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Discussions

Intercomparison of lidar, aircraft, and surface ozone measurements in the San Joaquin Valley during the California Baseline Ozone Transport Study (CABOTS)

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Abstract. The California Baseline Ozone Transport Study (CABOTS) was conducted in the late spring and summer of 2016 to investigate the influence of long-range transport and stratospheric intrusions on surface ozone (O_3) concentrations in California with emphasis on the San Joaquin Valley (SJV), one of two "extreme" ozone non-attainment areas in the U.S. One of the major objectives of CABOTS was to characterize the vertical distribution of O_3 and aerosols above the SJV to aid in the identification of elevated transport layers and assess their surface impacts. To this end, the NOAA Earth System Research Laboratory (ESRL) deployed the Tunable Optical Profiler for Aerosol and oZone (TOPAZ) mobile lidar to the Visalia Municipal Airport (36.315°N, -119.392°E) in the central SJV between 27 May and 7 August 2016. Here we compare the TOPAZ ozone measurements with co-located *in-situ* surface measurements and nearby regulatory monitors, and to airborne measurements from the University of California at Davis/Scientific Aviation Mooney and NASA Alpha Jet Atmospheric eXperiment (AJAX) research aircraft. Our analysis shows very small differences (<2 ppbv or $\approx 2\%$ at 2 km) between the lidar and *in-situ* aircraft measurements, lending confidence to the use of these data sets for more detailed analyses.

1 Introduction

The San Joaquin Valley (SJV) of California is one of only two “extreme” ozone (O_3) non-attainment areas remaining in the United States with a 2016 ozone design value, i.e. the 3-yr average of the 4th highest maximum daily 8-h average mixing ratio (MDA8), more than 20 parts-per-billion by volume (ppbv) greater than the recently (2015) revised primary National Ambient Air Quality Standard (NAAQS) of 70 ppbv (https://www3.epa.gov/airquality/greenbook/hdtc.html). Such high O_3 concentrations are harmful to human health (U.S. Environmental Protection Agency, 2014) and impair plant growth and productivity (Avnery et al., 2011a, b), adversely affecting both the $15 billion agricultural industry in the SJV and the iconic forests of the nearby Sequoia and Kings Canyon National Parks (Panek et al., 2013).

The need to better understand the causes for the high surface O_3 in the San Joaquin Valley has motivated several major air quality studies over the years including the San Joaquin Valley Air Quality Study (SJVAQS) in 1990 (Lagarias and Sylte, 1991), the Central California Ozone Study (CCOS) in 2000, (Reynolds et al., 2010) and the California Research at the Nexus of Air Quality and Climate Change (CalNex) field campaign in 2010 (Ryerson et al., 2013; Brune et al., 2016). More recently, this issue was addressed by the 2016 California Baseline Ozone Transport Study (CABOTS) organized and supported by the California Air Resources Board (CARB) (https://www.arb.ca.gov/research/cabots/cabots.htm). CABOTS was designed to investigate the contributions of background O_3 (Jaffe et al., 2018) and the influence of stratospheric intrusions (Lin et al., 2012a) and long-range transport from Asia (Lin et al., 2012b) on surface O_3 concentrations in the SJV during late spring and summer. Characterization of the vertical distribution of O_3 in the lower free troposphere above the SJV and upwind regions was a key objective of the campaign, and O_3 profiles were measured using three different techniques (lidar, aircraft, and ozonesondes) in various parts of California. Integration of these datasets requires that the measurements be validated and any potential differences between the various techniques be understood and characterized (Beekmann et al., 1995). In this paper, we compare O_3 measurements from the NOAA ESRL Tropospheric Optical Profiler for Aerosol and oZone (TOPAZ) lidar with *in-situ* measurements from nearby regulatory and research surface monitors, and from instruments flown aboard the UC Davis/Scientific Aviation Mooney (Trousdell et al., 2016) and Alpha Jet research aircraft based at NASA’s Ames Research Center (Hamill et al., 2016;Yates et al., 2015). These comparisons, together with those from the multi-lidar (including TOPAZ) and ozonesonde Southern California Ozone Observation Project (SCOOP) intercomparison conducted by the NASA-sponsored Tropospheric Ozone Lidar Network (TOLNet) immediately after CABOTS (Leblanc et al., 2018) provide this validation.

2 California Baseline Ozone Transport Study (CABOTS)

The CABOTS field campaign was conducted between mid-May and mid-August of 2016. The primary measurements (cf. **Figure** 1a) included electrochemical cell (ECC) ozonesondes (Johnson et al., 2002) launched daily from Bodega Bay (38.319°N, -123.075°E, 12 m asl) (6 May-17 August) and Half Moon Bay (37.505°N, -122.483°E, 9 m asl) (15 July-17 August) by the San Jose State University (SJSU), *in-situ* aircraft sampling of O_3 and other compounds above central California by the University of California, Davis (UC Davis)/Scientific Aviation

(Trousdell et al., 2016) and the NASA Alpha Jet Atmospheric eXperiment (AJAX) (Yates et al., 2015), and ozone and backscatter lidar measurements by the truck-based NOAA ESRL TOPAZ lidar system (Alvarez et al., 2011) at the Visalia Municipal Airport (VMA, 36.315°N, -119.392°E, 88 m above mean sea level, asl) (27 May-18 June and 18 July-7 August) (**Figure** 2). Surface O_3 measurements were also made at the ozonesonde and lidar sites, and at the UC Davis monitoring station at the Chews Ridge Observatory (36.306°N, -121.567°E, 1520 m asl) (Asher et al., 2018) in the Santa Lucia Mountains west of Visalia, as well as the extensive networks of regulatory surface monitors maintained by the California Air Resources Board and the San Joaquin Valley Unified Air Pollution Control District (SJVUAPCD).

The VMA was chosen for the TOPAZ operations because of its central location in the SJV, the availability of the runway and airspace for low approaches and aircraft profiles, and the presence of the co-located SJVUAPCD wind profiler and Radio Acoustic Sounding System (RASS) (Bao et al., 2008). The TOPAZ truck was parked on the west side of the VMA between the airport runway and the heavily-trafficked multi-lane CA-99 and adjacent San Joaquin Valley Railroad (SJVR) (**Figure** 2). The VMA is located about 10 km west of downtown Visalia (pop. 130,000) and lies about one-third (60 km) of the way from Fresno to Bakersfield (**Figure** 1a,b).

3 Ozone Measurement Platforms

3.1 NOAA/ESRL TOPAZ lidar

The TOPAZ differential absorption lidar (DIAL) system was originally developed for the profiling of O_3 and particulate backscatter in the planetary boundary layer and lower free troposphere from NOAA Twin Otter aircraft (Alvarez et al., 2011;Langford et al., 2011;Senff et al., 2010;Langford et al., 2012;Langford et al., 2010). The lidar was reconfigured for mobile ground-based measurements after CalNex, and deployed in this configuration to several field campaigns including the 2013 Las Vegas Ozone Study (LVOS) (Langford et al., 2015) prior to CABOTS. The lidar is installed in the back of a medium box truck (cf. **Figure** 2) truck equipped with an *in-situ* O_3 monitor (2B Technologies Model 205) that samples air 5 m above the surface and an Airmar 150WX weather station to measure temperature, pressure, relative humidity, and wind speed and direction. The eye safe lidar is built around a low pulse energy (~100 µJ), high repetition rate (1 kHz) quadrupled Nd:YLF pumped Ce:LiCAF laser that is re-tuned between each pulse to generate light at three different wavelengths from 286 to 294 nm with an effective repetition rate of 333 Hz for each wavelength (Alvarez et al., 2011). The laser pulses are transmitted and the lidar return signals collected by a coaxial transmitter/receiver equipped with a commercial (Licel) photomultiplier-based dual analog/photon counting system. This hybrid data acquisition system replaced the original fast analog data acquisition system that was optimized for aircraft operations (Alvarez et al., 2011;Wang et al., 2017) and increased the maximum useful range from ~3 to 6 km during the day, and to more than 8 km at night depending on the laser power, atmospheric extinction, and solar background light.

The truck-mounted version of TOPAZ incorporates a large scanning mirror above the vertically pointing transmitter/receiver to allow profile measurements at different slant angles. These slant profiles can be combined to create vertical profiles that start much closer to the ground than conventional vertically staring lidar systems (Proffitt and Langford, 1997). During CABOTS, the scanning mirror was moved sequentially between elevation angles of 90, 20, 6, and 2° with a 225-s averaging time at 90° and 75-s averaging times at the other 3 angles. The cycle was repeated approximately every 8 minutes and the vertical projections combined to create a single vertical profile starting at 27.5±5 m above ground level (agl). Note that this approach assumes a fair degree of horizontal homogeneity and the lidar slant paths were oriented parallel to the VMA runway (135°) over open farmland to avoid populated neighborhoods and local NO_x emissions associated with CA-99 (cf. **Figure** 2).

The O_3 profiles shown here were retrieved using two wavelengths (~287 and 294 nm) with 30-m range gates and a smoothing filter that increased from 270 m wide at the minimum range (800 m) to 1400 m wide at the maximum range (8 km). The effective vertical resolution increased from ~10 m near the surface to ~150 m above 500 m agl. The profiles were computed using an iterative technique (Alvarez et al., 2011) with the O_3 absorption cross-sections from Malicet *et al.* (1995). Temperature and pressure profiles interpolated from the 3-h National Centers for Environmental Prediction (NCEP) North American Regional Reanalysis (NARR) using the grid point closest to the TOPAZ lidar location were used to account for the temperature dependence of the O_3 cross-sections and to convert O_3 number densities to mixing ratios. The total uncertainties in the 8-min ozone retrievals are estimated to increase from ±3 ppbv below 4 km, to ±10 ppbv at the top of the profile. Profiles of the backscatter from aerosols, smoke, and dust were retrieved with 7.5 m resolution at 294 nm.

