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Summer ozone concentrations in the vicinity of the Great Salt Lake

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Abstract

Residents near the Great Salt Lake in northern Utah, USA have been exposed to ozone levels during recent summers exceeding the current United States National Ambient Air Quality Standard. Accurately forecasting those exceedances has been difficult as a result of the complex meteorological and photochemical processes fostering them. To help improve such forecasts, a low-cost field study was conducted during summer 2015 to provide comprehensive observations of boundary-layer ozone concentrations in the context of the prevailing meteorological conditions. A network of surface ozone sensors was supplemented by sensors mounted on vehicles, a public transit light-rail car, news helicopter, tethered sonde, and unmanned aerial vehicle. The temporal and spatial evolution of boundary-layer ozone concentrations were compared with the prevailing regional and local meteorological conditions on the basis of gridded operational analyses, surface weather stations, and additional sensors deployed for the field study. High ozone concentrations during June 2015 resulted primarily from local processes while smoke transported from distant wildfires contributed to elevated ozone concentrations during August. The Great Salt Lake influenced ozone concentrations along the Wasatch Front through several mechanisms, most importantly its impact on local wind circulations. The highest ozone concentrations were often found in a narrow zone between the Great Salt Lake and the urban regions to its south and east. Observations from multiple fixed site and mobile platforms during 18–19 August illustrate the complex variations in ozone concentrations as a function of elevation at the surface as well as vertically through the deep boundary layer.

Keywords: **Great Salt Lake; ozone; air quality; lake breeze; wildfires; thermally driven circulations; mobile observations**

1. Introduction

Air quality in northern Utah, USA has improved over the past two decades (Simon *et al.*, 2014; Whiteman *et al.*, 2014). However, the 2-million residents of the Wasatch Front (the urbanized region between the Great Salt Lake, GSL, and the Wasatch Mountains to its east, see Figure 1(a)) remain exposed to occasional poor air quality during both winter and summer. Episodes of high particulate concentrations during recent winters have received considerable attention from concerned residents, the medical community, businesses, and government officials (Lareau *et al.*, 2013). Although they generally receive less attention by the public, summer episodes of high ozone concentrations are a serious health concern for residents of the Wasatch Front, in particular children, the elderly, and those susceptible to asthma (Sousa *et al.*, 2013).

While particulates tend to be trapped in low-lying areas of the Wasatch Front during winter, deep boundary layers during summer afternoons combined with local and regional transport of ozone and its precursors can lead to high ozone concentrations both in the valleys and nearby mountains. Complex spatial and temporal variations in ozone concentrations are often superimposed upon a pronounced diurnal cycle with low concentrations in the morning and higher levels in the late afternoon (Arens and Harper, 2013). However, forecasting the timing and location of peak ozone concentrations in this region remains difficult for the Utah Division of Air Quality (DAQ).

The National Ambient Air Quality Standard (NAAQS) for ozone defined by the United States Environmental Protection Agency was lowered in 2015 to an 8-h average concentration of 70 ppb as a result of decades-long research on the health impacts of ozone exposure (Environmental Protection Agency, 2015). As a step towards complying with those standards and to address the challenges to forecast ozone levels along the Wasatch Front, the DAQ supported a low-cost field project referred to as the 2015 Great Salt Lake Summer Ozone Study ($GSLSO_3S$). $GSLSO_3S$ follows upon

