

**An Intercomparison of Ozone Measurements from
In Situ and Remote Sensors During the
2000 Texas Air Quality Study**

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Abstract

We have carried out a comparison among ozone-measuring platforms that operated during the 2000 Texas Air Quality Study in the vicinity of Houston, Texas. Instruments included an airborne differential absorption lidar (DIAL), airborne ultraviolet (UV) photometers and chemiluminescent sensors, a UV photometer at 250 m above mean sea level (MSL) on the Williams Tower in downtown Houston, and the UV photometers that are part of the surface monitoring network in the Houston area. We have used the airborne lidar as the link among all the measurement platforms, since its path frequently crossed the paths of the other aircraft and brought it close to the Williams Tower and many of the surface stations. To create the comparison data between the lidar and the stationary instruments we have compared mean ozone for the appropriate lidar range gate from flight segments that passed within 5 km of the surface stations or the Williams Tower. For comparison between the lidar and sensors on other aircraft, we have used flight segments in which the aircraft were separated horizontally in space by no more than 5 km and in time by no more than 5 min. We have found excellent agreement between the lidar and other airborne sensors over altitudes from several hundred meters to approximately 2 km MSL and over a range of ozone mixing ratios from 40–160 ppb. Root mean squared differences (*rmsds*) generally about 5 ppb. Agreement was excellent in the mean between the lidar and data collected at 250 m on the Williams Tower. For these measurements, the *rmsd* was 22 ppb, with this larger value due in part to an averaging time of 15-min for the Williams Tower data. The surface monitoring network generally reported values somewhat lower than those from the lidar. Measurement geometry and near-surface ozone structure may have been a significant factor in this result.

1 Introduction

The Houston area in Texas in recent years has developed severe problem with ozone pollution (e.g., Wert et al. 2003). In an effort to identify the causes of the area's ozone exceedances, the Texas Natural Resource Conservation Commission (now the Texas Commission on Environmental Quality, TCEQ) supported a major field campaign in August and September 2000 to measure ozone and the chemical and transport processes specifically involved in its evolution and dispersion around Houston. The Texas Air Quality Study 2000 (TexasAQS 2000) involved numerous universities, state and federal laboratories, and other organizations, and aspects of the field program have been described in recent publications including Kleinman et al. (GRL 2002) Brock et al. (2003), Neuman et al. (2003), Ryerson et al. (2003), and Wert et al. (2003).

Efforts to understand the distribution of ozone near the ground have historically focused on the chemical reactions that drive its production and removal in the atmosphere. It has become increasingly apparent, however, that atmospheric transport and mixing processes also play a significant role in determining the ozone distribution (e.g., Berkowitz and Shaw 1997, Doskey and Gao 1999, Zhang and Rao 1999, Fast et al. 2000, Fast et al. 2003, and Rao et al. 2003). In a separate study to investigate the relationship between the spatial distribution of ozone over Houston and the dynamic and thermodynamic structure of the boundary layer, Jiang et al. (2003) (not in citation list!!!) combined ozone measurements from numerous sources to produce a composite view of its distribution. For such a study to be successful, it is important to identify the uncertainties and biases that arise from instrumental and sampling errors among the various ozone-measuring systems. In this paper we describe comparisons of ozone measurements developed from coincident measurements obtained during the routine sampling in the field campaign. We have used the airborne differential absorption lidar operated by the Environmental

Technology Laboratory of the National Oceanic and Atmospheric Administration (NOAA/ETL) as the link among all of the ozone-measuring platforms.

2 The Data

During the TexasAQS 2000, ozone was measured by a numerous platforms whose relevant operating characteristics are summarized in Table 1. The individual measurement systems are discussed in more detail in the sections that follow.

2.1 Airborne lidar

During the TexasAQS 2000 campaign, NOAA operated its nadir-looking ozone/aerosol lidar on board a DC-3 research aircraft. This system is an ultraviolet differential absorption lidar (UV-DIAL) and has been described in detail in Alvarez et al. (1998) and Senff et al. (1998). The lidar emits 20 pulses per second (simultaneously at each of 5 wavelengths), and these are averaged to produce a backscatter profile for each wavelength every 10 seconds with 90-m range gate resolution. These profiles are then smoothed with a 5-gate sliding linear fit, and differences between a selected pair of smoothed profiles of different wavelengths are used to construct the ozone profile. Near the surface, the sliding linear fit is reduced to as few as two range gates, which causes a larger uncertainty in near-surface measurements by the lidar.

In addition, the lidar ozone profiles are corrected for aerosol backscatter and extinction effects. The magnitude of this correction term can be significant for certain DIAL wavelength pairs and is dependent on aerosol properties, such as extinction to backscatter ratio and backscatter and extinction wavelength dependence. These aerosol properties cannot be directly measured with the airborne lidar, so we assume reasonable values based on model calculations for various aerosol types. Because of multiple aerosol sources in the Houston area aerosol distributions were very inhomogenous, both horizontally and vertically. Therefore, one set of

aerosol parameters for an entire flight and all altitudes cannot be entirely accurate. Nevertheless, due to the lack of knowledge about the aerosol properties, we were forced to use an "average" set of aerosol parameters that worked for most of the conditions encountered during a flight. As a result, the ozone data may be biased for some flight segments and certain altitudes, for example when crossing a pollution plume. These biases can be on the order of 10 – 15 ppbv. Data that were likely to be affected by the aerosol bias have been flagged and are not included in this analysis.

2.2 TCEQ Surface Network

The Texas Commission on Environmental Quality operates a network of surface observing stations to monitor air quality in Texas (TCEQ 2003). These stations contain instrumentation to measure criteria pollutants, including ozone, as defined by the Environmental Protection Agency. The part of this network in the Houston area consists of 41 stations. Instruments used to measure ozone are Dasibi UV photometers (either of Models 1008–AH or 1003–AH). Data from these instruments are sampled at a rate of 1 s^{-1} and averaged by the data logger to 5-min intervals. Data are transferred to the TCEQ central office from each of the network stations via modem. Calibrations are performed every 28 days for each ozone sensor by automatically introducing calibration gases with five different ozone concentrations into the sensor. The ozone calibration gases are created by an ozone generator that has itself been calibrated with an ozone transfer standard. On-site system audits are performed at least once per year.

2.3 Williams Tower

In situ measurements of a number of chemical species, including ozone, were made at a height of 250 m MSL on the Williams Tower in downtown Houston. Ozone measurements at this site were collected using a ThermoEnvironmental (now Thermo Electron) UV photometer

(Model 49). This instrument has a precision of 1 ppb and an accuracy of $\pm 5\%$. The response time for this sensor is 20 s, and except for brief calibration periods, it was operated continuously during the field campaign. Data from this instrument were reported as 15-min averages.

