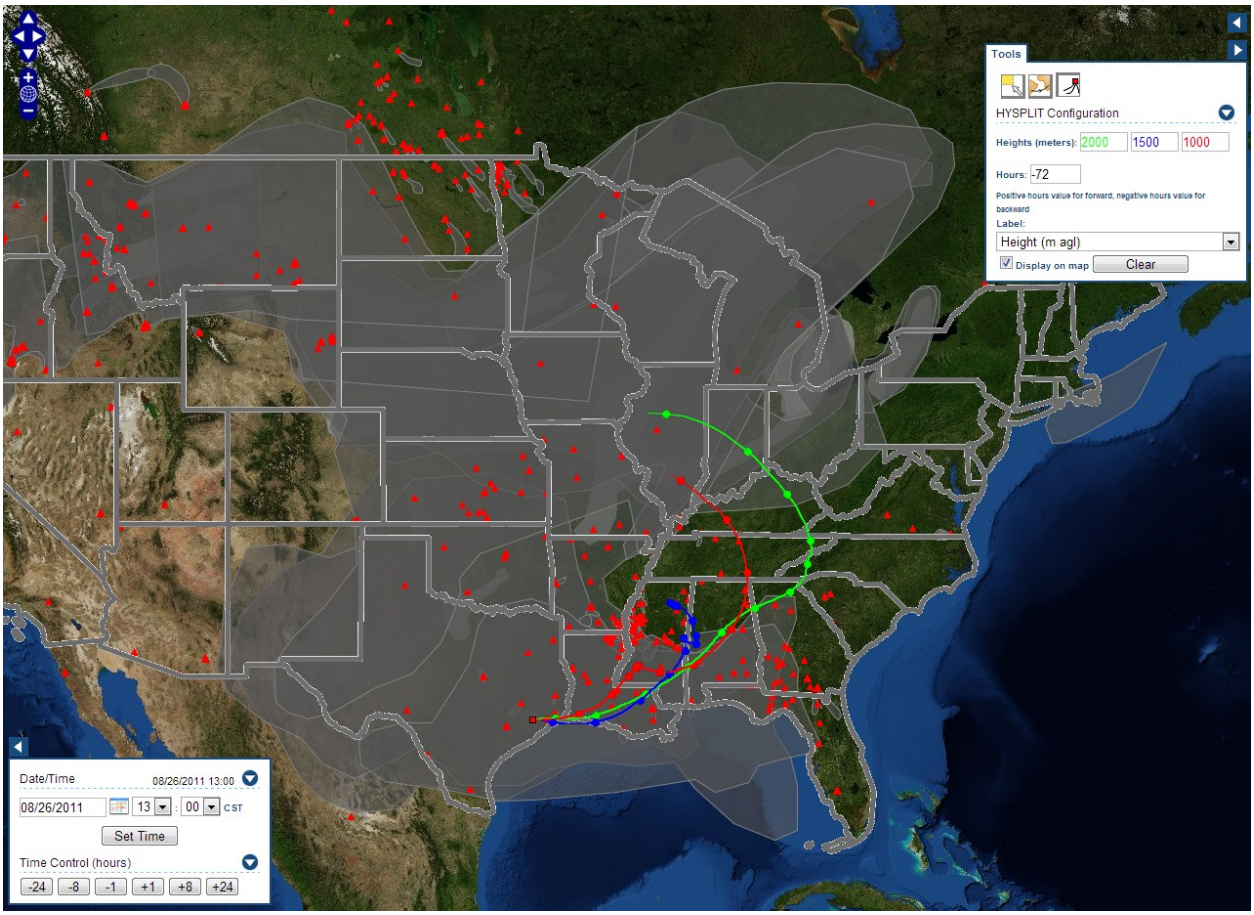


Figure 4-28: HMS Smoke and HYSPLIT 72-Hour Back Trajectories from AirNowTech.org on August 26, 2011

Aerosols from wildfires in the northwest were prevalent in the images from MODIS Aqua from August 23, 2011 through August 26, 2011. There is evidence of the aerosols originating in the northwest moving into the HGB area on August 26, 2011. The HYSPLIT backward trajectories pass through areas of high aerosol concentrations on August 25, 2011. The satellite images with AOD from MODIS Aqua support that aerosol concentrations were elevated on August 26, 2011 in the HGB area. There is support from HMS modeled smoke agreeing with AOD MODIS Aqua data exhibiting elevated levels of smoke in the HGB area. This information all supports the

conclusion that aerosols from wildfires in the northwest U.S. affected the air quality in the HGB area.

4.7 PATHFINDER SATELLITE OBSERVATIONS

The NASA maintains a fleet of satellites that use remote sensing technology to measure and report components of the atmosphere for analyses of weather, climate, and air quality. One of the satellites, the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO) launched in 2006, is a polar-orbiting satellite that circles the globe multiple times each day. CALIPSO carries the Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP) instrument, which measures reflectance from clouds and aerosols.

Because it is a LIDAR (Light Detection and Ranging) instrument, CALIOP produces high-resolution vertical profiles of aerosols and clouds. That is, components of the atmosphere can be isolated and identified by their altitudes. Most other instruments that measure aerosols can only provide a value for an entire atmospheric column from the surface of the earth to the instrument. Further, advanced algorithms are used to classify these components into various sub-types of aerosols or water vapor, such as dust, smoke, or ice crystals. However, the design of CALIOP limits its field of view, or width of its band of detection, to several km, compared to other satellite-borne instruments that cover very wide swaths, some as wide as several thousand km. Therefore, CALIOP only very rarely takes measurements of any particular part of the globe.

On August 26, 2011, CALIPSO passed along a path just east of Houston, very near to the Houston East (CAMS 1) monitoring site, at around mid-day between 1:41 CST and 1:54 CST. This orbit path is shown in Figure 4-29: *Close-up of Partial CALIPSO Orbital Path on August 26, 2011*. The satellite passed directly over Galveston and Mont Belvieu at roughly the time of the exceedance event on August 26, 2011. CALIPSO made roughly 14 complete orbits of the earth on that day.

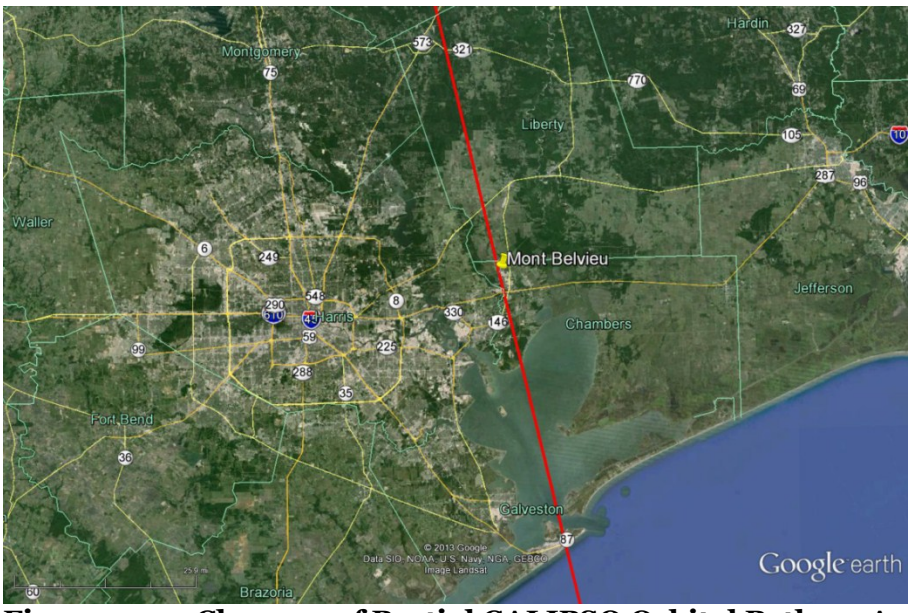


Figure 4-29: Close-up of Partial CALIPSO Orbital Path on August 26, 2011

All of the following CALIPSO/CALIOP images are courtesy of NASA. The Images are provided on the NASA website with accompanying guides to interpretation. Figure 4-30: *Attenuated*

Backscatter of Partial CALIPSO Orbital Path on August 26, 2011 plots total attenuated backscatter, which is a measure of reflectance from particles in the atmosphere between the CALIOP instrument and the surface. For ease of use, NASA divides each partial orbital into four zones indicated by different colors on the horizontal axis. The green zone includes the pass over the HGB area. NASA also provides a summary interpretation of this image: "signal strength has been color coded such that blues correspond to molecular scattering and weak aerosol scattering, aerosols generally show up as yellow/red/orange. Stronger cloud signals are plotted in gray scales, while weaker cloud returns are similar in strength to strong aerosol returns and coded in yellows and reds."

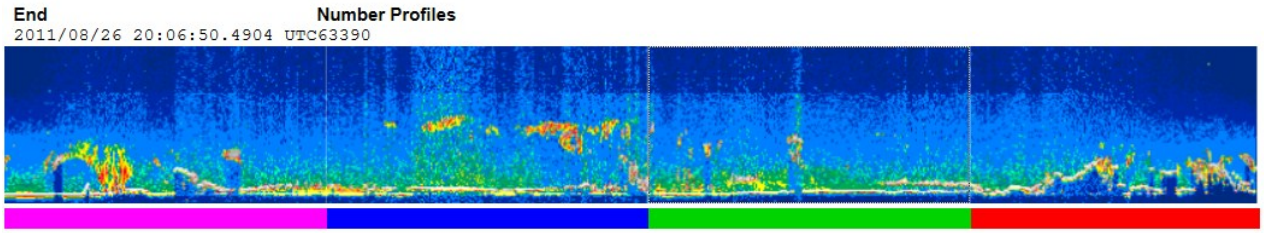


Figure 4-30: Attenuated Backscatter of Partial CALIPSO Orbital Path on August 26, 2011

Figure 4-31: *Total Attenuated Backscatter for the Partial CALIPSO Orbital Path on August 26, 2011* plots the vertical profile of the atmosphere for the portion of the orbit path indicated in green in Figure 4-35. Note this is a vertical profile so the vertical axis is altitude. Markers have been added to the horizontal axis to denote locations of features such as state boundaries to aid in locating areas of interest. All markers are approximate. The location of the Houston East (CAMS 1) monitoring site is highlighted in red. The yellow, red, and orange pixels over Texas and the Houston East (CAMS 1) monitoring site between the surface and about 4 km altitude indicate the presence of aerosols. North of Houston, CALIOP detected clouds (grey), as well as aerosols, at about 2 to 4 km altitude.

