The Red Butte Canyon Ozone Project

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Ryan Bares & Dave Eiriksson at the Knowlton Fork Red Butte Canyon Site. Photo credit: Logan Mitchell

Executive Summary

We deployed a transect of atmospheric Ozone (O_3) monitoring stations throughout Red Butte Canyon, a tributary canyon located above the University of Utah and adjacent to Salt Lake City. Red Butte Canyon is a United States Forest Service designated Research Natural Area and already has significant monitoring resources deployed in it that this project will leverage. This network produced a dataset with several applications ranging from: (a) probing the role of canyon flows in the transport of O_3 during stratospheric injections in the summer (b) examining the exchange of O_3 from the free troposphere with stagnant air in persistent cold air pools in the winter (c) the potential for using the site to assist in understanding and monitoring background O_3 concentrations, and (d) examining the impact of anthropogenic activities on O_3 formation. A better understanding of these outstanding questions is central in the implementation of successful O_3 mitigation policies in Utah.

Background and Significance

The urbanized Wasatch Front is bounded by mountains that have deep canyons incised throughout them. In the summertime, deep convection associated with strong thunderstorms passing over the mountains can inject stratospheric air with elevated levels of O_3 down the canyons and directly into the urbanized area leading to O_3 exceedances of National Ambient Air Quality Standards (NAAQS), set by the Environmental Protection Agency at 70 parts per billion (ppb) averaged over 8 hours. In the winter, long-lived thermal inversions known as Persistent Cold Air Pools (PCAPs) form within the valleys adjacent to the Wasatch mountains. Within PCAPs, O_3 plays an important role in the oxidant budget (Baasandorj et al., 2017; Womack et al., 2019; Baasandorj et al., 2018) that leads to the secondary formation of fine particulate matter ($PM_{2.5}$). Daily thermally driven canyon flows can provide a mechanism for injecting O_3 rich air from the free troposphere above PCAPs down into stagnant valley air masses. The Red Butte Ozone (RBO) monitoring network was established to observe how stratospheric injection and thermally driven canyon flows in different seasons contribute to NAAQS exceedances within the urban areas adjacent to the Wasatch Mountains.

Red Butte Canyon is a major tributary canyon that flows into the Salt Lake Valley's East side directly above the University of Utah (Figure 1). The canyon runs ~8 km west to east with an elevation gradient of ~800 meters. The canyon is unique in several ways that make it an excellent location for an O_3 monitoring network. First, it is a United States Forest Service designated Research Natural Area, which means that it is free from human activities that include fossil fuel combustion or development. Second, as a research area the canyon is host to multiple ongoing research projects and observational networks that span an array of objectives that include climate and water quality issues. Adding air quality measurement sites further enhances the value of this already unique area. Third, being directly situated above the University of Utah, canyon flows from Red Butte influence existing air quality and meteorological infrastructure at the University (Baasandorj et al., 2017; Bares et al., 2016; Bares et al., 2018). Lastly, Red Butte

Canyon directly lines up with the Utah Division of Air Quality's measurement site at Hawthorne Elementary (HW), thus a straight transect can be drawn from HW through the University of Utah and up the canyon spanning a range of human activities and elevations.

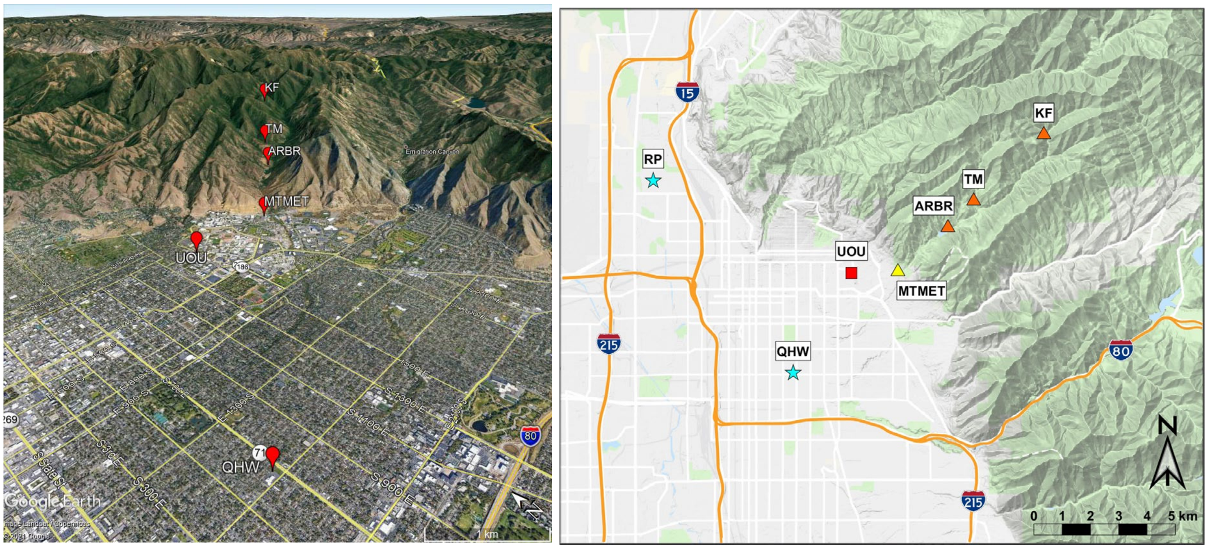

Figure 1. Map of the Red Butte Canyon stations. The left panel shows a Google Earth image looking at the transect that goes up the Red Butte Canyon. The Right panel shows an overhead view. The orange triangles indicate the new Red Butte Canyon sites that were installed. The yellow triangle indicates the MTMET site that was refurbished. The red square indicates the UOU site. The cyan stars indicated the Hawthorne (QHW) and Rose Park (RP) UDAQ sites.

Purpose

The RBO project aimed to investigate the climatology of O_3 over an elevation gradient in a major tributary adjacent to a metropolitan area experiencing O_3 exceedances. In addition, this one year project aimed to observe and characterize case studies illustrating the following atmospheric chemical and meteorological processes:

1.) The role of canyon flows in the transport of O_3 during stratospheric injections in the summer.
2.) Examining the exchange of O_3 from the free troposphere with stagnant air in persistent cold air pools in the winter.
3.) Understand and monitor background O_3 concentrations at multiple elevations, contrasting against O_3 concentrations in the urban atmosphere.
4.) Impact of anthropogenic activities on O_3 formation.