2.4 Airborne In Situ Measurements

2.4.1 G-1 Aircraft

The ozone instrument carried on the G-1 aircraft was a Model 49-100 ultraviolet photometer manufactured by Thermo Electron Corporation. System sensitivity was checked in flight every 1 h against an internal O₃ source. This source was standardized before and after the program against a NIST-traceable NO standard by gas-phase titration. Response over the period presented here was within the $\pm 2\sigma$ warning limits (corresponding to $< \pm 2\%$) for ground calibrations taken throughout the program. The RMS noise for background air was < 1 ppbv with an instrument time constant of ~ 4 s. Data from this sensor were sampled at a rate of 1 s^{-1} and reported as 10-s averages. The instrument was zeroed every hour through a charcoal cartridge. The data have been shifted in time to account for sampling and instrumental lags. With a sampling speed of approximately 100 m s^{-1} for the G-1, each reported value represents a path through the atmosphere about 1 km in length. The G-1 typically sampled at 500 meters above the surface, with occasional profiles to 2–3 km.

2.4.2 NCAR Electra

Two methods were used to measure ozone: a chemiluminescence (CL) instrument based upon the reaction between ambient ozone and NO added as a reagent gas [Ridley *et al.*, 1992], and a commercial, UV absorption instrument (Thermo Environmental Instruments Inc., Model 49). The CL instrument is taken as the primary measurement because it provides a continuous, rapid response, sensitive, linear ozone measurement; however, its response to ozone must be

calibrated. The UV instrument is based upon Beer's Law absorption, and thus, in principle, affords an absolute measurement.

Both of the instruments sampled through a common, rearward-facing inlet that extended 30 cm outside the aircraft skin. Ambient air was sampled through 0.64 cm o.d. PFA tubing. Immediately inside the fuselage, ultrapure 'zero' air with variable levels of ozone could be added to the inlet line through a three-way valve at a flow rate sufficient to displace all of the ambient sample stream, with the excess zero air flow vented through the inlet. Immediately downstream of this addition port, the flow was split to the two instruments. A 47 mm diameter, 20-30 micron pore-size PTFE filter preceded the UV absorption instrument.

The CL instrument and inlet were designed to sample at 10 Hz, but for this study the data were collected at 1 Hz. The reaction vessel design was closely based upon plans provided by B. A. Ridley and described by *Ridley et al.* [1992]. The ambient air and NO flows to the CL instrument were maintained at 500 and 4 standard cubic centimeters per minute (sccm), respectively. The reaction vessel pressure was maintained at 11 Torr. The ambient ozone measurements were corrected for the dependence of the instrument sensitivity to ambient water vapor as described by *Ridley et al.* [1992].

The UV absorption instrument was operated in the number density measurement mode; that is, without temperature and pressure correction through the instrument sensors. It was set to its standard span setting, which provided the direct absolute absorption measurement. A thermistor and a temperature-controlled pressure transducer (MKS Baratron, model 627A) monitored the temperature and pressure of the absorption cells to allow conversion of the measured ozone number densities to volume mixing ratios. The instrument was compared in the laboratory before and after the study with a reference UV absorption instrument; in both cases the

instruments agreed within 1%. The UV absorption instrument made a 2-s average measurement once every 10 s, and displayed the average of two consecutive measurements.

Before each flight, zero air with varying levels of ozone was generated and sampled simultaneously by both instruments through their common inlet to calibrate the CL instrument. Generated ozone in zero air was also measured several times during flights at varying altitudes. The sensitivity determined for the CL instrument remained constant within a 1.6% standard deviation through the field study. During flight, both instruments measured ambient ozone. For all 14 flights, the slope of the linear correlation between the UV and CL measurements with the intercept forced to zero was 1.002 ± 0.020 with a correlation coefficient of 0.979 ± 0.012 (average and standard. dev.). Overall, the data are believed to have an average accuracy within $\pm 1\%$, with a precision of the 1-second average data of 0.2 ppbv or better.

2.4.3 Baylor Twin Otter

Ozone measurements were also made from a Twin Otter research aircraft operated by Baylor University. The Baylor aircraft uses two commercial systems for measuring ozone that have been modified for fast time response. The first is a Dasibi 1008AH UV absorption analyzer. This device updates its output every 10 s and is oversampled, with the data logger recording an observation every 5 s. The second measurement system is a Thermo Environmental Instruments Model 42C NO/ozone chemiluminescence analyzer. This instrument supplies ozone measurements at a rate of 1 s^{-1} . The stainless steel sample inlet on the Twin Otter is located approximately 10 cm from the skin of the aircraft forward of the engine exhaust plume. Ambient air is supplied to the analyzers from a pyrex manifold through 0.25-in Teflon tubing equipped with in-line particulate filters. Before each flight, the analyzers were dynamically calibrated using gas substitution through actual sampling inlets and filters. A TECO 146C calibrator with a dilution system and an ozone generator on board the Twin Otter were used for this purpose. The

calibrator and other flow systems are periodically calibrated against a primary standard bubble meter (Gilian Instruments, Inc.).

3 Method of Comparison

There are three aspects of the ozone sampling that complicated instrument comparisons. First, in all cases that will be described in this paper, at least one of the instrument platforms was in motion. Moreover, in the aircraft–aircraft comparisons the flight patterns of the pairs of aircraft involved were generally not coordinated to facilitate the comparison. Second, there was often sharp horizontal variability in the ozone field because of ozone plumes that resulted from localized surface and stack emissions of chemical precursors. Finally, natural variability of ozone in the turbulent atmospheric boundary layer increased the statistical uncertainty of individual ozone samples. Thus we had the simultaneous conflicting needs to minimize the effect of horizontal variability of ozone and temporal changes in photolysis rates (requiring shorter averaging times) while maximizing the significance of pairs of samples that were to be compared (requiring longer averaging times).

Our averaging choices, given the conflicting requirements above, are necessarily somewhat subjective. We identified data segments for comparison from pairs of platforms that were separated by no more than 5 km in space and 5 min in time. Five minutes also seemed to be a natural interval for the TCEQ surface network, since those data are reported as 5-min averages. How comparison segments were determined specifically for each type of platform pairing is described below.

3.1 Lidar–surface

Fig. 1 shows the flight path of the NOAA DC-3 from 28 August 2000 together with the location of the measurement locations of the Williams Tower and of TCEQ’s surface ozone

monitoring network in the Houston area. This figure shows that on a number of occasions the path of the aircraft passed very close to a surface monitoring station. Because the terrain of the Houston area is virtually always less than 100 m above mean sea level (MSL), we selected the lidar range gates whose centers were closest to 100 m MSL for comparison. This avoided using range gates contaminated by the ground and was done after accounting for changes in DC-3 altitude. Fig. 2 shows a schematic of the data-selection criterion for these cases. All lidar samples that fell within a 5-km radius of a surface station were included in an average. This average was then compared with the 5-min value of ozone reported nearest the mean time of passage of the aircraft. In the best case, when the aircraft passed directly over a station, the lidar ozone value represented an average along a 10-km path. If the aircraft passed near the edge of the 5-km circle, the average was constructed from relatively few points.