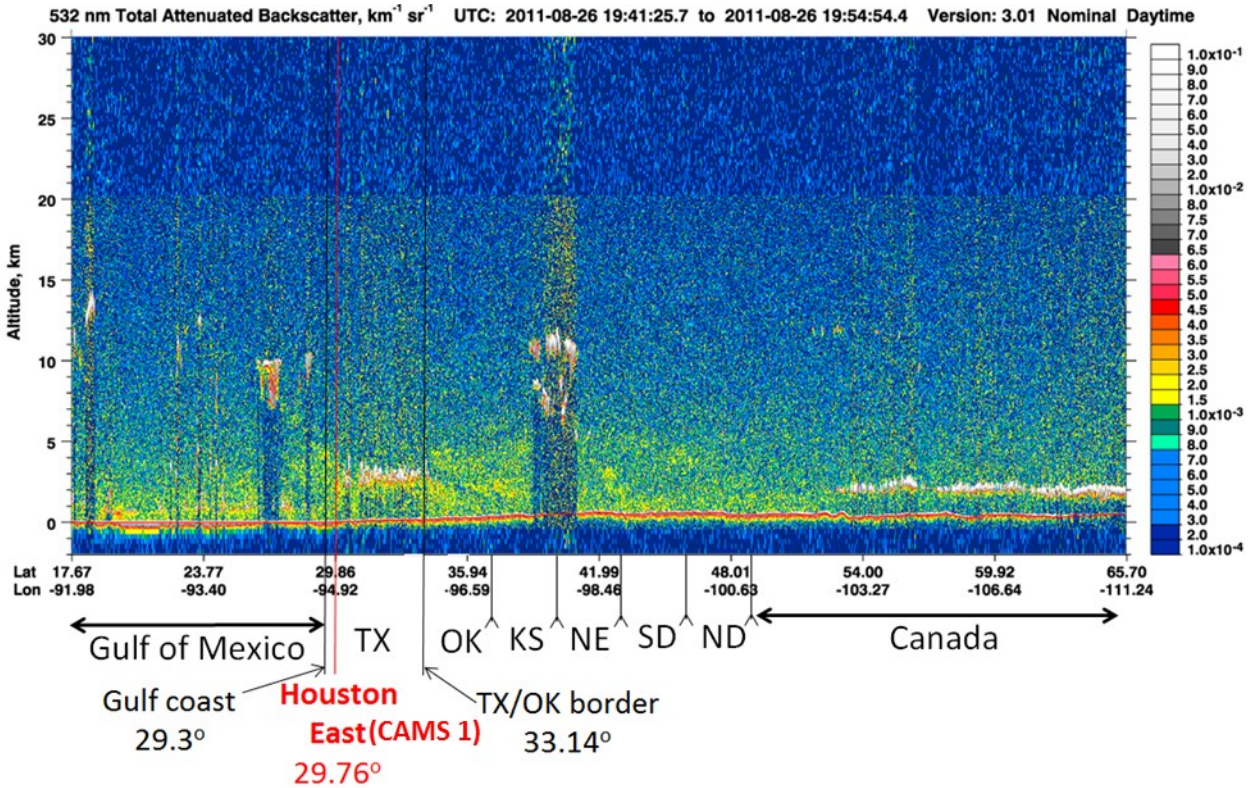


Figure 4-31: Total Attenuated Backscatter for the Partial CALIPSO Orbital Path on August 26, 2011

Figure 4-32: *Detail of Total Attenuated Backscatter for the Partial CALIPSO Orbital Path on August 26, 2011* shows detail of the previous figure to highlight the plume of aerosols stretching from the coast of the Gulf of Mexico at about 29.3° north latitude all the way to the Texas-Oklahoma border at about 33.14° north latitude along the satellite orbital path. Aerosols are noted in yellow, orange, and red from about 2 to 4 km altitude.

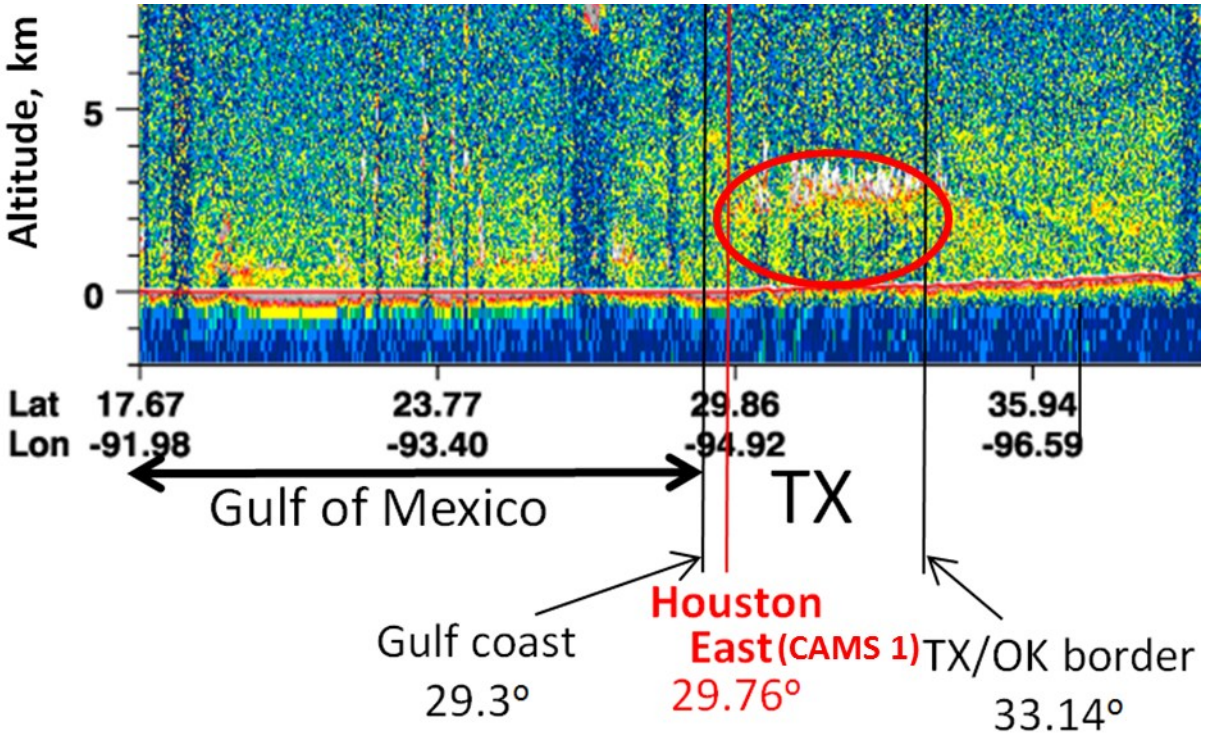


Figure 4-32: Detail of Total Attenuated Backscatter for the Partial CALIPSO Orbital Path on August 26, 2011

Using principles of light scattering and complex algorithms, NASA bins raw backscatter measurements into feature groupings such as clouds, aerosols, clear air, or unknown. These are shown in Figure 4-33: *Vertical Feature Mask for the Partial CALIPSO Orbital Path on August 26, 2011*. For example, orange areas in the figure indicate areas with backscatter that indicate aerosols, while light blue indicates clouds. Black areas in the figure indicate areas where there was insufficient backscatter for the instrument to "see" what was in the atmosphere. Usually, this occurs where cloud cover is too thick for light to penetrate.

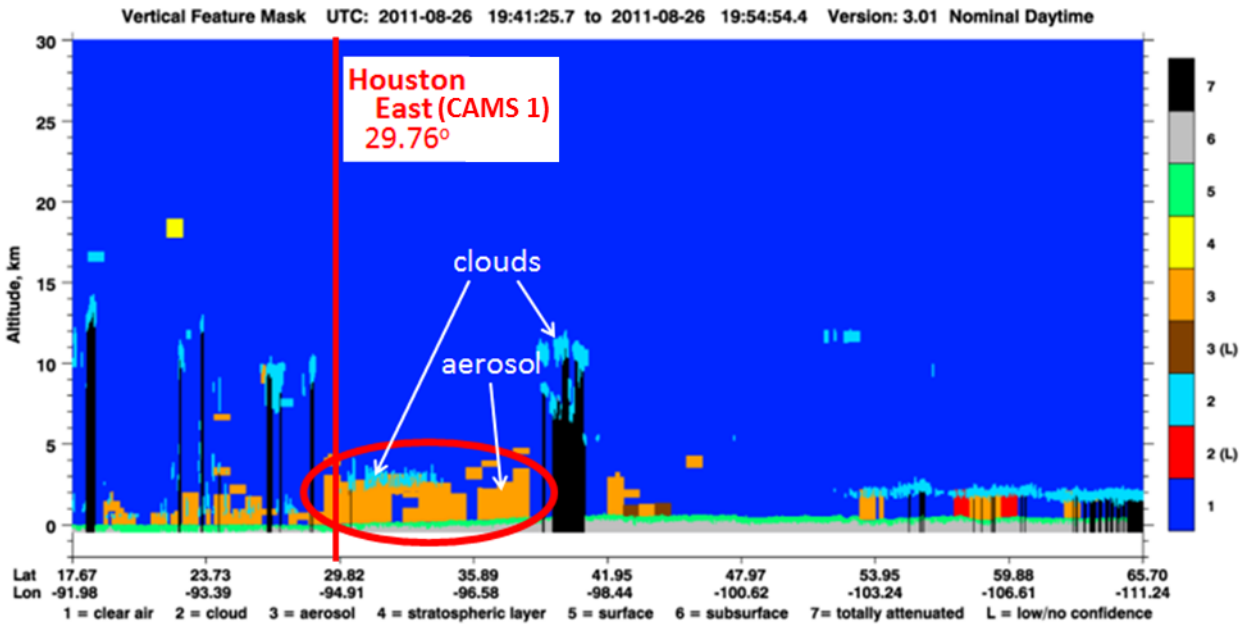


Figure 4-33: Vertical Feature Mask for the Partial CALIPSO Orbital Path on August 26, 2011

The Houston East (CAMS 1) monitoring site is indicated with a red vertical line. Figure 4-33 shows there was a large area north and south of the monitor that was impacted by aerosols on August 26, 2011. North of the Houston East (CAMS 1) monitoring site (to the right of the red vertical line) the aerosol plume extended from the ground up to about 4 km altitude and extended north well past the northern border of Texas. For reference, although CALIPSO did not pass over the panhandle of Texas on this orbit, the very northern border of the state in the panhandle is 36.5° north latitude.