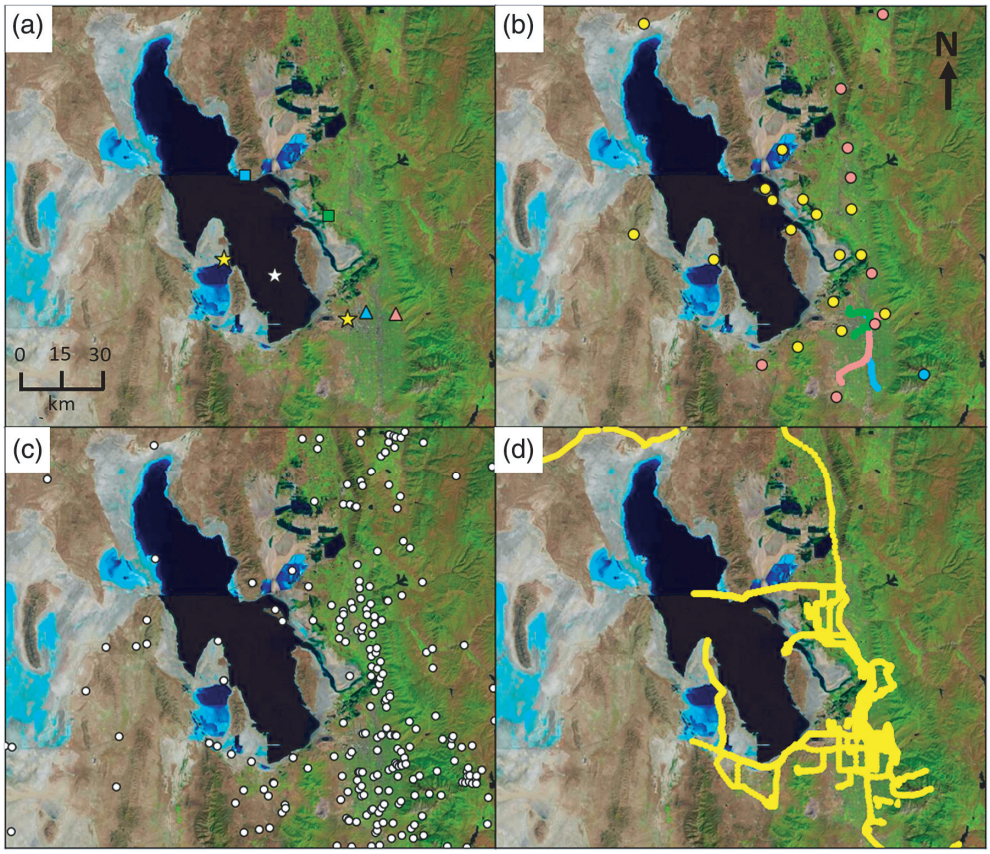

Figure 1. Location of selected instrumentation during GSLSO3S. (a) Specialized instrumentation including colocated, sodar, lidar, ceilometer, tethered sonde (green square); sodars (yellow stars); buoy (white star); ceilometer (red triangle); National Weather Service rawinsonde (blue triangle), and flight operations of UAV (blue square). (b) Ozone monitoring at permanent DAQ (red circles) and United States Forest Service (blue circle) sites, season-long sites (yellow circles) as well as routes of the light-rail car on red, green, and blue lines in the Salt Lake Valley. (c) Meteorological sites. (d) Cumulative ozone monitoring routes of vehicles (yellow).

DAQ field work during the 2010–2014 summers that indicated elevated ozone levels along the shores of the GSL (Arens and Harper, 2013). The objectives of the GSLSO$_3$S pilot study were to: (1) determine the areal and vertical extent of ozone concentrations over and surrounding the GSL during the summer and (2) improve understanding of the meteorological processes that control ozone formation near the GSL during summer to help DAQ forecast ozone concentrations along the Wasatch Front.

We provide here an overview of the GSLSO$_3$S with initial findings to highlight the complex spatial and temporal fluctuations in ozone commonplace during the summer along the Wasatch Front in the context of the prevailing meteorological conditions. The meteorological conditions favoring elevated ozone concentrations along the Wasatch Front are known (high pressure, light winds, and high temperatures) and the influence on air quality of thermally driven circulations arising from the GSL and nearby mountains is recognized (Doran *et al.*, 2002; Zumpfe and Horel, 2007). The sensitivity of ozone formation and transport to both mesoscale flow patterns and local thermally induced flows such as those arising from water bodies and mountains has been examined for decades (e.g. Lyons and Olsson, 1973; Doran *et al.*, 1998; Croes and Fujita, 2003; Fischer *et al.*, 2004; Seaman and Michelson, 2000; Banta *et al.*, 2005; Gheusi *et al.*, 2011; Stauffer *et al.*, 2011; Tsamalis *et al.*, 2014; Cleary *et al.*, 2015; Wentworth *et al.*, 2015), but not previously in the GSL basin. We present here a brief introduction illustrating how the Wasatch Front is a natural laboratory to understand the diverse factors affecting ozone production, transport, and destruction in metropolitan areas embedded within complex terrain.