A similar procedure was applied to the ozone measured at the Williams Tower. There were two significant difference between this comparison and that for the surface stations. First, the height of measurement at the Williams Tower was 250 m instead of at the surface. Second, ozone measurements were reported as 15-min averages. As will be discussed below, this may be significant for the Williams Tower results. Because the Williams Tower was a single location, there were relatively fewer points available for comparison.

3.2 Lidar-aircraft

The construction of the comparison between the NOAA lidar and the *in situ* aircraft measurements is more complicated than that for the lidar-surface measurements. For this comparison, we used occasions when the separation of the sampling paths of the aircraft was less than 5 km. We further required that the small spatial separation must have occurred with no more than a 5-min separation in time. We used MATLAB (r) to develop routines in-house to identify appropriate segments and thus automate the segment-selection process. Once the comparison

segments were selected, we chose the appropriate range gates from the NOAA lidar to correspond to the altitude of the other aircraft.

4 Results

4.1 Surface Network

Fig. 3 shows the comparison between the NOAA lidar and the surface stations for all available data during the field campaign. There is a clear correspondence between the two sets of measurements, but there is also obvious scatter. On two days in particular, 30 August and 12 September, there are a number of large outliers. Given the magnitudes of the lidar values for these points, it is possible that these are measurement errors on the part of the lidar. The reason for this is not clear, although time-height cross sections of the lidar data on 12 September (see Fig. 4) show much larger variability of ozone nearest the surface than elsewhere in the boundary layer. Excluding the two days with the large outliers, the root mean square difference *rmsd* between ozone from the near-surface range gate of the lidar and from the surface monitor in stations is 22 ppb, and the coefficient of determination r^2 is 0.36, which reflects the substantial scatter about the 1:1 line. (The root mean squared difference is equivalent to the root mean squared error relative to the 1:1 line.) Fig. 3 also shows that a much of the scatter is because the lidar tends to measure somewhat larger values of ozone than do the corresponding surface stations. While this could be an instrument issue, it is likely that the vertical structure of ozone near the surface may be responsible for this difference. Jiang et al. (2003) have the surface and lidar data discussed here to examine the vertical structure of ozone over Houston. They found that an ozone minimum at the surface is a persistent feature of its profile in the daytime boundary layer outside plumes of high ozone mixing ratio. They suggested that chemical processes such as NO titration may be responsible for this feature. If so, the bias reflected in these measurements may result from at

least in part from chemical modifications to the near-surface ozone profile rather than instrument error.

4.2 Williams Tower

The comparison between in situ measurements of ozone at 250 m the Williams Tower and the corresponding lidar range gates is shown in Fig. 5. Two contrasts between this comparison and the one with the surface stations are apparent. First, the scatter is a little larger, with $rmse=25$ ppb and $r^2=0.22$. Second, there is no apparent positive bias of the lidar with respect to the in situ measurements. We performed a linear least-squares fit to these data, with the result that $O_{3_{WmsTwr}} = 0.64 O_{3_{DIAL}} + 22$. However, the $rmse$ with respect to this fit remained at 25 ppb, which suggests that neither the non-unity slope nor the non-zero bias can be taken as significant. The lack of bias is in contrast to the comparison with surface measurements (Fig. 3), and is consistent with the hypothesis that surface removal processes for ozone account for at least some of the bias in that comparison.

At first look, the larger scatter is somewhat perplexing, since the range gates involved in the comparison are above the first one or two that one might expect to be affected by surface interference. However, the time-height cross section of Fig. 6 suggests an explanation. Because the Williams Tower is not far to the west of the Houston Ship Channel with its petrochemical industries, it is likely that it would often be in the path of any ozone plumes originating in that area. This is especially so since afternoon sea breezes would cause the Williams Tower to be regularly downwind of the Ship Channel. Fig. 6 clearly shows the edge of a plume of very high ozone concentration that is located on the boundary of a DIAL comparison segment (enclosed by vertical white lines). This comparison segment generated the annotated point in Fig. 5. In Fig. 6, each individual lidar profile (which corresponds to about 700 m in the horizontal) is visible. Inspection of the figure around the edge of the ozone plume shows that the ozone mixing ratio

can change by more than 50 ppb in 5 km or less. For such sharp spatial changes in ozone concentration, the 15-min averaging interval for the Williams Tower poses a problem. The aircraft was within the 5-km radius of the site (passing almost directly over it) for just over 2 min. During the other 13 min of the averaging interval, it seems likely that elevated concentrations from the nearby ozone plume influenced the Williams Tower measurements. The result is that the DIAL reported an ozone concentration of 83 ppb, while the Williams Tower value was 144 ppb—and both may have been correct. Thus, the large scatter in Fig. 5 may be more a result sharp spatial changes in ozone and of a mismatch of averaging intervals than of real instrument disagreement.

4.3 Lidar–aircraft

Fig 7 compares observations of ozone measured remotely by the airborne DIAL and in situ by other aircraft during TexAQS 2000. These comparisons occurred over a wide range of altitudes from the lower boundary layer to a little above the capping inversion (Table 1). In comparison with the Williams Tower and the surface monitoring network, the relatively small scatter between the airborne in situ measurements and the DIAL data is striking. Fig. 7a shows the comparison between the G-1 and the DIAL. With the exception of a single outlier, the data are clustered tightly around the 1:1 line. The outlier was from a flight path intersection that occurred on the eastern edge of the Ship Channel, where large ozone gradients are likely (see Fig. 6). Including the outlier, the *rmsd* for this comparison is 11 ppb, and $r^2=0.84$. Excluding the outlier, *rmsd*=7 ppb, and $r^2=.95$. There was no apparent systematic bias between the two measurement systems.

The comparison between the DIAL and the Electra (Fig 7b) showed similar low scatter and also a single outlier. Once again, the outlier was generated by a comparison that occurred on the southeastern edge of the Ship Channel. The *rmsd* for all data of the Fig. 7b is 11 ppb, but this

is dominated by the outlier. With the outlier excluded, the *rmsd* is 7 ppb. Similarly, with the outlier, $r^2=0.80$; without it $r^2=.92$. Unlike the other comparisons, there is a clear bias between the DIAL and the Electra measurements. Excluding the outlier, the best fit between the two sets of measurements is $O_{3_{Electra}} = 1.01O_{3_{DIAL}} - 6.2$. Thus, there is no significant gain discrepancy between the two systems, but the Electra values were, on average, 6 ppb less than those from the DIAL. For this fit, the root mean squared error was 4 ppb, which is an even firmer relationship than between the G-1 and the DIAL.