The vertical feature mask and information on polarization of the particles also measured by CALIOP can be used to determine more precisely particle shape and therefore type of aerosol (e.g., smoke, dust). Figure 4-34: *CALIPSO Aerosol Subtype Plot for the Partial CALIPSO Orbital Path on August 26, 2011* displays the results of the subtyping of detected aerosols. Note that the Houston East (CAMS 1) monitoring site lies at latitude 29.76° north. Just to the south of that location on the horizontal axis, there is a large parcel of "clean marine" air (indicated in blue) and likely from the Gulf of Mexico extending from the surface to about 3 km altitude. Adjacent to that to the north is a large parcel of "smoke" (indicated in black) which also extends from the surface to about 3 km altitude. This large parcel of smoke extends from roughly the Gulf of Mexico coast near Houston to about 31.5° north latitude, which is well north of Houston somewhere near the Davy Crockett National Forest in Trinity and Houston Counties. This large smoke plume covered the region at almost the exact same time, between 19:41 UTC and 19:54 UTC, as the one-hour ozone exceedance at the Houston East (CAMS 1) monitoring site. These times correspond to 2:41 p.m. to 2:54 p.m. local daylight time (LDT). Recall that the one-hour ozone exceedance occurred at 1:00 p.m. LDT, which when converted to local daylight time ("spring forward") is 2:00 p.m. LDT.

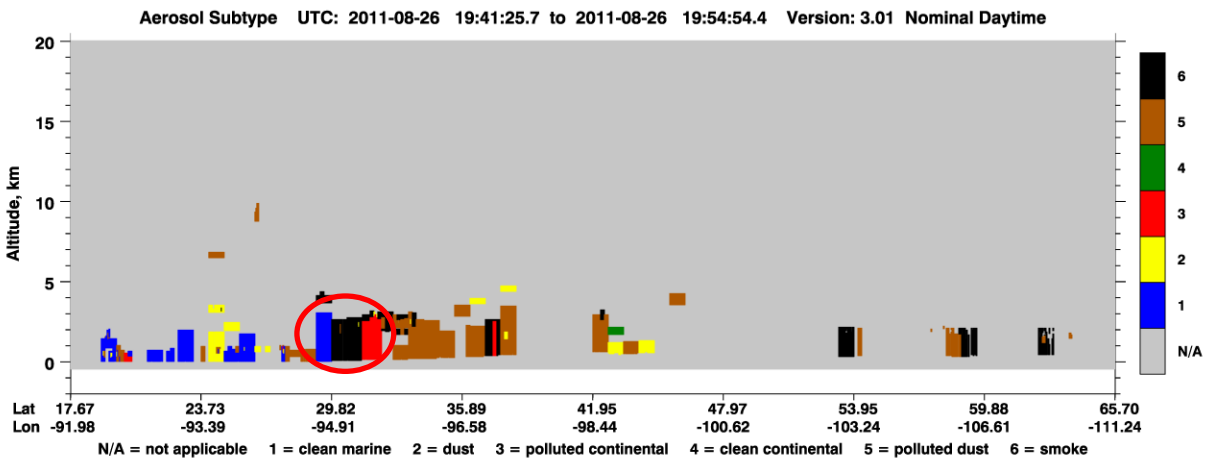


Figure 4-34: CALIPSO Aerosol Subtype Plot for the Partial CALIPSO Orbital Path on August 26, 2011

The CALIOP instrument detects backscatter from aerosol particles in two wavelengths: 532 nanometers (nm) and 1,032 nm. Because large and small particles have different light extinction properties, the ratio of backscatter from the two wavelengths can be used to determine whether detected aerosols are likely from biomass burning. A smaller ratio indicates the particles are likely larger, whereas a larger ratio indicates they are smaller, which suggests biomass burning. Figure 4-35: *Attenuated Color Ratio from Two Wavelengths Detected by the CALIOP Instrument on August 26, 2011* shows the ratio of the two wavelengths for the orbital path over the HGB area on August 26, 2011. The patch of light blue and bluish-green near the Houston East (CAMS 1) monitoring site, at about 3 km altitude, corresponds to small particles and suggests the aerosols detected by CALIOP were from biomass burning. The next figure, Figure 4-36: *Detail of Attenuated Color Ratio from Two Wavelengths Detected by the CALIOP Instrument on August 26, 2011* provides a more detailed view of the color ratio.

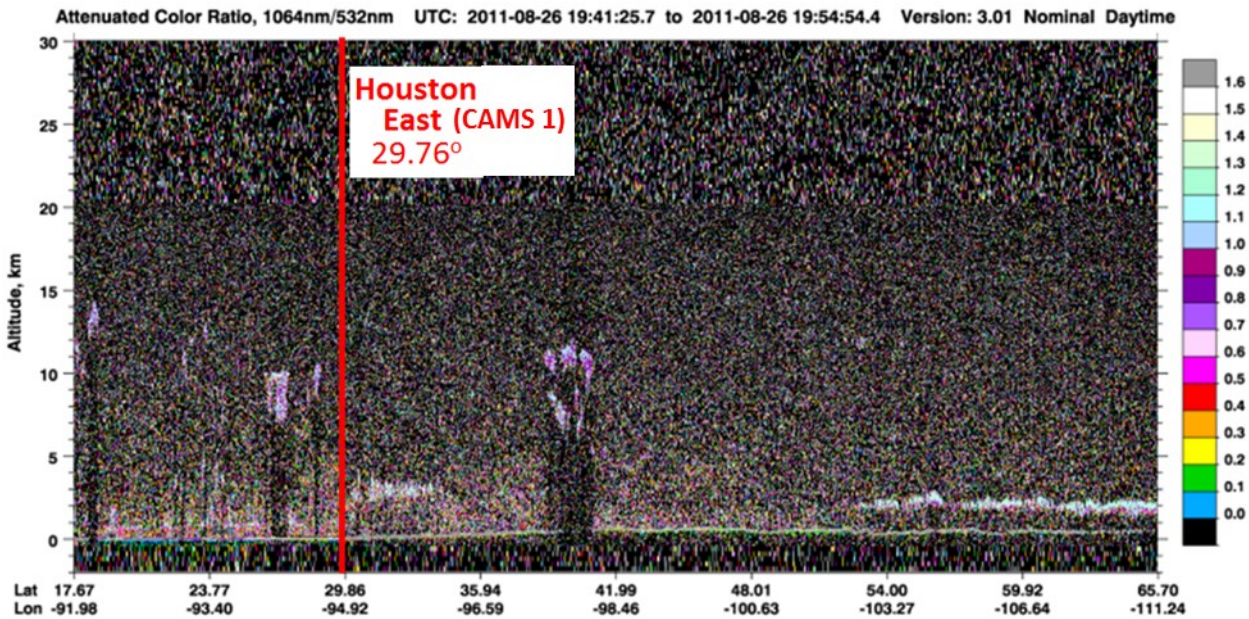


Figure 4-35: Attenuated Color Ratio from Two Wavelengths Detected by the CALIOP Instrument on August 26, 2011

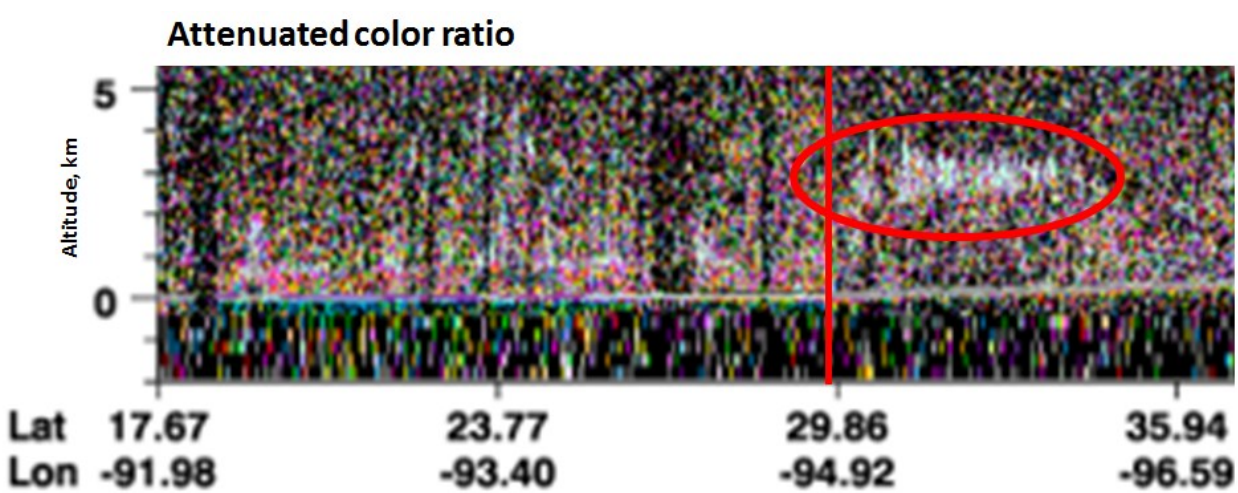
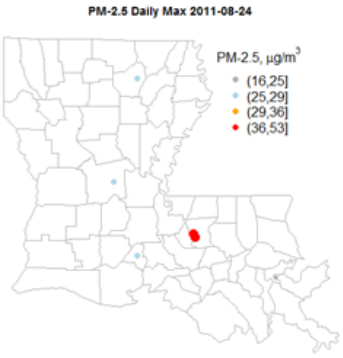


