

INFLUENCE OF TRANSPORT BY THE NOCTURNAL JET ON OZONE LEVELS IN CENTRAL TEXAS

2009 YEAR-END REPORT

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MARCH 12, 2010

ABSTRACT

KWKT tower in Moody, Texas has been the home to NOAA's CO, CO₂ and meteorological continuous-monitoring equipment since 2006. Additional instrumentation was installed in April, 2009 and the tower now hosts a number of continuous-sampling instruments at multiple levels (6m, 30m, 122m and 457m above ground level (AGL)), that measure ozone, carbon dioxide, carbon monoxide, and meteorological components (temperature, relative humidity, wind direction and wind speed) every 30 seconds. The primary purpose for this study is collecting the tower measurements to determine whether ozone levels in central Texas are influenced by the nocturnal transport of air that carries ozone and precursors from upwind sources. In addition to continuous tower measurements, an ozonesonde-launching intensive was conducted during late August and September, which is a time of year with many high ozone (O₃ > 80 ppb) days. Newly installed and already existing instrumentation at the site, data collection and quality assurance, and instrument calibration is discussed in detail. Major accomplishments, as well as difficulties, of the project are discussed. General seasonal trends and findings are presented, including quantification of diurnal and seasonal nighttime median wind, ozone, CO and CO₂ values. Evidence suggests that the low-level nighttime continental jet exists and affects ozone levels occasionally, but to what extent needs to be quantified further. High ozone levels can also be a result of non-jet N/NE winds that have travelled from the vicinity of Dallas before reaching the tower. In addition to study conclusions, recommendations for further study and unresolved issues are also discussed.

INTRODUCTION

PURPOSE

The purpose of this project is to determine whether ozone in central Texas is influenced by the nocturnal transport of air that carries ozone and precursors from upwind sources. In order to accomplish this determination, there are two primary objectives. The first is to characterize the frequency, strength, and direction of the nocturnal low level jet in central Texas. The second objective is to evaluate the effect of the low-level jet upon daytime and nighttime transport of ozone from urban and industrial sources in central Texas.

NOAA/ESRL currently has a lease to operate sensors installed on and at the base of the KWKT-TV tower near Moody Texas. Before the beginning of this project, the tower was instrumented at two levels for measuring winds, temperature, relative humidity, and at three levels for measuring CO and CO₂. In order to evaluate the transport of ozone from other areas, additional instrumentation was installed on the tower. The ongoing project also involved an ozonesonde balloon launch intensive during the 2009 ozone season in order to measure the vertical profile of winds and ozone through the jet.

BACKGROUND

Ozone formed at ground level during ozone pollution episodes mixes through the depth of the boundary layer during the course of the day. Typically the ozone concentrations at the surface erode during the night as a nocturnal inversion forms and decouples the surface from the upper air. However, it has been found that a residual layer of high ozone persists throughout the night above the nocturnal surface layer. This layer of enhanced ozone is then available the next morning to be mixed down to the surface where this residual ozone serves as an initiator for the daytime ozone chemistry.

The development and subsequent evolution of this nocturnal layer has been studied with episodic aircraft measurements but has not been monitored on a continuous basis over an extended period of time. Continuous ozone measurements were collected near the surface and at altitudes of 30 and 457m on a tall-tower near Waco, Texas in order to better understand the formation and transport of the elevated ozone layer and its contribution to surface ozone formation both locally and on a regional scale.

During the summer of 2006, wind, CO and CO₂ data were collected at the KWKT-TV tall tower site. When combined with back trajectory data, the wind speeds and directions measured at the tower helped identify source regions and industrial sources in central Texas. Preliminary

analysis of the 2006 data has also identified unique ratios between CO and CO₂ that allow discrimination between electric generating units and other industrial sources.

As part of TEXAQS 2006, a prototype analyzer was installed at the 457 m level on the KWKT tower along with an analyzer measuring at the near-surface height of 6 meters. The analyzers operated from July-December 2006. These measurements confirmed the maintenance of the nighttime residual ozone layer at the top of the tower, particularly during the summer months. Several high ozone episodes (O₃ > 80 ppb) were recorded during this campaign. Preliminary analysis (Andrews et al., 2009) indicated influence on the high ozone readings by transport from large urban regions (Houston and Dallas).

TOWER INSTRUMENTATION

Instrumentation was added to the tower site to measure ozone concentrations at 6m (surface), 30m and 457m. A meteorological measurement system was also installed at 6m to monitor conditions at the surface in order to create a more complete vertical profile. With the new instrument additions at the surface, 30 and 457 meters, the measurements provide a vertical wind profile of the jet during both day and night, as well as the ozone concentrations and transport contributions in central Texas. The new instrumentation is a good addition to the CO/CO₂ and meteorological measurements that have existed on the tower for several years.

Instruments	Wind Speed / Wind Direction	Temperature	Relative Humidity	CO	CO ₂	Ozone
Height AGL						
457 meters	X	X	X	X	X	O
122 meters				X	X	
30 meters	X	X	X	X	X	O
Surface/6 m	O	O	O			O

Table 1) KWKT instrumentation installed in April 2009 (O) and existed previous to April 2009 (X).

Data gathered at this site has the potential to assist researchers in investigating the contributions of ozone from urban and industrial sites, for emissions from new power plants, and as a benchmark for evaluation of other regional-scale phenomena at several different levels in the boundary layer of the troposphere. The project provides support for analysis and interpretation of this unique data set, which could yield important insights into regional scale ozone transport in central Texas. The success of the project could also validate the need for follow-up studies, which would propose to install additional instrumentation at intermediate levels of the tower.

INSTRUMENTATION

All the new ozone instrumentation installed at the WKT site is based on UV absorption at 254 nm. Two different ozone instrument models are now in use at the site, one larger unit housed in the trailer at the surface and a smaller, more portable, weatherproof model in two tower locations. A meteorological measurement system, similar to those previously existing at the 30m and 457 m-tower levels was also installed at the surface. The continuous CO and CO₂ analyzers have been operating at the site for several years and are briefly described.

SURFACE (6M) OZONE INSTRUMENT

A Thermo Scientific Ozone Analyzer, Model 49i O₃ Analyzer (Photo 1) was installed in the instrumentation trailer at the base of the tower. An inlet for this instrument was installed at 6 m AGL (Photo2). The Model 49i Ozone Analyzer is capable of taking observations at up to 1-minute time resolution. This system is currently implemented at 12 NOAA long-term surface ozone monitoring sites. A general description excerpted from the Thermo Scientific brochure for the Model 49i is as follows:

The Thermo Scientific Ozone Analyzer, Model 49i utilizes UV Photometric technology to measure the amount of ozone in the air from ppb levels up to 200ppm. The Model 49i is a dual cell photometer, the concept adopted by the NIST for the national ozone standard.

Dual range and auto range are standard features in this instrument. Because the instrument has both sample and reference flowing at the same time a response time of 20 seconds can be achieved. Temperature and pressure correction are standard features. User settable alarm levels for concentration and for a wide variety of internal diagnostics are available from an easy to follow menu structure.

Photo 1) *The Model 49i Ozone Analyzer is larger and less portable than the tower instruments, but has better precision and is less likely to drift.*





The analyzer, which can be operated remotely by computer, measures a range from 0.05 to 200 ppm with a precision of 1 ppb, so is well-suited for any surface-layer ozone conditions. The instrument also has very little drift and will run without maintenance for long periods of time, as proven at other NOAA monitoring sites.

Photo 2) The surface inlet mounted inside long conduit leads to a monitor that resides inside the instrument trailer. A radiation shield housing a T/RH probe is mounted next to the ozone inlet at the top of the conduit.

Preset Ranges	0-0.05, 0.1, 0.2, 0.5, 1, 2, 5, 10, 20, 50, 100 and 200 ppm
	0-0.1, 0.2, 1, 2, 5, 10, 20, 50, 100, 200 and 400 mg/m ³
Custom Ranges	0-0.05 to 200 ppm
	0-0.1 to 400 mg/m ³
Zero Noise	0.25 ppb RMS (60 second averaging time)
Lower Detectable Limit	0.50 ppb
Zero Drift (24 hour)	< 1.0 ppb
Span Drift	<1% full scale per month
Response Time	20 seconds (10 second lag time)
Precision	1.0 ppb
Linearity	+/-1% full scale
Sample Flow Rate	1-3 liters/min.
Operating Temperature	20 °C - 30 °C
Power Requirements	100 VAC, 115 VAC, 220-240 VAC +/-10% @ 150W
Size and Weight	16.75"(W) x 8.62"(H) x 23"(D), 55 lbs.
	425 mm (W) x 219 mm (H) x 584 mm (D), 25 kg
Outputs	Selectable Voltage, RS232/RS485, TCP/IP, 10 Status Relays, and Power Fail Indication (standard). 0-20 or 4-20 mA Isolated Current Outout (optional)
Inputs	16 Digital Inputs (standard), 8 0-10vdc Analog Inputs (optional)
Approvals and Certifications	US EPA Equivalent Method: EQOA-0880-047
	MCerts Certified: MC070096/00
	EN14626: 936/21203248/13 Report
	NF Certificate: 05/01

Table 2) Instrument specifications provided by Thermo Scientific Instruments for the Model 49i Ozone Analyzer.

TOWER (30M AND 457M) OZONE INSTRUMENTS

New ozone instrumentation was installed at the 30 m and 457m locations in April. The continuous measurements are made using a compact, light-weight analyzer manufactured by 2B Technologies of Boulder, Colorado. For 1-minute measurements the precision of the 2B analyzer (Photo 3) is about 1.3-1.5 ppb (one standard deviation) compared to the surface TEI 49i where the comparable precision would be 1.0 ppb. The accuracy of the 2B analyzer for continuous observations over a several-month operating period is also on the order of 1-2 ppb. More information about the analyzer is as follows from the 2B brochure:

The 2B Technologies Model 202 Ozone Monitor™ is designed to enable accurate and precise measurements of ozone ranging from low ppb (precision of ~1 ppb) up to 100,000 ppb (0-100 ppm) based on the well established technique of absorption of UV light at 254 nm. The U.S. Environmental Protection Agency (EPA) has assigned the method number "901-O₃ Model 202" to the Model 202 Ozone Monitor. The Model 202 Ozone Monitor™ is light weight (4.7 lb., 2.1 kg.) and has low power consumption (12V DC, 0.33 amp, 4.0 Watt) relative to conventional instruments and is therefore well suited for applications such as:

Vertical profiling using balloons, kites, RPVs and light aircraft where space and weight are highly limited

Long-term monitoring at remote locations where power is highly limited

The lightweight analyzer has low power requirements, a flow meter, and back-up pump which made it useful for our application on the tower. The instrument has a temperature operating range of 0-50°C, (but can operate at -20-50°C with modifications).

Photo 3) 2B Technologies Model 202 Ozone Monitor is small and lightweight with low power requirements.



For each of the two tower levels, a 2B ozone analyzer (blue unit in Photo 4) was procured and built into a weather-proof, temperature-regulated case. Supplemental components were added to enhance the long-term performance and data transmission such as:

- Temperature-controlled fans
- Large particle filter
- Zeroing cycle (to quantify drift)
- Computer control board
- Improved catalyst (MnO_2)
- Power supply (convert 110VAC to 12VDC)
- Upgraded pump with a 2-year minimum lifetime

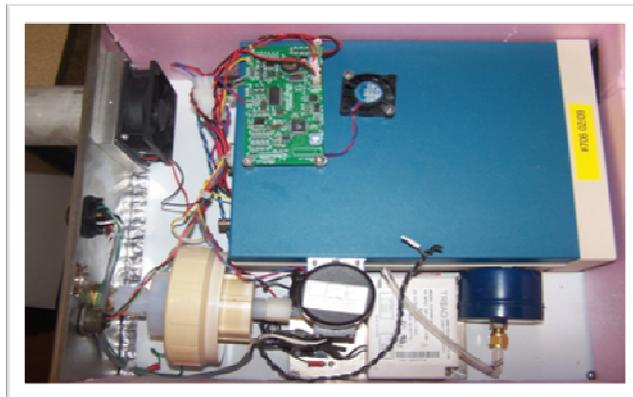


Photo 4) Inside a tower-mounted ozone instrument.

METEOROLOGICAL INSTRUMENTATION

An additional meteorological measurement system was installed at the surface level. This system combines several sensors, a Vaisala HMP45AC temp humidity sensor, a Met One Instruments Model T200A Platinum resistance temperature sensor, a Gill Instruments Wind Observer II, and a Met One Instruments Radiation Shield model 077. The specifications and other details on these instruments can be found at:

HMP45AC temperature/humidity sensor (Vaisala):

<http://www.campbellsci.com/hmp45c-l>

Model T200A Platinum resistance temperature sensor (Met One instruments):

http://www.metone.com/documents/T-200A_DS.PDF

Radiation Shield model 077 (Met One instruments):

<http://www.metone.com/documents/077AspiratorTemp.pdf>

Wind Observer II, Ultrasonic Anemometer (Gill Instruments):

http://www.gill.co.uk/products/anemometer/wind_ob2.htm

The Vaisala temperature/relative humidity probe has an accuracy of approximately 1% and can measure a range from 0.8% to 100% relative humidity. The Wind Observer II gives wind directions and wind speeds of up to 65 m/s with an accuracy of 2%. These combination meteorological systems have been operating at other sites and on the tower for many years with good success.