The relationship between the Baylor Twin Otter measurements of ozone and those from the DIAL system are similar to those for the other two aircraft (Fig. 7c). There is no apparent offset between the DIAL and the Twin Otter values. The *rmsd* is 5 ppb, and $r^2=0.94$.

5 Discussion and Conclusions

We have carried out a comparison among a variety of platforms used to measure ozone concentration during the TexAQS 2000 field campaign. Because of its spatial sampling characteristics, we have used the differential absorption lidar flown on board the NOAA DC-3 as the common instrument linking all of the other platforms together. A very appealing aspect of carrying out the comparison in this manner is that the results reflect the relative performance of the various instruments over the full range of measurement conditions and over the full period of the field campaign. This comparison has yielded the following notable results:

- Measurements from the surface monitoring network agree with those from the lowest-altitude range gate of the lidar typically within 22 ppb. This includes the effect of a tendency for surface stations to report lower values at moderate ozone mixing ratios.

- Measurements from the Williams Tower agree with lidar typically within 25 ppb, but with no tendency to report lower values than the lidar.
- The agreement between the DIAL and the in situ measurements of ozone by the aircraft is remarkably good. Excluding one outlier each from the Electra and the G-1 comparisons, the root mean squared error between the airborne in situ and lidar systems is 4–7 ppb. The only aircraft showing any systematic offset with respect to other systems was the Electra, which reported observations that appeared to be about 6 ppb low on average.

These results are very encouraging on a number of points. First, the airborne platforms, including the lidar, indicate that ozone variations of 5 ppb over horizontal distances of 5 km are significant. Further, because the comparison was carried out over altitudes ranging from a few hundred meters to several kilometers above the surface, they also indicate that there is no discernible height dependence to either the aircraft or the lidar results. Since the comparisons were carried out in environments of high ozone mixing ratio as well as low, it is reassuring to see that there is no particular deviation from a linear relationship over the entire range of ozone for any of the platforms compared. Such a deviation might be expected to occur if, for example, the algorithm designed to flag or correct saturated signals from the lidar (high ozone mixing ratio) were not effective. The data indicate that this is not the case and that the lidar data may be used with confidence at all altitudes. Finally, instrumental variability may be even less than the 4–7 ppb values of *rmse* because the data of the comparison were points of opportunity in which the flight direction of one aircraft was not purposely oriented to be parallel to the other. Thus, quite different ozone gradients could have been sampled by the two aircraft even though the sampling was carried out at nearly the same time and location. This

situation would have contributed a sampling error rather than a measurement error to the *rmse*.

Given the comparison between the airborne in situ sensors and the lidar, it does not seem likely that the increased scatter in the comparison between the lidar the data collected on the Williams Tower reflects a problem with the lidar measurements. There was no appreciable bias between the two sets of observations. We believe that the most likely cause for the increased scatter is the 15-min averaging interval for the Williams Tower data. We have shown that very large changes in ozone (>50 ppb) occurred over distances of the order of 5 km. If such a horizontal gradient were parallel to a modest wind (say, 5 m s⁻¹) and the lidar sampling path were perpendicular to the gradient, the 15-min mean ozone value measured on the Tower could be dramatically altered compared to what the lidar would measure in its 2.5-min-or-less passage through the comparison zone. This mechanism would produce differences of either sign. The good news in this comparison is that the Williams Tower measurements and those from the lidar showed no systematic differences. Thus, combining data from the Williams Tower and other platforms for well-matched averaging intervals is warranted.

In contrast to the comparison with data from the Williams Tower, the comparison between the lidar and the surface stations showed that the surface stations frequently reported somewhat lower values of ozone mixing ratio than the lidar. This may be a result of measurement geometry. Because of potential interference from the physical surface, we have used the lidar range gate closest to 100 m MSL for comparison with the surface sensors. As a result, any persistent vertical gradient in ozone would bias the comparison. A gradient in which ozone increases with height could be produced by surface removal mechanisms such as NO titration. Nevertheless, the *rmsd* between the surface values of ozone mixing ratio and those from the lidar was 22 ppb, which includes the effects of any

near-surface gradients. Horizontal or vertical differences in ozone that exceed this value are likely to be significant, and we have shown that such differences certainly occur.

In conclusion, we have compared ozone-measuring platforms from the 2000 Texas Air Quality Study using NOAA's airborne differential absorption lidar to tie the various platforms together. We have found outstanding agreement between the lidar and the in situ sensors aboard other aircraft. These may be freely combined in any analysis of ozone structure, although it may be desirable to adjust the data from the Electra for a small offset. We have found excellent agreement in the mean between the lidar and the in situ measurements at an altitude of 250 m on the Williams Tower in downtown Houston. The larger scatter in this comparison seem more likely to be a result of the 15-min averaging period for the Williams Tower data rather than instrumental imprecision. Finally, we have found good agreement between the lidar and ozone measured by the surface monitoring network. There is a tendency for surface values to be smaller than those measured by the lidar, but this is may be due in part to vertical gradients of ozone that can occur near the surface.

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Table 1. Ozone-measuring platforms used during the 2000 Texas Air Quality Study

Platform	Ozone Sensor	Sample Interval	Sampling Speed (m s ⁻¹)	Altitude (m AGL)	Sampling Dates
NOAA DC-3	Differential absorption lidar	10 s	70	0–2500	8/25, 26, 28–31, 9/1, 3, 6, 7, 12
TCEQ Surface Monitoring Network	Dasibi UV photometers	5 min	0	0	Continuous
DOE G-1	TECO Model 49	4 s	100	400–2500	8/25, 26, 31, 9/1
NOAA Electra	Chemiluminescence instrument referenced to a TECO 49	1 s	100	300–2500	8/25, 28, 30 9/1, 6
Baylor Twin Otter	Dasibi 1008AH UV absorption analyzer	5 s	65	280–450	8/26, 29, 30, 9/12
Williams Tower	TECO Model 49	15 min	0	250	Continuous

Figure Captions

Figure 1. Surface ozone monitoring stations (●), Williams Tower (★), and the flight path of the NOAA DC-3 in the Houston area on 28 August 2000. Inspection of the flight path shows that the DC-3 passed within 5 km of the Williams Tower and several of the surface monitoring stations on this day. These close approaches provided the data for the comparison of the DIAL ozone measurement with those of the surface stations.

Figure 2. Schematic of the comparison geometry between the NOAA DC-3's downward-pointing DIAL system and a surface monitoring station. Data within

Figure 3. Comparison of ozone reported in NOAA DIAL range gates nearest the surface with stations of the TCEQ ozone monitoring network. The 1:1 line is also shown.