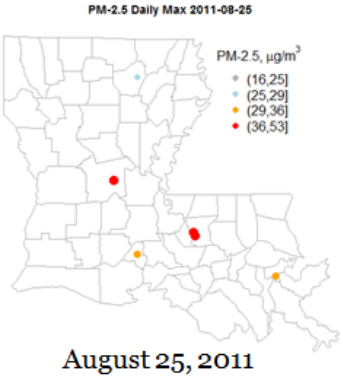
Figure 4-36: Detail of Attenuated Color Ratio from Two Wavelengths Detected by the CALIOP Instrument on August 26, 2011

4.8 MONITOR VALUES IN LOUISIANA DISPLAY WESTERLY TREND

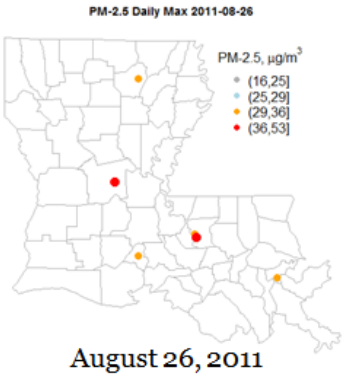
The TCEQ also analyzed ozone and $PM_{2.5}$ monitor values from Louisiana. The TCEQ plotted geographic representations of daily maximum $PM_{2.5}$ and ozone concentrations at monitors throughout Louisiana on August 24 through August 26, 2011. Figure 4 37: *Monitored Daily Maximum Hourly PM2.5 Concentrations in Louisiana August 24 through 26, 2011* and Figure 4 38: *Monitored Hourly Ozone Daily Maximums in Louisiana August 24 through 26, 2011* show daily maximum concentrations of $PM_{2.5}$ and ozone throughout Louisiana. From August 24, 2011 to August 26, 2011, the highest values statewide clearly move from east to west. This movement is consistent with the movement of wildfire emissions plumes moving across Louisiana into southeast Texas on a path that carries those emissions into the HGB area. The charts provide evidence of a causal relationship between wildfire emissions and an ozone exceedance at the Houston East (CAMS 1) monitoring site on August 26, 2011.



August 24, 2011



August 25, 2011



August 26, 2011

Figure 4-37: Monitored Daily Maximum Hourly $PM_{2.5}$ Concentrations in Louisiana August 24 through 26, 2011

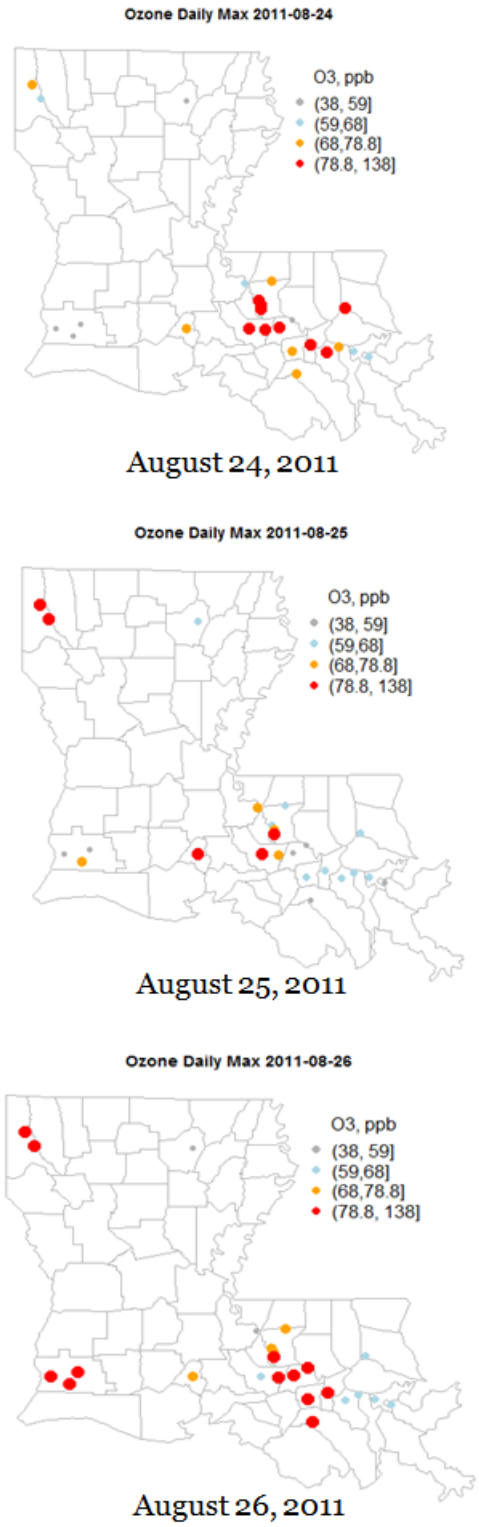


Figure 4-38: Monitored Hourly Ozone Daily Maximums in Louisiana August 24 through 26, 2011

CHAPTER 5: NO EXCEEDANCE BUT FOR THE EXCEPTIONAL EVENT

5.1 ANALYSIS OF A SURROGATE DAY

5.1.1 Introduction

The Texas Commission on Environmental Quality (TCEQ) chose to develop an analysis of a surrogate day comparing a high ozone day as similar to August 26, 2011 as possible that does not contain smoke from significant numbers of wildfires. To select this day the TCEQ relied on comparisons of large-scale wind patterns, visual inspections and quantitative comparisons of local-scale complex wind patterns (acute flow reversal days), and quantitative comparisons of important meteorological metrics. This section documents the steps taken to identify a suitable surrogate day for August 26, 2011.

Selection of potential surrogate days first used the Hybrid Single Particle Lagrangian Integrated Trajectory (HYSPLIT) model (Draxler and Rolph, 2013) to identify days with similar large-scale wind patterns similar to August 26, 2011 that could have transported wildfire emissions to the Houston East (CAMS 1) monitoring site. The TCEQ then used surface level backward trajectories to match the small-scale wind currents at the Houston East (CAMS 1) monitor. Lastly, the TCEQ compared other important meteorological parameters.

The TCEQ initially started with 124 candidate surrogate days from the years 2009 through 2011. Five-day (120-hour) back trajectories were computed for each candidate day. The TCEQ also generated 120-hour back trajectories for August 15 through September 15, of the years 2009 through 2011 to capture large-scale meteorological patterns. To capture larger scale meteorological conditions, the TCEQ analyzed back trajectories ending at the Houston East (CAMS 1) monitoring site well up in the mixing layer (800 meters above ground) above ground. These back trajectories terminated at the receptor site, the Houston East (CAMS 1) monitoring site, at 13:00 Local Standard Time (LST). Eighty-four trajectories out of a possible 93 back trajectories were computed. The remaining days could not be computed due to missing data or a lack of complete 120 hour trajectory output.

The remaining 84 back trajectories were analyzed with the HYSPLIT model's clustering tool. The clustering tool identified seven clusters of days with similar wind patterns for the August 15 to September 15 time period. Upon visual inspection, three of seven clusters were determined to be sufficiently similar to August 26, 2011. These clusters are displayed in Figure 5-1: *Selected HYSPLIT Clusters (3, 4, and 5) Containing Candidate Surrogate Days*. Cluster 4, in the middle panel, contains August 26, 2011, but Clusters 3 and 5 are sufficiently similar to August 26, 2011 to be considered for further analysis.

Of the 124 days identified as potential surrogate days, application of the HYSPLIT clustering tool and visual inspection yielded 29 candidate surrogate days for further analysis. Surface back trajectories using TCEQ surface level ambient monitoring were analyzed for these 29 days to determine which displayed sufficiently similar local-scale wind patterns to August 26, 2011.

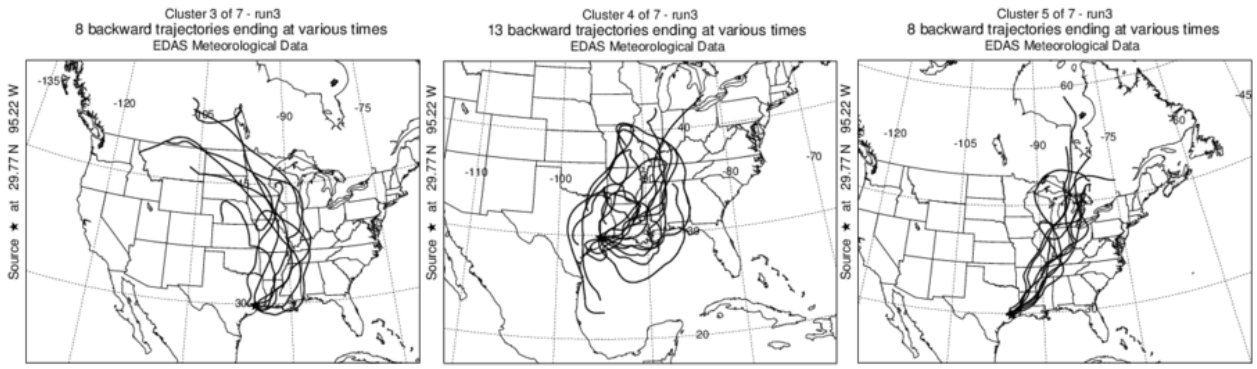


Figure 5-1: Selected HYSPLIT Clusters (3, 4, and 5) Containing Candidate Surrogate Days

5.1.1 Surface Trajectories

For each of the 29 candidate surrogate days selected in Section 5.1.1, a single surface back trajectory model was run. Each back trajectory ended (or terminated) at the Houston East (CAMS 1) monitoring site at the end of the hour in which the daily one-hour maximum ozone value was measured. These trajectories were then compared to the trajectory computed for August 26, 2011, to identify those most similar. Each surface level back trajectory uses the wind direction and wind speed data available from all TCEQ monitoring sites in the Houston Galveston Brazoria (HGB) area. The backward trajectory heights originate at 10 meters height, the height of the wind monitoring sensor and travels six hours back in time. The surface trajectory model uses a distance-weighted Shepard's modified algorithm, or "Shepard's method" (Shepard, 1968), to compute trajectories. The model has no vertical motion so back trajectories are only tracked in two dimensions at a height of the wind monitoring sensor, 10 meters.