3.2 UC Davis/Scientific Aviation Mooney

The University of California at Davis and Scientific Aviation, Inc. (http://www.scientificaviation.com), conducted a series of research flights above the SJV during the summer of 2016 using a Scientific Aviation single-engine Mooney TLS or Ovation aircraft as part of the CARB-supported Residual Layer Ozone Study (RLO) (https://www.arb.ca.gov/research/apr/past/14-308.pdf). Several of these flights overlapped with the TOPAZ operations during CABOTS, as did some of the 12 additional flights funded by the U.S. EPA and the Bay Area Air Quality Management District (BAAQMD). The Mooney carried a 2B Technologies Model 205 O_3 monitor, an Eco Physics Model CLD 88 (NO) with a photolytic converter to measure NO and NO_2, and a Picarro 2301f Cavity Ring-Down Spectrometer (CRDS) to measure CO_2, CH_4, and H_2O (Trousdell et al., 2016). The 2B O_3 data were sampled every 1-s, which corresponds to a mean distance of 75 m at the typical level leg flight speed.

3.3 NASA Alpha Jet Atmospheric eXperiment (AJAX)

The NASA Ames Alpha Jet Atmospheric eXperiment (AJAX) (Hamill et al., 2016) sampled O_3 and other tropospheric constituents above California during CABOTS using a two-person trainer fighter jet based at Moffett Field, CA (MF, 37.415° N, -122.050° E). The Alpha Jet carried an external wing pod with a modified commercial UV absorption monitor (2B Technologies Inc., model 205) to measure O_3 (Ryoo et al., 2017;Yates et al., 2015;Yates et al., 2013) and a (Picarro model 2301-m) cavity ringdown analyzer to measure CO_2, CH_4, and H_2O (Tanaka et al., 2016). A second wing pod carried a non-resonant laser-induced fluorescence instrument to measure formaldehyde (CH_2O) (St. Clair et al., 2017). The aircraft is also equipped with GPS and inertial navigation systems to provide altitude and position information, and the NASA Ames developed Meteorological Measurement Systems (MMS) to provide highly accurate pressure, temperature, and 3-D wind data. The 2B O_3 data, taken every 2 s, are averaged over 10 s to increase the signal-to-noise ratio, giving an overall ozone uncertainty of 3 ppbv at 10-s resolution. The overall uncertainties for the CO_2 and CH_4 measurements are typically less than 0.16 ppmv and 2.2 ppbv, respectively, when the 3-Hz data are binned to 3 s (Tanaka et al., 2016).

4 Results and Comparisons

The TOPAZ measurements were conducted over two 3-week intensive operating periods (IOPs) in the late spring (27 May to 18 June) and summer (18 July to 7 August) of 2016. A total of 440 hours of lidar data were recorded during the first (1654 profiles over 22 days) and second (1686 profiles over 21 days) IOPs with an average of more than 10 hours of nearly continuous measurements per day. The skies above Visalia were mostly cloud free during the study, with only a few profiles truncated by high clouds during IOP1. However, during IOP2 the SJV was fumigated by smoke from the Soberanes Fire (https://inciweb.nwcg.gov/incident/4888/) that started on 22 July about 200 km west of Visalia near Big Sur.

4.1 Comparisons between lidar and surface measurements

The NOAA 2B ozone monitor operated continuously at the VMA throughout the TOPAZ deployment with the system response checked during each IOP by an external mobile calibration source operated by CARB. These calibration checks revealed a 3% low bias in the 2B measurements that has been corrected in the data shown here. **Figure 3** plots time series (Pacific Daylight Time, PDT, or UT-7 h) of the 1-min averaged *in-situ* surface mixing ratios (gray dots) measured 5 m above the ground from each IOP together with the TOPAZ mixing ratios retrieved from a height of 27.5±5 m (black line) and a range of ~800 m along the slant path above the agricultural fields to the southeast (cf. **Figure** 2). **Figure** 4a is an enlarged view of the VMA surface measurements (gray line) from 9-13 June together with the mixing ratios from the 27.5 m TOPAZ measurements (filled black circles). Also plotted are the 1-h average ozone mixing ratios measured 6.7 m agl by the CARB regulatory API/Teledyne 400 monitor located on N. Church Street in Visalia (102 m asl) about 10 km to the east of VMA (solid black line), and measured 5 m above the ground by the SJVUAPCD API/Teledyne 400 monitor in Hanford (82 m asl) about 22 km to the west of VMA (dotted black line). The four sets of measurements agreed fairly well during the day but diverged markedly at night and in the early morning when O_3 was removed by surface deposition and titration by NO_x within the surface layer. The losses were greatest at the VMA monitor which was located in the TOPAZ truck next to the heavily-trafficked CA-99 and SJVR railroad line. Titration by NO was undoubtedly much greater here, but there were no NOx measurements available to confirm this hypothesis. Much smaller losses were measured by the rural Hanford monitor and intermediate losses were measured by the Visalia monitor which is located on a downtown rooftop. **Figure 4**b shows that while the 27.5 m TOPAZ measurements were usually larger than the VMA *in-situ* measurements, the correspondence approaches 1:1 when the comparison is restricted to daytime measurements made after the nocturnal inversion had dissipated (0900 to 1800 PDT) and when the winds were southeasterly and away from the highway and nearby developments (125 to 145°) and greater than 2.5 m s^{-1}.

Figure 5 compares the 27.5 m TOPAZ O_3 measurements to the regulatory O_3 surface measurements from the monitors at Visalia (8.5 km) and Hanford (24 km) described above, and from the slightly more distant SJVUAPCD monitors at Parlier (34 km) and Porterville (43 km). The TOPAZ mixing ratios were slightly higher than those at Visalia and Hanford, but lower than those at Parlier and Porterville, which are closer to the Sierra foothills and measure some of the highest O_3 concentrations in the SJVAB. The degree of correlation decreased with distance as expected, yet remained quite good as far as 43 km from the VMA at Porterville. This suggests that the O_3 measurements acquired at the VMA during CABOTS can be considered representative of the central San Joaquin Valley.

4.2 Comparisons between lidar and aircraft measurements

4.2.1 UC Davis/Scientific Aviation Mooney

The RLO flights were executed as a series of 2 to 3-day deployments with as many as 4 flights per day lasting 2 to 3 hours each between Fresno and Bakersfield. Two of these deployments, RLO2 (2-4 June), and RLO4 (24-26 July), overlapped with the first and second TOPAZ IOPs, respectively, and included low approaches at VMA on most of the flights with spiral profiles near VMA on several. Both deployments occurred as warm temperatures (>40°C) and weak anticyclonic winds associated with synoptic high-pressure systems resulted in the buildup of surface ozone across the South Coast and San Joaquin Valley Air Basins. The highest measured MDA8 O_3 in the SJVAB during the first IOP was recorded on 4 June at Clovis (91 ppbv), which lies about 65 km northwest of VMA (cf. **Figure** 1b). The highest reported MDA8 O_3 during the second IOP (and the year) was recorded on 27 July at Parlier (101 ppbv), which lies midway between Clovis and the VMA. The monitors at Visalia and Hanford reported MDA8 concentrations of 72 and 88 ppbv, respectively, on 4 June, and 83 and 85 ppbv on 27 July. **Figure** 3 shows that the highest O_3 mixing ratios measured by the VMA surface monitor and TOPAZ (27.5 m agl) were also recorded on these two days.

The flight tracks from all of the Mooney sorties during the RLO2 and RLO4 deployments are plotted in **Figure** 6a. FLT29 (RLO4) was a transit flight from the Scientific Aviation home base near Sacramento to Fresno. The remaining RLO flights were between Fresno and Bakersfield as noted above. The two EPA/BAAQMD deployments (27-29 July and 4-6 August) were of longer duration than the RLO flights with morning and afternoon sorties that placed more emphasis on cross-valley measurements and transects to the coast (**Figure** 6b) including profiles above the South Bay (EPA1) and Chews Ridge (EPA2). The afternoon flights during both series included legs to Visalia.

Figure 7 shows the sections of the RLO and EPA/BAAQMD flight tracks that passed within 5 km of TOPAZ (dashed black circles). Most of these flights included low passes below 10 m along the VMA runway that approached to within ~350 m horizontally of the TOPAZ truck and within 1000 m of the center of the 27.5 m agl TOPAZ slant path measurements (cf. **Figure** 2). **Figure 8** shows time series of the 27.5 m TOPAZ and 5 m *in-situ* measurements during all of the RLO and EPA/BAAQMD low approaches together with the ozone measured by the aircraft between the surface and 25 m agl. All of the aircraft measurements lie within 10% of the O_3 retrieved by TOPAZ with the exception of the much higher values (>100 ppbv) measured by the Mooney around 1400 PDT on 3 June (**Figure 8**a, see below). **Figure 9** compares the aircraft and lidar O_3 measurements made during 5 of the profiles conducted by the Mooney near the VMA. FLT19 was conducted in the early afternoon of 3 June, and FLT33, FLT35, FLT36, and FLT37 were conducted over the 24-hour period beginning just after local midnight on 25 July. The four consecutive TOPAZ profiles acquired during the time required for the Mooney to reach the top of each profile (~15-30 minutes at a climb rate of ~2.2 m s^{-1}) are plotted in each panel. The gray envelopes show the lidar 4-profile mean ±10%. The consistency between consecutive profiles reflects the combined effects of atmospheric variability and the precision of the lidar measurements.

Overall, the agreement between the TOPAZ and Mooney measurements in **Figure 9** is quite good, with some notable differences. Most of these arise from the coarser vertical resolution of the lidar retrievals, which smooth out abrupt concentration changes such as those seen at the top of the boundary layer (~0.8 km agl) in **Figure 9**a, and between 2 and 3 km in **Figure 9**e where several narrower layers are smoothed into one broad layer in the lidar profile. **Figure 9**e also shows that the agreement between the lidar and aircraft measurements is better at low altitudes where the addition of the slant path measurements significantly improves the effective vertical resolution of the lidar. Fine-scale variability in O_3 also contributes to some of the observed differences, particularly on 3 June where the aircraft-measured O_3 concentrations varied by as much 25 ppbv during the low approach over the VMA runway. This unusually large variability is also seen in the large and rapid changes in the lidar measurements near the top of the boundary layer (**Figure 9**a) and challenges the assumptions about horizontal homogeneity used in the calculation of the TOPAZ vertical profiles near the surface.