Figure 4. Time-height cross section of DIAL ozone measurements from 12 September. White colors are data out of range and black represents data flagged as invalid. The vertical white lines enclose a measurement interval during which the lidar was within 5 km of a surface station. During this period, the mean ozone from the lidar range gate nearest the surface was 52 ppb, while the comparison station reported a 5-min average value of 44 ppb.

Figure 5. As in Fig. 3, but the comparison is between DIAL data and those collected at a height of 250 m on the Williams Tower. The outlier discussed in the text is noted.

Figure 6. As in Fig. 4, but for a DC-3 pass over the Williams Tower on 25 August 2000. Note that the comparison interval, within the vertical white lines, is on the edge of a plume of very high ozone concentration.

Figure 7. Comparison between observations of aircraft sampling ozone in situ and DIAL measurements of ozone for occasions when flight paths were separated by less than 5 km and 5 min. Comparisons are between the airborne DIAL and (a) DOE G-1, (b) NOAA Electra, and (c) Baylor Twin Otter.

**Flight Path of NOAA DC-3 over
Houston's Surface Monitoring Stations - 28 August 2000**

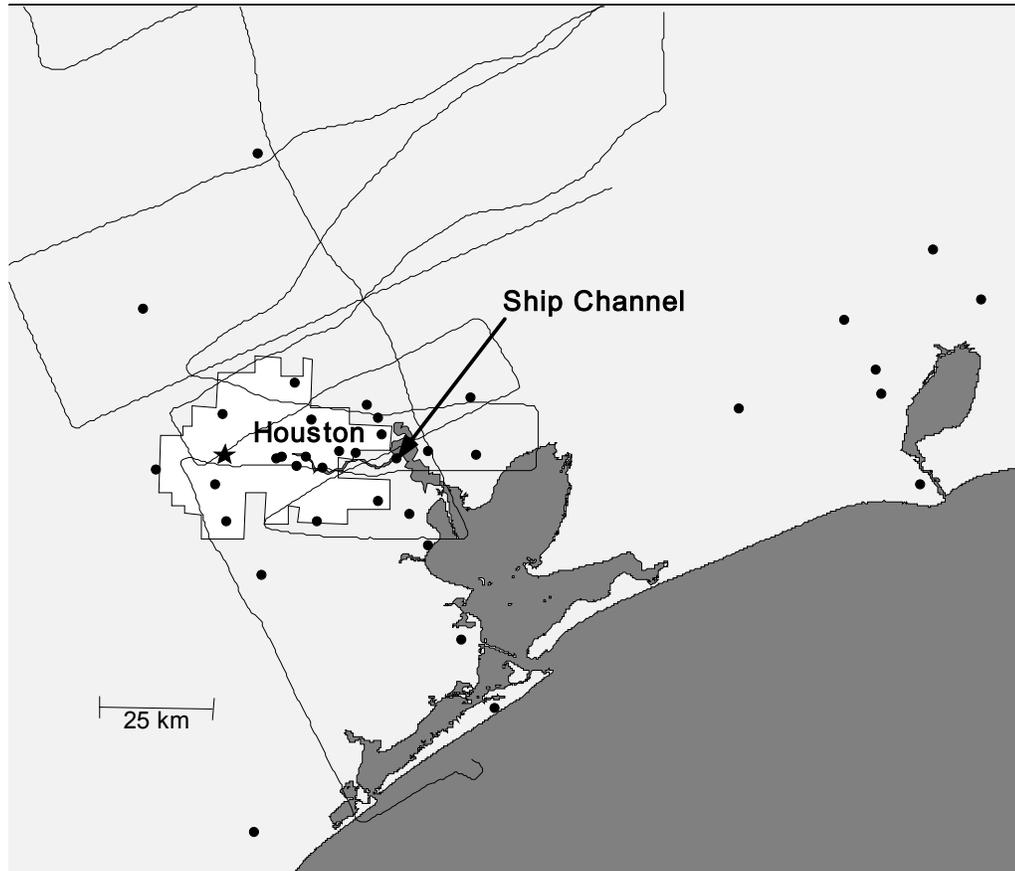


Figure 1.

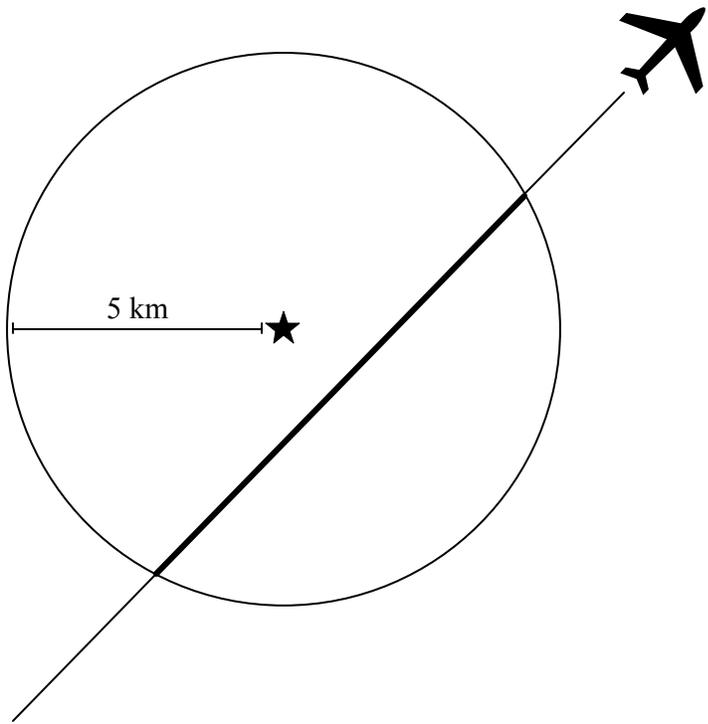


Figure 2.