CONTINUOUS CO AND CO₂ ANALYZERS

The CO₂ and CO analysis system at WKT was been developed for deployment at sites in the NOAA Earth System Research Laboratory's (ESRL) Carbon Tracker Tall Tower Observing Network. The design is largely derived from the original CO₂ and meteorological sampling equipment deployed at the NOAA ITN, LEF, WKT and AMT tall tower sites (Zhao, Bakwin et al. 1997; Bakwin, Tans et al. 1998), but with modifications to minimize sensitivity to environmental conditions (such as room temperature). The precision and long-term stability of the systems in the field are typically better than 0.1 ppm for CO₂ and 6 ppb for CO, as determined from repeated measurements of a suite of standard gases and comparison with flask samples of air collected at the sites. The instrumentation is fully automated and includes sensors for measuring a variety of engineering parameters, such as temperature, pressure and flow data, that are inputs for automated quality control algorithms. Each analyzer has three sample inlets for profile sampling, and a complete profile is obtained every 15 minutes.

The CO instrument used at WKT is the Thermo Electron Corporation 48C trace-level CO Analyzer:

The Model 48C Gas Filter Correlation (GFC) CO Analyzer measures low CO concentrations. The Model 48C is based on the principle that carbon monoxide (CO) absorbs infrared radiation at a wavelength of 4.6 microns. Because infrared absorption is a nonlinear measurement technique, it is necessary for the instrument electronics to transform the basic analyzer signal into a linear output. The Model 48C uses an exact calibration curve to accurately linearize the instrument output over any range up to a concentration of 10,000ppm. The sample is drawn into the analyzer through the SAMPLE bulkhead. The sample flows through the optical bench. Radiation from an infrared source is chopped and then passed through a gas filter alternating between CO and N₂. The radiation then passes through a narrow bandpass interference and enters the optical bench where absorption by the sample gas occurs. The infrared radiation then exits the optical bench and falls on an infrared detector.

The LI CO₂/H₂O Gas Analyzer is the CO₂ instrument used at WKT:

The LI-7000 CO₂/ H₂O Gas Analyzer is a high performance, dual cell, differential gas analyzer. It uses a dichroic beam splitter and two separate detectors to measure infrared absorption by CO₂ and H₂O in the same gas stream. At the heart of the LI-7000 is an innovative optical bench that can be dismantled and cleaned by the user without the need for factory recalibration.

GRANT TASK FULFILLMENT

In order to execute the study and fulfill the tasks of the grant, ozone and meteorological instrumentation was installed, measurements were collected and QA/QC'd, and an ozone launch intensive was conducted for three weeks during the 2009 summer season. During the Spring and Summer seasons, monthly status reports, three preliminary reports and this summarizing report were emailed to the Project Leader. The following section summarizes accomplishments and details difficulties encountered of fulfillment of each task.

TASK 1 - PROCURE AND INSTALL ADDITIONAL INSTRUMENTATION ON THE KWKT-TV TOWER

ACCOMPLISHMENTS

In order to complete Task 1, one instrument (TEI 49i Ozone Analyzer) was installed at the surface, and two instruments (2B O₃ Analyzers) were mounted on the tower at 30 and 457 meters. A meteorological sensor package (wind speed, wind direction, temperature and humidity) was also installed at the surface site.

The ozone instrument installed at the surface was ready for use without much modification, except that the instrument calibration pump was rewired to allow remote calibration without the need for manual local operation. The instrument was calibrated against a NIST-calibrated ozone standard.

A meteorological measurement system, similar to the instruments existing at 30 and 457m, was installed at the surface (see Meteorological Instrumentation section for instrument specifications). The system collects measurements of wind direction, wind speed, temperature and relative humidity. In order to install the system and the ozone instrument at the surface level, an inlet was erected far above the trailer to minimize any possible interference to the meteorological and ozone

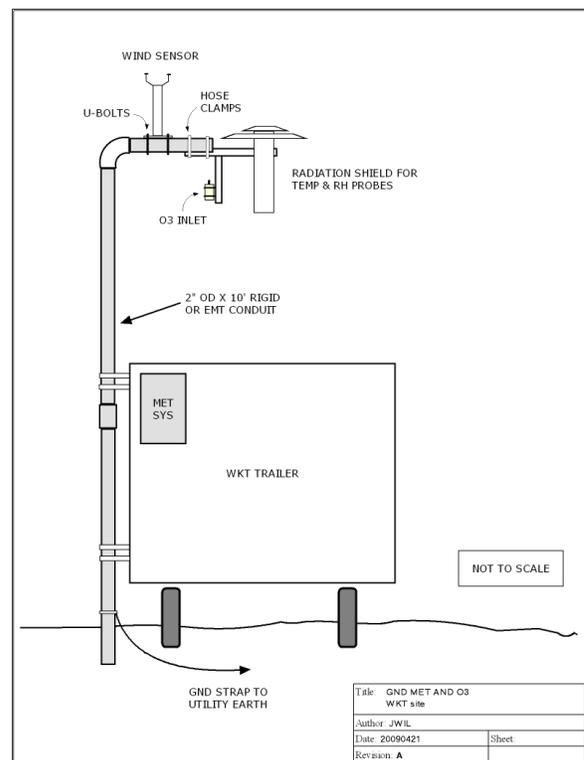


Diagram 1) Surface ozone inlet and meteorological system installation required installing conduit that reached well above the trailer roof.

measurements. The system and ozone inlet were mounted on the constructed conduit inlet above the trailer at 6m AGL (Photo 5). To protect the inlet line and electronic cables as well as to provide a home to the meteorological system, conduit was purchased, anchored into the ground and stabilized with guy-wires (Diagram 1).



Photo 5) *The surface meteorological system measures wind speed and direction, temperature, relative humidity. The orange and white bell in this photo protects the ozone inlet line from moisture.*

For installations on the 30m and 457 m-levels (Photos 6 and 7), two 2B Ozone Monitors were purchased and mounted inside weatherproof steel enclosures. Multiple components were added to the original instrument in order to weatherproof it and communicate data to the surface (detailed in Tower Ozone Instrumentation section above). The analyzers are mounted at the actual sampling level on the tower

eliminating the need for an impractically long intake line to reach a surface instrument. The instruments are interfaced with the meteorological equipment at each level for power and data transmission. Data transmission to the surface shelter takes place through a radio transmitter.



Photo 6) *Ozone instrument mounted at 30 m and Photo 7) 457 m.*

The elevated ozone instruments were calibrated previous to being mounted on the tower, and are continually calibrated against the surface instruments. If the calibration drifts over the course of the study, the errors can be identified and adjusted during the Quality Assurance processing included in the project. The surface and tower instrument calibrations are traceable

to NOAA/ESRL/GMD network standard that is regularly compared with the NIST maintained Standard Reference Photometer (SRP).

In addition to the instrumentation installation, monthly reports on the status of the instruments and data collection were generated and delivered via email.

DIFFICULTIES IN COMPLETING TASK

The only difficulty encountered during the completion of Task 1 was due to inclement weather despite calculated planning of the tower climb. During the installation process, the 30-meter ozone instrument was mounted without any problems, but due to the rainy Texas April weather, the tower climbers had to be rescheduled for installation of the 457m instrument. An additional trip to Texas was required to fulfill this task.

TASK 2 - COLLECT TOWER MEASUREMENTS FOR THE SPRING SEASON AND TASK 3 - COLLECT TOWER MEASUREMENTS FOR THE SUMMER SEASON

ACCOMPLISHMENTS

Task 2 and Task 3 of the grant included collecting hourly measurements from all the instruments. Hourly measurements for the spring (April 1- June 30, 2009) and summer (July 1 – September 30, 2009) seasons were collected (and, at the time this report was finished, all data through the end of February 2010 as well). The measurements collected at the site are automatically saved in a single data system for all instruments except the surface ozone analyzer, which is separately accessed on a remote computer application each week and the data downloaded.

At the end of each season, the data was QA/QC'd and analyzed to determine the day and night average wind speed, modal wind directions, and average ozone concentrations measured at the tower. The hourly averages were created for the meteorological data, though some finer resolution (30-second and one-minute) tower ozone data was produced, as well as the ozone hourly averages. The CO and CO₂ continuous measurement data was also QA/QC'd for the spring and summer seasons. The procedures to QA/QC the data were specific to each instrument output. Therefore, four different processes were used for the QA/QC of the data. For surface ozone data, computer programs were written to initially QA/QC the data and data not meeting quality requirements was removed, though this is quite rare for this instrument because it is so stable and protected from the elements. The data was then adjusted with calibration factors that were created with an initial NIST-standardized calibrator and the occasional remote calibration of the instrument. The surface data was then plotted and visually checked for any outliers.

The tower ozone instruments were initially calibrated against the NIST-standardized ozone calibrator in the laboratory. Both instruments have a “zero cycle” that scrubs all the ozone from the instrument intake each day for 10 minutes. Over time, these zero values are used to calculate whether the instrument is drifting. If drift occurs, the data is adjusted for this value. So far, it appears that the instruments have not drifted. Additionally, during the ozonesonde intensive, the ozonesondes were calibrated to the surface instrument and the ozonesondes then launched. The ozonesonde launch data was then compared with tower instrument values. These values appear to correlate well much of the time. The process for quality assurance with the tower ozone instruments involved writing programs that removed the zero cycle data and removed any instrument spikes or obvious outliers to the dataset. The 30-second data was then visually inspected and one-minute and hourly averages created from the resulting data.

The wind direction files were processed into one-hour modes and the wind speed files into one-hour averaged data. Wind direction at each level was checked for reasonableness against the other layers. Although at times, wind directions are expected to vary, the overall wind direction during the night (when the winds are stronger) is generally similar for the three levels, indicative of good quality measurements at all levels. During the ozonesonde intensive, the wind direction and wind speed values on the tower were checked against those from the ozonesonde launches that had GPS equipment on them. This provided another quality and reasonableness check for the tower data.

The CO and CO₂ data were filtered with previously-created computer code and then visually checked. Flags are added to the carbon data to give the user a quality reference. The carbon data for 30m, 122m and 457m were processed into data files. The created files include hourly averages and the original data resolution, which is variable for the different levels. The data is offered in several formats and on a publically-available ftp site.

All data, which come from the instruments in Greenwich Mean Time (GMT), were translated into Texas Local Standard Time for ease of the data user. The resulting GMT and LST files reside on an ftp site available to the public.

Monthly reports regarding the status of the instrumentation and data collection were written and sent via email. Two preliminary reports, one for each season, were written summarizing the ozone, CO, CO₂ and meteorological data. The reports identified findings, trends or conclusions, and characterized the conditions that are associated with ozone transport. The written reports were sent via email.

DIFFICULTIES IN COMPLETING TASK

Difficulties encountered were minimal, but one issue was that the time required to QA/QC ozone, CO, CO₂, and meteorological data was much longer than expected. Much of the data was collected as 30- second averages, so there was a tremendous amount of data to process and then visually check for outliers.

One difficulty during the QA/QC process that will be remedied is that the ozone data did not include flags from the instrument during the “zero cycle”. Though most of the zero cycles were removed automatically, though some of the zero calibration values needed to be edited out by hand. New software to reprogram the boards on the instruments has already been written and will be added during the next tower climb in April 2010.

TASK 4 - CONDUCT OZONESONDE MEASUREMENTS DURING THE PEAK OZONE SEASON

ACCOMPLISHMENTS

Bryan Johnson and Laura Patrick launched twenty-one ozonesondes (two were tethered and then launched) from a site near the KWKT-TV tower. Though only fifteen were required, eighteen of these were GPS-equipped ozonesondes. The preparation stage of this task required pre-conditioning and testing of the ozonesondes in the laboratory and also before launch at the tower. This preparation and then packaging and shipping of the ozonesondes and related equipment for the intensive was a large process.

Excluding very rainy days, ozonesondes were launched for three weeks during the peak of the summer ozone season (late August and September). Two ozonesondes were launched on nights that were the most likely to demonstrate high ozone and transport.

The ozonesonde data was processed and vertical profiles of wind speed, direction, temperature, relative humidity and ozone concentrations were developed for each launch. As part of the QA/QC process, comparisons to Houston-based ozonesonde launches were made, as well as to the tower data.

A preliminary report for the ozonesonde balloon launch intensive was written and emailed to the project manager. The report discussed procedures, data analysis, and findings. The data from this ozone campaign is publically available on an FTP site.



Photo 8) Bryan Johnson prepares for a tethered evening ozonesonde launch.

DIFFICULTIES IN COMPLETING TASK

Though no difficulties occurred during the preparation or QA/QC stages of this task, several difficulties to the completion of Task 4 occurred during the ozonesonde intensive itself. During the first few days after arrival at KWKT tower, the site was burglarized and several data collection computers were stolen. The door to the trailer was ripped off during the burglary and needed to be replaced. The steps taken to remedy this situation include the replacement of the door, installation of additional locks, notification of the police and tower security personnel, and replacement of the data computers.

Another difficulty encountered was a long stretch of rain toward the end of the intensive. Instead of launching the ozonesondes during the heavy rain, which lasted about a week, Laura Patrick returned to the site at a later date to conduct four launches.

TREND ANALYSIS AND FINDINGS

In order to characterize the nighttime low level jet, wind speeds and directions, ozone, CO, and CO₂ values were analyzed for diurnal and seasonal trends. Nighttime and daytime measurements were separated to identify whether the nighttime and/or daytime data showed differing seasonal patterns. Back trajectories were created for special cases, particularly during very high or very low concentration ozone events.

