A Novel Approach for Monitoring Vertical Profiles of Boundary-Layer Pollutants: Utilizing Routine News Helicopter Flights

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Abstract

Air quality varies greatly in space and time across urban locales. However, criteria pollutants are typically monitored routinely at a relatively small number of surface sites within each metropolitan area, and routine vertical profiles of pollution are typically unavailable. We illustrate that a news helicopter provides an effective sensor platform to provide spatiotemporal analyses and vertical profiles of pollutant concentrations. We are unaware of any other air quality study that has utilized routine helicopter flights, despite the ubiquity of helicopters in urban environments across the world. Particulate and ozone concentration profiles have been collected since 2015 from sensors installed on a news helicopter that travels primarily over the metropolitan areas of northern Utah. The air quality data are retrieved in real time, archived, combined with surface-based observations, and disseminated in terms of time series and maps on a website for research, forecasting, and public awareness. Large vertical variations in particulate pollution concentrations were observed during the 2015-2016 winter associated with meteorological cold-air pool episodes. During the 2015 and 2016 summer seasons, ozone concentrations frequently exhibited complex spatial and temporal variations arising from many interrelated factors, including local terrain-forced circulations, lake breezes, and distant wildfires.

1. Introduction

Fixed-wing (e.g., aeroplane) and rotary-wing (e.g., helicopter) aircraft measurements of criteria air pollutants such as ozone (O_3), particulate matter with diameter less than 2.5 microns ($PM_{2.5}$), and their chemical precursors have been conducted for several decades. Major scientific field campaigns are often conducted with aircraft to better understand atmospheric chemistry and the variability of pollutants on global (Tsutsumi et al., 2003; Ryder et al., 2015; Roiger, 2016) to local scales (Baidar et al., 2015; Shaw et al., 2015). These studies are in some cases supplemented with profiles obtained from balloon-borne instrument packages and satellite. A number of aircraft campaigns have been conducted on urban air pollution, e.g., the 2006 Megacity Initiative: Local and Global Research Observations (MILAGRO) campaign in Mexico City (Molina et al., 2010), the 2014 Front Range Air Pollution and Photochemistry Experiment (FRAPPE) in Colorado (Sullivan et al., 2016) and the 2010 California Research at the Nexus of Air Quality and Climate Change (CalNex 2010) in California (Ryerson et al., 2010). However, most aircraft air quality studies are expensive, and the information they provide is typically limited to a few days or weeks specific to the field campaign. In addition, the voluminous data collected during such field campaigns are generally used for scientific analysis and are rarely available in real-time for local monitoring or decision-making.

Efforts are underway in nearly every metropolitan area in the United States to improve monitoring of criteria pollutant concentrations by deploying regulatory-standard and low-cost sensors at additional fixed sites as well as relying increasingly on mobile sensor platforms (e.g., Van Poppel et al., 2013; Huang et al., 2015; Jang et al., 2016; Van den Bossche et al., 2015, 2016; Yu et al., 2016). Routine daily helicopter flights are ubiquitous in urban areas worldwide for diverse needs (e.g., news reporting, law enforcement, medical and business transport, tourism, and energy exploration). We are unaware of other researchers who may have developed the capabilities to utilize routine helicopter flights for air quality monitoring within the urban boundary layer. In this study, we describe the instrumentation setup and benefits of utilizing routine helicopter flights for real-time urban air quality monitoring on the basis of a few representative cases.

Utah's heavily urbanized Wasatch Front experiences poor air quality episodes most commonly during winter and summer. In the winter, the surrounding topography traps pollutants during cold-air pools (Lareau et al., 2013; Whiteman et al., 2014). During the summer, hot and sunny conditions interact with local emissions and, if present, smoke from distant wildfires to result in high ozone (Horel et al., 2016). Due to the complex topography, meteorology, and emissions in the Wasatch Front region, forecasting air quality has proven to be highly challenging (Lareau et al., 2013; Horel et al., 2016; Crosman and Horel, 2016). The real-time air quality measurements taken by the Utah Division of Air Quality (UDAQ) are available at only a few fixed locations and are insufficient to describe the spatial variability in air quality (Whiteman et al., 2014). In addition, the complex meteorology and topography results in significant vertical variations in pollutants. Both wintertime and summertime ground-based air quality studies have stressed the need for a better understanding of the vertical profiles of pollutants in this region (Silcox et al., 2012; Horel et al., 2016).

In response to the need for routine vertical pollutant measurements along the Wasatch Front, a news helicopter was instrumented beginning in June 2015 with ozone and PM_{2.5} sensors. These measurements were relayed in real-time for display on a publically-available webpage. While helicopter measurements have been utilized in short-term air quality field campaigns, this is the first study to our knowledge to instrument a news helicopter to provide ongoing, routine, real-time observations of spatial and temporal air quality data. In this study, we describe the

setup, benefits, and preliminary findings of our novel approach to routinely monitor air quality throughout the boundary layer.