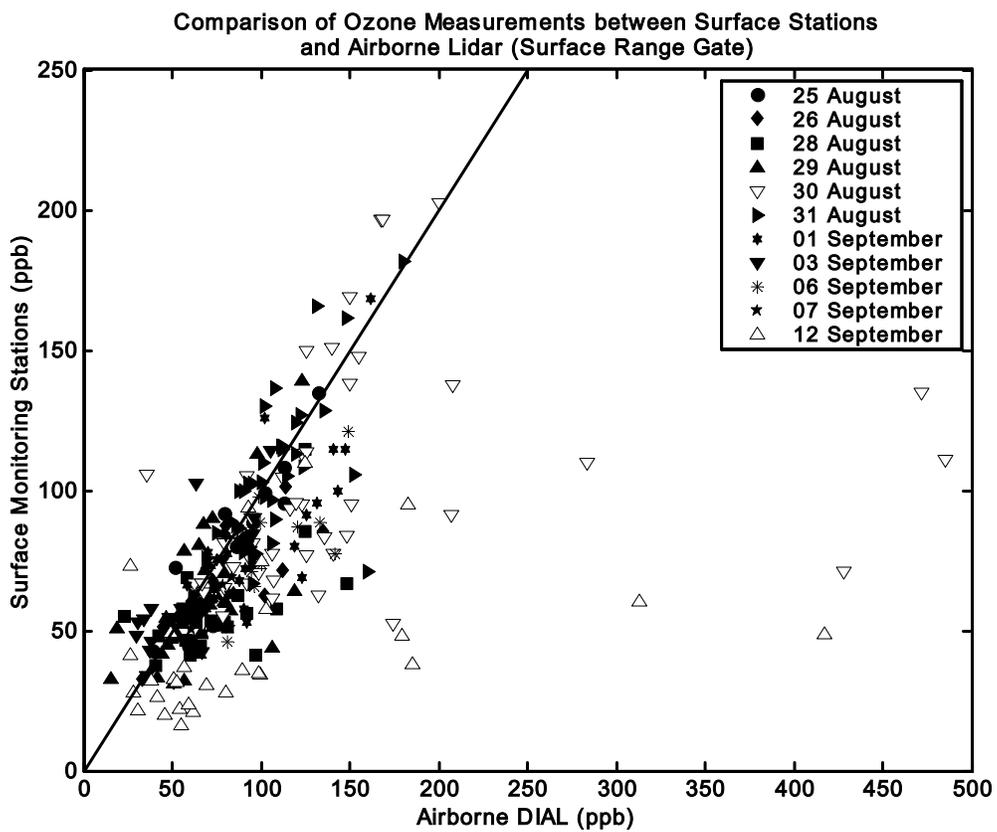


Figure 3.

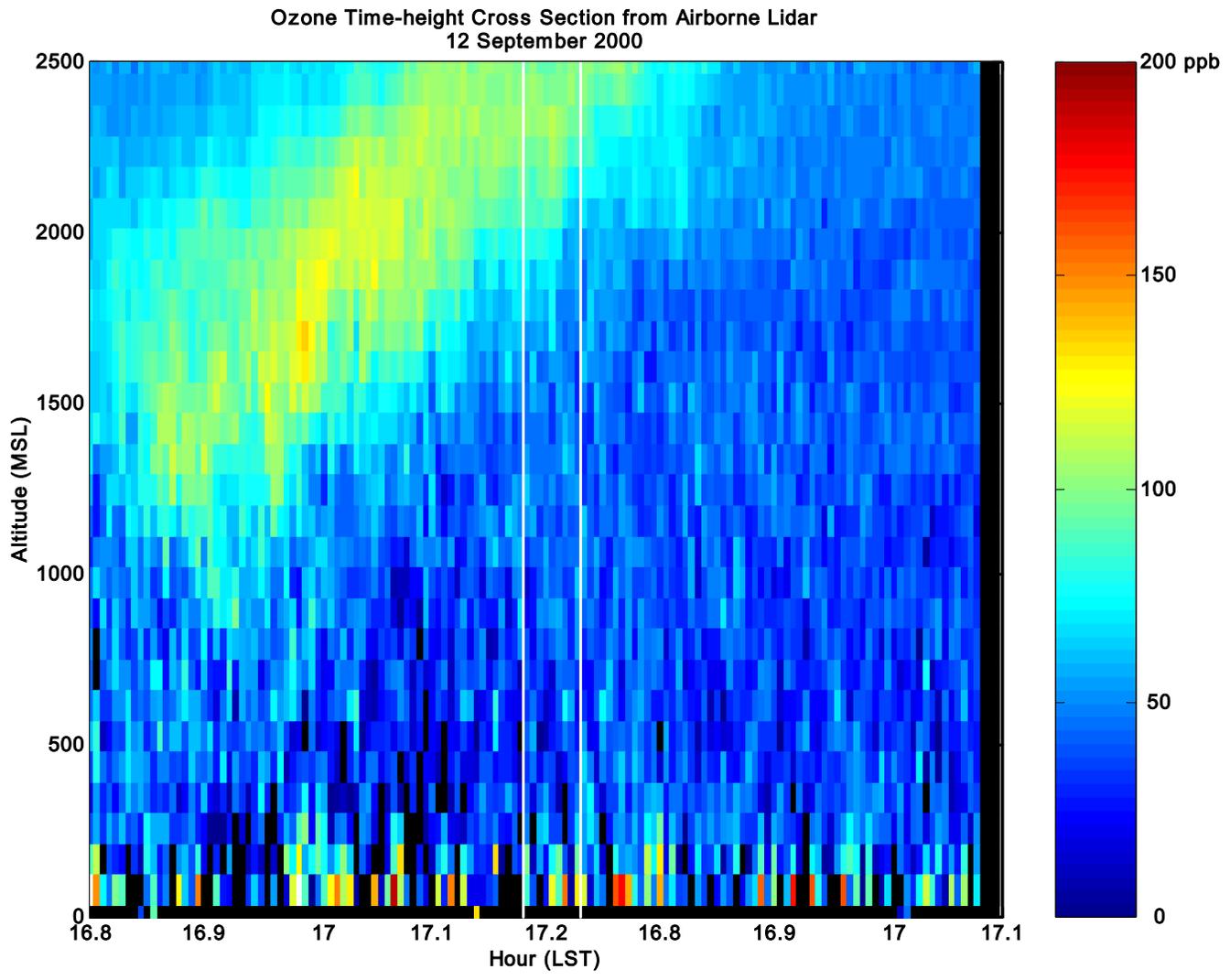


Figure 4.