The lidar profiles from 26 July (**Figure 9**e) also show large profile-to-profile changes in the narrow high O_3 layer lying just above the top of the nocturnal boundary layer (~0.3 km asl). The 25 and 26 July measurements (**Figures** 9b-9e) were made several days after the Soberanes Fire started and the low altitude "layer" near 400 m in **Figure 9**e is actually a short-lived puff of smoke and elevated O_3 from the fire. This is more obvious in the expanded view of the profiles shown in **Figure 10**a. Only two of the four lidar profiles from **Figure 9**e are plotted: the first profile coinciding with the aircraft measurements (solid trace, ±10%) and the profile acquired 16-24 minutes later when the puff had mostly disappeared (dashed trace). The corresponding lidar backscatter measurements are plotted in **Figure 10**b, and **Figure 10**c shows the NO_2 and H_2O profiles measured by the aircraft. The backscatter measurements show that the TOPAZ retrievals are unaffected by strong backscatter gradients, which can create second-derivative like inflection points in the DIAL O_3 profiles (Kovalev and McElroy, 1994). The relative homogeneity in the aircraft

NO_2 and H_2O profiles confirms that the high O_3 layer seen in the lidar measurements was not an artifact caused by interferences from these species (Proffitt and Langford, 1997).

4.2.2 NASA Alpha Jet Atmospheric eXperiment (AJAX)

AJAX conducted 4 research flights over the SJV while TOPAZ was operational, with 2 additional flights (21 June and 7 July) between the two IOPs. The Alpha Jet executed descending spiral profiles from 4 to 5 km down to the surface that ended in low approaches on three of these flights: AJX190 on 3 June, AJX191 on 15 June, and AJX195 on 21 July. The aircraft also conducted a very low approach (~5 m) at VMA on 28 July (AJX196) but did not execute a full profile. The first and last flights (AJX190 and AJX196) coincided with the high ozone episodes mentioned earlier and the third flight (AJX195) also occurred during a period of high pressure. The second flight (AJX191) was conducted as a deep closed low moved into the Pacific Northwest, however, bringing unseasonably cool temperatures (26 °C) and strong surface winds to the SJV. This cyclonic system advected a large Asian pollution plume across the valley in the middle troposphere, but surface ozone remained low with the peak MDA8 O_3 concentration in the SJVAB only reaching 59 ppbv at the Sequoia-Kings Canyon monitor.

Figures 11 and **12** are similar to **Figures** 6 and 7, but instead show the AJAX flight tracks. The first AJAX flight (AJX190) on 3 June during IOP1 overlapped with the UC Davis/Scientific Aviation RLO2 deployment. AJX191 took place about two weeks later in IOP1, and AJX195 occurred several days prior to the RLO4 deployment in IOP2. AJAX also executed profiles (not shown here) above and upwind of Chews Ridge on AJX190 and AJX191 and near Bodega Bay on AJX191 and 195 and sampled the Soberanes Fire plume on AJX196.

Figure 13 displays coincident AJAX and TOPAZ profiles in plots similar to those shown for the Mooney in **Figure** 9, but with an extended vertical axis to reflect the higher range of these profiles. The points in **Figure 13** are sparser than those in **Figure 9** in part because of the 10-s averaging time, and in part because the Alpha Jet executed its profiles with an airspeed of about 110 m s^{-1} and a climb rate of 8 m s^{-1} compared to the corresponding values of 60 m s^{-1} and 2.2 m s^{-1} for the Mooney.

The agreement between the Alpha Jet and TOPAZ measurements is well within the combined uncertainties on all days except for 3 June (**Figure 13a**) when the measured aircraft and retrieved lidar concentrations differ by as much as 12 ppbv (20%) at 2.5 km asl and 20 ppbv (~50%) at 5.2 km asl. The Alpha Jet arrived on station at VMA about 3 hours after the Mooney completed its profile to 3 km, which was is in good agreement with the lidar measurements (cf. **Figure 9**a). The agreement between the TOPAZ and AJAX measurements is much better at lower altitudes and the 2-s O_3 measurement made during the Alpha Jet low approach on 3 June (filled yellow circles in **Figure 8**a) also agrees well with both the lidar and surface measurements. The Google Earth plot in **Figure 14** shows that the differences between the two profiles near the surface and at high altitudes in **Figure 13**a are due, at least in part, to significant horizontal variability in O_3 during the measurements. Spatial differences between the lidar and aircraft will always limit any intercomparison, but **Figures** 9 and 13 suggest that the horizontal variability is at a minimum above the boundary layer in the lower free troposphere. The scatter plot in **Figure** 15 compares the mean TOPAZ mixing ratios at 2.0±0.5 km asl with the corresponding in-situ measurements from the AJAX and Scientific Aviation aircraft. The mean lidar (65.4±6.5 ppbv) and in-situ (64.0±6.3 ppbv) measurements from the 8 profiles plotted in **Figures** 9 and 13 differ by less than 2 ppbv or about 2%.

5 Summary and Conclusions

The lidar, aircraft, and ozonesonde profiles acquired during the 2016 CABOTS field campaign provide an unprecedented look at the vertical distribution of lower tropospheric O_3 above California during late spring and summer. The good agreement between the low elevation TOPAZ measurements and the collocated and regional (<45 km) surface monitors suggests that the measurements made at the VMA during CABOTS can be considered representative of the central San Joaquin Valley. The excellent agreement between the NOAA TOPAZ lidar profiles and the Scientific Aviation and AJAX aircraft measurements suggests that all of these O_3 measurements can be used with confidence.

The coordinated lidar and aircraft sampling of O_3 above the central San Joaquin Valley during CABOTS also illustrates the synergy between the two types of measurements. Lidar can provide long time series of the O_3 (and backscatter) vertical distributions above a fixed location while the aircraft can place the lidar measurements within a larger spatial context and measure other important parameters. This synergy is illustrated by the two time-height curtain plots displayed in **Figure 16**. **Figure 16a** shows the continuous TOPAZ measurements from a 14-hour time span on 25-26 July with the Mooney flights from FLT 35, 36, and 37 superimposed. The aircraft measurements made within 5 km of VMA are highlighted by colored squares outlined in white. **Figure 16b** is similar, but shows 10-hours of continuous TOPAZ measurements from 15 June with the AJAX measurements (AJX191) superimposed.

Although the CABOTS ozonesondes were launched too far away from the VMA to allow quantitative comparisons with the lidar, TOPAZ was relocated to the NASA Jet Propulsion Laboratory (JPL) Table Mountain Facility (TMF) in the San Gabriel Mountains immediately after CABOTS for the Southern California Ozone Observation Project (SCOOP), a multiple lidar and ozonesonde intercomparison organized by the NASA-sponsored Tropospheric Ozone Lidar Network or TOLNet (https://www-air.larc.nasa.gov/missions/TOLNet/) at the NASA Jet Propulsion Laboratory (JPL) Table Mountain Facility (TMF) (Leblanc et al., 2018). The results from the SCOOP intercomparison and those presented here complete the inter-validation of the CABOTS lidar, aircraft, and ozonesonde profile measurements.

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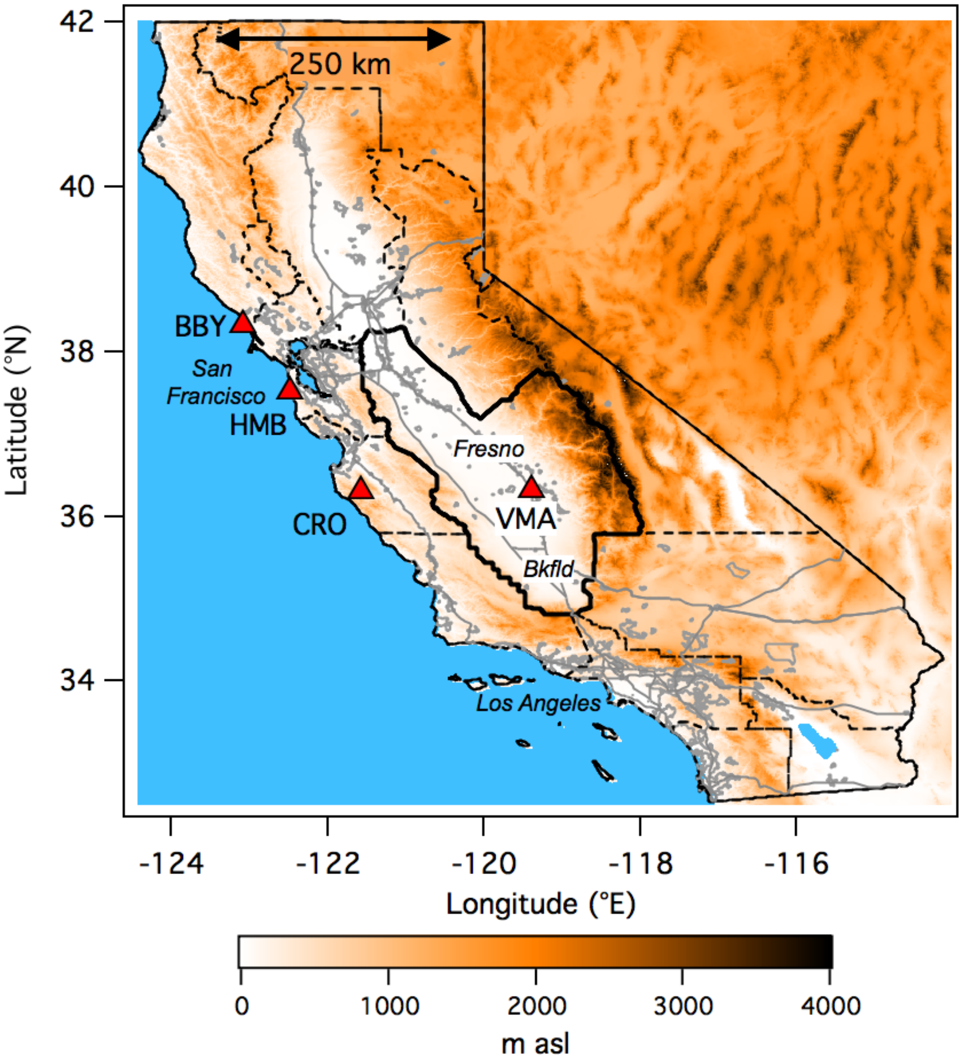

Figure 1. (a) Topographic map showing the air basins of California (dashed black lines); the San Joaquin Valley Air Basin (SJVAB) is outlined in heavy solid black. Interstate highways and urban areas are shown in gray. The filled red triangles show the CABOTS measurement sites at Bodega Bay (BBY), Half Moon Bay (HMB), Visalia Municipal Airport (VMA), and Chews Ridge Observatory (CRO).