2. Materials and Methods

2.1. The KSL-TV “Chopper 5” Helicopter

KSL-TV has the only dedicated news helicopter in Utah (Figure 1). As shown in Figure 1B, helicopter flights during summer 2015, winter 2016, and summer 2016 seasons were most frequent within the Salt Lake Valley along the interstate 15 corridor, coinciding with routine traffic reports. The helicopter also flies for breaking news when needed, which explains the less frequent but occasional flights outside of the urban Wasatch Front (Figure 1B). As shown in Figure 1D, about 70% of the flights occur between 1500 and 1800 MST. The helicopter typically flies 3-6 times per week, with a median flight duration of 56 minutes. The horizontal speed of the helicopter ranges between 10 m s^{-1} when hovering and between 40 and 70 m s^{-1} when traveling.

2.2. Air Quality Measurements and Instruments

The helicopter was outfitted with air quality instruments beginning in June 2015 (Figure 1C). The instruments and requisite inlet tubes of length $\sim 3 \text{ m}$ were configured to not affect flight operations. The inlets located on the exterior side of the helicopter were also configured to minimize dynamically-induced pressure effects. The helicopter speed variations did not noticeably impact the ozone or $\text{PM}_{2.5}$ measurements, which generally agreed with fixed site observations when the helicopter flew at low altitude close to those sites (not shown). Some minor effects of airflow dynamics on the measurements are to be expected without more sophisticated instrumentation to compensate for aircraft speed and inlet effects. As will be discussed in the next section, our goal was to provide estimates of air quality within 5% accuracy for mapping the location and elevation of large horizontal and vertical gradients in pollution. The following instruments were installed on the helicopter (Figure 1C):

- **PM_{2.5}**: ES-642 dust monitor with $\text{PM}_{2.5}$ cyclone from Met One Instruments Inc.
[precision: $3 \mu\text{g}/\text{m}^3$ accuracy: 8% of NIOSH 0600].

- **O₃**: Model 205 Dual Beam Ozone Monitor (O₃) from 2B Technologies [precision: 2% accuracy: 2%].
- **Atmospheric pressure**: Campbell Scientific 106 Barometer (pressure) [precision: 0.03 mb accuracy: 0.3-1.5 mb].
- **Data logging**: Campbell Scientific CR1000 data logger.
- **GPS**: Garmin GPS18X-5HZ 010-00321-37 GPS Receiver.

The CR1000 datalogger collects samples from the ES-642 (PM_{2.5}), 2B 205 (O₃), CS 106 barometer, and the Garmin GPS18X-5HZ every 2 seconds, and then averages and logs observations every 10 seconds. A Sierra Wireless Airlink Raven XT cellular modem is used to transmit bursts of the 10-s data to the University of Utah Center for High Performance Computing every 5 min. The on-board pressure sensor is also utilized to restrict cellular communications when the helicopter flies at higher altitudes. The transmitted data is then processed for near-real time display.

2. 3. *Measurement Goals and Real-time Display*

The overall goal is to utilize a news helicopter flying routinely over the Wasatch Front to cost-effectively monitor air quality above the surface. Other technologies such as sensors mounted on free-flying or tethered balloons or unmanned aerial vehicles are not able to monitor air pollutant concentrations in the boundary layer across a metropolitan area routinely without dedicating large amounts of equipment and human resources. Our objectives are to utilize the air quality data to: 1) study the meteorological and air chemistry drivers for abrupt changes in pollutant concentrations throughout the boundary layer and 2) provide data in near-real time (http://meso2.chpc.utah.edu/gslso3s/cgi-bin/current_map.cgi) for use by state, federal, and private sector air quality forecasters as well as the general public.

3. **Results and Discussion**

Transects and vertical profiles of pollutant concentrations from ~ 330 helicopter flights have been collected to date. In this section we highlight vertical and spatial variations of PM_{2.5} and ozone during three high-impact pollution episodes.