WIND SPEEDS AND DIRECTIONS

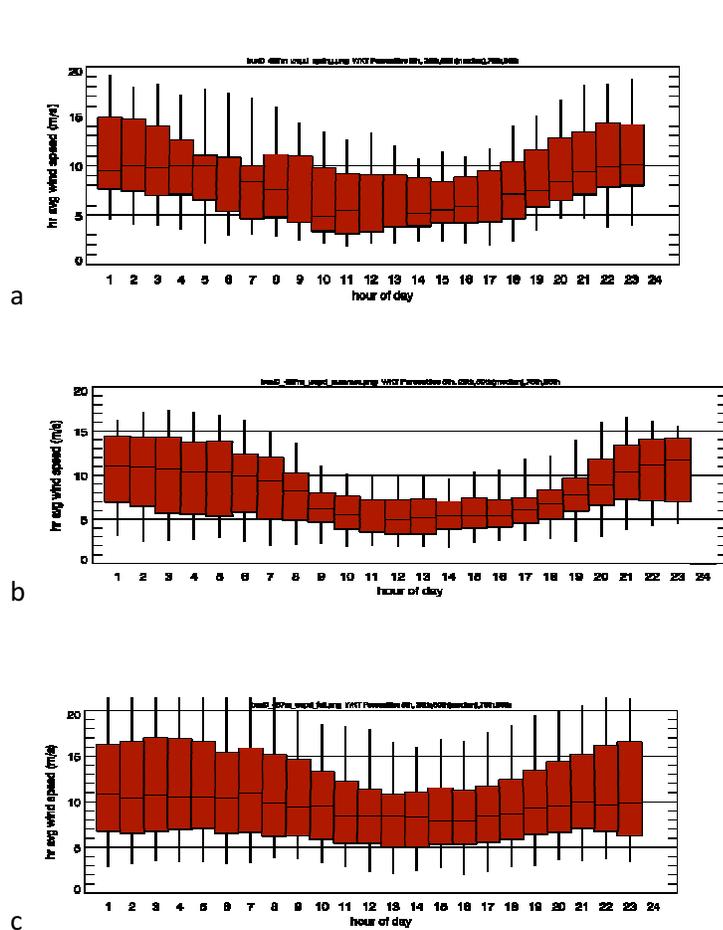


Figure 1) WKT wind speed percentiles 5th, 25th, 50th (median), 75th, 95th at 457m during **a)** spring (May, Jun), **b)** summer (Jul, Aug, and Sep) and **c)** fall (Oct, Nov, Dec). The summer season had slower midday wind speeds at all tower levels.

Wind speeds were monitored at 6 m, 30m and 457m, and were collected as 30-second averages. An expected result of the analysis was that the hourly-averaged wind speeds were faster and more variable at the 457-m level than at the surface or 30 m. The nighttime wind speeds at 457 meters were almost double their daytime values, this being true particularly in the summer season. During the summer season, midday winds were slower and less variable than evening winds. Additionally, the midday summer wind speeds were slower and less variable than spring or fall wind speeds (Figure 1).

Monthly nighttime wind speed percentiles are shown in Figure 2 and verify the increase of wind speeds with height. May and September have the slowest

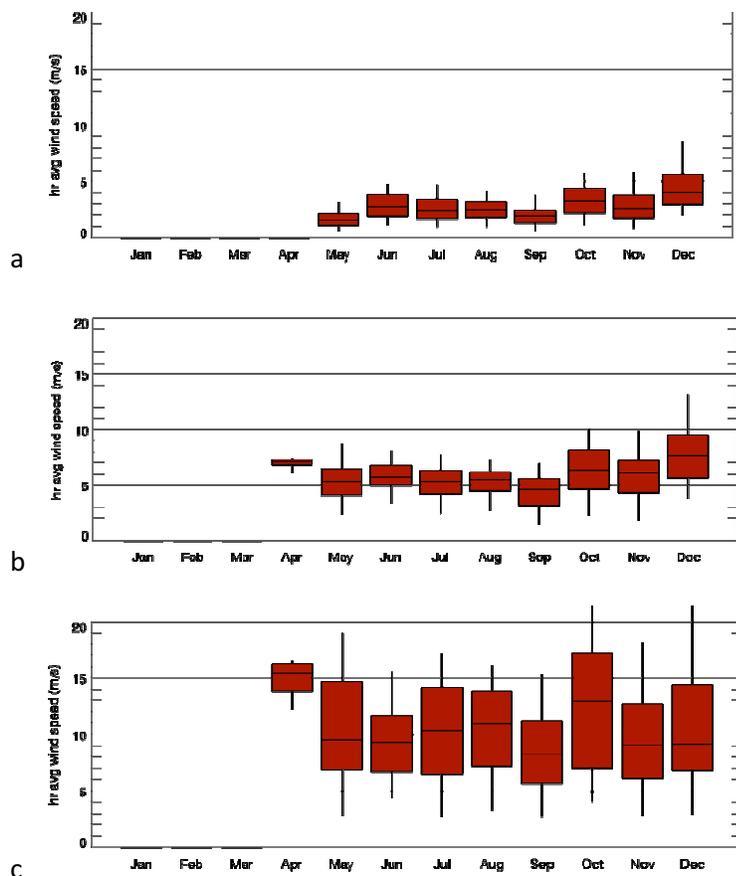


Figure 2) WKT nighttime wind speed percentiles 5th, 25th, 50th (median), 75th, 95th a) 6m, b) 30m and c) 457m.

associated wind directions. During all months, the nighttime wind speeds (marked by blue diamonds) are primarily from the S/SW direction and are faster than the daytime wind speeds (marked by red “x”s). According to HYSPLIT back trajectories, when the wind direction approaches the tower from the S/SW, this fast moving air has come from the Gulf of Mexico usually without intercepting any major urban areas. The ozone mixing ratios associated with this direction are usually lower, likely due to this very “clean” air originating near the Gulf of Mexico.

The May and June (spring) nighttime wind directions in Figure 3 show the winds very often from the S/SW, but sometimes from the NE direction (Dallas vicinity). As spring turns into summer, the winds are predominantly from the S/SW direction and in July, S/SW is the primary direction measured at the 457-meter level. Winds from the S/SW are also predominant during August, bringing “cleaner” air from the Gulf of Mexico. Occasionally during August, the winds come from the direction of major metro areas before arriving at the tower, bringing more polluted air with more ozone and ozone precursors. During September, the upper-level winds shift and come from more

median winds. May and September are also the months found to have more high ozone days than other months.

Varying wind speeds with altitude, particularly high speeds aloft and lower speeds near the surface, contribute to the formation of a nighttime boundary layer. Although the wind speeds at 457m almost double at night, those at lower levels do not.

Wind speeds are influenced by wind direction. Wind directions were monitored at the 6m, 30m and 457m tower levels, and were collected as 30-second averages.

Figure 3 shows the hourly-averaged wind speed and

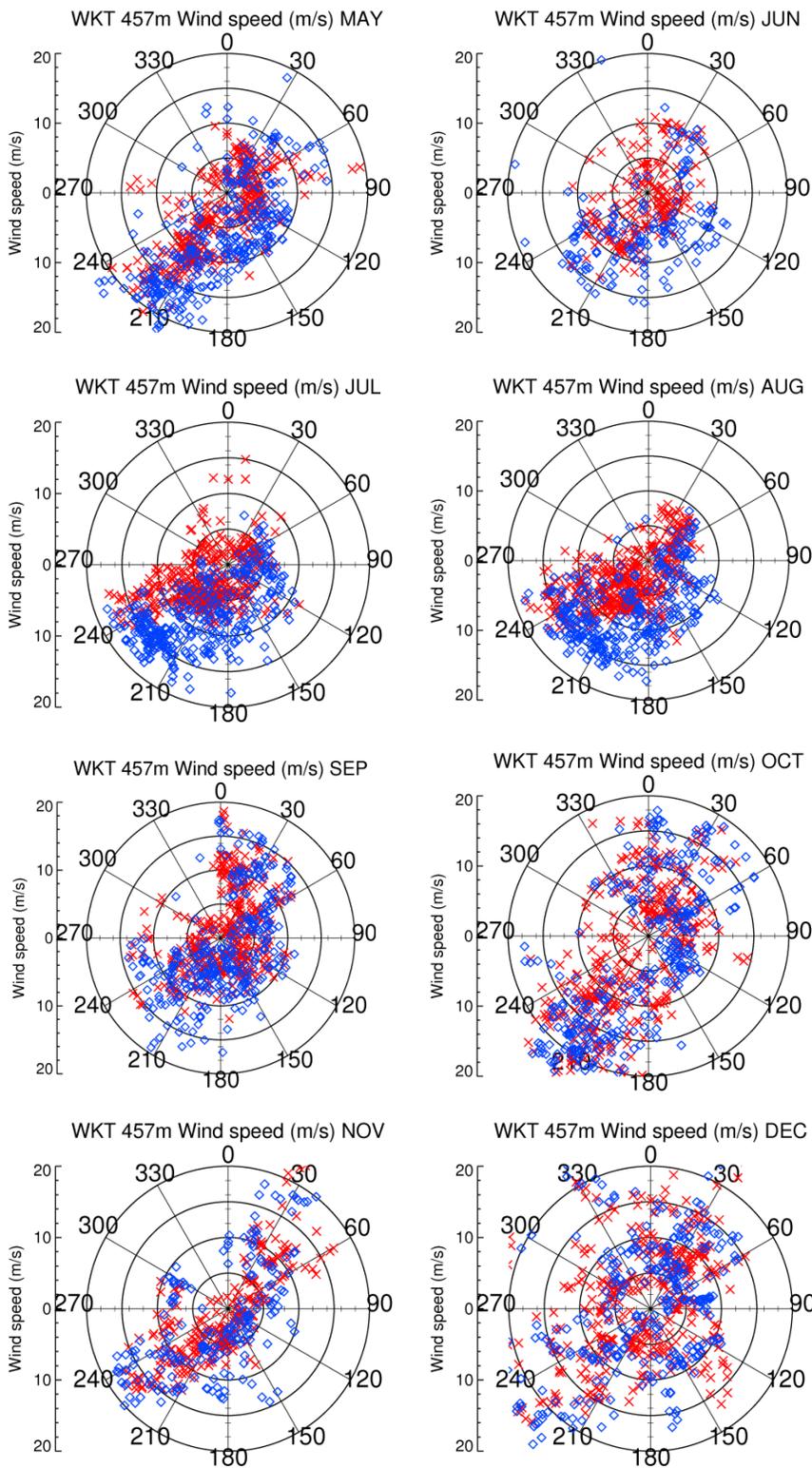


Figure 3) Wind directions and correlating wind speeds at 457-m for May – Dec, 2009. Blue diamonds represent nighttime and red “x”s daytime .

variable directions, bringing polluted air from the NE direction (Dallas/Fort Worth vicinity) and S/SE (Houston vicinity), as well as the S/SW.

Overall, the fastest wind speeds measured at the 457-m tower level are from the S/SW direction and likely originate in the vicinity of the Gulf of Mexico.

CO AND CO₂

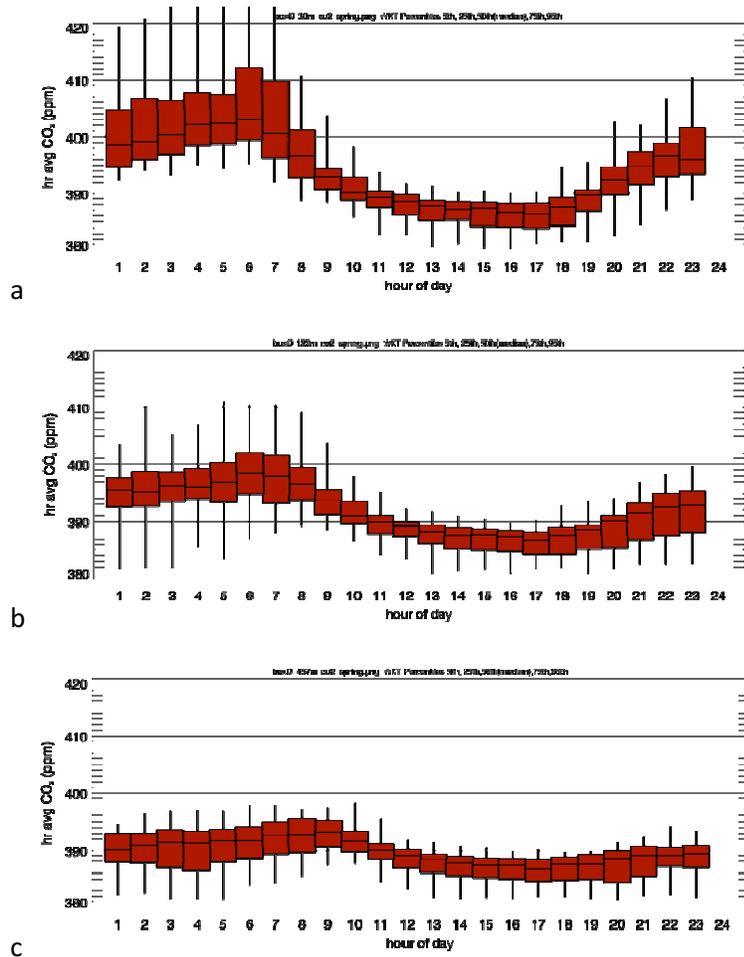


Figure 4) WKT CO₂ percentiles 5th, 25th, 50th (median), 75th, 95th during spring (May, Jun) at **a)** 30m, **b)** 122m and **c)** 457m. The summer diurnal CO₂ is similar, but has less range between daytime and nighttime values.

CO and CO₂ were monitored at the 30 m, 122m and 457m tower levels. Samples, carried down from the three tower levels through a long intake line, are analyzed at variable time intervals.

As expected, CO₂ was found to have more pronounced diurnal cycles at altitudes closer to the surface (Figure 4). The tower is located in a rural area comprised primarily of farmland with some riparian zones. Since CO₂ flux is strongly correlated with leaf temperature, during the times of day with the highest irradiation, CO₂ uptake is the highest. This temperature/CO₂ relationship also leads to the conclusion, which is verified by tower data, that the larger range of diurnal temperatures in spring, which is higher than in the summer, contributes to a larger springtime diurnal CO₂ flux. Although the diurnal range of spring CO₂ values was larger, the median monthly concentrations of CO₂ (Figure 5) were lower in the summer season, reflecting that CO₂ uptake has a strong dependency on irradiation and photosynthesis.