The TCEQ determined that five days had sufficiently similar large and local-scale wind patterns to August 26, 2011 to consider as final candidates for a surrogate day. Figure 5-2: *Surface Backward Trajectories for Candidate Surrogate Days* plots each of the computed surface trajectories for August 26, 2011 and the final candidate days. Inspection of back trajectories suggests that regional and local wind patterns on August 27, 2009 were most similar to August 26, 2011. August 27, 2009 has the feature that the surface level trajectory wind arrives from northwest of the Houston East (CAMS 1) monitoring site and it contains a clear flow-reversal pattern or a pattern where the wind changes directions dramatically. In addition, the time of peak ozone differs by only two hours from August 26, 2011 15:00 LST versus 13:00 LST.

A second potential candidate is September 15, 2011. This day's flow reversal is sharp and occurs on a Northwest to Southeast access like August 27, 2009 or August 26, 2011. However, it starts from the Northeast as opposed to the Northwest. Flow reversal on September 15, 2011 is very similar to August 27, 2009 in shape and wind speed, and its overall wind speed would appear to be lower than either August 27, 2009 or August 26, 2011. This difference in wind speeds could increase this day's potential for ozone production. In addition, the peak one-hour ozone measurement on September 15, 2011 occurred at 12: LST, a difference of only one hour from August 26, 2011.

Another potential surrogate day is September 3, 2009, which has a very acute flow reversal. September 3, 2009 exhibits similar wind speeds at peak ozone time but behaves differently before and after peak ozone hours. This trajectory meanders in a very small area for all of the six

hours of the trajectory, unlike the August 26, 2011 trajectory. August 29, 2009 exhibits flow reversal, but the reversal is not as sharp as the flow-reversal as August 26, 2011.

The surface level back trajectory for August 17, 2010 exhibits a sharp flow reversal along an axis from Northeast to Southwest, which is very different from the Northwest to Southeast flow reversal axis observed on August 26, 2011. Wind speeds on August 17, 2010 were also faster overall than wind speeds on August 26, 2011. The difference in wind speed is a critical factor in distinguishing August 17, 2010 and August 26, 2011 because wind speed is critical in the formation of ozone.

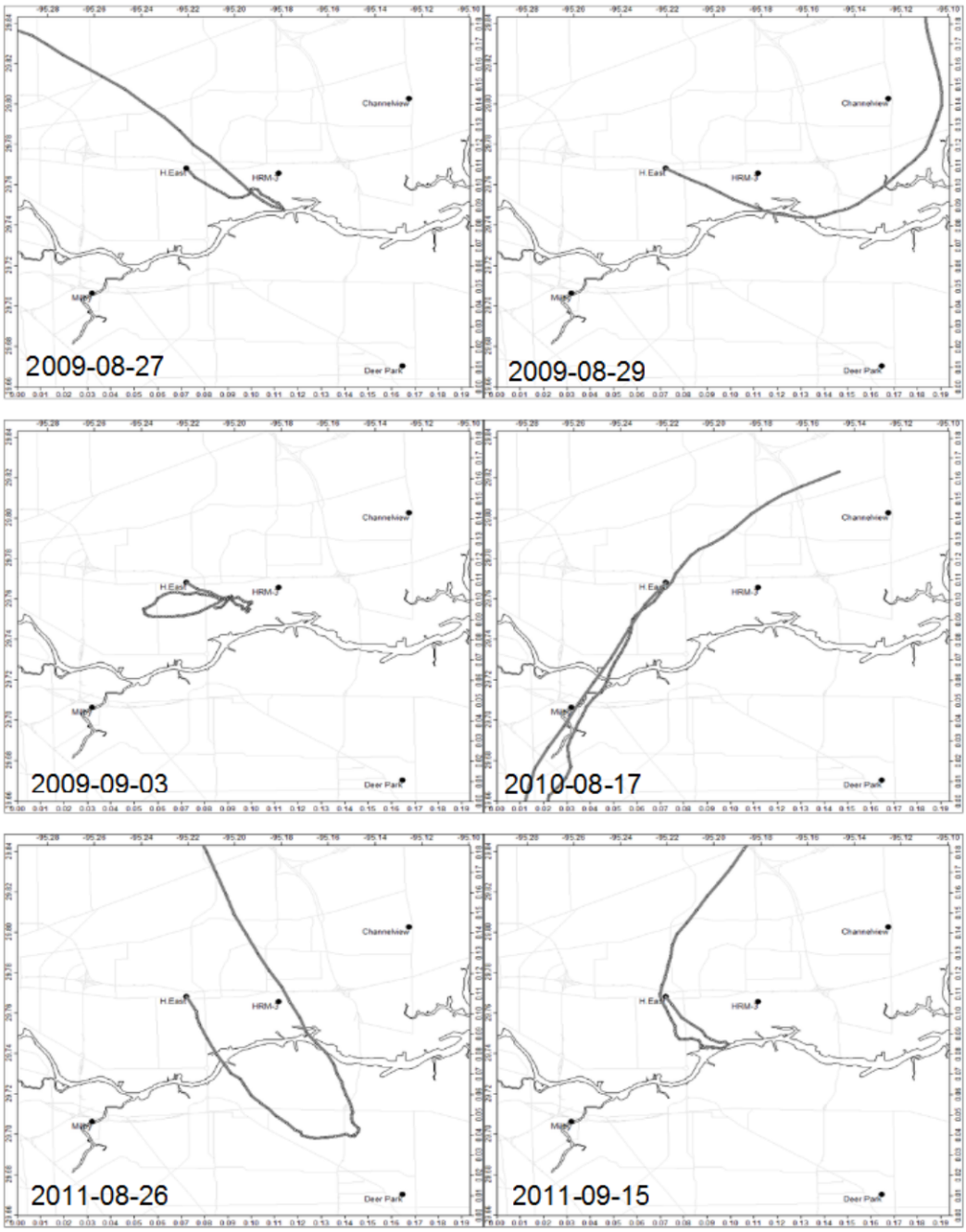


Figure 5-2: Surface Backward Trajectories for Candidate Surrogate Days

5.1.2 Surrogate Days

As discussed above, five days were determined to be suitable as final candidates for surrogate comparison based on HYSPLIT trajectory clustering local-scale back trajectory comparison. Selection of a final surrogate day from these five candidate days entails further comparison of ozone concentrations and measures of sinuosity of measured wind speeds and directions. Table 5-1: *Maximum One-Hour Ozone on Final Candidate Surrogate Days* lists maximum ozone concentrations for each day and the hour when that maximum ozone was observed. The highest one-hour ozone concentration observed on any candidate day was 113 ppb on September 3, 2009 at 12:00 LST, which is below the one-hour ozone standard, as were all final candidate surrogate days. Two other candidate days measured one-hour ozone below 75 ppb: August 29, 2009 at 69 ppb and August 17, 2010 at 73 ppb.

Table 5-1: Maximum One-Hour Ozone on Final Candidate Surrogate Days

Date	Maximum Ozone Concentration (ppb)	Hour of Maximum Concentration (CST)
Exceptional Event Day		
August 26, 2011	128	13:00
Final Candidate Surrogate Days		
August 27, 2009	111	15:00
August 29, 2009	69	19:00
September 3, 2009	113	12:00
August 17, 2010	73	16:00
September 15, 2011	107	12:00

5.1.3 Sinuosity

A quantitative comparison of wind speeds from the candidate surrogate days can be performed using a measure that compares the net distance traveled by back trajectories versus the total distance traveled over their entire paths. This measure, known as sinuosity, is derived from the name of the sine curve in mathematics. Sinuosity is defined as the ratio of the distance from the start point of a trajectory to the ending point of the trajectory to the sum of all distances from one time step to the next from beginning to end of the trajectory. A trajectory traveling straight in one direction will have a ratio close to one. A trajectory that reverses flow will have a ratio closer to zero. Comparison of the lengths of trajectories can reveal the extent to which winds were straight or variable over the path of a trajectory. Straight winds are associated with lower ozone concentrations, while variable winds tend to be associated with higher ozone concentrations. Table 5-2: *Sinuosity Results for Final Candidate Surrogate Days* reports results of the sinuosity analysis. These results suggest that August 27, 2009 is most similar to the target day in terms of sinuosity than other days. The day with the greatest difference is September 3, 2009, which is evident from its circular trajectory.

Table 5-2: Sinuosity Results for Final Candidate Surrogate Days

Date	Sinuosity	Difference Between August 26, 2011 and Candidate Day
Exceptional Event Day		
August 26, 2011	0.56	----
Final Candidate Surrogate Days		
August 27, 2009	0.42	0.14
August 29, 2009	0.81	-0.25
September 3, 2009	0.12	0.44
August 17, 2010	0.23	0.33
September 15, 2011	0.82	-0.26

5.2 METEOROLOGICAL COMPARISONS BETWEEN EXCEPTIONAL EVENT DAY AND SURROGATE DAY

The TCEQ took care to select a day that was similar not only with respect to local and regional wind patterns. The TCEQ also compared the two days on the basis of other meteorological factors as well. Table 5-3: *Comparison of Meteorological Conditions for August 26, 2011 and August 27, 2009* is a synopsis of general meteorological conditions to emphasis the similarities between the smoke-affected day and the surrogate day. Unless noted, all parameters are taken from the Houston East (CAMS 1) monitor to make the comparison more precise. The only parameter not measured at the Houston East (CAMS 1) monitor is the solar radiation, which comes from the Clinton (CAMS 403) monitoring site. From all the parameters shown below, the most outstanding parameter difference is the value of ozone. All other parameters are similar, suggesting that meteorology is similar on both days. The TCEQ also found fewer upset emission reported on August 26, 2011 than on the surrogate day. The primary difference between the ozone formation potential on both days is the presence of a significant smoke plume.

Table 5-3: Comparison of Meteorological Conditions for August 26, 2011 and August 27, 2009

Parameter at Houston East	August 26, 2011 (Smoke Event)	August 27, 2009 (Surrogate Day)
Houston East 6 a.m. to 14 p.m. LST, Average Wind Speed (miles/hour)	3.6	2.0
Temperature High/Low (F°)	98/78	91/78
1-Hour Ozone (ppb)	128	111
Surface Pattern	High Pressure over Texas	High Pressure over Texas
Average Solar Radiation (Langley/minute) from 6 a.m. to 14 p.m. LST at Clinton Dr.	0.678	0.503
Flow Reversal	Present and acute	Present and acute
Cloud Cover	Clear Skies	Partly Cloudy
Precipitation (inches)	0	0
Relative Humidity (%)	53	69

To illustrate meteorological similarities, meteorological surface maps from the National Oceanic and Atmospheric Administration (NOAA) are compared. Figure 5-3: *Afternoon Meteorological Surface Analysis for August 26, 2011 (Top) and August 27, 2009 (Bottom)* show large-scale synoptic meteorological conditions on August 26, 2011 and August 27, 2009. These maps are rich in meteorological information for larger scale meteorological events. These include features such as frontal boundaries, tropical cyclones, temperatures, wind directions, and surface pressures. The following paragraphs illustrate the similarities on the smoke-affected day and the surrogate day.