2. The 2015 Great Salt Lake summer ozone study

This project would not have been possible without the air quality and meteorological instrumentation in place year-round along the Wasatch Front. The Utah DAQ supports a network of permanent federal equivalent method ozone sensors and the United States Forest Service maintains an ozone sensor in the nearby Wasatch Mountains as well (Figure 1(b)). These stations report continuously at 15–60 min intervals. A total of 16 additional 2B Technologies ozone sensors operated by the DAQ or University of Utah were calibrated

Table 1. Summary of poor air quality episodes during summer 2015 and Intensive Observing Periods (IOPs).

Period	Conditions	Ozone (ppb)
3 June	Evening thunderstorm	Over 70 ppb at Salt Lake Valley stations
17 June–3 July	Ridging and hotter than normal	Peak ozone over 70 ppb somewhere every day
IOP 1: 17–18 June	Strong lake breeze front on 18th	Ozone peak values in excess of 80 ppb along frontal boundary aloft
IOP 2: 15–16 July	Deep boundary layer up to 3000 m AGL with afternoon convection	Peak ozone concentrations barely exceeding 70 ppb
IOP 3: 10–12 August	Monsoonal conditions	8 h average over 70 ppb in Salt Lake Valley
16–24 August	Regional smoke transport	Elevated ozone and PM2.5 concentrations at times exceeding 35 $\mu g\,m^{-3}$

and deployed for the summer (Figure 1(b)). Those stations reported at 5–60 min intervals. Over 200 automated surface meteorological stations (Figure 1(c)) typically measuring temperature, moisture, and wind are operated by federal, state, commercial, and educational institutions as well as the general public (Horel *et al.*, 2002). Boundary layer profiles of wind and aerosol concentrations at several locations were provided by a Halo Photonics lidar, two Vaisala ceilometers, and three Atmospheric Systems mini-sodars deployed for the summer by the University of Utah (Figure 1(a)). These supplement the twice-daily profiles of temperature, moisture, and wind from the rawinsondes launched by the National Weather Service at the Salt Lake Airport.

Multi-day periods near the middle of June, July and August were targeted in advance for more intensive observations (Table 1). During these periods, University of Utah students and researchers operated 1–4 vehicles carrying 2B Technologies ozone sensors (Figure 1(d)). Utah State University and Weber State University researchers operated an unmanned aerial vehicle and tethered sonde, respectively during these periods to obtain vertical profiles of ozone.

Novel sources of data for this project included 2B Technologies ozone sensors mounted on a public-transit light rail car operating on electrified Utah Transit Authority routes and the KSL-TV helicopter. The reporting intervals for these ozone observations were 1 min and 10 s, respectively. The ozone sensor was enclosed in a box on top of the light rail car that ran on one of three different routes from early morning to late evening on 71 of the 92 summer days (Figure 1(b)). The ozone sensor, data logger, and communication system onboard the helicopter were activated at the discretion of the pilot during 41 days from mid-June through August. Although the pilot's primary duties were to cover afternoon traffic throughout the Wasatch Front, he also transited many other locales to cover major news events, including traffic accidents and fatalities, wildfire outbreaks, and ongoing search and rescue operations.

The spatial and temporal variability in ozone concentration in both urban and rural locations were monitored continuously via cell phone, radio, or ethernet connections with redundant local storage at many locations. A suite of web pages were developed before and during the summer to view air quality and meteorological observations as well as post field notes and short summaries of preliminary results (see http://meso2.chpc.utah.edu/gslso3s/).