Carbon monoxide is an ozone precursor and involved in the formation of ozone, in the presence of NO_x and VOCs. CO is a product of vehicle exhaust and industrial emissions, so typically peaks during the day. Carbon monoxide is one of the important trace gases because its concentration in the troposphere directly influences the concentrations of tropospheric hydroxyl (OH). During the day, CO in the atmosphere reacts strongly with hydroxyl radicals to form carbon dioxide and HO₂ radicals, which can then react with NO_x to form O₃ (a rate of reaction is dependent on atmospheric temperature).

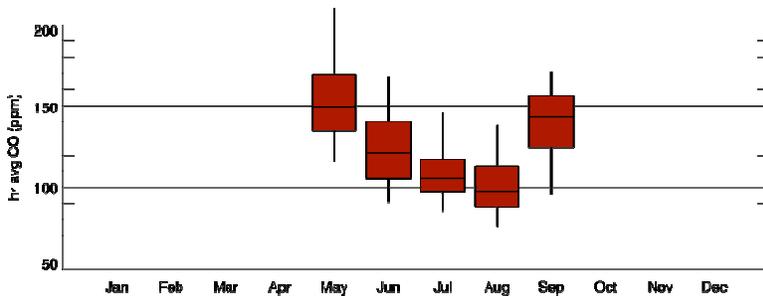


Figure 5) WKT nighttime CO₂ percentiles 5th, 25th, 50th (median), 75th, 95th at 122m show decreasing values through August.

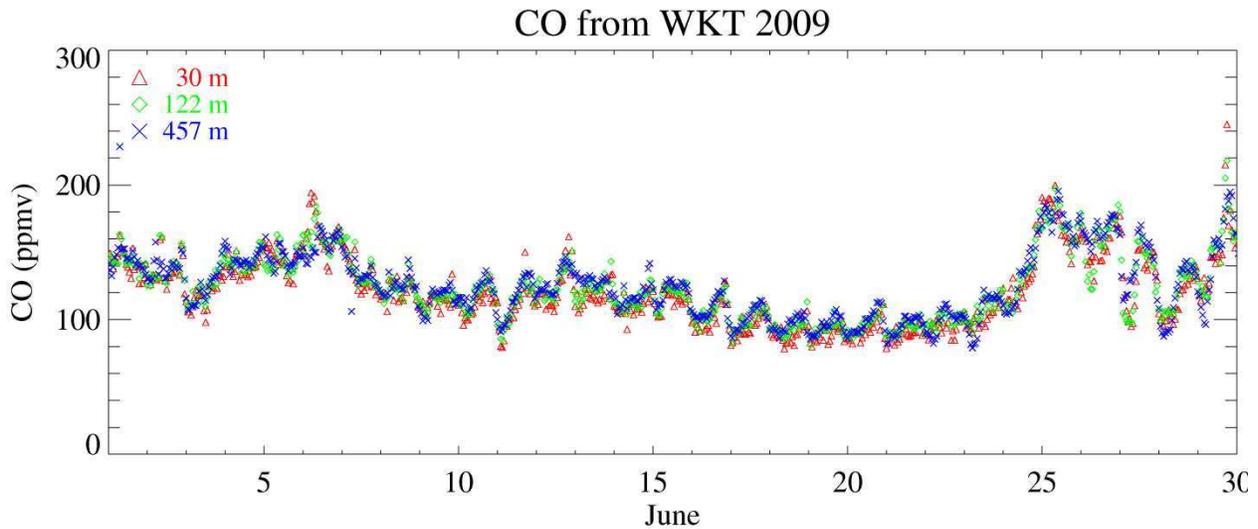


Figure 6) June hourly-averaged CO at the 30-m (red), 122-m (green) and 457-m (blue) tower levels.

Although CO concentrations are largely variable during the course of a day and a month (Figure 6), calculated CO medians show no real diurnal cycle at the 30-m or 122-m tower levels. However, median CO concentrations at the 457-m tower level (Figure 7) show a slight diurnal cycle, increasing during the daytime.

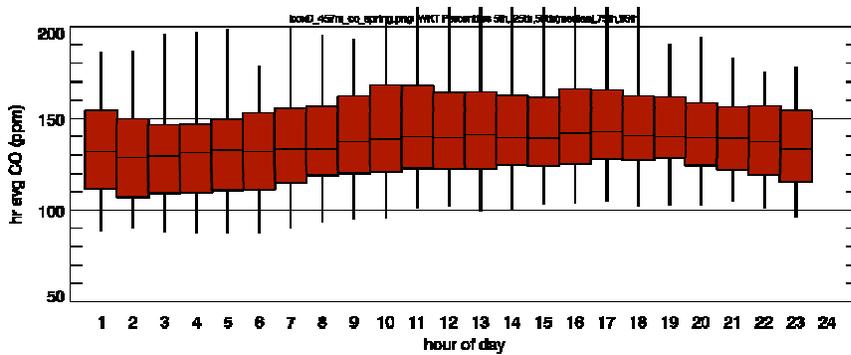


Figure 7) WKT CO percentiles 5th, 25th, 50th (median), 75th, 95th at 457m during a) spring (May, Jun) .

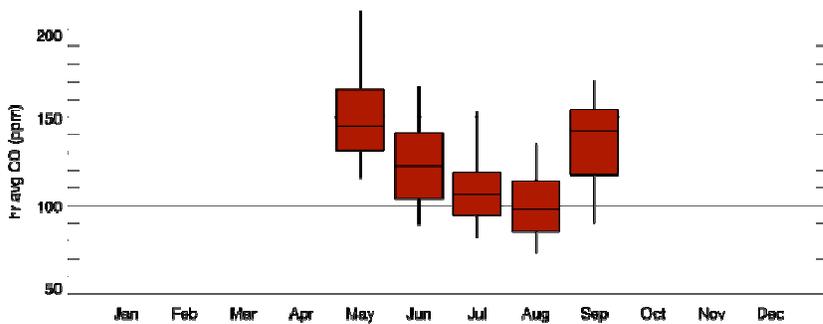


Figure 8) Monthly WKT nighttime percentiles 5th, 25th, 50th (median), 75th, 95th at 457m for CO (ppm).

In general, seasonal CO values are characterized by a peak in the spring, which decrease in the summer. WKT Tower CO values (Figure 8) vary monthly and decrease throughout August and then rise again in September. One reason for the summer decrease of CO is the increase in the availability of the hydroxyl radical (OH) in the summer (from increasing UV). Another reason for the summer decrease of CO, is that the seasonal cycles for CO and O₃ are influenced by the seasonal exchanges of different air mass types due to the seasonal shift of wind directions (see section above). Air masses originating over land contain higher concentrations of O₃ and CO, due to the higher continental background concentrations, and sometimes due to the contribution from regional pollution. In the months of summer, as the wind direction becomes predominantly S/SW, winds bring relatively “clean” air from the Gulf of Mexico. So months with this predominant flow, June through August, are associated with lower CO.

OZONE

Ozone was collected at one-minute resolution at 6m, and 30-second resolution at 30m and 457m. Ozone data measured at each level was transmitted to the surface data collection system via the meteorological package.

Ozone tower measurements have a diurnal cycle with a minimum in early morning and a maximum in the late afternoon (Figure 9). Ozone formation occurs as the result of volatile organic compound (VOC) oxidation in the presence of nitrogen oxides (NO and NO₂) and sunlight, so the high levels in the late afternoon are the result of the solar-driven production. The low levels in the morning are caused by a combination of factors: deposition on surfaces, the reaction between NO and ozone to produce NO₂ and O₂, and vertical mixing becomes slower at night. The slower, nighttime mixing due to a nighttime boundary layer (NBL), exists at the 6-m and 30-m tower levels, but does not appear to affect the 457m tower level. The large difference in wind speeds from the ground to the top of the NBL prevents ozone from vertically mixing with the faster moving upper-layer of air and replenishing whatever ozone has been deposited or chemically consumed in the NBL. As a result, the higher nighttime speeds aloft lower the range of diurnal ozone values at 457 meters (Figure 9c).

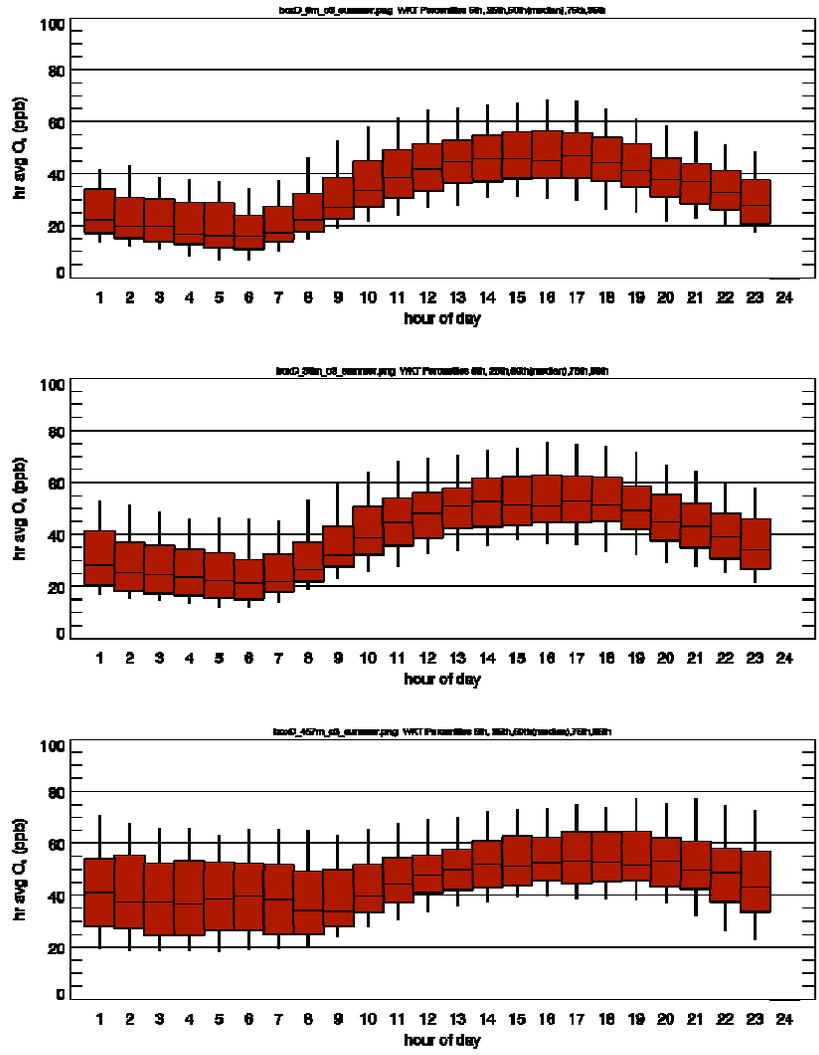


Figure 9) WKT O₃ percentiles 5th, 25th, 50th (median), 75th, 95th during summer (Jul, Aug, Sep) at a) 6m, b) 30m and c) 457m.