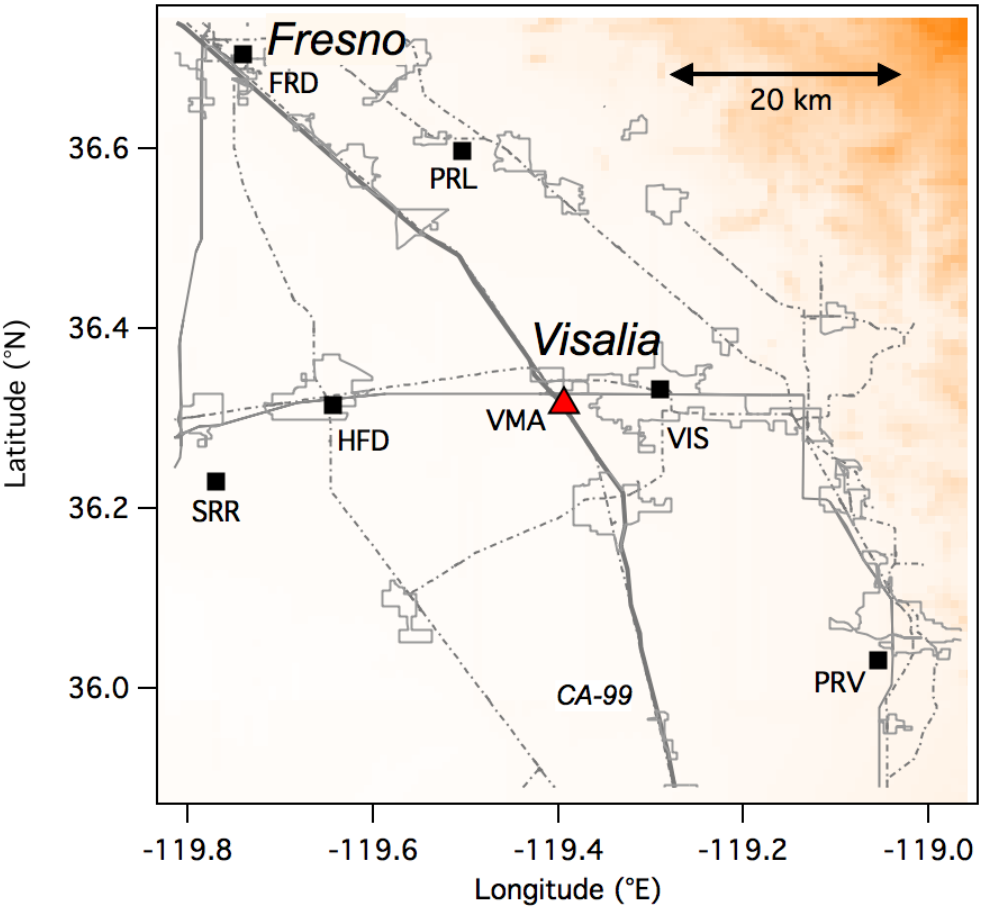

Figure 1. (b) Same as (a), but showing an enlarged view of the area surrounding the VMA. The solid and dot-dash gray lines represent the major highways and railroads, respectively, with the heavier solid line showing CA-99 (see text). The filled black squares show the 6 closest regulatory O_3 monitors active during the CABOTS campaign: Visalia (VIS), Hanford (HFD), Santa Rosa Rancheria (SRR), Fresno-Drummond St. (FRD), Parlier (PRL), and Porterville (PRV). The elevation scale is the same as in (a).

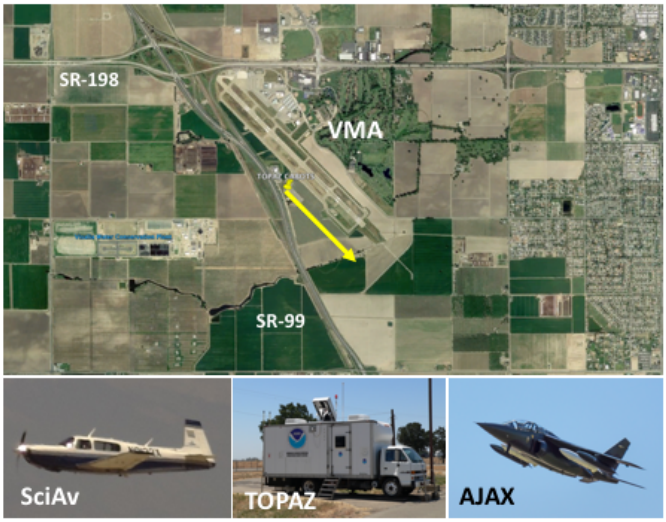

Figure 2. Aerial view of the Visalia Municipal Airport (VMA) showing the location of TOPAZ and the 1 km lidar slant path line of sight (yellow line). The Scientific Aviation Mooney and AJAX Alpha Jet are shown flanking the NOAA ESRL TOPAZ truck below the Google Earth image. Mooney and TOPAZ photos by A. Langford. Alpha Jet photo by W. von Dauster.

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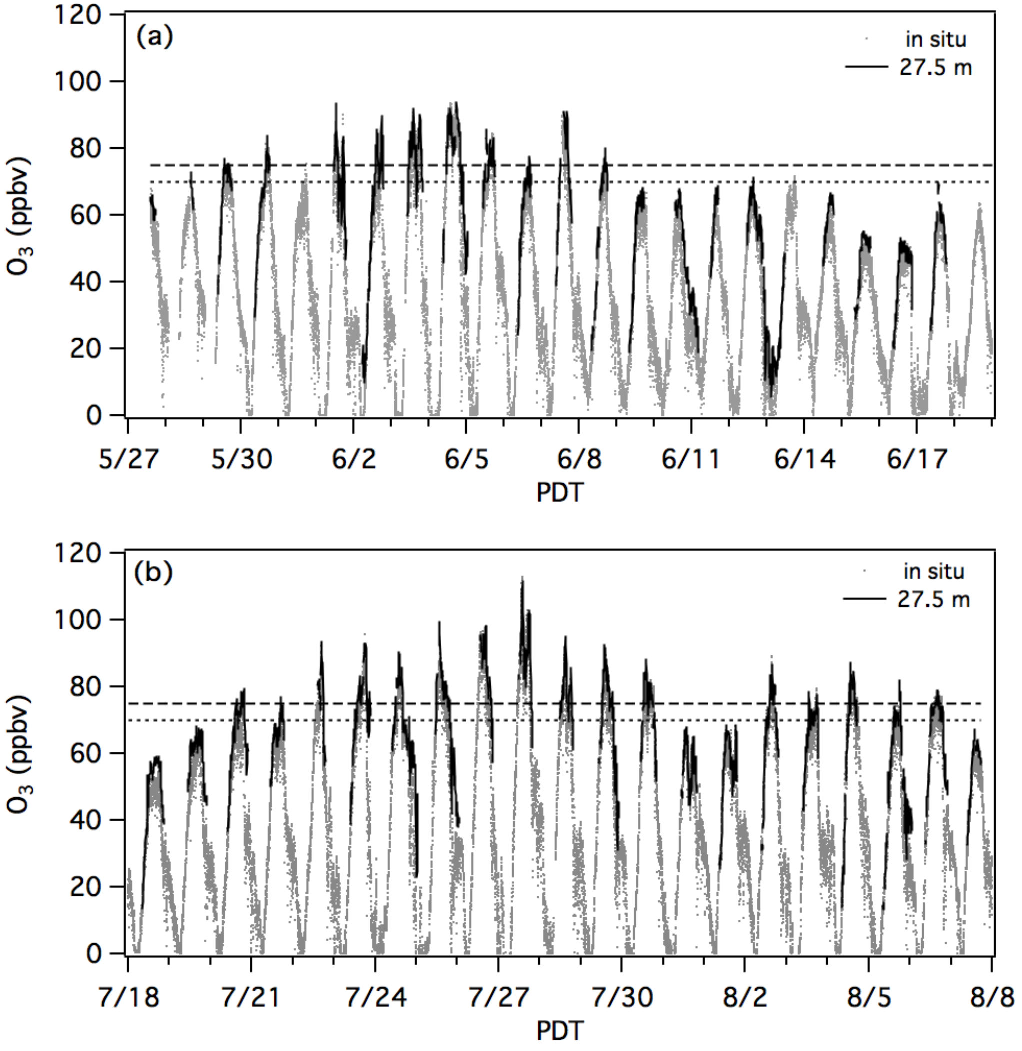

Figure 3. Time series plots (PDT) of the in-situ O_3 (gray dots) and retrieved O_3 concentrations at 27.5 m (black line) during the first (a) and second (b) IOPS. The dashed and dotted lines respectively show the 75 and 70 ppbv O_3 NAAQS and the 70 ppbv California 8-h O_3 standard in effect during CABOTS.