3. Initial findings

Figure 2 summarizes the 8-h maximum ozone concentration at the Hawthorne DAQ site (QHW in Figure 3(a)) in the Salt Lake Valley during summer 2015 compared with the previous four summers. High ozone concentrations were observed during June, early July and the latter half of August 2015 as a result of favorable meteorological conditions for ozone formation at those times (i.e. strong ridging aloft during June and regional transport of wildfire smoke during August). Similar episodes of high ozone arising from wildfires and large-scale ridging were observed during 2012 and 2013, respectively. A deeper and well-mixed boundary layer with enhanced winds speeds tended to prevail during much of July and early August, which resulted in reduced buildup of ozone precursors. Ozone levels exceeded the 8-h average 2015 NAAQS during 18 days at Hawthorne, more often than during any other recent summer (e.g. 13 days in 2012).

The Farmington Bay site (O3S02) recorded the most (19) exceedances of the 2015 NAAQS followed by Hawthorne (QHW), Badger Island (BGRUT), and Saltaire (QSA) with 18, 17, and 16 exceedances, respectively. See Figure 3(a) for locations of these sites. Those cumulative summaries highlight the multiple environments in which high ozone concentrations can occur, e.g.: lakeshore with wide expanses of highly reflective exposed lake bed (BGRUT); urban Wasatch Front (QHW); and the interface between the lake and urban environment immediately to the north of the Salt Lake Valley (O3S02 and QSA).

The ozone air pollution roses in Figure 3 summarize the ozone concentrations as a function of wind direction during the night (2000–0800 h local) and day (0800–2000 h local). The prevailing wind directions at night tend to be oriented down slopes, canyons, and valleys and towards the GSL. Nocturnal titration of ozone by NO_x emissions lowers ozone concentrations within

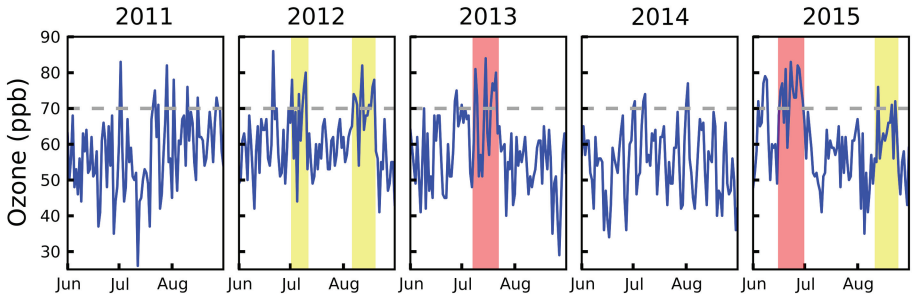

Figure 2. Daily maximum 8-h ozone concentrations at the Hawthorne DAQ site in the Salt Lake Valley for, summer months from 2011 to 2015. Periods dominated by extensive meteorological ridging aloft or local and regional transport of wildfire smoke are highlighted by pink and yellow shading, respectively. The NAAQS for ozone (70 ppb) is denoted by the dashed line.