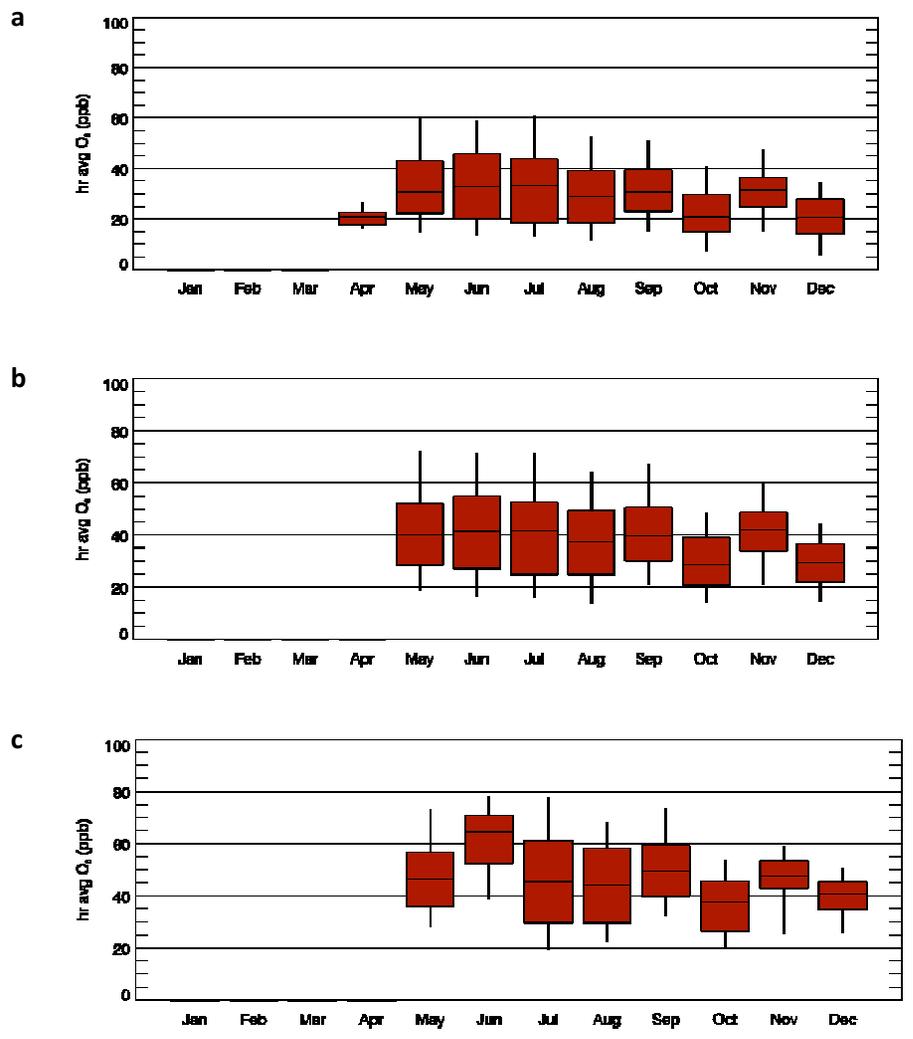
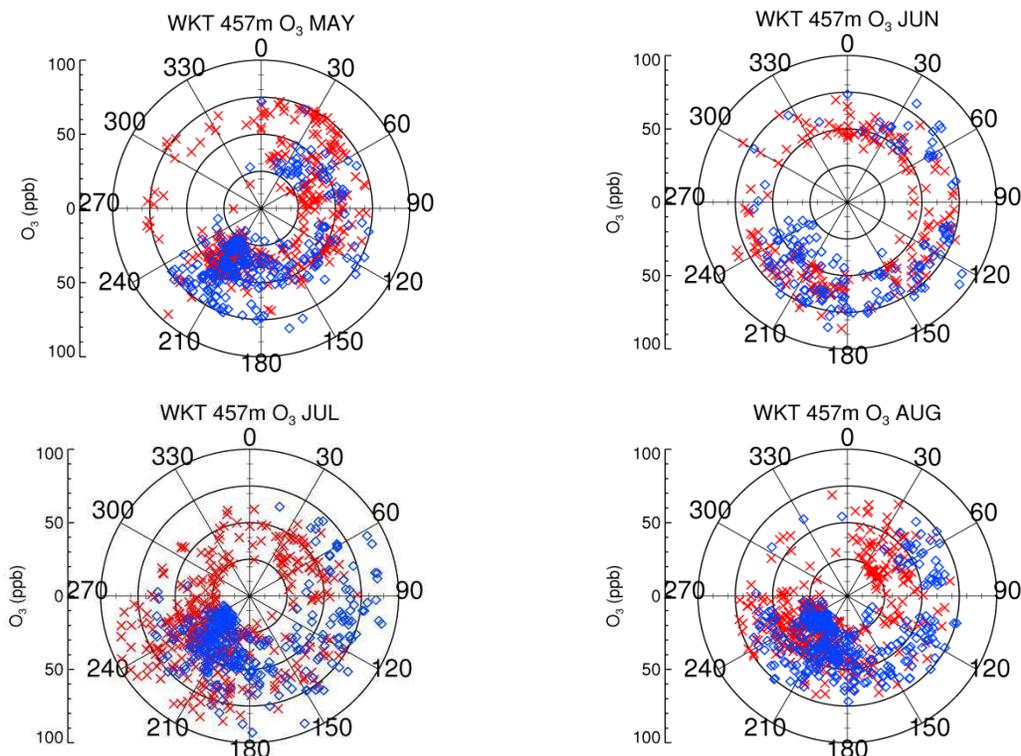


Figure 10) Monthly WKT nighttime O₃ percentiles 5th, 25th, 50th (median), 75th, 95th during a) 6m, b) 30m and c) 457m.

Ozone, due to its dependency on UV, also has a slight seasonal cycle at the WKT site. The nighttime monthly ozone percentiles (Figure 10) follow somewhat expected patterns at the three levels in that the ozone medians increase from May to June. The 457-m (Figure 10c) June median must be excluded because of missing data (a 10-day stretch of low-ozone), which would effectively lower the median by quite a bit. However, the ozone data does not completely correlate with UV, as the medians for August and later months do not follow a decreasing pattern into the winter that UV does.

Monthly wind-direction plots indicate that the wind directions are shifting and may be partially responsible for deviations from a primarily UV-controlled cycle. For instance, September should theoretically have a lower median value as the UV decreases, but it has a slightly higher median than August. Ozone wind directions (Figure 11) show that August has a primarily S/SW component for nighttime values, but September wind directions shift to S/SE and N/NE. If the winds come through Austin (S), Houston (SE) or Dallas (NE) they will likely have higher CO and O₃.



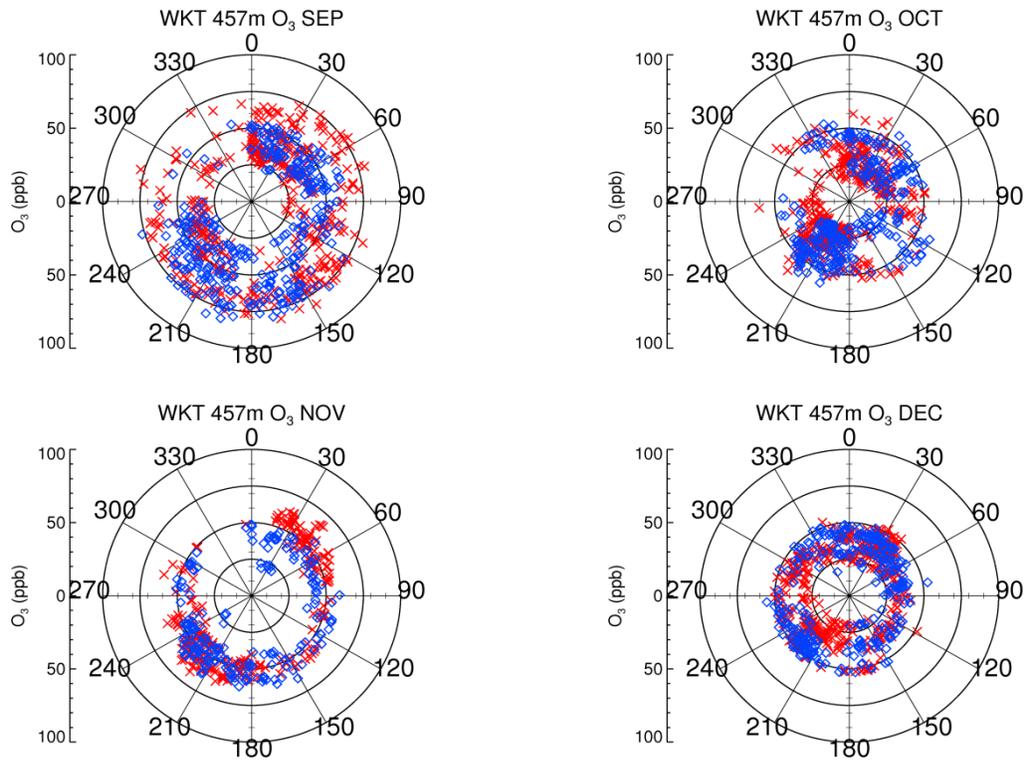


Figure 11) Wind directions and correlating ozone values at 457-m for May – Dec, 2009. Blue diamonds represent nighttime and red "x"s, daytime.

NIGHTTIME CONTINENTAL JET

The existence of a low-level nighttime continental jet is a feature consistently observed in the tower wind measurements. The nighttime boundary layer forms, leaving slow wind speeds in the lower layer, while the adjacent overlying layer winds increase in speed. In many cases, this jet seems unassociated with higher ozone and in fact, often brings lower concentrations from the Gulf. Previous reports have numerous examples of the strong S/SW flow transporting

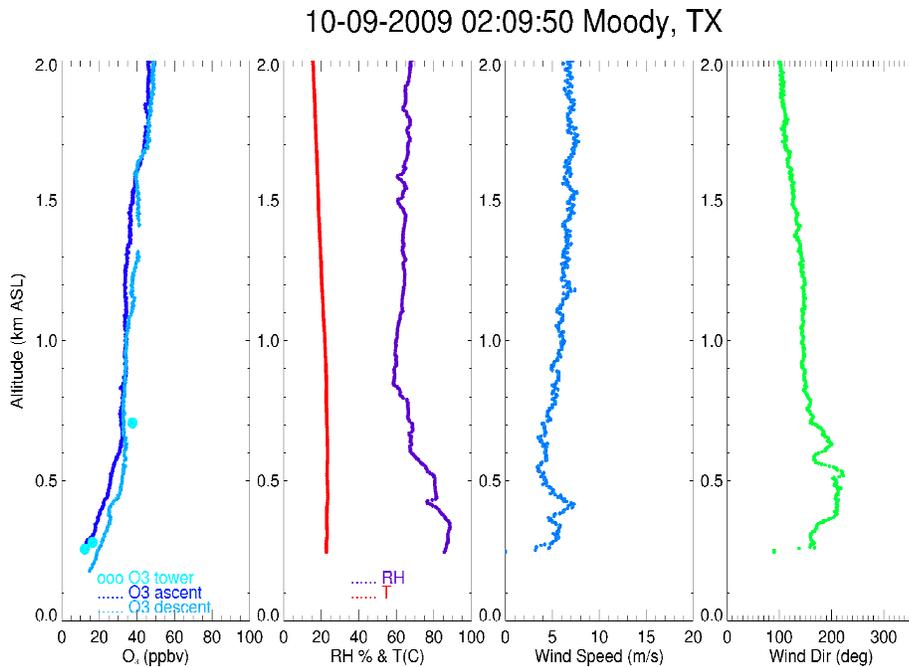


Figure 12) An ozonesonde flight on Sept 10, 2009 shows the continental nighttime jet as the moister and faster southerly flow between 350 and 600 masl.

ozone concentrations during ozonesonde ascent and descent (2.5 hours later) show no increase at jet altitudes.

During another week of September (Figure 13), there were several days of relatively higher ozone values. The nighttime measurements at the 457-m level are very different than those at the surface and 30-m level. Through the use of HYSPLIT back trajectories (Figure 14), the difference in wind speeds and slightly different southerly directions can account for this disparity. Likely, there are more chemical and depositional processes at work at slower speeds, but there is also a difference in ozone concentrations due to how far the winds have travelled in a similar amount of time. For example, at 0100 on Day 246, the 457-m winds (green line marked by A) came from the vicinity of Houston 24 hours earlier, whereas the 6-m and 30-m level air came from only half as far away due to slower wind speeds. For C and D, the pattern is

ozone “clean” air from the Gulf of Mexico.

During the ozonesonde campaign at the tower site, the nighttime continental jet appeared in the vertical profiles, but did not appear to be associated with increased ozone values (Figure 12). At the altitude of the lower-level jet layer (300-600 m above sea level (ASL) in Figure 12), the wind speeds increase and the wind direction shifts to the S/SW. However, the

similar with the upper-level air coming from the vicinity of the Austin and San Antonio metro areas.

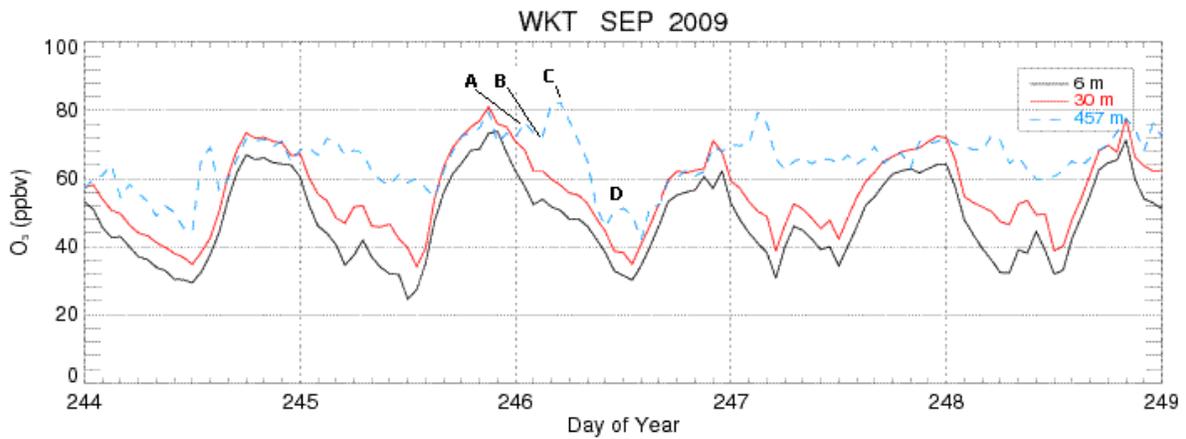


Figure 13) Hourly-averaged ozone for September 1-5 (Day 244-249), 2009.

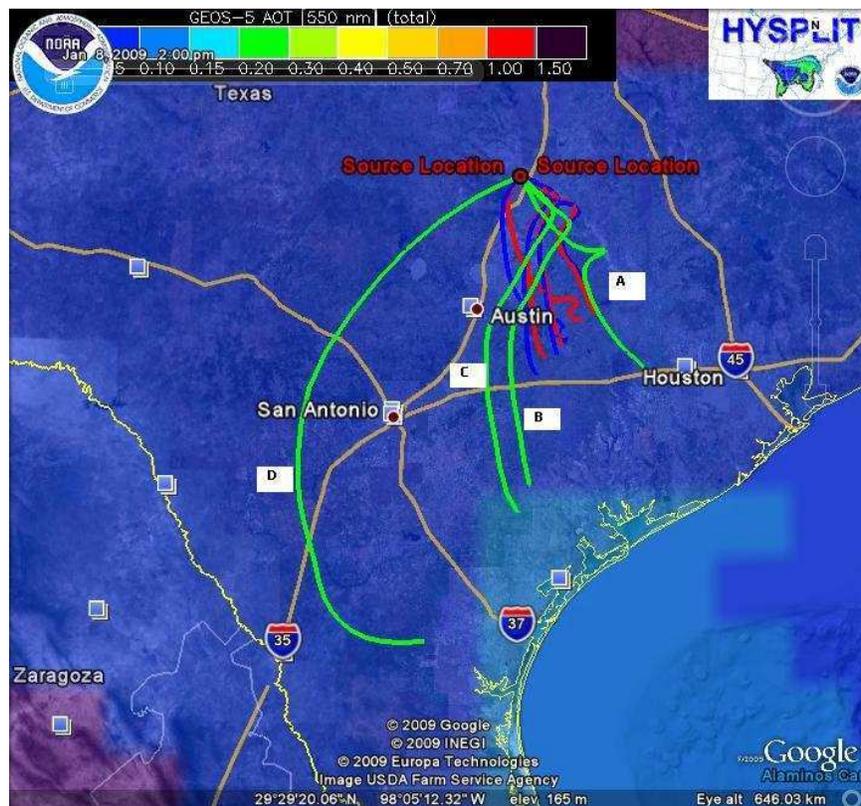


Figure 14) HYSPLIT back trajectories of September 3 (Day 246) run at different times A-D. A- 0100, B- 0200, C- 0400, D- 1200.