A better understanding of these coupled atmospheric chemical and meteorological processes is central in the implementation of successful O_3 monitoring and mitigation policies in Utah.

Methods

We deployed 2B Technologies Dual Beam O_3 Monitors (Model 205, 2B Technologies, Boulder CO) at three sites throughout Red Butte canyon at existing GAMUT (**G**radients **A**long **M**ountain to **U**rban **T**ransitions) climate stations and refurbished the instrumentation at the existing MTMET site located at the mouth of the canyon (Figure 1). All analyzers were calibrated and tested for precision and accuracy in a laboratory setting and are directly traceable to EPA's O_3 reference standards. Span, zero, flows, temperature measurements and the accuracy of observations in the presence of water vapor were all tested in the Utah-Atmospheric Trace gas and Air Quality lab (U-ATAQ) at the University of Utah. Span and zero tests were performed using the lab's Teledyne T700U Dynamic Dilution Calibrator with O_3 photometer and generator, and the lab's Teledyne T701 Zero Air Generator. Flow and temperatures were independently verified by nationally certified flow meters and temperature measurements. Water vapor DewLines were verified by running a gas of known O_3 concentration from the T700U through a Li-610 (LI-COR, Lincoln, NE) portable dew-point generator while varying the concentration of H_2O.

After all Model 205 instruments were verified to be performing within an acceptable range, they were installed at the selected field sites. To accommodate the increased power demands of the added O_3 sensors, solar arrays were upgraded from 40 Watt panels to 60 Watt panels and additional 100aH batteries were installed. Analog signals from the 2B instruments were recorded at 1 minute intervals using the existing CR3000 dataloggers (Campbell Scientific, UT) that are on site for the GAMUT network.

We used the existing radio telemetry network installed for GAMUT to transmit the data to servers at the University of Utah's Center for High Performance Computing at hourly frequency where it was incorporated into an existing publicly available data display and portal: MesoWest (http://utahaq.chpc.utah.edu/). Data are displayed in near-real time and are currently available for download.

In addition to the Model 205's in the field, the U-ATAQ lab (located at UOU site) operates a Teledyne T400 Photometric Ozone Analyzer. This provided accurate and frequently calibrated data adjacent to the mouth of the canyon and provided a measure of O_3 that is not within the path of canyon air flows.

Table 1. Site characteristics.

Site Code	Latitude	Longitude	Elevation (m)	Inlet Height (m)
KF	40.81012	-111.76695	2012	6
TM	40.78905	-111.79641	1762	6
ARBR	40.78056	-111.80722	1672	6
MTMET	40.76657	-111.82821	1523	1
UOU	40.76630	-111.84760	1436	36
QHW	40.73437	-111.87218	1306	6

In addition to the O_3 sensors, Red Butte Canyon sites (KF, TM, and ARBR) contain existing instrumentation used to measure related climate variables. These climate variables were recorded at 1 minute intervals and include wind speed and direction, air temperature, relative humidity, and incoming and outgoing shortwave and longwave radiation. Wind speed and direction were measured using the R.M. Young 05103 wind monitor, air temperature and relative humidity were measured using the Elektronik EE08 probe, and radiation variables were measured using the Hukseflux NR01 net radiometer.

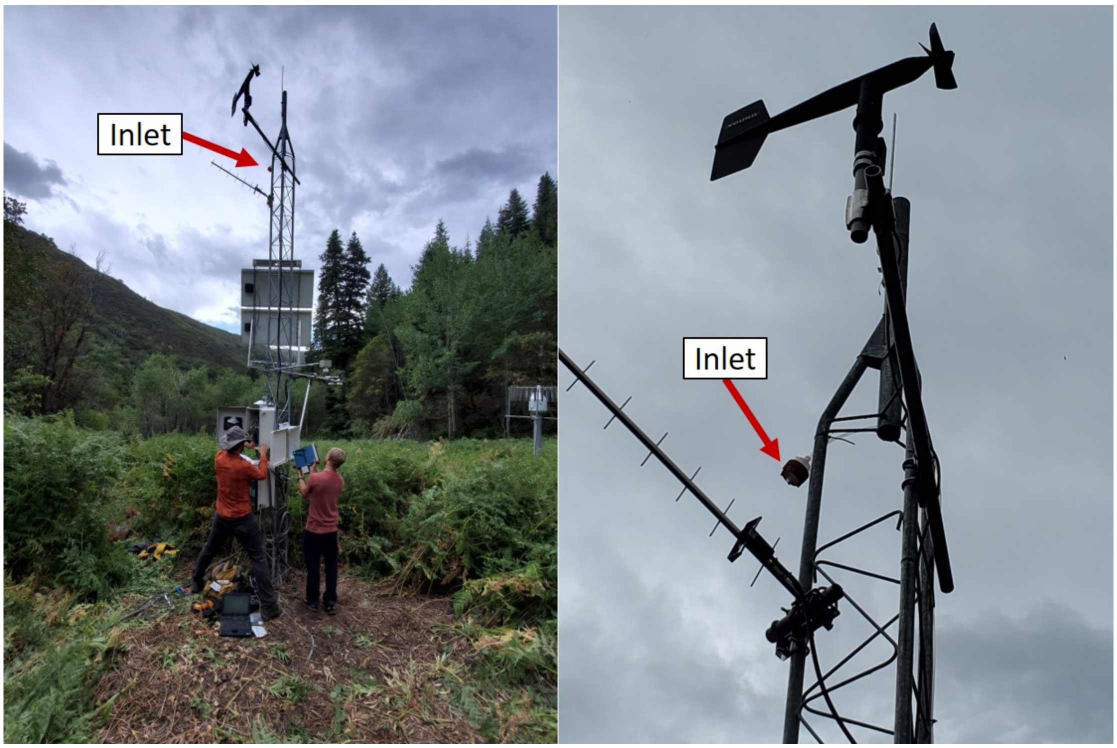

Figure 2. Photos of the KF site. In the left photo, Dave Eiriksson (left) is wiring the data logger and Ryan Bares (right) is installing the 2B ozone analyzer in the environmental enclosure. The right photo shows a closer view of the inlet at the top of the 6m tower.