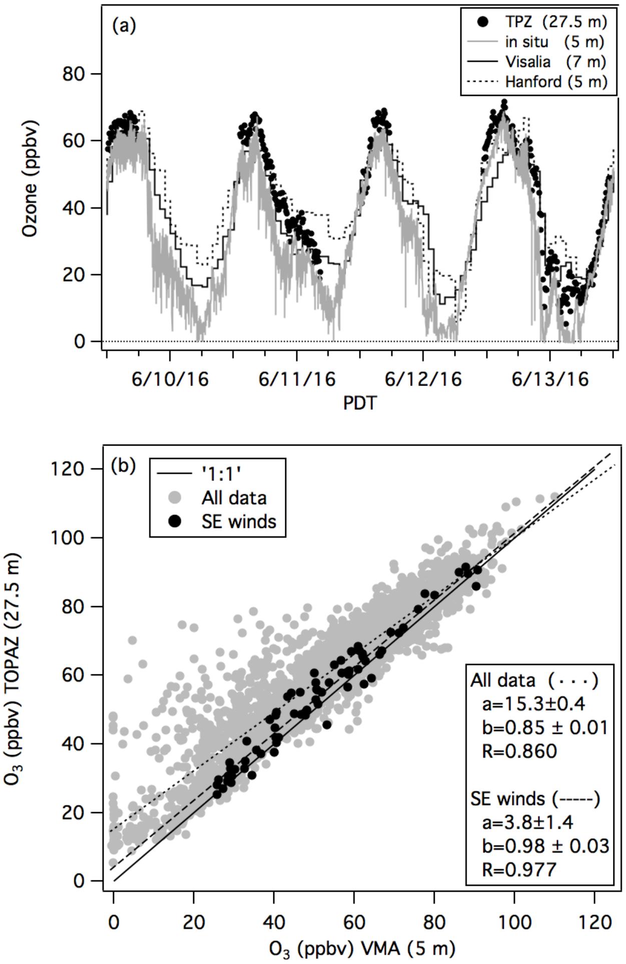

Figure 4. (a) Four-day time series (9-13 June) showing the O_3 concentrations in air sampled 5 m above the TOPAZ truck (gray line) and the O_3 mixing ratios at a height of 27.5±5 m and distance of 800 m retrieved from the TOPAZ measurements (filled black circles). The solid black and dotted staircase lines show the 1-h measurements from the Visalia and Hanford regulatory monitors. (b) Scatter plot comparing the 27.5 m TOPAZ measurements to the interpolated 5 m *in-situ* measurements. The filled gray circles (with dotted fit) show the entire CABOTS data set and the filled black circles (with dashed fit) correspond to daytime measurements (0900 to 1800 PDT) and southeasterly (125 to 145°) winds greater than 2.5 m s^{-1}. The solid line shows 1:1.

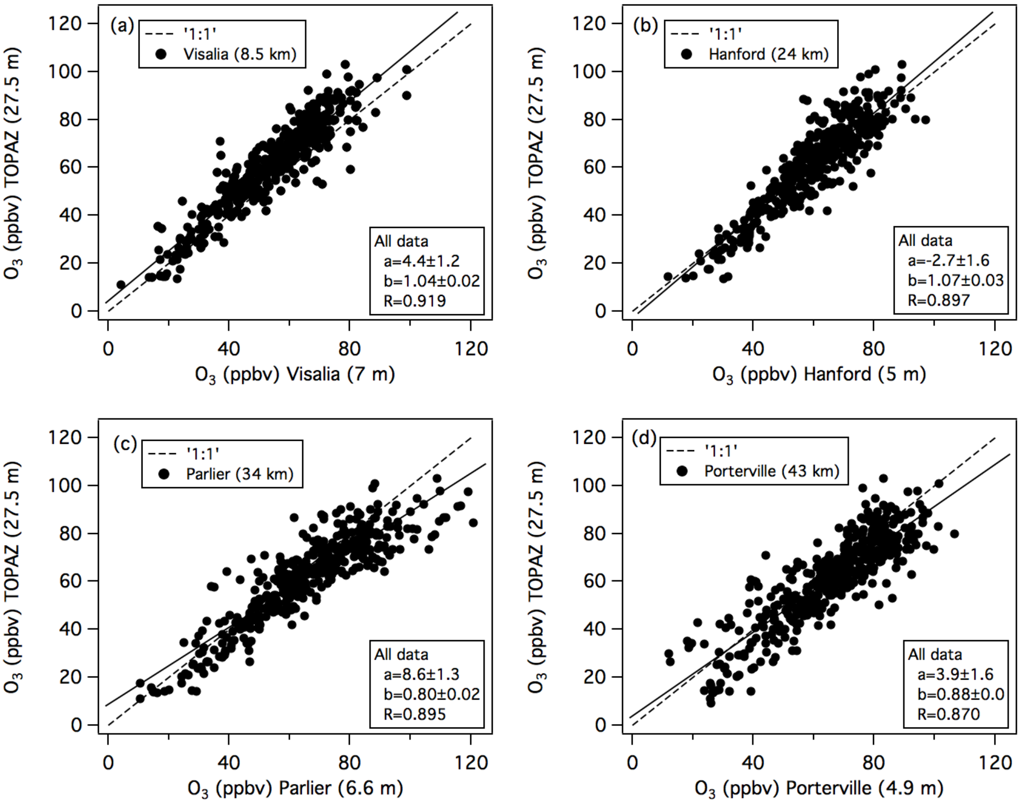

Figure 5. Scatter plots comparing the 27.5 m TOPAZ measurements with the 1-h measurements from the regulatory monitors at (a) Visalia-N. Church Street, (b) Hanford, (c) Parlier, and (d) Porterville. The measurements in the upper box and x-axis label refer to the distance from the VMA and sampling height above ground, respectively. The Visalia monitor is operated by the California Resources Board. The remining three are operated by CARB and the SJVUAPCD. The TOPAZ measurements are interpolated to the 1-h time base of the regulatory measurements for the comparison. The *a* + *bx* linear fit parameters (±1 standard deviation) in the lower boxes refer to the solid lines.

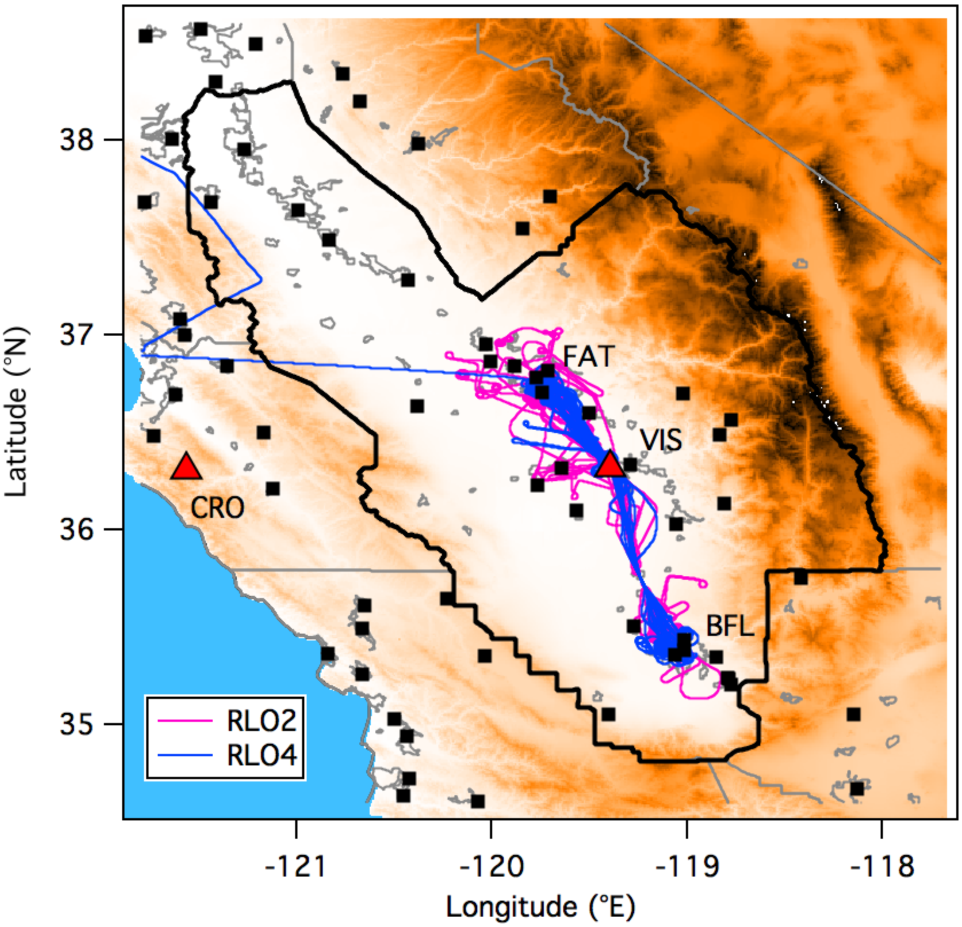

Figure 6. (a) Map of the San Joaquin Valley showing the RLO flight tracks coincident with the TOPAZ measurements (RLO2 and RLO4). The filled black squares show the regulatory surface monitors. The CABOTS sampling sites at CRO and VMA are marked by red triangles. The other abbreviations are the Fresno (FAT), Visalia (VIS), and Bakersfield (BFL) airport codes.