The previous examples indicate no clear evidence that the nighttime continental jet is contributing to higher ozone levels in Central Texas on a regular basis. However, Figure 15 shows that for several days (Days 269 through 273) the lower-level nighttime continental jet appears to be bringing higher ozone to the area.

For example, on the evening of Day 272, the direction shifts to S/SW, the wind speeds increase, but the 457m-wind speeds continue to climb. Ozone concentrations stay the same in the early evening and then jump to high levels during the night and early a.m. Coincidentally,

an ozonesonde was launched that night, but didn't catch the period of very high ozone. In Figure 15, evenings of Day 269 and 270 have very similar events occurring, but to a lesser extent than the evening of Day 272.

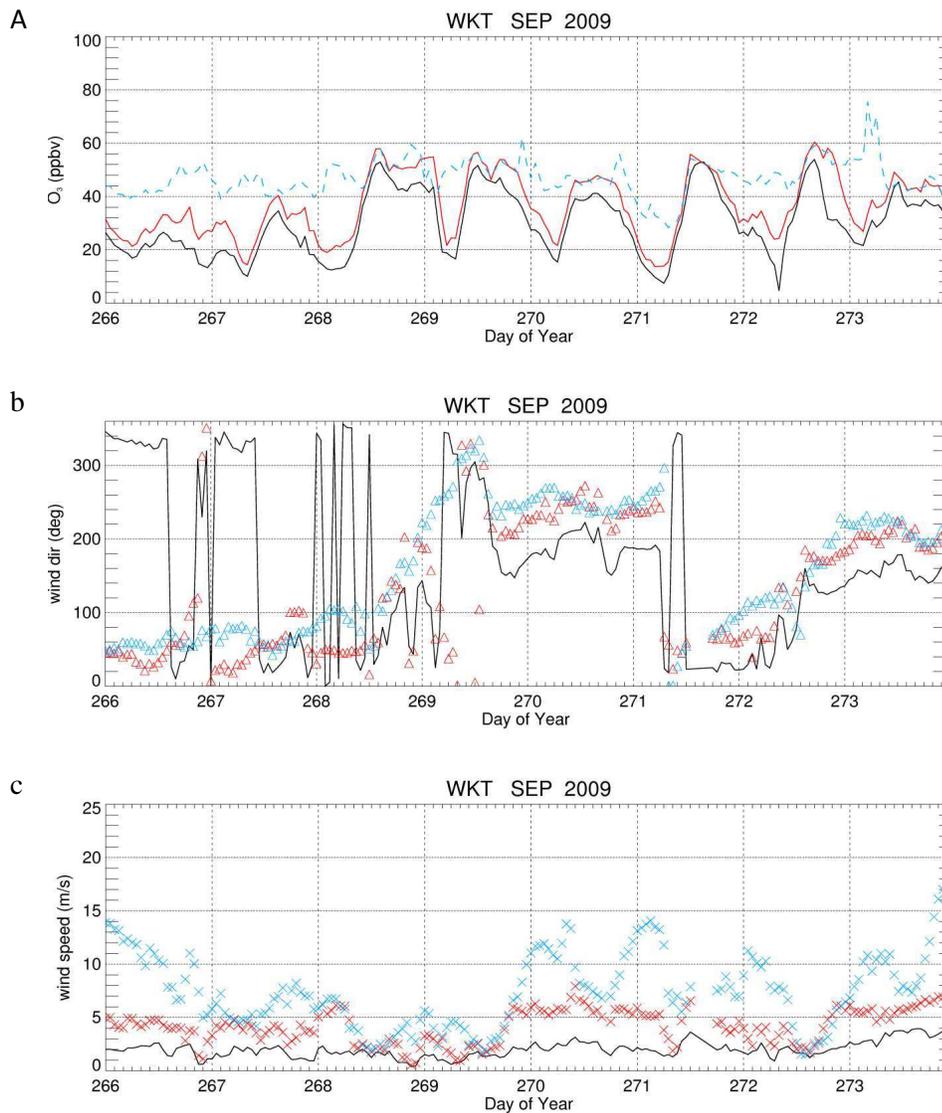


Figure 15) Hourly-averaged data for a) ozone, b) wind direction, and c) wind speed at 6m (black), 30m (red) and 457m (blue).

CONCLUSIONS

Through the use of newly-installed and existing tower instruments and by conducting an ozonesonde campaign, we have been able to characterize a low-level nighttime jet during spring and summer. In addition, we identified and quantified CO, CO₂, O₃ and wind parameter diurnal and seasonal trends at the tower location.

Initial conclusions from this study are that the nighttime low-level jet exists but only occasionally brings high ozone concentrations into the tower area. Although we see the existence of the nighttime jet, the ozonesonde intensive data did not show that the fast, southerly winds consistently enhance ozone concentrations at night. However, the nighttime boundary layer characteristics were evident in much of our evening, nighttime and early morning data. Many of the events investigated show the low-level nighttime jet generally transporting “clean” (low-ozone) air from the Gulf of Mexico. The strength of the jet inhibits vertical mixing between the lower ozone concentrations in the NBL. While ozone values at the upper-tower level on many occasions do not decrease at night the extent to which this may initiate ozone formation the next day has not been determined in the results obtained to date. Several examples in the tower data, particularly in late September, show characteristics of a low-level nighttime jet transporting high O₃ to the tower area.

RECOMMENDATIONS

Further studies are needed in order to quantify how often the jet is contributing to higher ozone concentrations in the tower area. Likely, with the measurements from the tower, this task can be accomplished with further analysis and statistical tools.

Although the spring and summer seasons have been well investigated, the fall and winter measurements will be further investigated in a subsequent report for an improved view of the role shifting transport plays on O₃ concentrations.

An interesting feature present in the data is industrial plume signatures. Due to the high temperatures of combustion in industrial production, CO/CO₂ ratios have a specific signature. The O₃ data and CO/CO₂ ratios can be used to quantify the plumes, which may be useful to determining the area CO and O₃ budgets.

AN IMPORTANT PIECE THAT REMAINS UNRESOLVED IS THAT OF NOX MONITORING. NOX IS IMPORTANT TO THIS STUDY IN THAT IT IS A PRECURSOR FOR O₃. IN URBAN AREAS, NO₂ CAN ALSO BE A TEMPORARY SINK FOR O₃. AFTER RUNNING THE NO ANALYZER DURING THE OZONESONDE CAMPAIGN, IT BECAME CLEAR THAT A MONITOR WITH A

LOWER THRESHOLD AND BETTER PRECISION WOULD BE NECESSARY TO QUANTIFY THE NO AT THE RURAL TOWER SITE.

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Task 5- Write and Submit a Final Report:

The grantee continues to provide monthly status reports via email while writing the final report. The Final Report shall be delivered to the TCEQ Project Manager electronically (i.e. via file transfer protocol (FTP) or e-mail) in Microsoft Word format no later than November 30, 2009. The Final Report shall include the following components:

An executive summary or abstract.

A brief introduction that discusses background and objectives of the project. Include references and relationships to other studies if applicable.

A discussion on the pertinent accomplishments, findings, and difficulties encountered for each grant activities description task.

Conclusions, unresolved issues and recommendations if any, to be considered for a subsequent study.

The Final Report shall provide a comprehensive overview of activities undertaken and data collected and analyzed during the Grant Activity. The purpose is to highlight major activities and key findings, provide pertinent analysis, describe problems encountered and associated corrective actions, and detail relevant statistics including parameter accuracy and precision.

The report should address the primary objectives of this study: 1) to describe the daytime and night time meteorology, 2) to characterize the Low Level Nocturnal Jet, and 3) to analyze the transport of ozone from urban and industrial sources. The final report will include an executive summary, as well as chapters explaining the instrumentation, measurements, QA/QC procedures, findings and trend analysis, and a final chapter with conclusions and recommendations for further study.

The report will be delivered via email to the project manager. Data collected during the study will be provided via ftp site, maintained for at least 90 days after December 31, 2009.

Preliminary Ozonesonde Intensive Report
 Laura Patrick, Sam Oltmans, and Arlyn Andrews
 November 23, 2009

Bryan Johnson and Laura Patrick conducted an ozonesonde intensive in order to characterize the nighttime continental jet and determine any impacts on local ozone concentrations. We travelled to Moody, TX to launch ozonesonde balloons near the WKT tower from Aug 24-Sep 11. Due to rainy weather, we left and then Laura returned Sep 27-Oct 1 to get four more profiles. To have a well-rounded picture of ozone, winds, and other constituents, we launched seventeen balloons and two tethered balloons at various times of the day (Table 1).

Balloon and type of profile	GPS	FLT#	Date GMT	Date local	Time GPS	Time local
100g balloon	NO	MY001	8/25/2009	8/25/2009	16:43	11:43
100g balloon (snagged nearby tower)	YES	MY002	8/26/2009	8/26/2009	12:34	7:34
100g balloon	YES	MY003	8/27/2009	8/27/2009	11:54	6:54
100g balloon	YES	MY004	8/30/2009	8/30/2009	22:42	17:42
100g balloon	YES	MY005	8/31/2009	8/31/2009	23:15	18:15
100g balloon	YES	MY006	9/1/2009	9/1/2009	15:37	10:37
Tether (sunset) 1200 gram balloon	YES	MY007	9/2/2009	9/1/2009	0:01	19:01
1200g balloon	NO	MY008	9/2/2009	9/1/2009	3:44	22:44
100g balloon	YES	MY009	9/2/2009	9/2/2009	21:59	16:59
100g balloon	YES	MY010	9/3/2009	9/3/2009	23:01	18:01
100g balloon	YES	MY011	9/4/2009	9/4/2009	10:59	5:59
Tether (early a.m.) 800g balloon	YES	MY012	9/5/2009	9/5/2009	11:02	6:02
800g balloon	YES	MY013	9/5/2009	9/5/2009	20:05	15:05
100g balloon	YES	MY014	9/7/2009	9/7/2009	11:30	6:30
payout reel release (5 min ascent)	YES	MY015	9/8/2009	9/8/2009	22:04	17:04
100g balloon	YES	MY016	9/10/2009	9/10/2009	7:10	2:10
100g balloon	YES	MY017	9/10/2009	9/10/2009	20:50	15:50
100g balloon	YES	MY018	9/28/2009	9/28/2009	22:27	17:27
100g balloon	YES	MY019	9/29/2009	9/29/2009	7:38	2:38
100g balloon	YES	MY020	9/30/2009	9/30/2009	7:24	2:24
100g balloon	NO	MY021	10/1/2009	10/1/2009	2:08	21:08

Table 1) Detailed ozonesonde launch information for our Moody Texas intensive ozonesonde campaign. Plots and ozonesonde data files are cataloged by these flight numbers on the FTP site.

Ozonesonde Flights

Before launching, each ozonesonde was freshly prepared with new solutions and was carried to the inlet of the surface instrument and the two instruments' readings compared. Ozonesonde GPS functions were also checked on the ground with a handheld GPS monitor before launch. In this way, the ozonesonde was checked for potential errors.