Deviations

The RBO project had two major deviations from the intended plan. The first was that the sites were unable to maintain power for a few weeks during the winter solstice due to insufficient sunlight, resulting in a brief data outage. The second issue was the result of the COVID-19 pandemic that impacted scheduled field work and interrupted the planned calibration schedule.

In mid-December of 2019 all three RBO sites began to gradually lose power because the additional power drain from the O_3 instrumentation was greater than that supplied by the solar panels. We anticipated that this might happen, but we were hopeful that it wouldn't cause an issue. Finally, on Dec 12th 2019, the ARBR site voltage dropped low enough that the site temporarily lost power. We made the decision to temporarily shut down all three O_3 instruments from Dec 16th 2019 to Jan 24th 2020 until there was enough incoming solar radiation to once again operate the instruments continuously. This procedure was done smoothly and all three instruments were successfully restarted in January. Despite this shutdown, we were still able to capture the most significant Persistent Cold Air Pool (PCAP) event in early December 2019.

The COVID-19 pandemic presented a substantial challenge to the calibration plans during the project. All employees of the University of Utah were under mandatory travel restrictions and were not allowed to visit any field sites in the spring of 2020. This delayed all of our research group's typical field work, and since the instrumentation was operating well, we decided to forgo the calibration of the instruments through the summer. We do not anticipate that forgoing the calibration had a substantial impact on the measurements, since the O_3 analyzers are typically able to maintain reliable calibrations for extended periods.

Results

This project successfully installed the RBO monitoring network and collected over a year of measurements that continues through the present. Of the four coupled atmospheric chemistry and meteorological processes outlined in the Purpose section above during the year of operation, we were able to clearly document case studies illustrating three. In the following section we will first provide an overall description of the measurements, then discuss the ozone climatology observed at the sites, and then finally we will discuss individual case studies.

Overall data description

The three main RBO sites were installed in September 2019, with the exception for TM, were a data logger had a technical issue that delayed the start of data collection at that site by a month, to October 2019. Table 2 shows a count of the number of unique days and 8-hour averages exceeding the 70 ppb National Ambient Air Quality Standard (NAAQS). The MTMET and UOU sites both had data outages during several elevated O_3 episodes, so the numbers at those sites represent minimum counts. It is interesting to note that the number of days and hours of > 70 ppb O_3 show that elevated O_3 levels were most frequently observed in the middle of the canyon at the ARBR site. This may be an indicator of NO_x-O_3-VOC photochemistry and photochemical aging of air masses as air is transported up the canyon from the SLC metro area during the afternoons.

Table 2. Number of unique days and 8-hour averages exceeding 70 ppb.

Site	**# of days with 8hr O_3 > 70 ppb**	**# of hours with 8hr O_3 > 70 ppb**	**Max 8hr O_3 (ppb)**
KF	8	45	92
TM	20	98	93
ARBR	38	215	100
MTMET	13*	72*	89*
UOU	12*	52*	84*
QHW	12	48	85

* MTMET and UOU have data gaps during the highest ozone episodes, so the counts and max represent minimum values.