3.1 Ozone Episode 27 June 2016

Ozone concentrations exceeding the National Ambient Air Quality Standard (NAAQS) are frequently observed in the summer (~10 days on average) along the Wasatch Front. However, ozone forecasting skill is very low due to many complex and interrelated local meteorological factors (Horel et al., 2016). During the Great Salt Lake Summer Ozone Study (GSLSO₃S), the KSL helicopter provided insight into a 20 ppbv gradient in ozone that was observed within the Salt Lake Valley on several summer afternoons. On 18 June 2015, the helicopter fortuitously flew through a strong Great Salt Lake breeze front (Blaylock et al., 2017). The lake breezes had a clear impact on the spatial ozone distribution for this event. While the 18 June 2015 high ozone case has been analyzed and modeled (Blaylock et al., 2017), over a half-dozen additional cases where lake-breezes impacted ozone have been identified. One of these cases was 27 June 2016 (Figure 2), when the lake breeze circulation in concert with light winds (not shown) and a subsidence inversion (depicted by potential temperature increasing with height between 1500 and 3000 m AGL in Figure 2B) resulted in elevated ozone concentrations. This case contrasted sharply with 18 June 2015 in that the vertical gradient in ozone was more pronounced on 27 June 2016 (Figure 2B). Ozone concentrations as high as 90 ppbv were observed in the northern Salt Lake Valley in the lowest 400 m of the boundary-layer, while cleaner air was observed aloft and over the Wasatch Mountains (Figure 2A). While previous helicopter flights have observed high ozone aloft associated with distant wildfires (Horel et al., 2016), the air above 2000 m AGL on 27 June observed elevated ‘background’ regional ozone levels in the 55-60 ppbv range. Since the regional background values vary from day-to-day from 35-60 ppbv, obtaining these readings from the helicopter assists air quality forecasters to identify local vs. regional transport impacts and to help identify biases in air chemistry forecast models.

3.2. Wildfire 23 July 2016

While air quality monitors are occasionally deployed for wildfires through the Wildland Fire Air Quality Response Program, these deployments are typically for incidents where numerous structures are at risk or large downstream smoke impacts are expected. The helicopter

provides a unique opportunity for air-quality monitoring of PM_{2.5} concentrations near wildfires because wildfires are often breaking news stories. The helicopter can also fly high enough to sample elevated smoke plumes from distant regions (e.g., California, Pacific Northwest).

As an illustration of such capabilities, a grass fire at Antelope Island State Park, northwest of Salt Lake City, was started by lightning on 22 July 2016. The West Antelope Fire consumed 15,111 acres before being contained on 26 July. Figure 3B (3C) provides MODIS imagery before (after) the fire took place, with a burn scar apparent across much of the island in the northwest corner of Figure 3C. The smoke plume from the fire sporadically impacted the Salt Lake Valley between the 23 and 25th of July (not shown). On the afternoon of 23 July, the helicopter flew near the West Antelope Fire between 1540 and 1600 UTC and intersected the smoke plume (Figure 3A), with PM_{2.5} concentrations over 50 µg m⁻³ observed from the main fire plume, while PM_{2.5} concentrations over 25 µg m⁻³ were noted in the general vicinity of the fire (Figure 3D).

3.3. Cold-Air Pool 9 February 2016

Wintertime cold-air pools result in high-impact periods of poor air quality along the Wasatch Front. While the boundary-layer thermal and momentum profiles within cold-air pools was extensively studied during the 2010-2011 Persistent Cold-Air Pool Study in the Salt Lake Valley, the vertical distribution of PM_{2.5} and chemical precursors during those cold-air pools was not documented adequately (Silcox et al., 2012; Lareau et al., 2013; Whiteman et al., 2014). On average, the PM_{2.5} NAAQS of 35 µg m⁻³ is exceeded on 18 days each winter season (Lareau et al. 2013). The cold-air pool vertical depth from a laser ceilometer at a fixed location the Salt Lake Valley averaged around 500 m during the 2010-2011 winter season (Young and Whiteman, 2014).

The helicopter made several flights during high pollution episodes during the 2015-2016 winter. A long-duration cold-air pool occurred between 2-16 February 2016 with 24-hr PM_{2.5} concentrations exceeding the NAAQS in the Salt Lake Valley on 8 of those days. Visually, large changes in visibility are observed between clean air conditions preceding a cold-air pool and during the height of a polluted cold-air pool episode (Figure 4A-B). The vertical structure of the pollution also varies considerably during winter cold-air pools, from a hazy layer without a clear

189 visible upper boundary to a shallow polluted layer in the lowest 100-300 m of the lowest portions
190 of the Salt Lake Valley.