Nighttime Continental Jet

As seen in Table 1, balloons were launched at various times of the day and night. In order to capture the night jet, we launched three ozonesondes at approximately 2 a.m. Figure 1

10-09-2009 02:09:50 Moody, TX

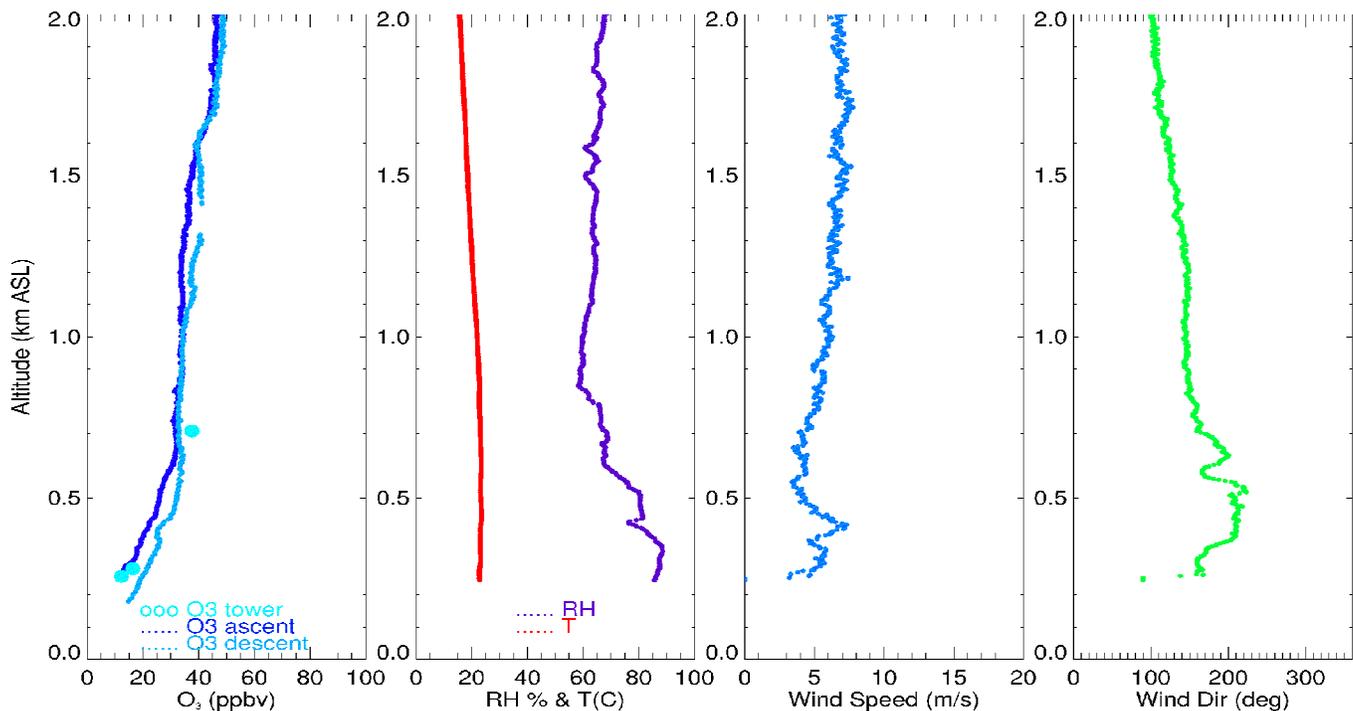


Figure 1) Flight MY016 shows the continental nighttime jet as the moister and faster southerly flow between 350 and 600 masl.

best captures the continental nighttime jet between 350 and 600 masl during Flight MY016 on September 10th. The wind speed values and relative humidity are elevated and the wind direction is southerly in this altitude range. Ozone mixing ratios do not appear to be affected by this faster and moister, southerly flow. The jet does not occur consistently at this site. On the two other nights that we launched in the very early a.m., there were features of elevated wind speed near these altitudes, but the relative humidity and ozone were not enhanced and the wind direction was not southerly like on Flight MY016.

Development and Dissipation of Nighttime Boundary Layer

The development of the nighttime boundary layer was of interest, so several launches took place in the late evening (9 p.m. and 10:45 p.m.), as well as a few in the earlier evening. The evening launches were valuable in determining any development of a nighttime jet. In Figure 2a, which shows a late night launch preceding a high ozone day, we have no ascent data in the very lower region due to a reception problem, but do have good descent data and tower data for the ascent time. The tower and surface data indicate loss right at the surface, but no real boundary layer formation at launch time or even at landing time (1:15 a.m. LT). Another launch (MY021- Figure 2b) at 9:10 p.m. LT shows the same minor surface loss and no ozone enhancements.

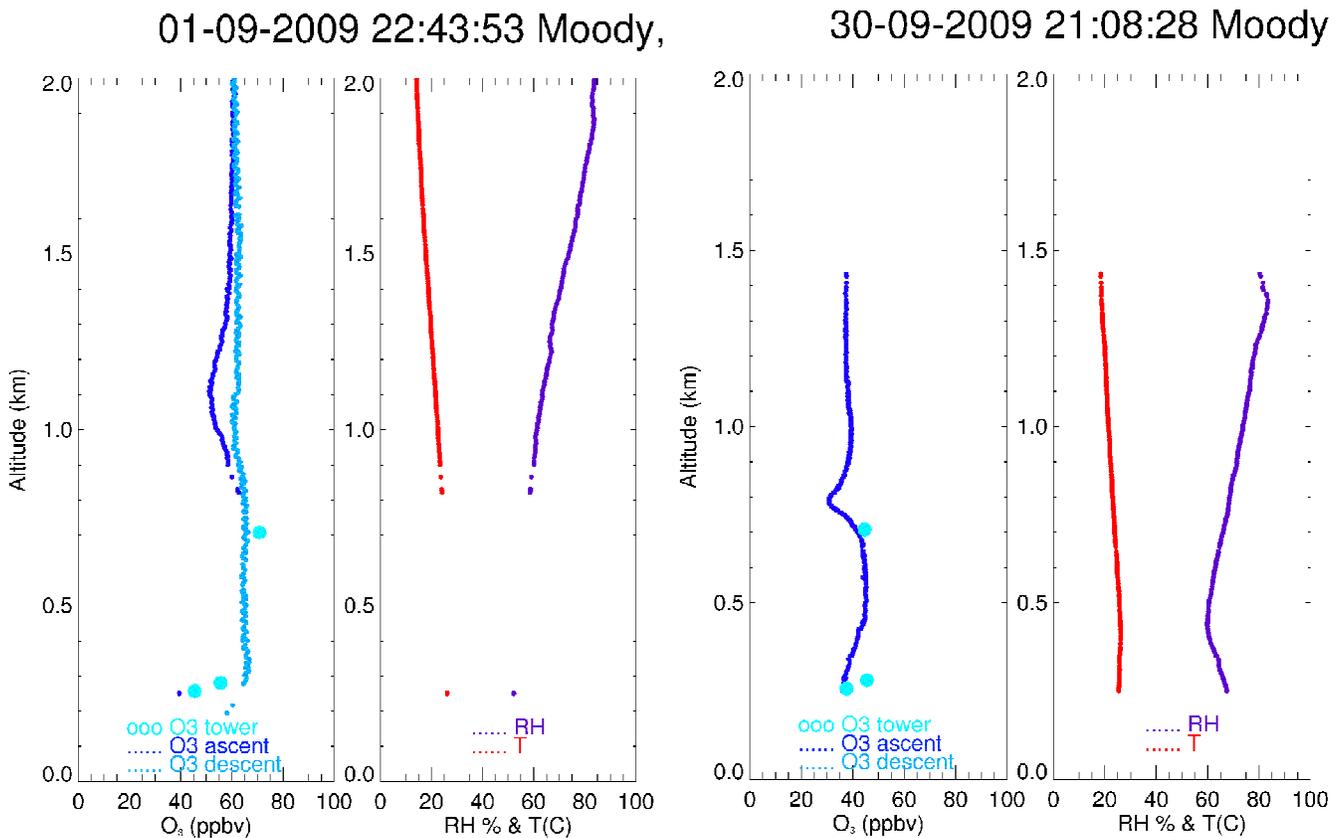


Figure 2 a) Late evening flight with missing ascent data, but good descent and tower data (during ascent) showing loss at the surface, but no ozone enhancements (MY0018). b) Another earlier flight shows a similar pattern of loss (MY0021).

Many early morning flights (launched between 5 -7 a.m. LT) show a definite increasing gradient from surface (251 m) up to 600 m, but there is no ozone enhancement occurring along this region (Figure 3 is a typical profile). Although we do not appear to have observed a nighttime continental jet during these early morning flights, a nighttime boundary layer often exists, generally within the tower's altitude range.

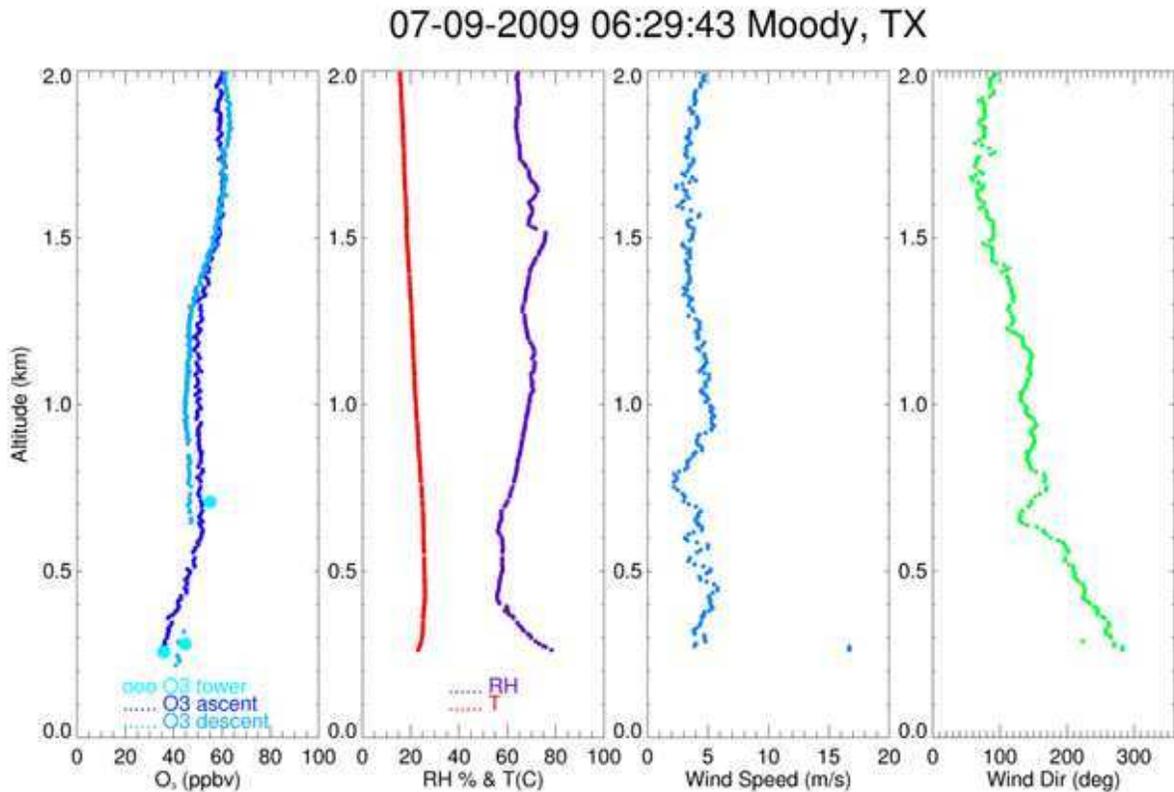


Figure 3) A typical early morning plot, with a definite gradient in the nighttime boundary layer region, but no ozone enhancement region.

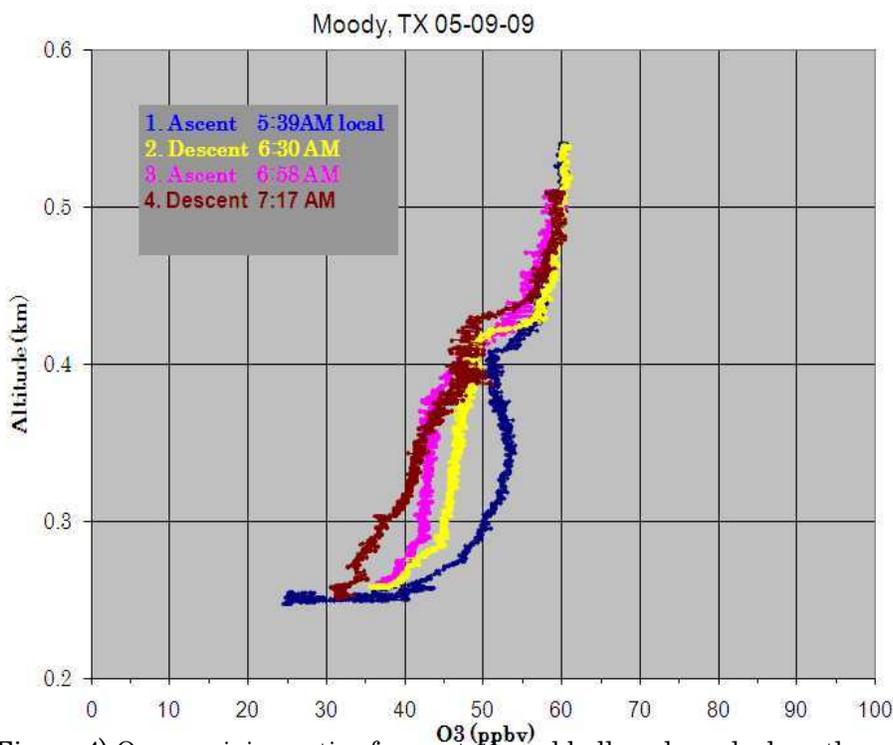


Figure 4) Ozone mixing ratios from a tethered balloon launch show the evolution of the early morning ozone mixing ratios. All figures show altitude in meters above sea level. Ground level at the tower is 251 masl.

Two balloon launches were tethered. During each of these sessions, the balloon was able to reach between 250 – 300 m above ground level. The goal with the tethers was to watch the evolution of the morning and evening ozone concentrations. In Figure 4, the ozone levels continue to drop through the two hours we were flying the balloon. Thirty-meter tower ozone values (would be at 281 m if shown on this plot) generally reach their minimum at ~8 a.m.

Shortly after the last descent, ozone values below 450 m ASL likely began their daytime increase.

Mid-Afternoon Profiles

Even though we were looking at the nighttime continental jet, we purposefully launched ozonesondes during the peak time of day for ozone mixing ratios (3-5 p.m.). Mid-afternoon ozone profiles showed what we expected to see, which is well-mixed ozone concentrations and no boundary layer. We observed several days of relatively high ozone. Figure 5 shows an ozonesonde with high ozone in several altitude regions (surface to 2.75 km and 4 to 6 km).