On August 26, 2011, a stationary front stretched from northeast Texas through central Mississippi and Alabama. A surface high pressure system was centered off the coast of southeast Texas. Skies over southeast Texas were clear with temperatures in the mid 90 degree Fahrenheit range. The clear skies extended over much of the southeast United States (U.S.). Winds over southeast Texas and the Houston area were light. Hurricane Irene was centered off the coast of South Carolina causing winds over the southeast U.S. to flow cyclonically around the center. This resulted in winds generally out of the north over Arkansas and Mississippi.

Similarly, the surrogate day August 27, 2009, observed similar meteorological conditions as mentioned above. A weak front stretched from West Texas through Oklahoma. A surface high pressure system was also centered over southeast Texas. Skies were partly cloudy on this day with cloudier conditions extending further over the southeastern U.S. Temperatures were in the low 90 degree Fahrenheit range. Tropical Storm Danny was centered in the Atlantic off the coast of the southeastern U.S. Winds over southeast Texas and throughout Louisiana and Mississippi were generally light.

To summarize, meteorological conditions were similar for the surrogate and the exceptional event day. They both observed high pressure in the Houston area, weak frontal boundaries, and generally sunny, clear, warm days with light winds.

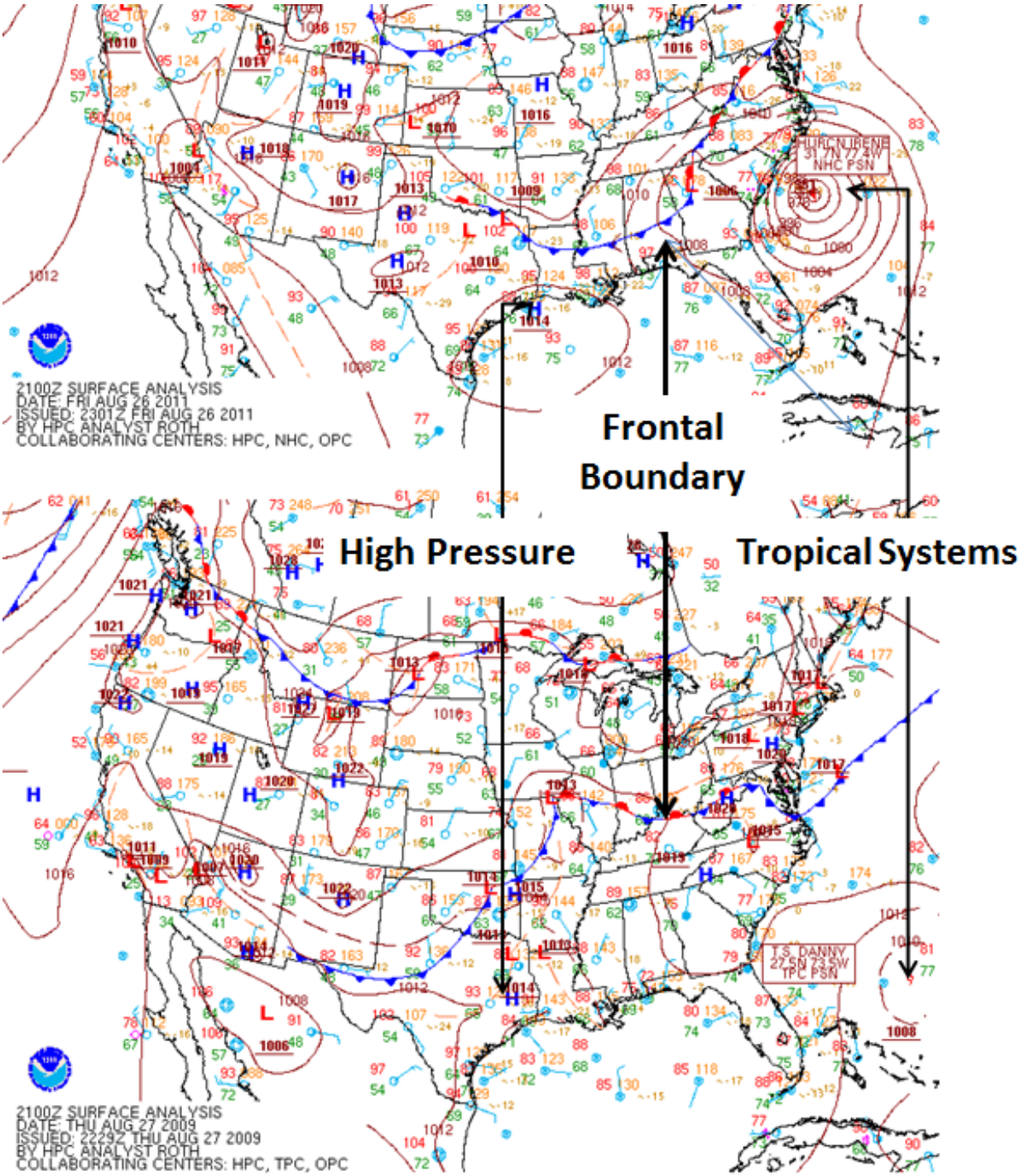


Figure 5-3: Afternoon Meteorological Surface Analysis for August 26, 2011 (Top) and August 27, 2009 (Bottom)

5.3 COMPARISON OF HIGHLY REACTIVE VOLATILE ORGANIC COMPOUNDS

The TCEQ also compared diurnal profiles of two highly reactive volatile organic compounds (HRVOC) – propylene and ethylene – at four automated gas chromatograph (AutoGC) instruments near to the Houston East (CAMS 1) monitoring site. Those AutoGC sites are listed in Table 5-4: *Neighboring AutoGC Monitoring Sites*. Each of these sites measures the concentration of more than 40 volatile organic compounds (VOC) on an hourly basis. The TCEQ chose two of these species, the HRVOCs propylene and ethylene that are commonly found in the Houston Ship Channel area and often associated with high ozone measurements. All four AutoGC sites are generally upwind of the Houston East (CAMS 1) monitoring site. To compare HRVOC values of the two species on August 26, 2011 and August 27, 2009, the TCEQ created diurnal profiles of both species at each monitoring site based on data from August of the years 2009 through 2011. The distribution of measurements at each hour was plotted in the form of curves for the 25th, 75th, and 95th percentiles as well as the median. The diurnal profile for both days was then laid over the diurnal curves and compared. This method provides an estimate of the normal range of both HRVOCs and the ability to compare the diurnal profiles of both days against one another and the historical distribution of HRVOC measurement for that time of year.

Table 5-4: Neighboring AutoGC Monitoring Sites

AutoGC Site	Distance from Houston East (CAMS 1) (miles)	Relative Direction from Houston East (CAMS 1)
Clinton (CAMS 403)	3.25	Southwest
Houston Regional Monitoring (HRM) Site #3	2.57	East
Lynchburg Ferry (CAMS 1015)	8.39	East
Deer Park (CAMS 35)	8.73	Southeast

Figure 5-4: *VOC Comparison of August 26, 2011 and August 27, 2009 (Ethylene)* and Figure 5-5: *VOC Comparison of August 26, 2011 and August 27, 2009 (Propylene)*. While no one diurnal profile can be thought as typical, the curves defined by the median and 75th percentile estimates may provide a representative picture in terms of in terms of pattern and measurement level. Ethylene on August 26, 2011 follows a typical, diurnal pattern in terms of patterns at the Clinton (CAMS 403) and Houston Regional Monitoring site #3 (HRM 3) although it has early morning and early afternoon peaks that are near or above the 95th percentile line. The early afternoon peaks at the Clinton (CAMS 403) and HRM 3 monitoring sites are approximately 3.5 parts per billion by Carbon (ppbC) and 7 ppbC respectively. Ethylene on August 27, 2009 also follows a typical pattern at these two sites although it is generally lower in concentration.

At the two easternmost AutoGC sites, Lynchburg Ferry (CAMS 1015) and Houston Deer Park (CAMS 35), ethylene also follows a typical diurnal pattern for ethylene although with slightly different outcomes. At the Houston Deer Park (CAMS 35) monitoring site, ethylene on August 26, 2011, generally lies above the 75th percentile curve and has a late morning peak of approximately 12.5 ppbC. Ethylene patterns at these two sites on August 27, 2009 are typical although ethylene levels at the Lynchburg Ferry (CAMS 1015) monitoring site are almost always higher than August 26, 2011 and push past the 95th percentile line at several different hours. Given wind speed and direction on August 26, 2011, it is possible that the late morning peak of

12.5 ppbC ethylene measured at the Houston Deer Park (CAMS 35) monitoring site could have influenced ozone levels measured in the early afternoon at Houston East (CAMS 1) monitoring site.

If the only difference between August 27, 2009 and August 26, 2011 at Houston East (CAMS 1) monitoring site is the presence of smoke and wildfire emissions, it is unlikely that a 4ppbC increase in ethylene would yield a 17 ppb increase in ozone needed to reach 128 ppb at the Houston East (CAMS 1) site. On an aggregate basis, the comparison of ethylene on August 27, 2009 and August 26, 2011 does not suggest that ethylene concentrations were capable of generating a measurement of 129 ppb by themselves at the Houston East (CAMS 1) site on August 26, 2011. The more likely cause of elevated ozone at the Houston East (CAMS 1) site on August 26, 2011 is that ethylene and fire emissions both contributed to the measurement of 128 ppb and that the exceedance would not have occurred without the contribution from fire emissions. This scenario becomes even more likely when one remembers the finding of Section 3.6: *Southeast Texas Monitoring Sites* where 18 of 19 monitors in the HGB area all measured daily maximum one-hour ozone values above the 95th percentile. Some factor beyond a localized or typical HGB ozone exceedance was contributing to ozone formation throughout the area.