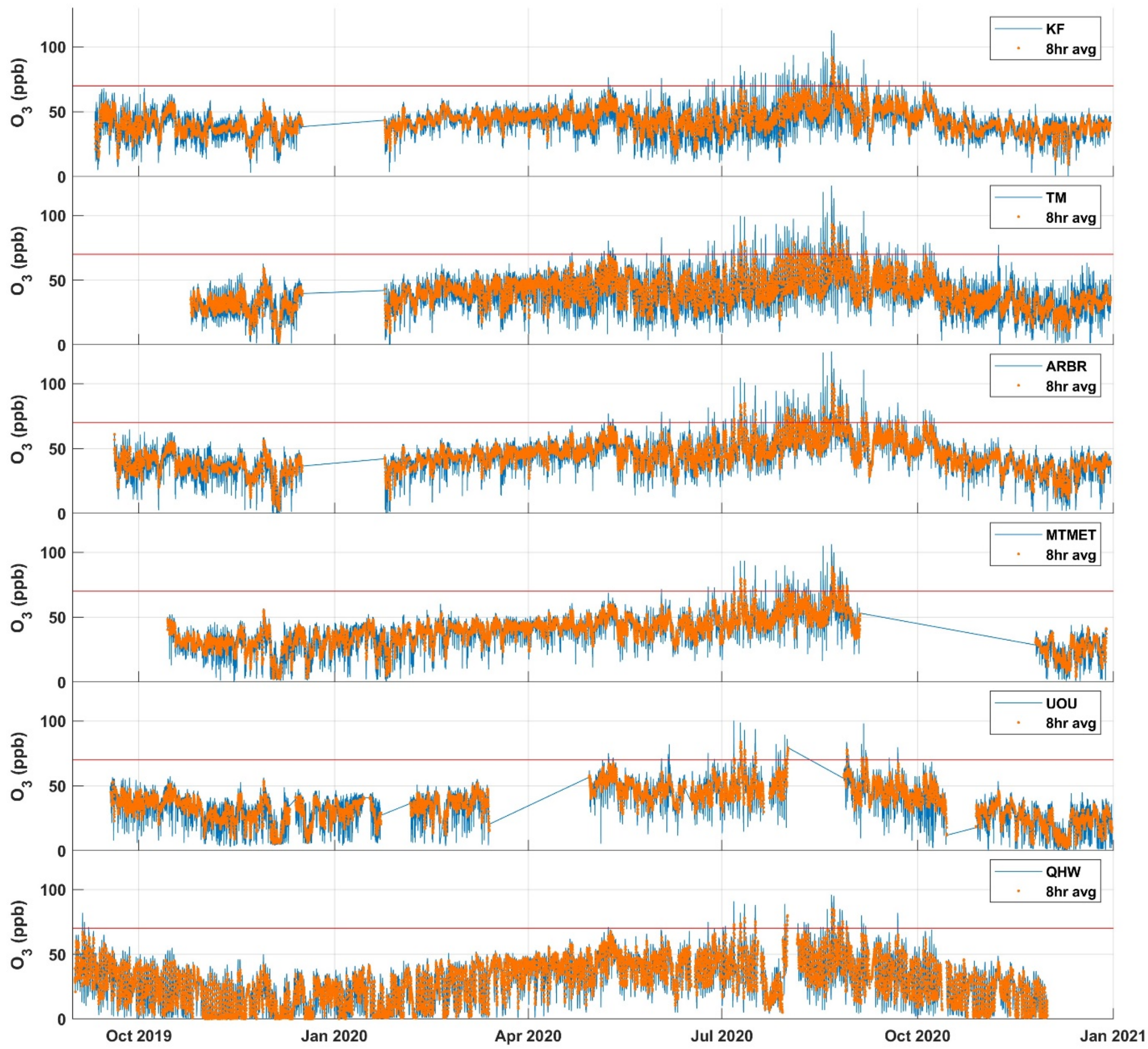

Figure 3. Ozone concentrations at all of the Red Butte Ozone stations for the project duration. Blue lines show the original data (1-minute resolution at KF, TM, ARBR, UOU; 5-minute at MTM; 1-hour at QHW) and orange dots show 8-hour averages. The red line is 70 ppb.

Ozone climatology

Next, we examine the diel O_3 profile at RBO sites during three-month seasonal windows over the past year (Figure 4). Three month windows are denoted as follows: DJF: Dec 2019-Feb 2020; MAM: Mar-May 2020; JJA: Jun-Aug 2020; SON: Sep-Nov 2020. In DJF there was a visible daytime enhancement at all of the stations except for KF, indicating that the highest elevation site was completely separated from the urban air mass. This result is similar to the findings reported in (Fiorella et al., 2019). O_3 concentrations at KF were also highest compared to all of the sites, indicating that KF was likely observing free tropospheric background concentrations. The amplitude of the diel cycle at Hawthorne (QHW), within the city, was largest while the amplitude was much more dampened at the RBO sites, suggesting that on

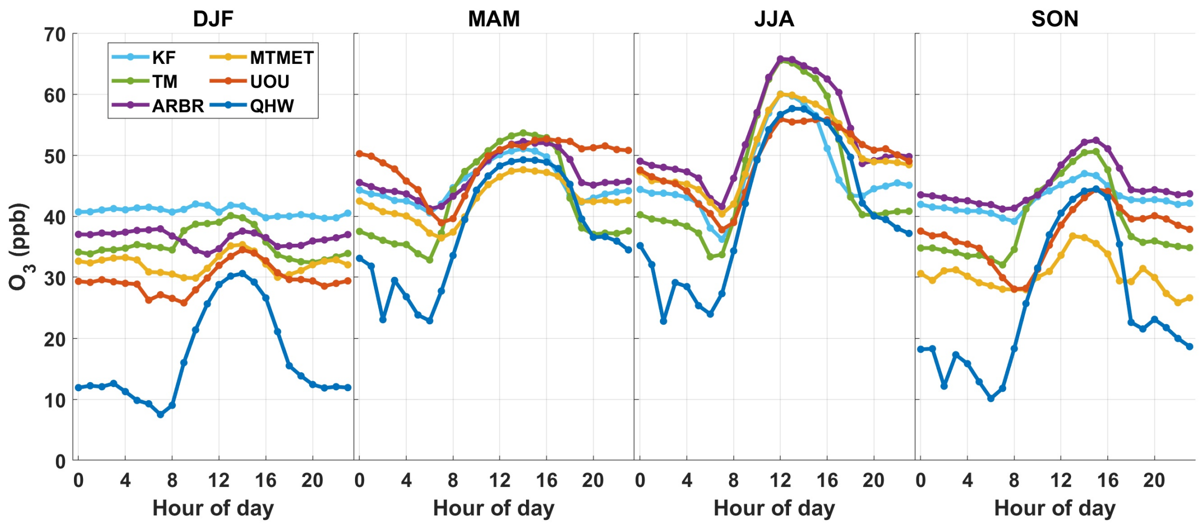

Figure 4. Diel profile of ozone at the Red Butte O_3 stations during three-month seasons. DJF: Dec 2019-Feb 2020; MAM: Mar-May 2020; JJA: Jun-Aug 2020; SON: Sep-Nov 2020.

average they were exposed to lower levels of NO_x resulting in less NO_x titration of O_3 at RBO sites. In MAM every site had elevated mid-day concentrations, suggesting that none of the sites were sampling free tropospheric concentrations unaffected by urban emissions. One intriguing feature apparent at the UOU site is that elevated afternoon concentrations persisted through the evening until the early morning hours. This pattern is also somewhat apparent in JJA, but to a lesser degree. It is unclear whether these elevated nighttime concentrations are due to lower levels of NO_x titration at that site or if they are a result of O_3 production from NO_x and VOC urban precursor emissions. JJA is the peak O_3 season, and during that period we observed the highest midday concentrations at the ARBR and TM sites. It is important to remember that UOU and MTMET both had data gaps in the JJA and SON time periods with elevated O_3 concentrations, so the diel profiles may be slightly different if those data sets were complete. The finding of elevated O_3 at ARBR and TM is consistent with the generalized observation of elevated O_3 occurring downwind of urban cores as O_3 is regenerated from reactions with NO_x and VOCs (U.S. EPA, 2013). The lack of similarly high O_3 at KF during this time period suggests a spatial or elevation constraint on the extent of elevated O_3 downwind of the Salt Lake City urban center. Finally, during the SON time period all of the sites continued to display diel cycles in O_3, indicating that they were not experiencing free tropospheric conditions. The ARBR site continued to have the highest concentrations compared to all of the other sites.

One intriguing observation about the TM site is that in MAM, JJA, and SON the nighttime O_3 concentrations decreased much further than the two other RBO sites. This feature may point to some unexplained nighttime O_3 chemistry related to the distance of the site up the Red Butte Canyon or it could also be a function of atmospheric mixing occurring at the TM site. The TM site sits at the confluence of two small sub-drainages within Red Butte Canyon and that may be contributing to complexities in mixing at that site.

One of the project objectives was to investigate the potential for using a Red Butte Canyon site to understand and monitor background O_3 concentrations. The highest elevation KF site had the highest potential for usage as a background site; however, this site exhibited a prominent diel cycle for nearly the entire year. Given this diel cycling, it appears that this site is likely still being influenced by photochemical production of ozone from Salt Lake City. This, coupled with the finding that the site is decoupled from the valley air mass during wintertime suggests that it would not be the ideal site to monitor background conditions.