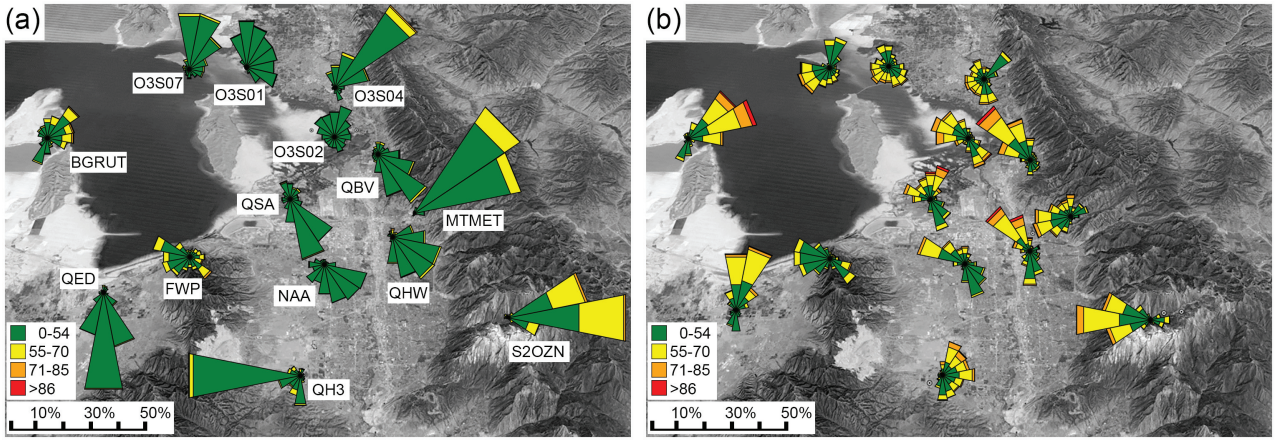

Figure 3. Ozone wind roses over the entire summer during: (a) night (2000-0800 LT) and (b) day (0800-2000 LT). The length of each of the 16 cardinal direction colored wedges represents the percentage of time the ozone concentrations fall within each colored range when the wind is blowing from that direction according to the scales in the lower left of each frame.

the urban corridor. However, such titration is reduced over the rural western lakeshore (BGRUT) as well as at sites exposed to regional ozone background levels (e.g. high elevation site FWP) or ones experiencing frequent down slope/canyon flows (e.g. O3S04, MTMET, QH3, and S2OZN). The prevailing wind directions during late morning often remain similar to those at night. However, flows by late afternoon tend to be locally up slopes, canyons, and valleys and generally away from the GSL. The pollution roses in Figure 3(b) help to capture that diversity in local wind regimes as well as the tendency for peak ozone concentrations to occur during late afternoon. Hence, northern Salt Lake Valley stations (e.g. QHW, NAA, QSA) exhibit lower ozone concentrations in the morning when the winds are directed towards the GSL and higher ozone concentrations in the afternoon when the winds are blowing away from it. Locations at a canyon mouth (MTMET) and deep within a narrow canyon (S2OZN) of the Wasatch Mountains exhibit up canyon flows during the day indicating ozone transport away from the urban areas into the nearby Wasatch Mountains. Higher ozone concentrations tend to be transported across the western lakeshore at BGRUT as a result of a east-northeast mountain-plain flow from the Wasatch Mountains towards the GSL Basin during the night and morning. Finally, the summer's prevailing synoptic-scale flow from the west-southwest is evident at the crest of the Oquirrh Mountains (FWP located 1500 m above the GSL) and accompanied there by low to moderate ozone levels. The highest ozone concentrations (in excess of 55 or 70 ppb) during the afternoon tend to be when the winds are from northerly directions in the central sections of the Salt Lake Valley and upslope on its fringes.

Table 1 summarizes episodes during the 2015 summer that are being examined in more detail by the authors. We use here the 18–19 August period to illustrate some of the complexities in the distribution of ozone observed during the summer. Wildfires across the upstream arc from California to Washington led to transport of smoke across the Wasatch Front during this period. Extensive media coverage focused on the diminished visibility during this period leading locally to PM2.5 concentrations exceeding 35 $\mu g\,m^{-3}$ at many locations on 19 August (not shown), which is far above that observed during the rest of the summer (e.g. seasonal means were below 5 $\mu g\,m^{-3}$). Estimates of brown carbon from a Magee Scientific AE42 aethalometer indicated enhanced brown carbon concentrations attributable to wood smoke during this period as well (not shown).

Ozone concentrations between 50 and 60 ppb (with limited diurnal variation) during 18–19 August are evident in Figure 4 at the high elevation site FWP.