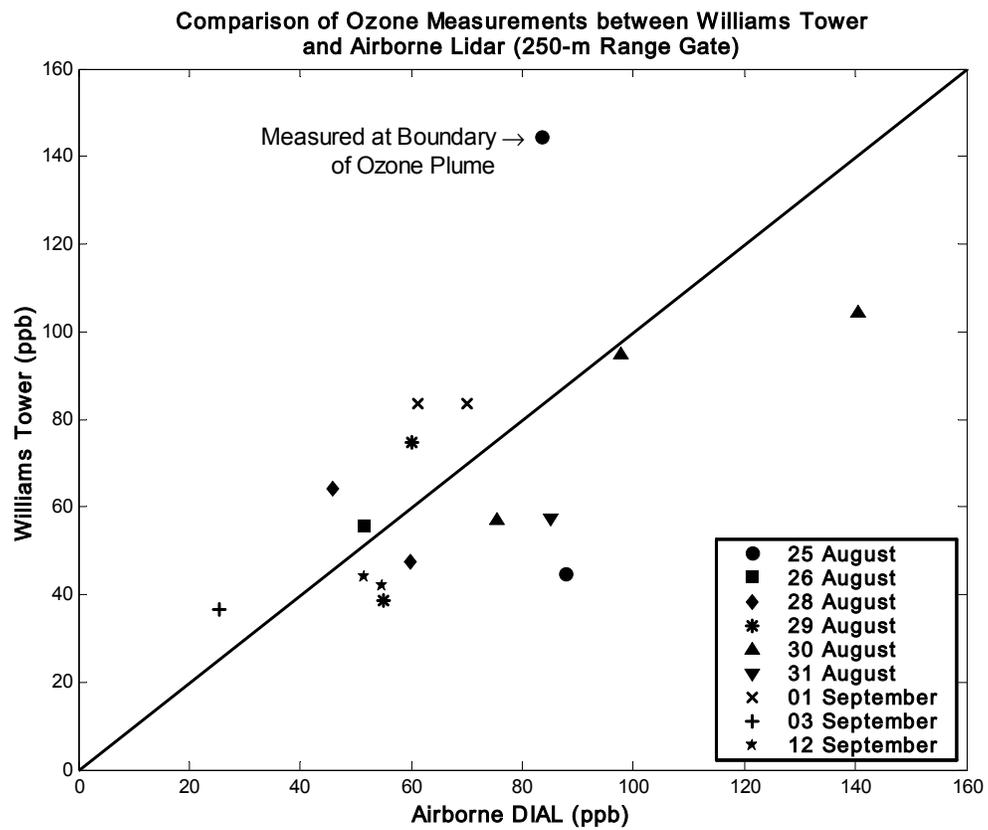


Figure 5.

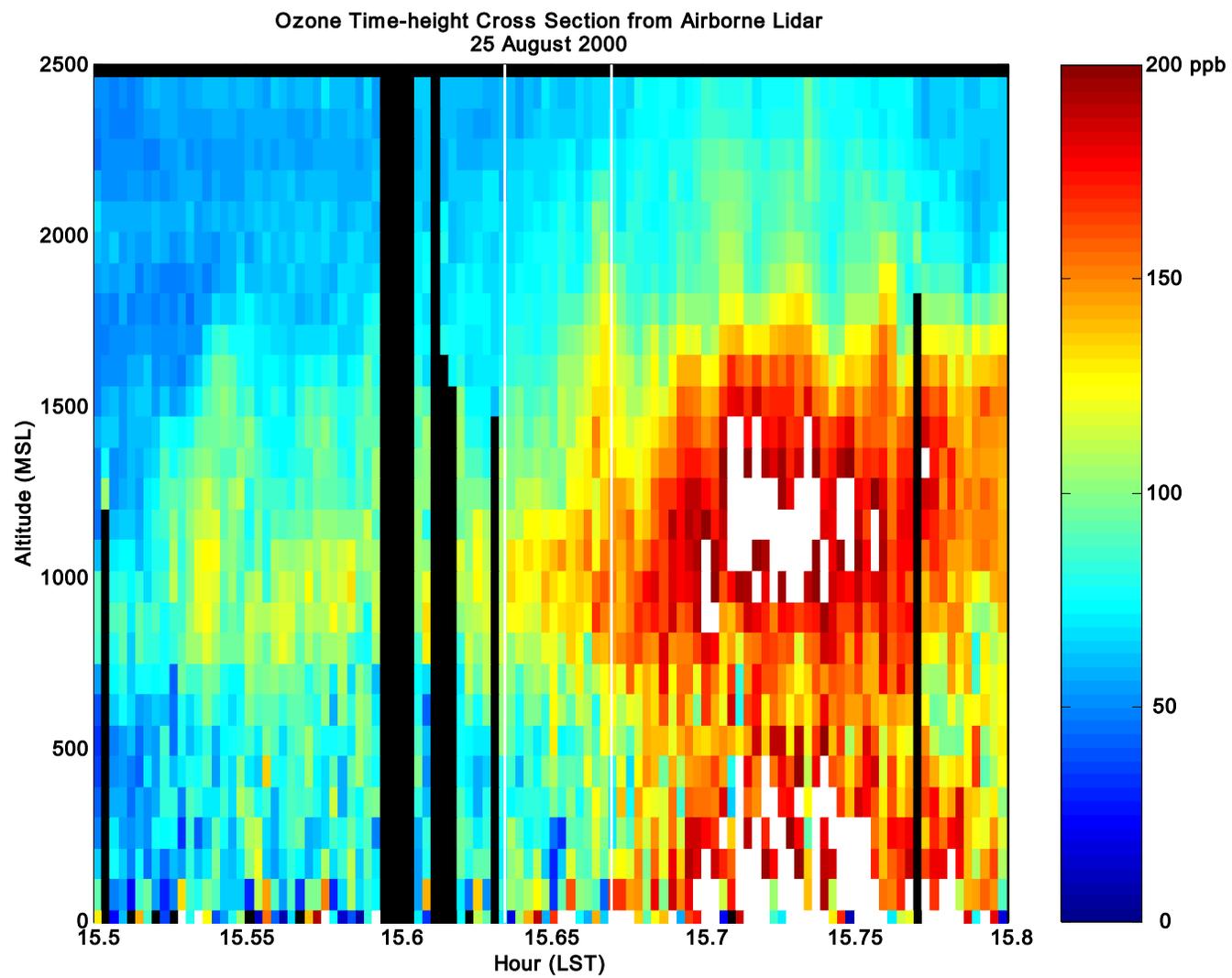


Figure 6.