The comparison of propylene, the other HRVOC specie analyzed, is comparatively shorter. Although propylene is generally higher on August 26, 2011 than August 27, 2009, it is well within typical concentrations and the difference between the two days does not appear significant. The one exception to this finding is that the Houston Deer Park (CAMS 35) monitoring site measures a late morning peak of propylene that appears to be associated with the ethylene peak previously mentioned. Unlike ethylene however, neither Clinton (CAMS 403) nor HRM #3 monitoring sites measured a propylene peak in the early afternoon. Nevertheless, with this one exception, there does not appear to be a significant different August 26, 2011 and August 27, 2009 with respect to propylene.

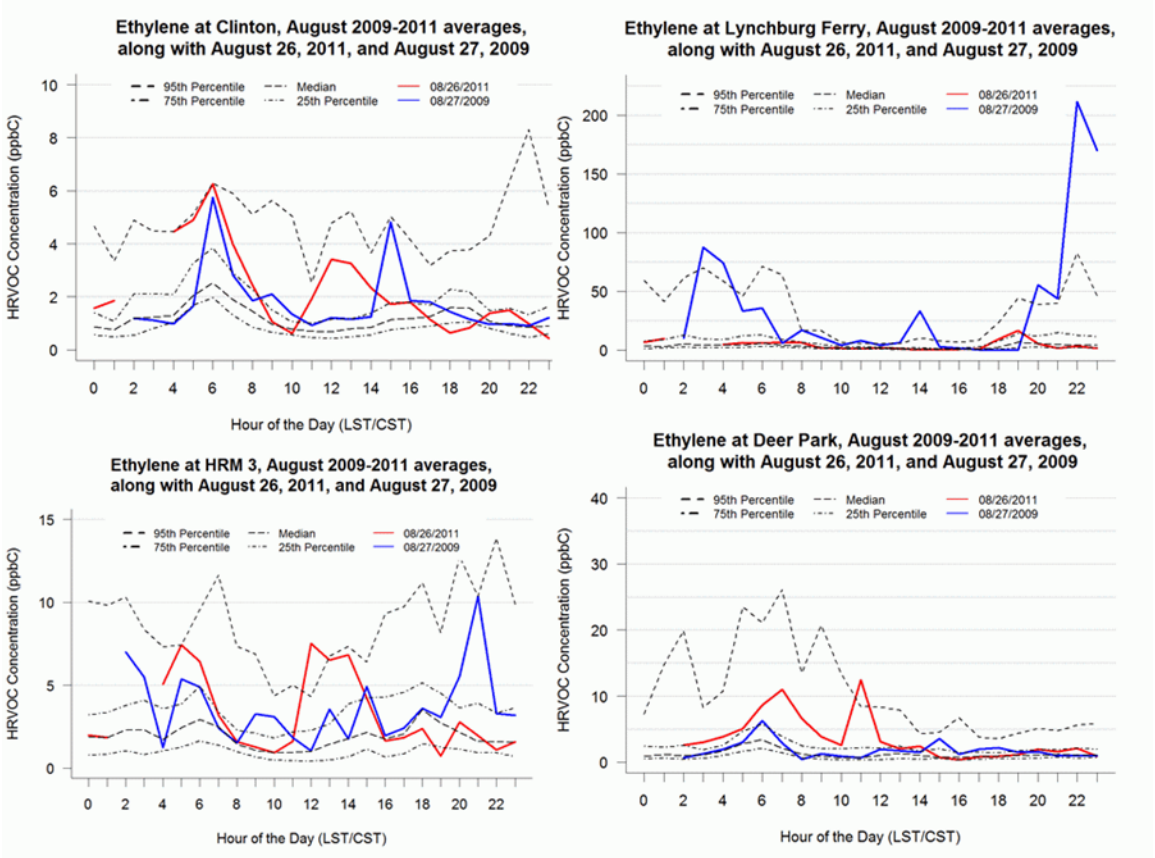


Figure 5-4: VOC Comparison of August 26, 2011 and August 27, 2009 (Ethylene)

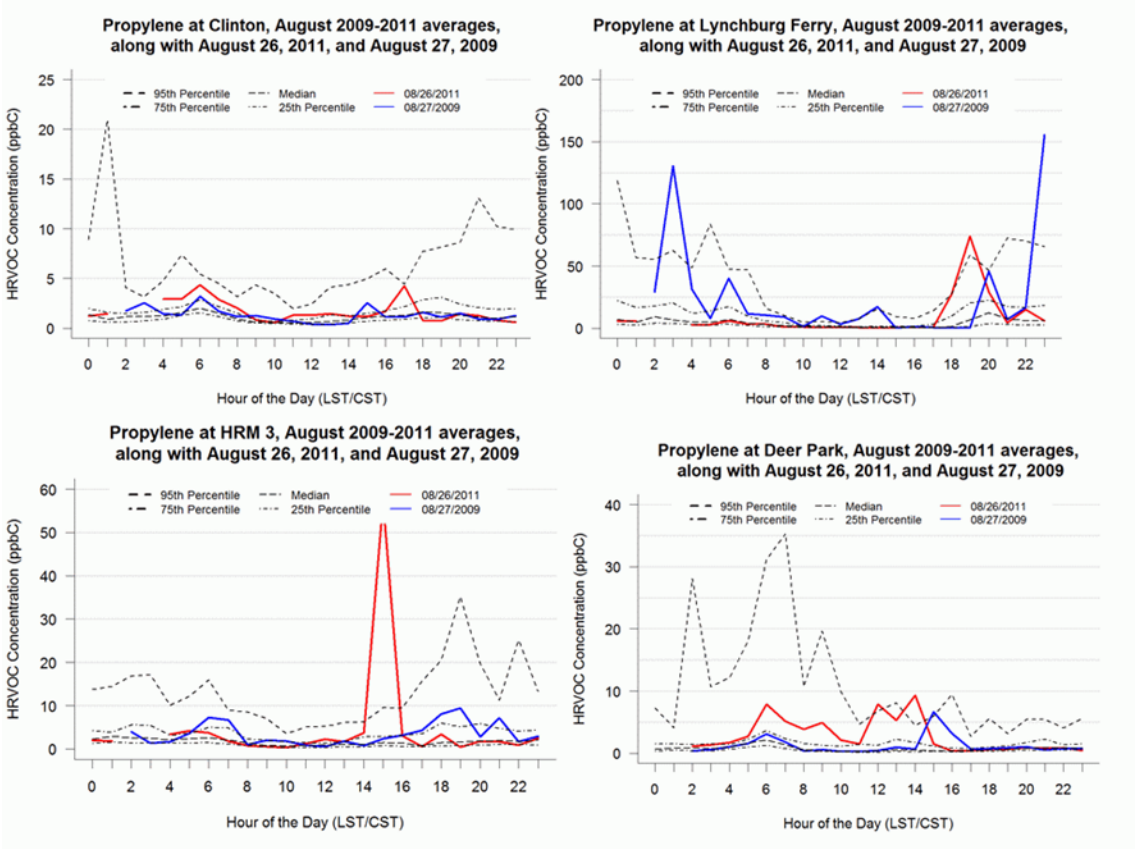


Figure 5-5: VOC Comparison of August 26, 2011 and August 27, 2009 (Propylene)

5.4 CONCLUSIONS

Candidate surrogate days were identified using HYSPLIT clustering of backward trajectories for all days between August 15 and September 15, 2009 through 2011. Comparison of local scale wind patterns and back trajectories to the exceptional event day, August 26, 2011, led to the identification of five candidate surrogate days with similar wind patterns. The computed "sinuosity" ratios of these five days were then compared to identify which were most similar to the smoke-affected day in terms of "straightness." The candidate surrogate day found to be most similar to August 26, 2011 was August 27, 2009. August 27, 2009, the surrogate day, had a similar back trajectory, flow reversal, and sinuosity value. The surrogate day also observed similar non-wind meteorological conditions, such as relative humidity, precipitation, and other conditions to August 26, 2011. Furthermore, regionally meteorological conditions for August 26, 2011 and August 27, 2009 were similar. Both days observed high pressure in the HGB area, weak frontal boundaries, and generally sunny, clear, warm days with light winds. Finally, although a difference in local emissions of ethylene was found, ethylene levels found on August 26, 2011 are not believed sufficient to create an exceedance without the contribution from fire-related emissions transported into the HGB area on August 26, 2011.

Given the meteorological and photochemical similarities between August 26, 2011 and August 27, 2009, the primary differences between the two days are the presence of an ethylene plume in the late morning or early afternoon, the widespread occurrences of high ozone measurements in the HGB area, and the presence of substantial smoke and wildfire-generated emissions on August 26, 2011. The surrogate day had a peak ozone one-hour value of 111 ppb while August 26,

2011, measured a maximum one-hour ozone value of 128 ppb. Fire emissions from outside Texas must be considered as a cause of the one-hour ozone exceedance that occurred on August 26, 2011

CHAPTER 6: DOCUMENTATION OF THE PUBLIC COMMENT PROCESS

In following the requirements listed in Title 40 of the Code of Federal Regulations (CFR) §50.14(c)(3)(i), *Treatment of air quality monitoring data influenced by exceptional events*, the Texas Commission on Environmental Quality (TCEQ) posted this Exceptional Events Demonstration Package on the Agency website for public comment from August 7 through September 7, 2014. In accordance with 40 CFR §50.14(c)(3)(v), the TCEQ is documenting the public comments received in this section. All comments received during the comment period will be included in the submission.

CHAPTER 7: CONCLUSIONS

On August 26, 2011, the Houston-Galveston-Brazoria (HGB) area experienced an exceptional event that affected air quality throughout the area but most especially at the Houston East (CAMS 1) monitoring site. On that day, 18 of 19 monitors reporting data in the HGB area reported maximum one-hour daily maximum ozone values greater than the 95th percentile for 2009 through 2011. During the early afternoon hours of August 26, 2011, the Houston East (CAMS 1) ozone monitor measured an exceedance of the one-hour ozone National Ambient Air Quality Standard (NAAQS). In the days leading up to August 26, 2011, there were several large areas in the northwestern and southern United States (U.S.) experiencing wildfires. Unfortunately, these wildfire areas lay underneath the path of air parcels on their way to the HGB area. Smoke, nitrogen oxides (NO_X), and other pollutants from these fires mixed with the air overhead and were transported into the HGB area just in time to form significant plume of ozone. Without this wildfire-created ozone, there would have been no exceedance at the Houston East (CAMS 1) monitoring site that day.