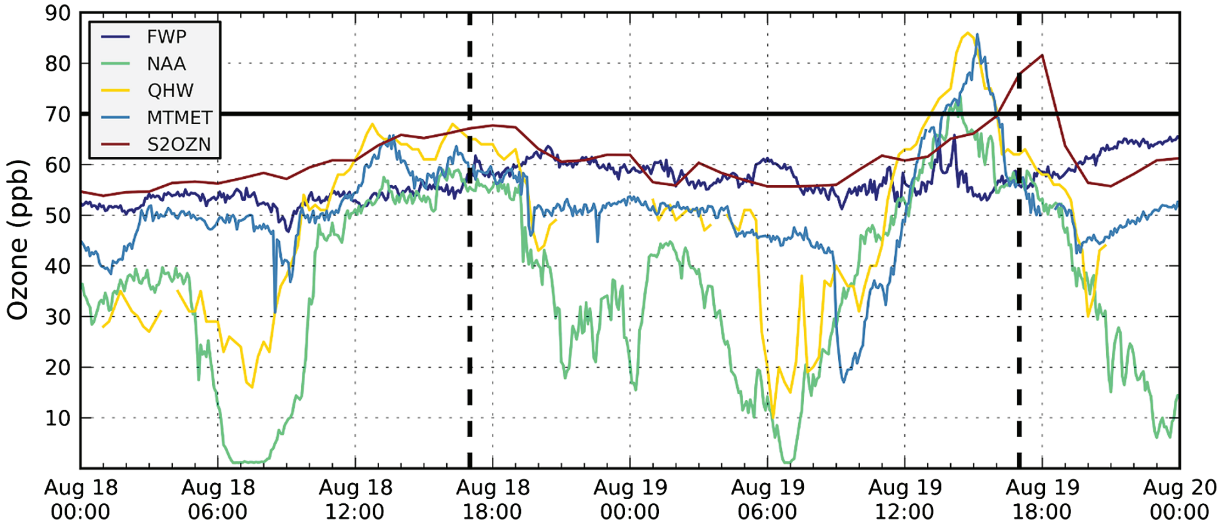

Figure 4. Ozone concentrations at selected sites during 18–19 August 2015. Locations labeled in Figures 3(a) and 5. The NAAQS for ozone (70 ppb) is denoted by the solid black line and 1700 LT each day is denoted by dashed lines.