Finally, examining the diel profiles throughout the year, one consistent feature is that the QHW site always has the lowest nighttime O_3 concentrations. This is expected due to nighttime NO_x titration within then urban nighttime boundary layer. More intriguing is that at no point in the year does QHW have the highest midday concentrations, and during the peak O_3 season of JJA the TM and ARBR sites have on average 8 ppb higher O_3 concentrations than QHW.

Case Study 1: Oxidant exchange during a PCAP event (Nov 26-Dec 8, 2019)

One of the primary goals of this project is to examine the exchange of O_3 from the free troposphere with wintertime stagnant air masses during Persist Cold Air Pool (PCAP) events and examine the relationship with anthropogenic emissions. Oxidant exchange is a key ingredient in formation of secondary $PM_{2.5}$ that contributes to poor air quality conditions in Salt Lake City (Baasandorj et al., 2017). In early December 2019, a PCAP event in the Salt Lake Valley led to two days of exceedances of the 24-hour $PM_{2.5}$ National Ambient Air Quality Standards (NAAQS) at the Hawthorne UDAQ site (QHW). Figure 5 shows the chemical species while Figure 6 shows the wind speed and direction for this overall event.

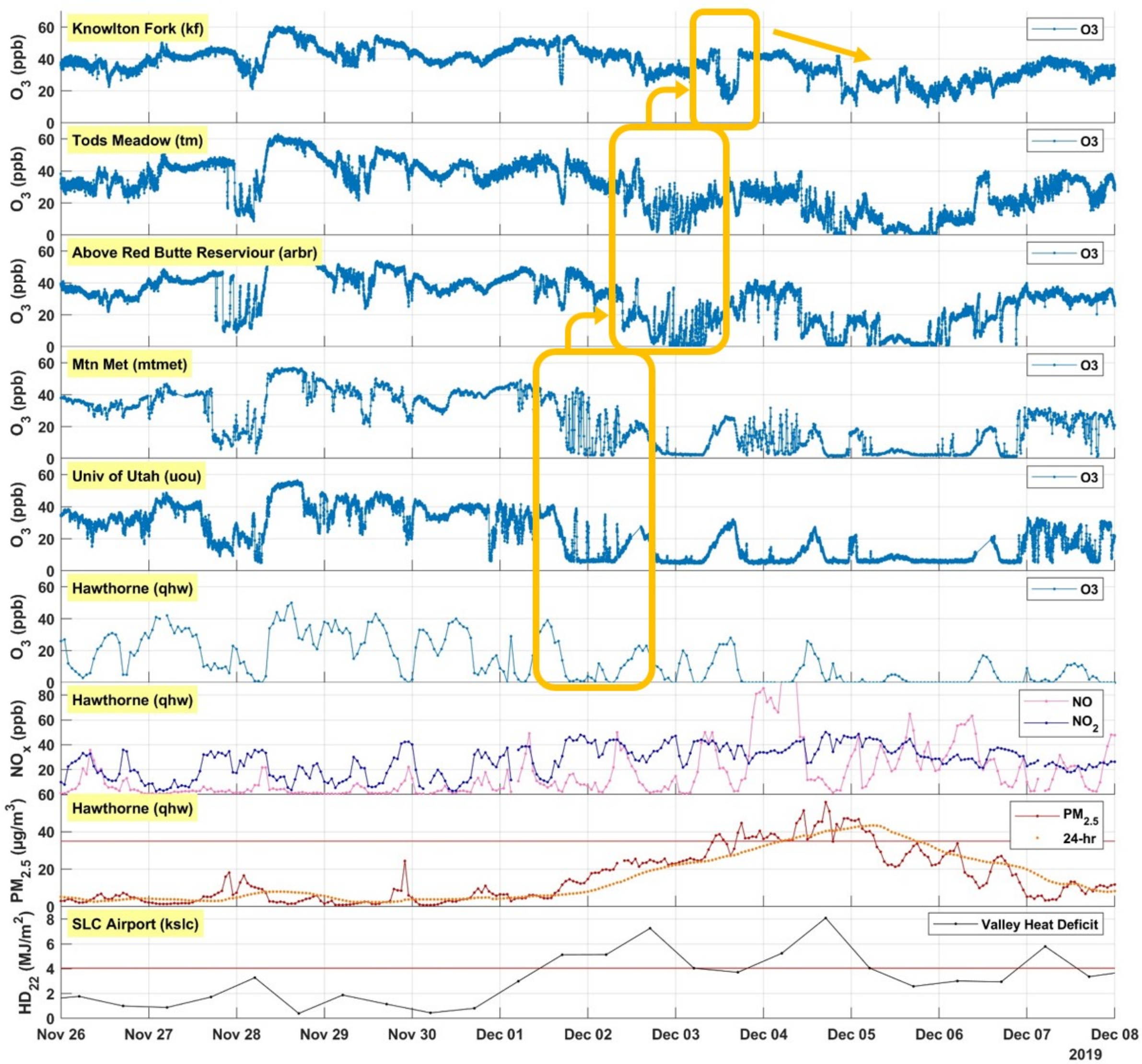

Figure 5. Oxidant exchange during a PCAP event. Top six panels show Red Butte Ozone sites in order of elevation and the bottom three panels show NO_x and $PM_{2.5}$ at the QHW site and the Valley Heat Deficit (Whiteman et al., 2014). Yellow boxes show the progression of to the top of the PCAP where oxidant exchange occurred up Red Butte Canyon over a 24-hour period.