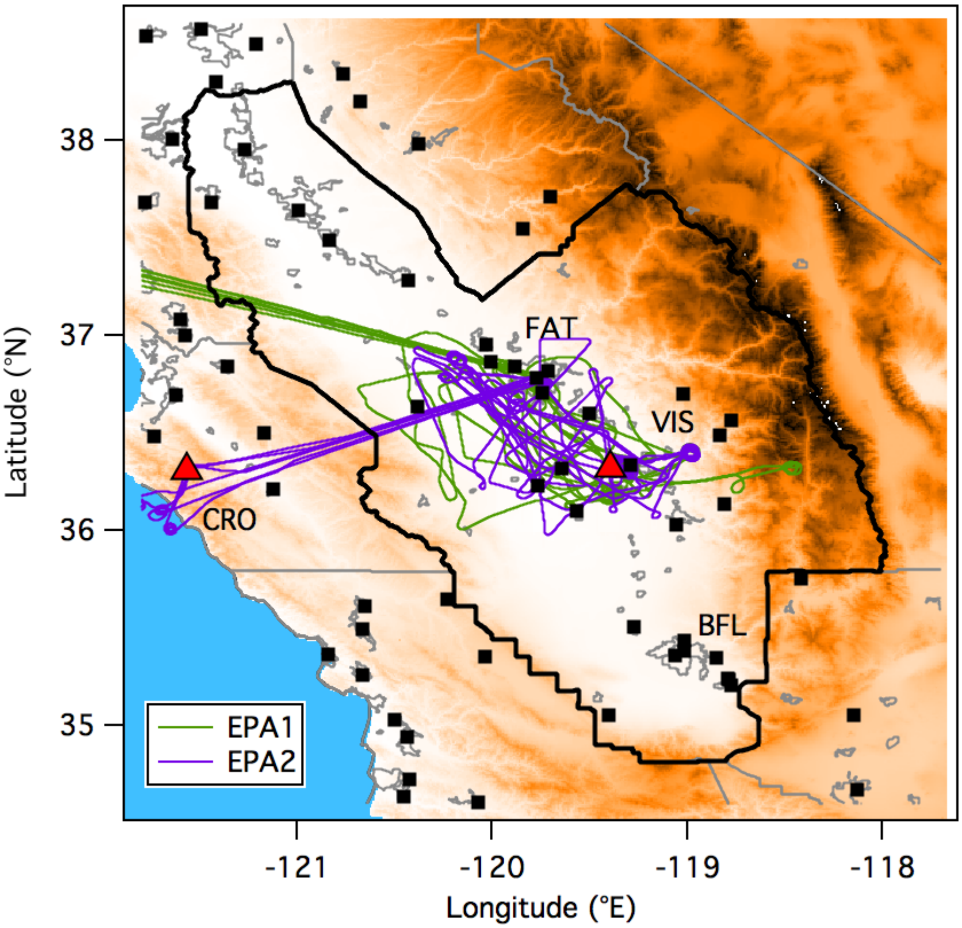

Figure 6. (b) Same as (a), but with the EPA/BAAQMD flight tracks (EPA1 and EPA2).

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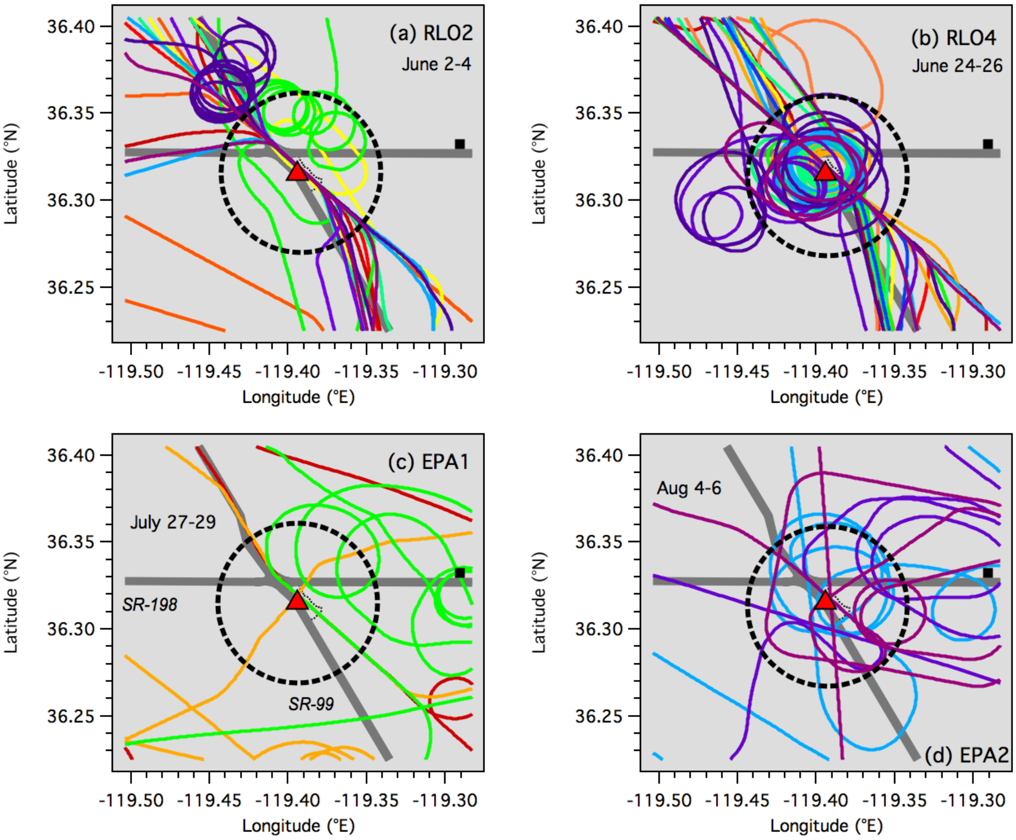

Figure 7. RLO and EPA/BAAQMS flight tracks in the vicinity of TOPAZ. (a) RLO2 (2-4 June), (b) RLO4 (24-26 July), EPA1 (27-29 July), and (d) EPA2 (4-6 August). The red triangle marks the location of TOPAZ and the dashed black circles show the 5 km radius used for the profile comparisons. The black square represents the Visalia-N. Church St. O_3 monitor.

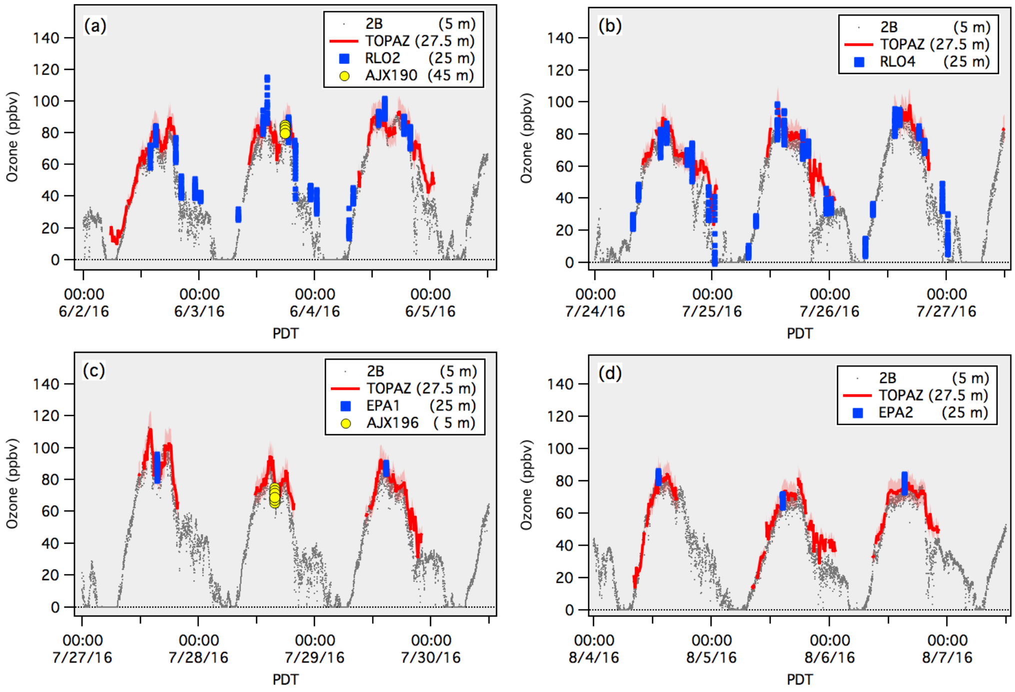

Figure 8. Time series of the surface in-situ O_3 (gray dots) and 27.5 m TOPAZ O_3 (red line) measured during the RLO and EPA/BAAQMD low approaches. The light red envelop shows the ±10% limits of the TOPAZ measurements. The blue squares represent the 1-s Scientific Aviation measurements made between the surface and 25 m agl. The filled yellow circles in (a) and (c) show 2-s measurements from AJAX low approaches (see text).

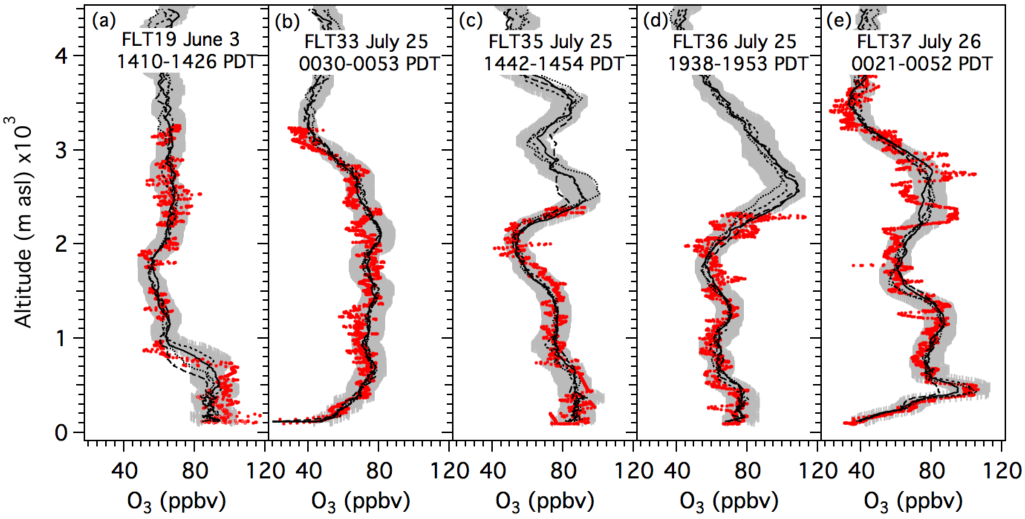

Figure 9. Profile plots comparing the TOPAZ (black lines) and Scientific Aviation (red squares) O_3 measurements on (a) FLT19, 3 June, (b) FLT33, 25 July, (c) FLT35 25 July, (d) FLT36, 25 July 25 July and (e) FLT 37, 26 July. The dotted, short dash, solid, and long dash lines show the four consecutive 8-min lidar profiles acquired during the aircraft profiles. The gray envelopes show the short dash lidar profile ±10%.