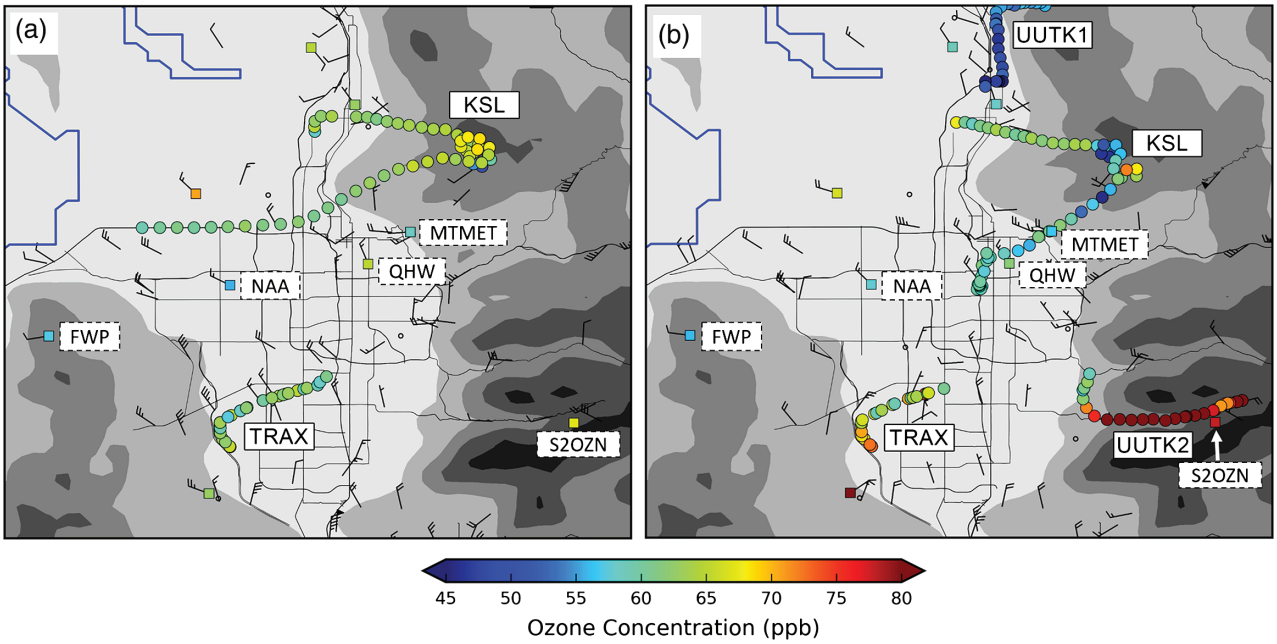

Figure 5. (a) Ozone concentration according to the scale at fixed sites at 1700 LT 18 August (squares with locations of stations in Figure 4 highlighted) and from the TRAX light rail car (every min) and KSL helicopter (every 30 s) from 1650 to 1720 LT 18 August. Surface wind vectors at 1700 LT (half and full barbs denote wind speeds of 1 and 2 m s^{-1}, respectively). Terrain is indicated by successively darker grey shades at 500 m intervals with the approximate shoreline of the Great Salt Lake outlined in blue. (b) As in (a) except for 19 August with ozone from two additional vehicles, UUTK1 and UUTK2, available every minute.

These high background ozone levels probably reflect the impacts of the upstream wildfires on the production and transport of ozone at this time (Jaffe, 2011; Jaffe and Wigder, 2012). However, urban sites (e.g. NAA and QHW) exhibit strong diurnal cycles with titration at night and early morning and rapidly increasing ozone concentrations during the day (see Figure 4). The reduced visibility and higher $PM_{2.5}$ concentrations during the afternoon of 18 August (>25 μg m^{-3}) led to a targeted helicopter flight around 1700 LT 18 August to supplement the surface ozone observations available from fixed sites and the light rail car (Figure 5(a)). To obtain video footage from above the smoke layer, the helicopter spiraled up and down over the Wasatch Mountains (Figure 5(a)). As shown in Figure 6(a), the well-mixed and deep boundary layer contained nearly constant ozone concentrations through 3500 m MSL (~2200 m AGL). Further aloft, ozone concentrations increased to nearly 70 ppb at 4400 m MSL until the helicopter ascended briefly into the capping stable layer with improved visibility and ozone levels below 50 ppb.

During the following afternoon, ozone concentrations spiked in the northern Salt Lake Valley between 1500 and 1600 LT and then dropped rapidly (Figure 4) from the effects of a weak synoptic weather feature