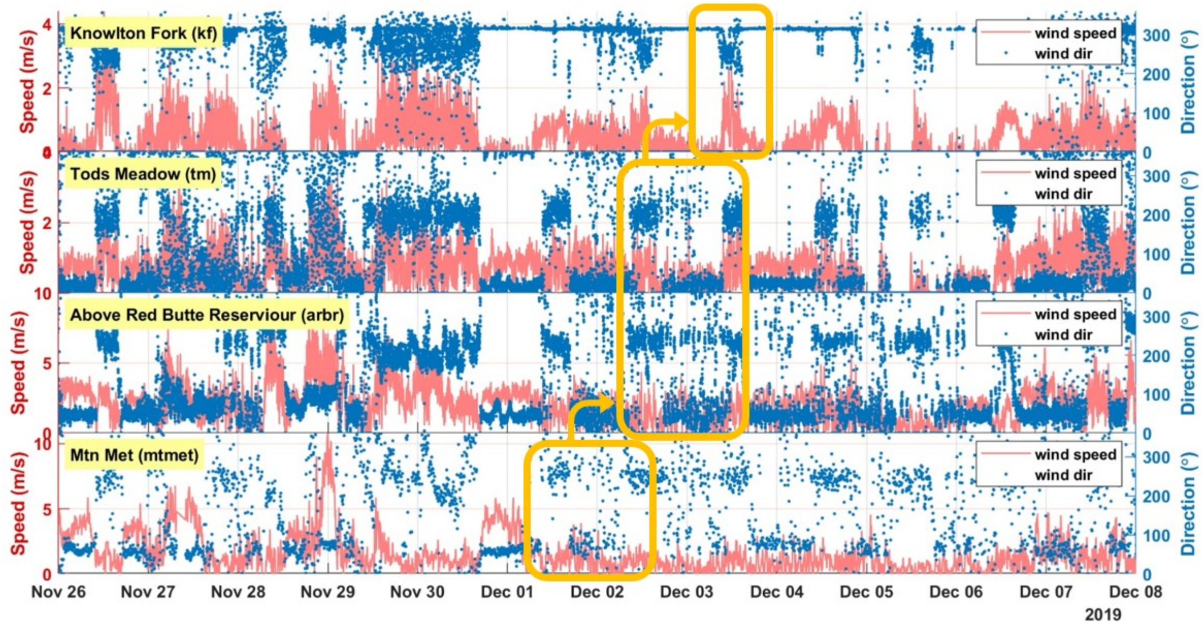

Figure 6. Wind speed and direction during a PCAP event at Red Butte Ozone sites. Yellow boxes show the times when small changes in winds caused rapid oscillations in ozone concentrations as the top of the PCAP progressed up the Red Butte Canyon.

Before investigating the main PCAP, it is worth examining in detail how canyon flows interact with O_3 concentrations during winter PCAPs. A clear example of this was observed during a brief event on Nov 27-28 (Figure 7). During this event, O_3 concentrations at MTMET decreased as they became titrated in the urban air mass. Then, as the wind direction at ARBR shifted from blowing up canyon (~240°) to down canyon (~60°), the O_3 concentration at ARBR toggled back and forth between concentrations at MTMET at the entrance of the canyon and KF higher up in the canyon. After a few pulses of air were transported and mixed up the canyon, the O_3 concentration at KF began to gradually decrease. This toggling or sloshing of air through Red Butte Canyon is a consistent feature and is likely the dominant mechanism by which oxidant rich air is transported into PCAPs in the Salt Lake Valley. Quantifying the net mass transfer through tributary canyons like Red Butte in these conditions will be important to understand how tributary canyons affect oxidant exchange during PCAP events.

Next we examine the main PCAP event. On Dec 1, the Valley Heat Deficit increased above the 4.04 MJ m^{-2} threshold, creating the thermodynamic conditions to form a PCAP (Whiteman et al., 2014) (Figure 5). At that time, O_3 at QHW became completely titrated, and NO_2 reached a steady state at ~40 ppb. That evening, there were large oscillations of O_3 at the UOU and MTMET sites associated with small shifts in winds, suggesting that the top of the PCAP was near the elevation of these sites (~1500m) but had not yet extended up the Red Butte Canyon to the ARBR site. $PM_{2.5}$ at QHW began increasing that evening. On the evening of Dec 2, the top of the PCAP extended further up in elevation, resulting in complete O_3 titration at QHW, UOU, and MTMET, while there were abrupt oscillations in O_3 concentrations at the ARBR and TM sites (~1700m). However, KF remained above the PCAP. On Dec 3, a brief shift

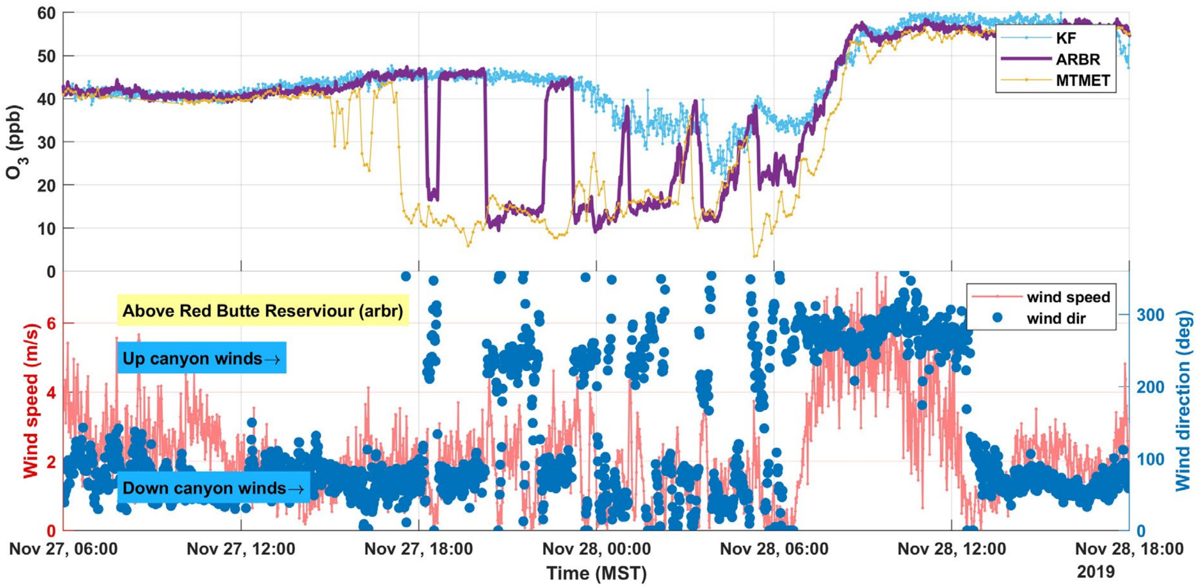

Figure 7. Detailed relationship between O_3 at three sites in Red Butte Canyon (top) with wind speed and direction at ARBR (bottom). Note: this figure only includes O_3 from three sites to simplify the figure, but the same patterns were observed across all of the sites as can be seen in Figure 5

in the winds and decreased stability strength (lower Valley Heat Deficit) led to transport of O_3 titrated air up the canyon to the KF site (~2000m), resulting in a few hours of low O_3. On Dec 4, the Valley Heat Deficit rose again and O_3 concentrations fell at all of the stations until on Dec 5 every site was within the titrated valley air mass except for the KF site. The Valley Heat Deficit then fell and stayed below 4.04 MJ m^{-2} for a couple of days, allowing the PCAP to begin to break up and $PM_{2.5}$ at QHW began to decrease while O_3 at all of the sites increased.