The Texas Commission on Environmental Quality (TCEQ) has entered a preliminary/informational "flag" into the Air Quality System (AQS) monitoring data records for that day. Through the accumulated weight of evidence gathered in this document, the TCEQ has demonstrated satisfactorily that it has met the requirements set down in the federal clean air act and the Exceptional Event Rule (EER) and that the exclusion of monitoring data from this day at the Houston East (CAMS 1) monitoring site is warranted. The TCEQ now asks the U.S. Environmental Protection Agency (EPA) to concur with the TCEQ and enter an exceptional events "flag" into the appropriate AQS data records. The TCEQ also requests that after this flag is entered that the data from the Houston East (CAMS 1) monitoring site for August 26, 2011 not be used in regulatory activities associated with classification of metropolitan areas with respect to ozone.

The TCEQ has met the requirements set forth in the EER in the following manner:

1. The exceptional event affects air quality.

The Houston East (CAMS 1) monitoring site observed a daily maximum one-hour ozone concentration of 128 parts per billion (ppb) during the 1:00 p.m. to 2:00 p.m. LDT monitoring hour. The TCEQ has met the rule requirement by showing that fire-related emissions from outside the state caused high levels of ozone and ozone precursors to be transported into the HGB area and cause an exceedance of the one-hour ozone NAAQS. More specifically, the TCEQ has demonstrated the causal relationship between fire-related emissions and high ozone levels in the HGB area both theoretically and empirically, including August 26, 2011 (Chapter 4: *A Clear Causal Relationship Between Fire Emissions and Higher Ozone*). Further, the TCEQ has shown through analysis of a surrogate day similar to August 26, 2011, that a one-hour ozone NAAQS exceedance would not have occurred without the fire-related emissions.

2. The event is not reasonably controllable or preventable.

The fires causing the high levels of ozone and ozone precursors in the HGB area occurred outside the State of Texas in the Lower Mississippi River Valley. Consequently, Texas had no opportunity to prevent or control for those emissions.

3. The event is either caused by human activity that is unlikely to recur at a particular location or a natural event.

The large majority of wildfires burning around the U.S. on the days leading up to August 26, 2011 were believed to be natural in origin. Some, however, may have been caused by human activity. Wildfires, by their very nature, limit the probability of those events recurring at the same location in the near future. Even if the fires started again at the same locations, those locations are outside of Texas and beyond the authority of the State of Texas to control or prevent.

4. There is a clear causal relationship between the measurement under consideration and the event.

In Chapter 4: *A Clear Causal Relationship Between Fire Emissions and Higher Ozone,* the TCEQ provides strong evidence supporting the relationship between wildfires and enhanced levels of ozone – even after long transport distances. The literature review also cites three clear cases of previous ozone enhancement caused by fire-related emissions that transported into the HGB area. At least one of these events involved transport over even longer distances than are considered in this exceptional event. An exhaustive analysis of HYSPLIT trajectories demonstrated that the causal was clearly more than a plausible consideration. These analyses show that trajectories to the Houston East (CAMS 1) monitoring site passed over large wildfire areas while the fires were in progress and that emissions very likely entrained in those air parcels and transported to the HGB area. These analyses also show that air parcels from higher in the atmosphere subsided quickly when arriving in the HGB area bringing emissions and higher ozone levels from higher up in the atmosphere. The finding of Section 3.6: *Southeast Texas Monitoring Sites*, where 18 of 19 monitors in the HGB area measured daily one-hour maximum values greater than the 95th percentile on August 26, 2011 also points to the causal relationship between smoke, wildfire-related emissions and ozone in the HGB area. Finally, satellite imagery and computer modeling images provide strong support for the causal relationship that affected air quality on August 26, 2011. Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO) measurements clearly indicate that between the surface and about 4 km altitude a broad smoke plume was transported into the HGB area on August 26, 2011. Geostationary Operational Environmental Satellites (GOES) satellite imagery as well as National Oceanic and Atmospheric Administration interpretations document the smoke plumes in southeast Texas as well. The total weight of this evidence makes a strong case concluding that fire-related emissions caused the exceedance at the Houston East (CAMS 1) monitoring site.

5. The event is related to a measured concentration in excess of normal historical fluctuations.

In Chapter 3: *Normal Historical Fluctuations at the Houston East (CAMS 1) Monitoring Site*, the TCEQ demonstrates that the measured daily one-hour maximum ozone value at Houston East (CAMS 1) monitoring site, 128 parts per billion (ppb), was well outside the normal historical fluctuations at the site. When compared to nearly 700 seasonal ozone observations collected over three years (2009 through 2011) August 26, 2011 was shown to lie in the top 1 % of daily seasonal maximums. When compared to over 1,000 observations on an annual basis for the same time, August 26, 2011 also lay in the top 1 %. Analysis of diurnal ozone profiles for Houston East (CAMS 1) monitoring site involving 3,500 data points for the month of August in 2008 through 2012 also showed that August 26, 2011 was an outlier. A review of ozone monitoring data for August 26, 2011 revealed that a large majority of the ozone monitoring sites throughout southeast Texas had unusually high one-hour daily maximum ozone measurements.

Even more compelling is the fact that 18 of 19 ozone monitoring sites in the HGB area reported one-hour daily maximum ozone values that were greater than each site's 95th percentile on August 26, 2011.

6. There would have been no exceedance but for the exceptional event.

Chapter 5: *No Exceedance but for the Exceptional Event*, compares August 26, 2011, to a very meteorologically similar day (August 27, 2009) where the only significant difference between the two days is the presence of fire-related emissions over the HGB area on August 26, 2011. The one difference in local emissions of ethylene is not likely to have caused an increase of 17 ppb in the maximum one-hour measurement at Houston East (CAMS 1) monitoring site. Without the extra ozone and precursors contributed by wildfires outside of Texas, the one-hour ozone NAAQS exceedance of 128 ppb would not have occurred. The similar day in 2009 only had a maximum one-hour measurement of 111 ppb – a difference of 17 ppb that is, at the very least, partially attributable to the fire-related emissions.

7. The TCEQ followed the required public comment process.

Since submittal of this document was not a SIP revision or a rule action, the TCEQ was not required to hold public hearings or go before its commission prior to submittal to the U.S. EPA. This document was posted on the TCEQ website for 30 days, and copies of all comments received from the public are included in the final submission.

8. The state complies with 40 Code of Federal Regulations (CFR) §51.930, which requires the state to take appropriate and reasonable actions to warn, educate, and protect the public from exceedances of the one-hour ozone NAAQS.

It is demonstrated through implementation plan revisions that the HGB area, one of the country's largest and fastest growing metropolitan areas, has put into place one of the most innovative and effective set of control strategies in the U.S (Chapter 1: *Introduction*). The HGB Attainment Demonstration and Rate of Further Progress State Implementation Plan have gone through a very rigorous evaluation process photochemical modeling, peer review, public review, and the thorough review of the U.S. EPA. TCEQ control strategies for the HGB area have consistently passed the rigorous U.S. EPA review applied to SIP revisions. In addition to its effective control strategies, the TCEQ leverages contemporary media tools to provide up-to-the-minute air quality updates to people in the HGB area with electronic mail, its website, local media outlets that notify the public, and Internet links to other air quality resources like the U.S. EPA, AirNow, AirNowTech, and many other sites. On its own website, the TCEQ makes air quality data available to the public within one to two hours of its collection in the HGB area. The TCEQ also actively supports public awareness campaigns such as the "Take Care of Texas Program." Through the Texas Emissions Reduction Plan (TERP) program, Rider 8 program, and air quality research funds, the TCEQ has spent hundreds of millions of dollars annually to help citizens reduce ozone causing pollution and better understand the complexities of ozone reductions so that the TCEQ and stakeholders in the HGB area and other areas throughout the state can continue working together to reduce ozone levels even more.

This , is the TCEQ case for the EPA's concurrence on the exceptional event flag with respect to the events of August 26, 2011, at the Houston East (CAMS 1) monitoring site. The TCEQ believes that it is submitting a strong, persuasive, and clear case for excluding the exceptional event occurring on August 26, 2011.

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APPENDIX A: PRESS RELEASES/MEDIA REPORTS

U.S. EPA guidance suggests the inclusion of news reports to support Exceptional Events evidence:

Air agencies can provide the following information to help establish the occurrence and geographic extent of the event: special weather statements, advisories, news reports;

This appendix provides various web related news reports (links) that support that the wildfires did happen, that some were not reasonably controllable or preventable as in the case of lightening.

These links provide include documents of fires and smoke on or around August 26, 2011 Additionally, reports from the climate and wildfire reports were collected from the National Oceanic and Atmospheric Administration (NOAA) and the United States Forest Service (USFS). Web links to documents are provided below

http://wildfiretoday.com/2011/08/25/lightning-starts-fires-in-the-northwestern-united-states/

http://www.noaawatch.gov/headlines/fire_wx.php

http://www.blm.gov/or/districts/burns/files/BU_FireUpdate_August252011_6pm.pdf

http://www.blm.gov/or/districts/burns/files/BU_FireUpdate_August262011_7am.pdf

http://www.thewildlifenews.com/2011/08/23/idaho-montana-forest-fires-heating-up/

http://articles.cnn.com/2011-08-26/us/california.fire_1_propane-tank-yosemite-national-park-wildfire?_s=PM:US

http://alg.umbc.edu/usaq/archives/004293.html

Plains states experienced elevated ozone levels today (August 26, 2011) with Kansas, Oklahoma, Texas, Georgia, and Florida reporting Code Orange (Unhealthy for Sensitive Groups) ozone levels. NOAA's Hazard Mapping System (HMS, bottom left) shows smoke from various fires continuing to cover a large part of the country.

http://alg.umbc.edu/usaq/archives/2011_08.html

http://www.ssd.noaa.gov/PS/FIRE/DATA/SMOKE/2011/2011H280420.html