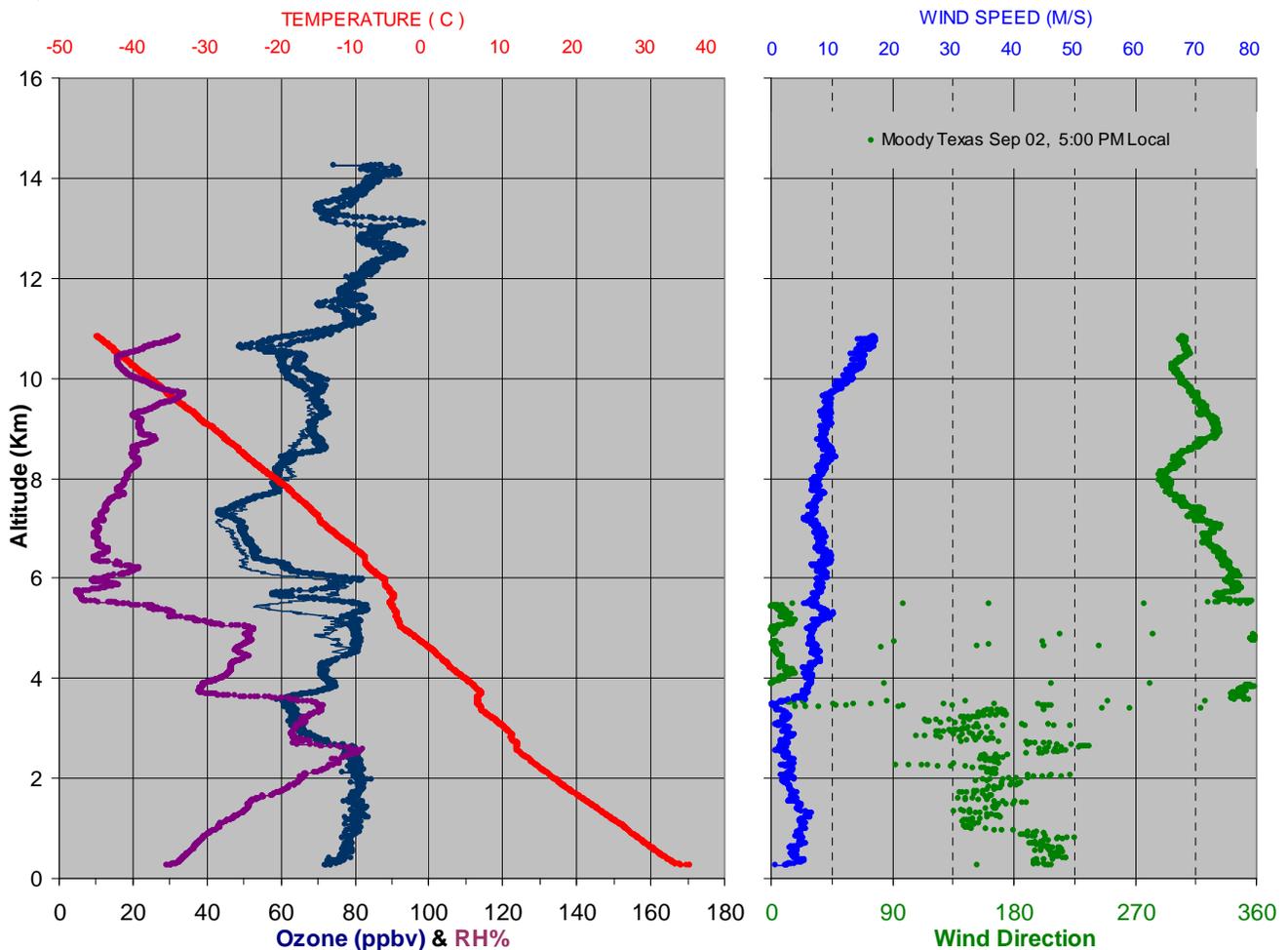


Figure 5) A full ozonesonde profile of ascent (thick dark blue line) and descent (thin dark blue line). The temperature is in red and the axis is on the top of the plot. Relative humidity in percent is in purple, wind speed (m/s) in blue (axis on top) and wind direction (degrees) in green.

Investigating these altitude regions with ARL's Hybrid Single Particle Lagrangian Integrated Trajectory Model (HYSPPLIT), we found that the two enhancements have two different ozone source regions. In Figure 6, trajectories were calculated at tower instrument heights and appear to be coming from the Houston area. The upper range of enhanced ozone between 4 and 6 km (trajectory calculated at 5000 m), appears to have a source region in California. During this time period, there were extensive wildfires in California, which were likely the source of the enhanced region of ozone.

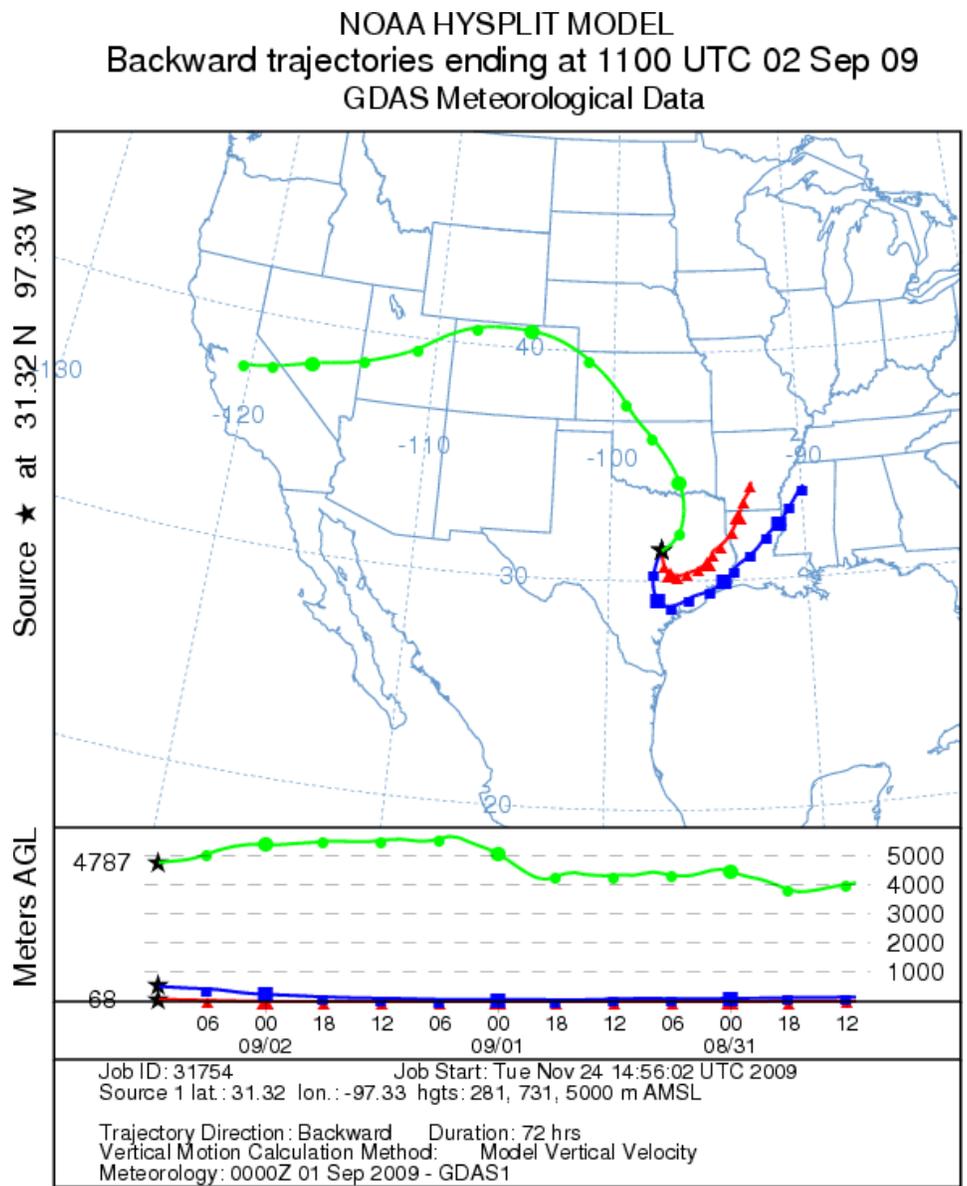


Figure 6) Altitudes with enhanced ozone were likely the result of two different source regions. At the lower profile altitudes, the source region was likely Houston and the upper profile altitudes from the California wildfires. Red line (281 m ASL or 30-m tower instrument), blue line (731 m ASL or 450-m tower instrument), and green line 5000 m ASL.

Another of our ozonesonde flights the previous night also shows an enhancement in the 4 to 5 km altitude region, as shown in Figure 7. These enhanced ozone regions are also likely a result of the same wildfires.

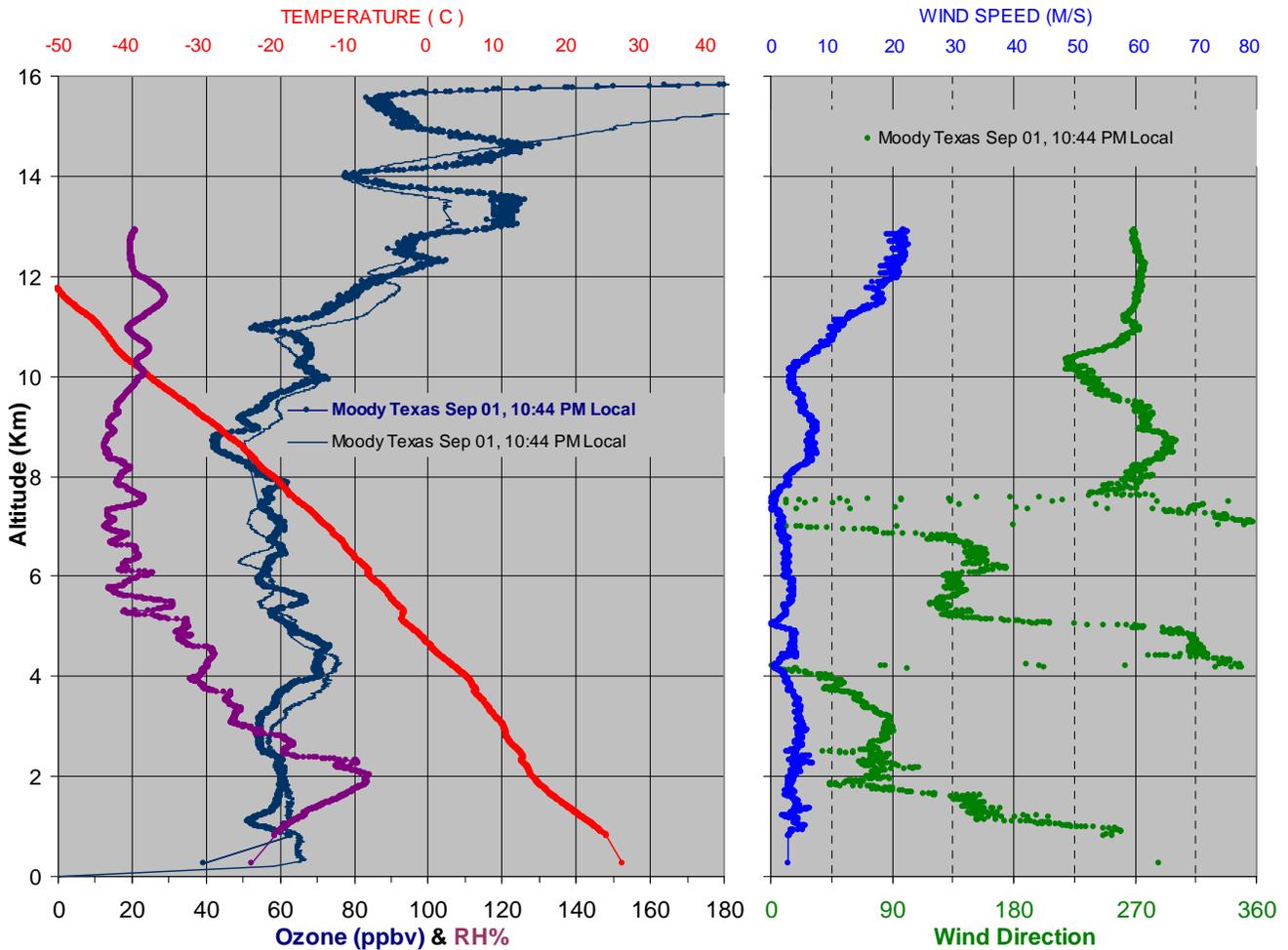


Figure 7) An ozonesonde from September 1, that shows an ozone enhancement from the California wildfires in the 4-6 km asl region.

Upon further investigation, we found enhanced concentrations on September 1st at our tower site in Erie, CO that were also likely a result of these same fires.

Tower Performance during Campaign

Although the tower site was burglarized late on August 27th and a few data computers, we are not missing any tower data during August and September. The data loggers were able to capture and save the data while we were getting new computers up and running.

The tower instruments appear to reflect ozonesonde values well at the surface and at 457 m AGL, although there is some question as to whether the zero on the 30-meter

instrument has drifted. The 30-meter instrument shows ~5 ppbv higher than the ozonesonde on some comparisons, but during a few launches has the exact values. We are looking into whether this zero has drifted at all and will then determine whether the data will need to be adjusted.

Nitrous Oxide Monitoring

We monitored NO during the intensive with a loaner instrument from 2B Technologies. We tested this instrument against a standard and found that it was unable to measure low concentrations with any reasonable level of precision. The 2B Technologies NO instrument designer feels that version of the instrument can really only be used in polluted areas. Nonetheless, we ran the monitor at the site surface, hoping to see if we picked up any pollution events. When we returned the instrument to the company, the instrument was far off calibration. Thus, we are not releasing the NO data and will be investigating another company for NO instruments that have a lower detection limit and higher precision.

Data

The ozonesonde data was processed and placed on the tower data ftp site. Plots were also created from the data that may be viewed for the full profiles as well as plots that focus on the first two kilometers.

Conclusion

Although we believe we can see the existence of the nighttime jet, the ozonesonde intensive data does not show that the fast, southerly winds produce significant enhancement to the ozone concentrations at night. However, the nighttime boundary layer is evident in much of our evening, nighttime and early morning data.