The progression of mixing in Red Butte Canyon can be clearly seen by again comparing the O_3 concentrations at MTMET, ARBR, and KF through this event (Figure 8). The top of the PCAP can be seen at MTMET starting in the evening of Dec 01. Then, starting in the evening on Dec 02 the top of the PCAP moves up the canyon to the ARBR site. Then, in midday on Dec 03 the O_3 titrated air is transported up to the KF site. The process then resets and repeats since this was not an exceptionally strong thermodynamic PCAP event.

The detailed temporal evolution of these events clearly shows the complex role of oxidant exchange in the mountain valleys that surround Salt Lake City such as Red Butte Canyon that contribute to chemical formation of secondary $PM_{2.5}$ within PCAP air masses. We expect that the RBO network will play an important role in quantifying oxidant exchange in future studies examining secondary $PM_{2.5}$ formation in the coming years.

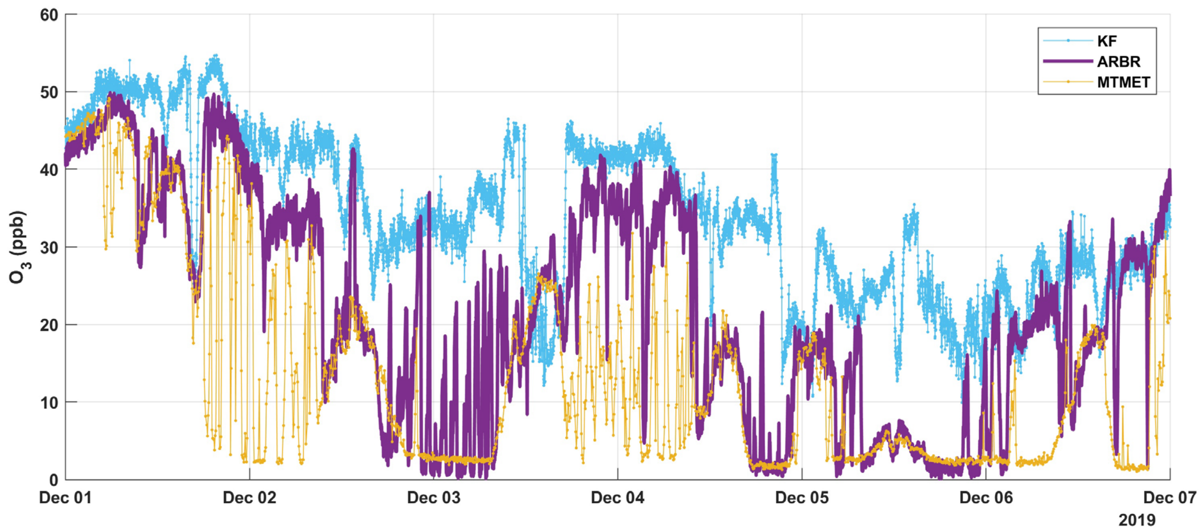

Figure 8. Detailed relationship between O_3 at three sites in Red Butte Canyon during a Persistent Cold Air Pool (PCAP) event. Note: this figure only includes O_3 from three sites to simplify the figure, but the same patterns were observed across all of the sites as can be seen in Figure 5

Case Study 2: Elevated summertime concentrations (Aug 17-24, 2020)

Another goal of the project was to investigate the role of canyon flows in the transport of O_3 during stratospheric injections in the summer. This would have manifested in elevated O_3 concentrations observed first at KF, then showing up at the lower sites with strong down canyon winds. These conditions do not occur every year and in in the summer of 2020 we did not observe this phenomenon. Instead, for this case study we will examine a week-long period in August 2020 when we observed the highest O_3 concentrations of the summer.

Figure 9 shows O_3 concentrations and the 8-hour averages during the entire weeklong period at each of the sites, while Figure 10 shows the concentrations from two of those days plotted in a single panel to examine the timing of O_3 changes during those days. During this 7-day period we see nearly synchronous O_3 variability across the Red Butte Ozone network sites. On Aug 17 there was an abrupt peak in midday O_3 that peaked at 124 ppb at ARBR, but it was a relatively short lived feature so the 8-hour average only peaked at 82 ppb at that site. However, on Aug 21 and 22 there were high O_3 concentrations that were sustained for several hours, leading to exceedances of the 8-hour ozone at every RBO site. The highest concentration measured was 124.9 ppb at ARBR on Aug 21 and the 8-hour average from that time was 99.87 ppb.