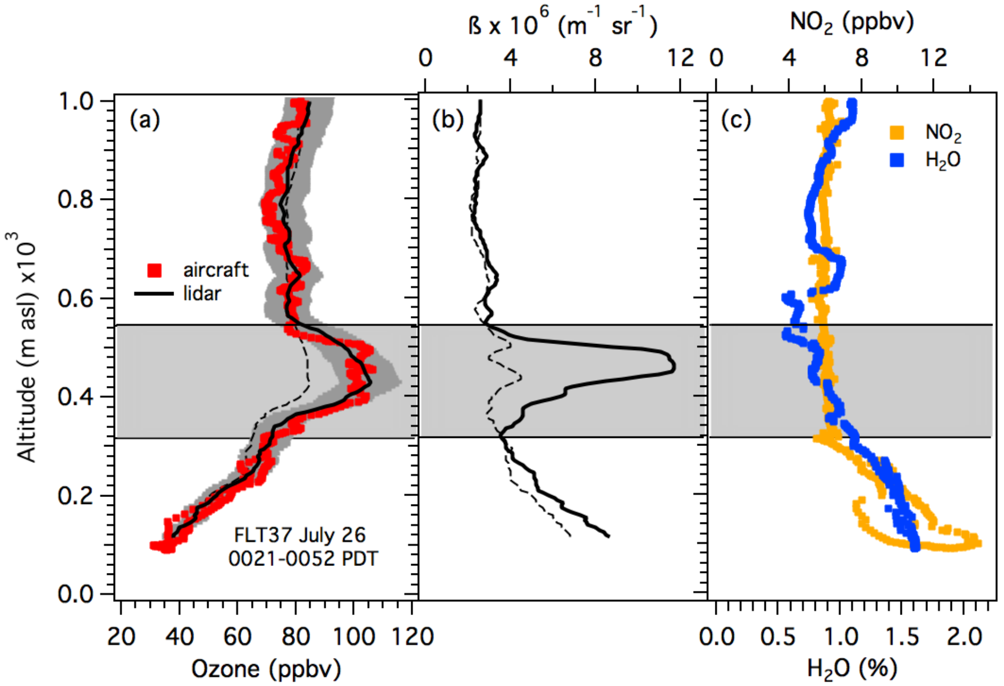

Figure 10. (a) Expanded view of the lidar and aircraft O_3 profiles from Figure 9e plotted with coincident: (b) lidar backscatter, and (c) aircraft NO_2 and H_2O profiles. The solid black profile (±10% in gray) in (a) shows the lidar profile coinciding with the aircraft measurements below 1 km; the dashed black line shows the profile measured 16-24 minutes later. Likewise, for the backscatter profiles in (b). The horizontal gray band highlights the smoke puff from the Soberanes fire.

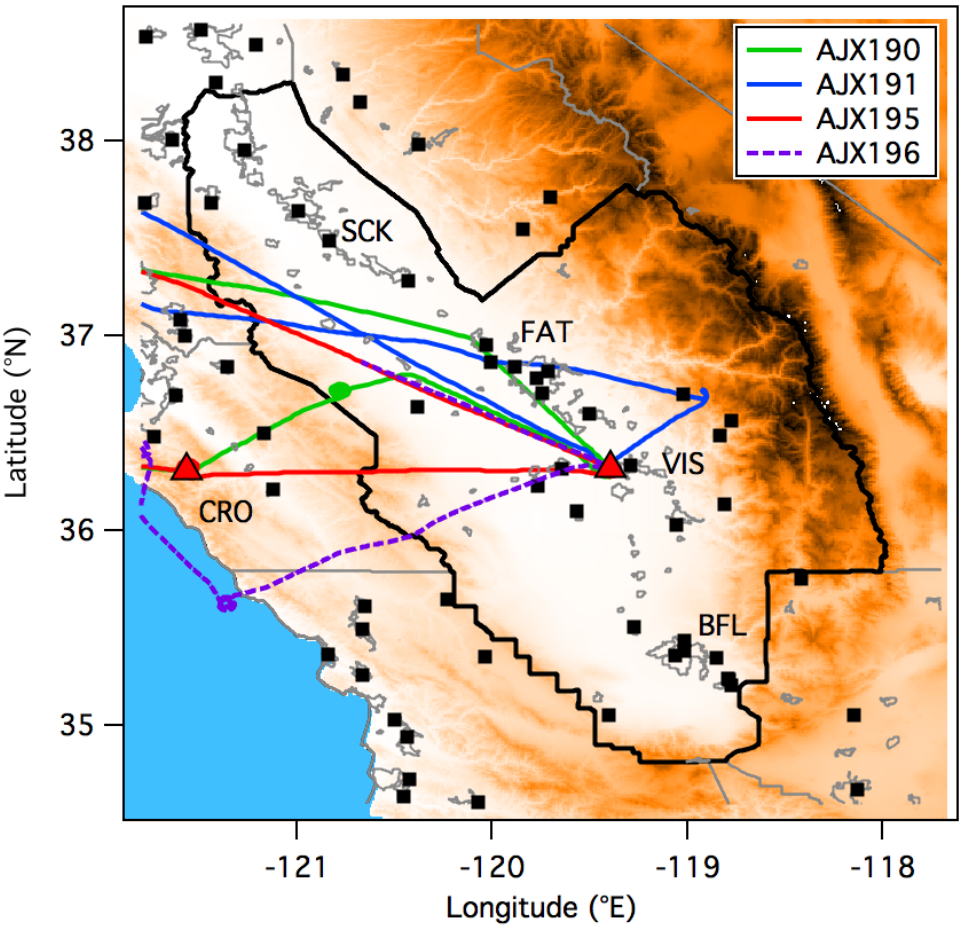

Figure 11. Map of the San Joaquin Valley showing the AJAX flight tracks on 3 June (AJX190), 15 June (AJX191), 21 July (AJX195), and 28 July (AJX196). The abbreviations and symbols are the same as in Figure 6.

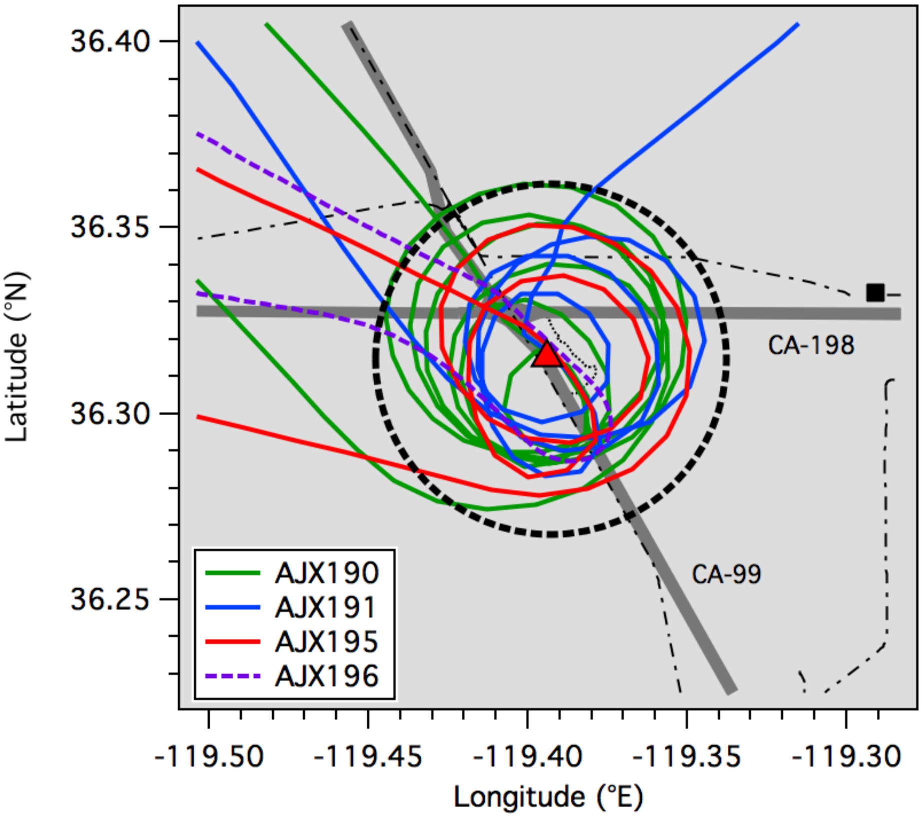

Figure 12. AJAX flight tracks in the vicinity of the VMA (red triangle). The black square represents the Visalia-N. Church St. O_3 monitor and the dashed black circle marks the 5 km radius window used for the profile comparisons. The heavy gray lines show the major highways and the black dot-dash lines the railroads.