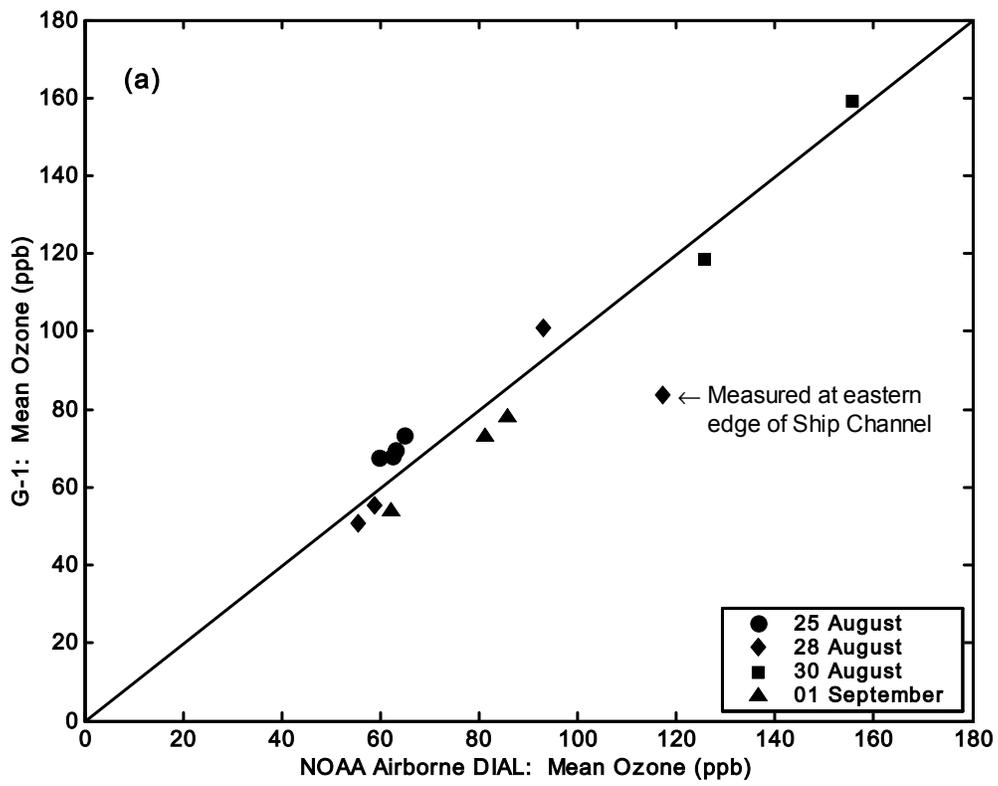


Figure 7a.

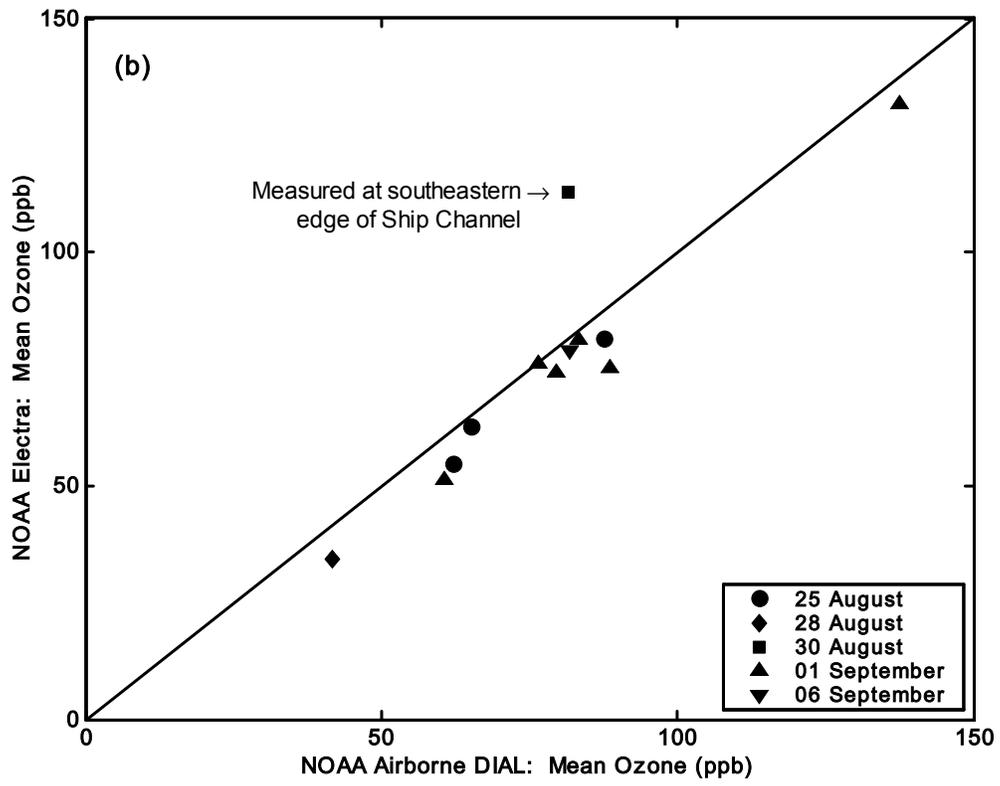


Figure 7b.

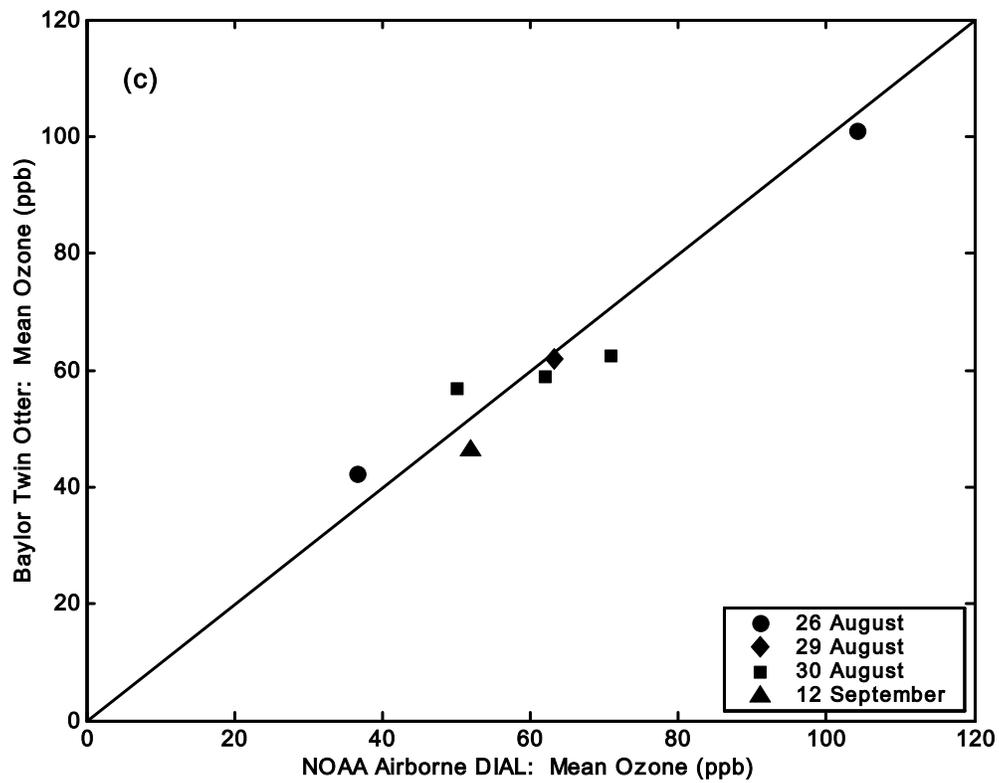


Figure 7c.