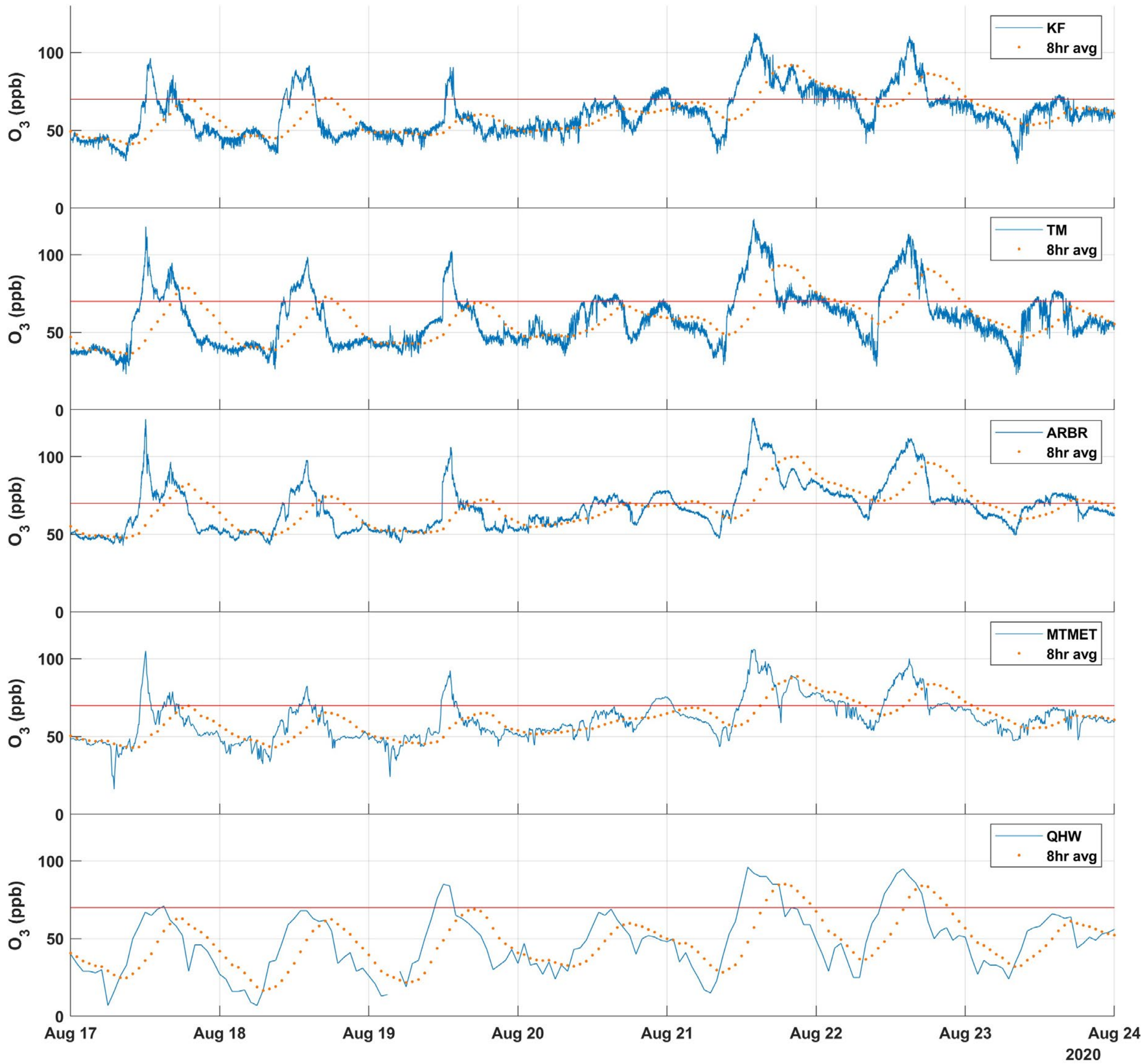

Figure 9. O_3 measurements and 8-hour averages during case study 2 at each RBO site. Note that UOU is excluded because it was not operational during this time period.

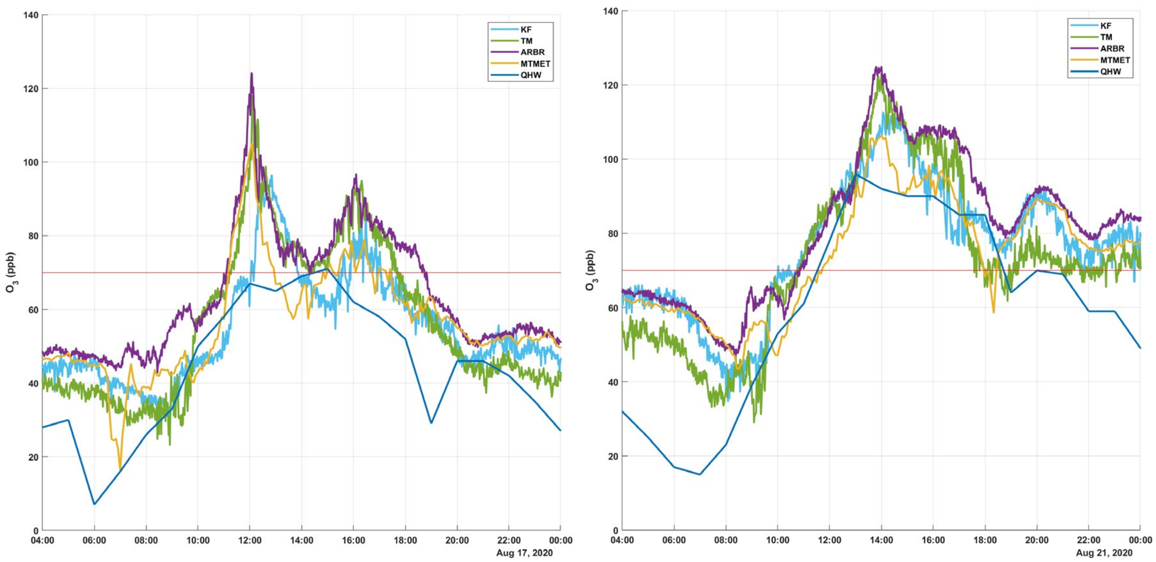

Figure 10. Ozone on Aug 17 (left) and Aug 21 (right) during case study 2 at the RBO sites. Note that UOU is excluded because it was not operational during this time period. Time is in MST (UTC-07)

Future Directions

It is our intention to continue operating the RBO monitoring network for the foreseeable future. The data collected from this network will be useful for projects that seek to quantify the mass flux of O_3 from canyons around the Salt Lake Valley and projects investigating the chemistry of secondary particulate formations such as AQUARIUS (Air Quality Research in the western US; https://atmos.utah.edu/aquarius/). Additionally, the RBO network could provide valuable insight into differences in the composition of stratified layers within the Planetary Boundary Layer and the residual layer of the atmosphere, which could be further explored in the planned investigations mentioned above.

Data Management

Historic data is currently available for download on the MesoWest data API. We will also submit a Quality Assured version of the data to the Hive data repository in the coming year.

Acknowledgments

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