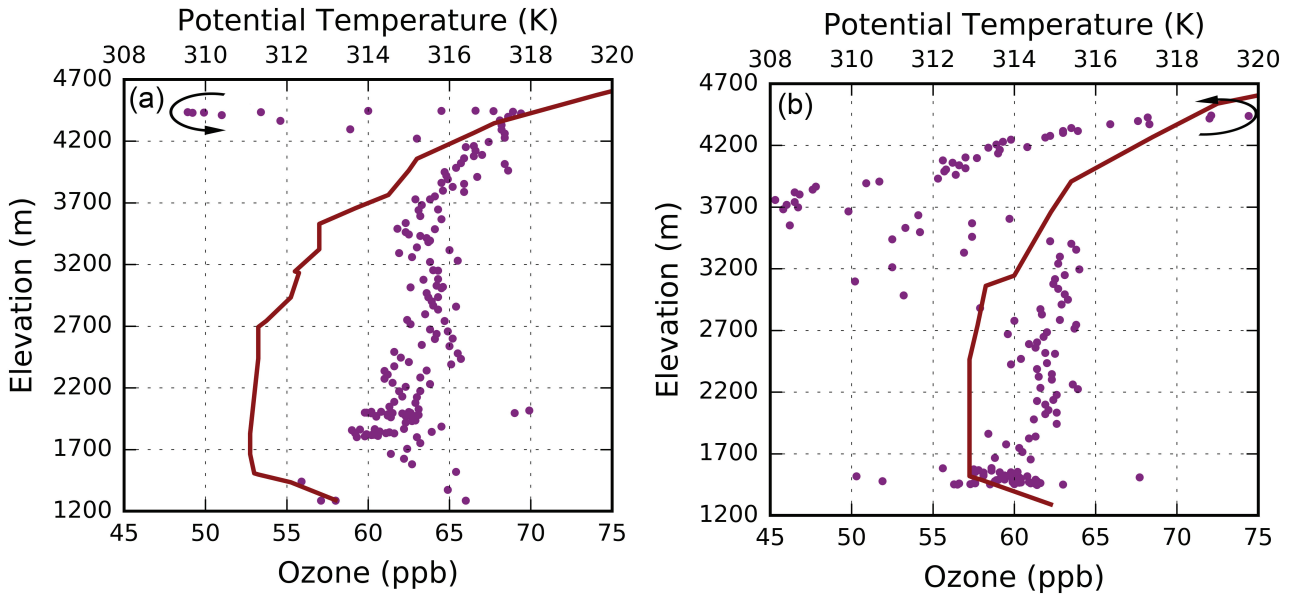

Figure 6. (a) Potential temperature (K) versus elevation (MSL) from the 1700 LT 18 August 2015 KSLC rawinsonde (red line). Ozone (purple dots) at 10 s intervals from sensor onboard the helicopter versus elevation from 1650 to 1720 LT 18 August. Helicopter path at the top of its flight indicated by the arrows. (b) As in (a) except for 19 August.

enhancing the up-valley flow that afternoon (Figure 5(b)). That led to higher ozone concentrations in the southern end of the Valley at 1700 LT observed at Herriman (QH3) and by the sensor onboard the light rail car (Figure 5(b)). The high ozone concentrations evident at S2OZN in the Wasatch Mountains at 1700 LT (Fig. 4) are confirmed by the observations available from one of our vehicles transiting the nearby canyon highway. Figure 6(b) illustrates that the helicopter intersected cleaner air between 3500 and 3900 m whereas the peak concentrations exceeded 70 ppb at its highest elevation.

4. Summary

The outcomes of this study exceeded the original goals identified at the outset of the project due to: (1) the unique mix of season-long monitoring of ozone, other pollutants, and surface and boundary layer meteorological conditions; (2) opportunistic observations from sensors onboard diverse mobile platforms; and (3) reliance on real-time communications to help position sensors and evaluate the data collected as the season progressed. Nearly all the data collected during GSLSO$_3$S are accessible via the web resources at http://meso2.chpc.utah.edu/gslso3s/.

The GSLSO$_3$S study was the most extensive field study undertaken related to summer ozone along the Wasatch Front. The observations obtained continuously from over two-dozen fixed sites as well as from sensors onboard vehicles, a light rail car, and a helicopter highlighted the complexity of the spatial and temporal variations in ozone near the GSL. While titration tended to lower ozone concentrations when the light rail car crossed heavily trafficked roadways, those repetitive transects on over two-thirds of the summer days would have been impractical by any other means. In addition, the helicopter provided invaluable information on ozone concentrations in the boundary layer that would be difficult to obtain from research aircraft given the flight restrictions arising from the Salt Lake International Airport, nearby Hill Air Force Base, and several other small airports.

While the typical diurnal cycle of lower ozone during the night and early morning relative to late afternoon was most common at all the urban locations, less nocturnal titration and greater dependence on local and regional wind circulations were evident at rural sites on the western shore of the GSL or at high elevation to the west (FWP) and east (S2OZN) of the Salt Lake Valley. Thermally driven circulations (whether up/down slope, mountain/valley, or land/lake breezes) clearly affected ozone levels throughout the region. Some of the highest concentrations were observed in the zone sandwiched between the GSL and the urban regions to its south and east. The observations available from multiple platforms during 18–19 August highlight the impacts of regional and local wind circulations on ozone production and transport.

Further research using data from the GSLSO$_3$S is underway to improve understanding and forecasting of the local high ozone episodes as well as help provide insight into the interactions between air chemistry and boundary-layer meteorology wherever thermally driven circulations are present. More work is required to understand the complex linkages between biogenic and anthropogenic emissions of precursor chemicals leading to ozone formation and the impacts of local, regional and global transport of ozone and its precursors. Of highest immediate interest to us is to relate the spatial and temporal variations in ozone during

$GSLSO_3S$ to the many meteorological drivers. Using numerical model sensitivity experiments, we intend to test hypotheses regarding the physical state that may have influenced the summer 2015 air quality season along the Wasatch Front: e.g. a wet spring leading to enhanced hillside vegetation and biogenic precursors; early season shallow lake thermocline leading to shallow boundary layer over the GSL; and increased albedo from the exposed salt flats enhancing photochemical production.

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