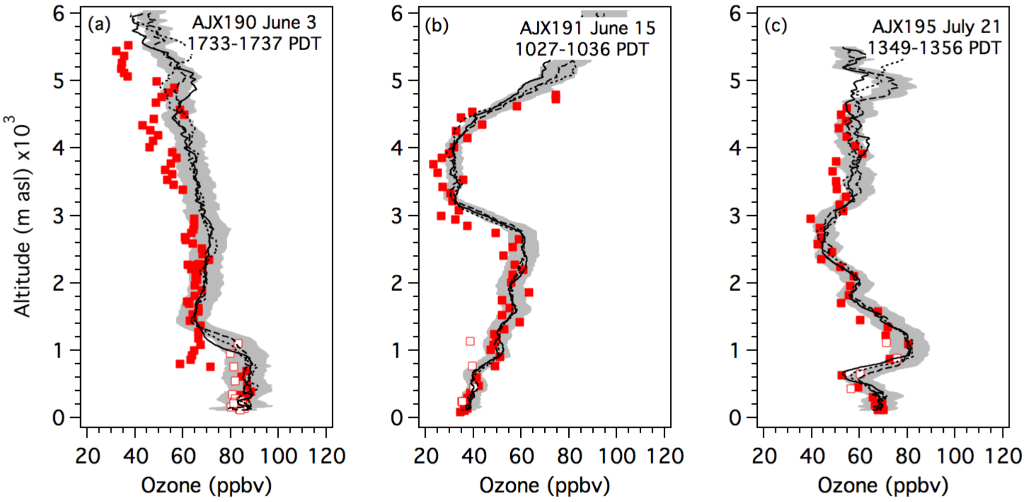

Figure 13. Profile plots comparing the TOPAZ (black lines) and 10-s AJAX (red squares) measurements on (a) AJX190, 3 June, (b) AJX191, 15 June, and (c) AJX195, 21 July. The closed squares correspond to the Alpha Jet descent and the open squares the subsequent climb out. Note the differences between these measurements. The dotted, dashed, and solid lines show the order of the three 8-min lidar profiles that bracket the AJAX profile. The gray envelopes show the short dash lidar profile ±10%.

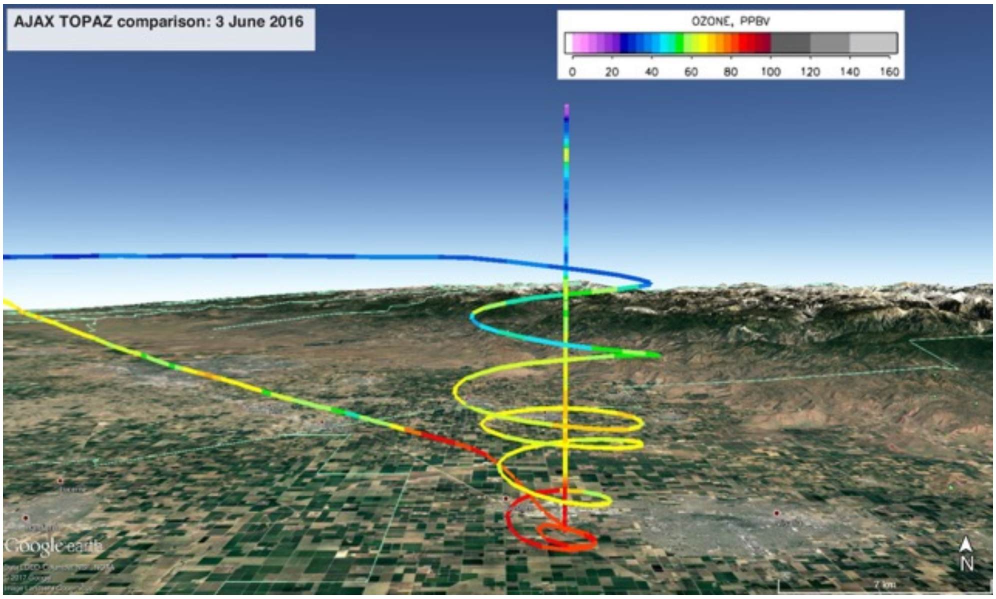

Figure 14. Google Earth image of the TOPAZ and AJAX profiles from 3 June 2016 showing the spatial variations across the ~8 km diameter spiral profile by the Alpha Jet during its descent and climb out over the VMA.

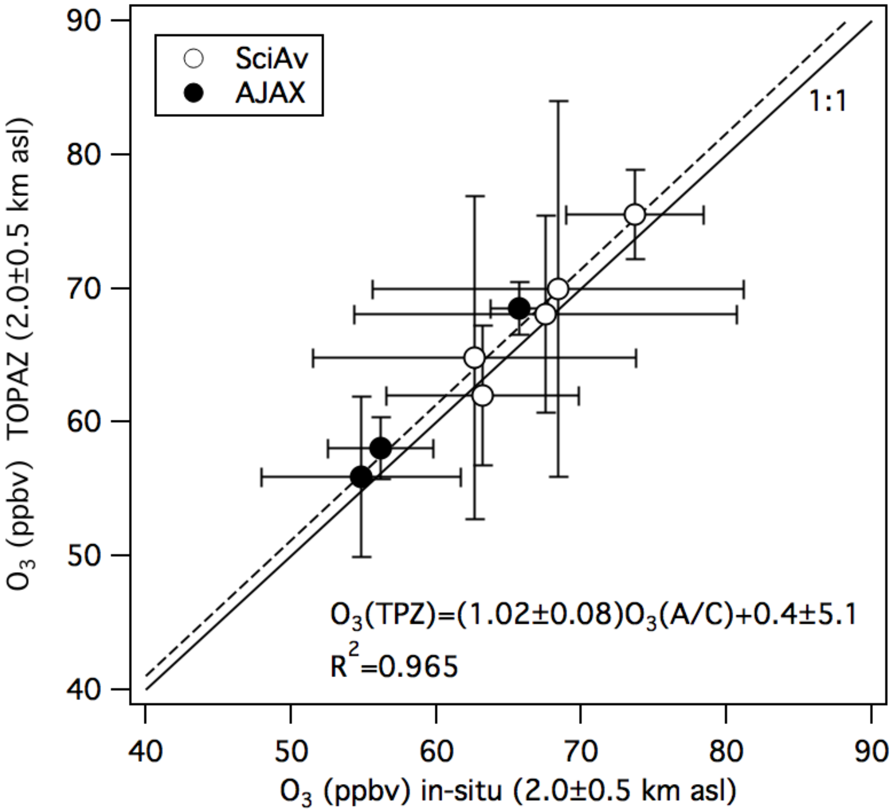

Figure 15. Scatter plot comparing the TOPAZ and in-situ aircraft O_3 measurements at 2.0±0.5 km asl from Figures 9 and 13. The error bars show the standard deviations of the 1 km column averages. The mean TOPAZ (65.4±6.5 ppbv) and in-situ (64.0±6.3 ppbv) mixing ratios from the 8 profiles differ by less than 2 ppbv or ≈2%.

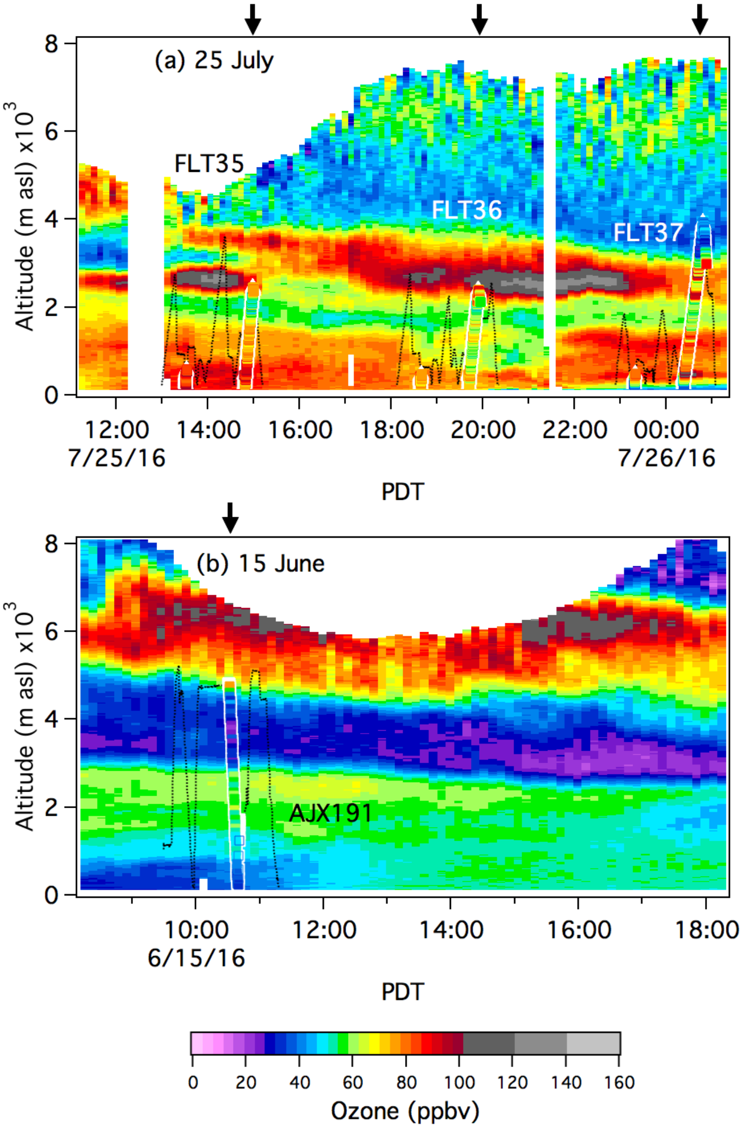

Figure 16. Time-height curtain plots of the TOPAZ ozone measurements from (a) 25-26 July with the Scientific Aviation profiles from FLT35, 36, and 37 superimposed, and (b) 15 June with the coincident AJAX profile superimposed. The aircraft measurements made within 5 km of VMA (arrows) are highlighted by squares and colorized using the same scale as the TOPAZ data. The high O_3 layers around 3 km asl in (a) are related to the Soberanes Fire; the dashed circle in the lower right corner highlights the measurements plotted in Figure 10a.