191 Research aircraft use a variety of transect and porpoising techniques to obtain
192 meteorological and pollution profiles (e.g., Karion et al., 2013; Parish et al., 2016). Figure 4
193 provides an example of the PM_{2.5} concentration data collected on 9 February 2016 during which
194 the helicopter pilot conducted porpoising maneuvers at our request so that the depth and vertical
195 structure of the polluted layer was better observed. On 9 February 2016, the helicopter pilot
196 porpoised between 100 and 1800 m AGL in the eastern Salt Lake Valley into the Utah Valley
197 (Figures 4C and 4E). Below 600-800m AGL, elevated PM_{2.5} concentrations in excess of 40 µg
198 m⁻³ were observed, while above that level the helicopter rapidly penetrated into the clean air
199 above the cold-air pool, with PM_{2.5} concentrations between 0 and 10 µg m⁻³ (Figures 4D and
200 4E). Spatial variations in the depth and concentrations of PM_{2.5} were observed as well. The
201 largest differences were noted in the vertical profiles between the Salt Lake and Utah Valleys
202 (Figure 4C and 4E). In the Utah Valley, the vertical extent of the pollution layer was 100-200 m
203 shallower, and the PM_{2.5} concentrations within the cold-air pool were about 20 µg m⁻³ lower than
204 in the Salt Lake Valley (Figures 4C and 4E).

206 4. Conclusions.

207 Intra-urban variations in air pollution are of high interest due to their potential impacts on
208 resident exposure (Jiao et al., 2015; Ito et al., 2016) This study is the first to our knowledge to
209 utilize a daily news helicopter to cost-effectively collect ongoing profiles of air quality and
210 disseminate that data via a publically-accessible webpage
211 (http://meso2.chpc.utah.edu/gslso3s/cgi-bin/current_map.cgi). Case studies from the continually
212 growing sample of flights over multiple seasons in the boundary-layer along Utah's Wasatch
213 Front illustrate the complex spatial and temporal variations in pollutant concentrations evident
214 throughout the year. While intensive short-term field campaigns are critical to understand the
215 processes leading to high-pollutant concentrations, it is to be expected that they will not capture
216 the rich diversity in situations faced daily by air quality forecasters.

217 The need for the current instrumentation to remain on the KSL helicopter is expected to
218 continue into the foreseeable future, and complements an ongoing mobile surface air quality
219 measurement effort using sensors mounted on Utah Transit Authority light rail trains. Future

work includes additional validation and scientific analysis of the vertical air quality profiles in concert with other auxiliary data sets. The helicopter will also aid a National Oceanic and Atmospheric Administration aircraft air quality study in 2017. The use of the helicopter for routine monitoring of urban air quality also provides an example of the types of urban air pollution questions that might be answered by using unmanned aerial vehicles, although there are many technical and logistical issues to overcome for their use in urban areas (Brady et al., 2016; Chang et al., 2016). For example, the Federal Aviation Administration currently restricts drones from flying above 133 m over most urban areas hosting airports.

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Figures

Figure 1. Overview of KSL-TV helicopter and air quality instrumentation. (A) Installing the air quality instruments on the KSL-TV helicopter. (B) Frequency map of helicopter flight coverage across northern Utah from helicopter flights during summer 2015, winter 2016, and summer 2016 (red colors indicate frequent flights while blue colors indicate infrequent coverage). (C) Helicopter instrumentation box and sensors. (D) Histogram of flight time percentages in Mountain Standard Time (MST).

Figure 2. Example summer ozone spatial and vertical air quality data collected by KSL-TV helicopter. (A) Plan view of helicopter ozone (circles, in ppbv according to color scale) over the Salt Lake Valley on 27 June 2016 between 2220 and 2330 UTC. Square symbols represent Utah Division of Air Quality and University of Utah fixed surface measurements. Mesowest weather station wind speed observations are shown by wind barbs (full barb = 2.5 m s^{-1}). (B) Vertical profile of ozone (ppbv) data shown in (A) (circles, in ppbv) and potential temperature (K, red line). Potential temperature derived from nearby rawinsonde observations.

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Figure 3. Example summer $\text{PM}_{2.5}$ air quality data collected by KSL-TV helicopter. (A) Plan view of $\text{PM}_{2.5}$ between 1500-1600 UTC 23 July 2016 (circles, in $\mu\text{g m}^{-3}$ according to color scale) over the Salt Lake Valley on 27 June 2016 between 2220 and 2330 UTC. Square symbols represent Utah Division of Air Quality and University of Utah fixed surface measurements. Mesowest weather station wind speed observations are shown by wind barbs (full barb = 2.5 m s^{-1}). (B) and (C) MODIS 7-2-1 imagery showing the region on (B) 13 July 2016 and (C) 27 July 2016. (D) Time series of $\text{PM}_{2.5}$ observations and elevation of helicopter for observations in (A).

Figure 4. Example winter PM_{2.5} air quality data collected by KSL-TV helicopter. Webcam imagery looking south from University of Utah during (A) clean-air conditions on 2 February 2016 and (B) cold-air pool conditions on 10 February 2016. (C) A visual example of the shallow nature of cold-air pools often observed in the Salt Lake Valley from December 2009. (D) Time series of PM_{2.5} observations ($\mu\text{g m}^{-3}$, orange line) and elevation (m, blue line) of helicopter between 2315 UTC 9 February and 0045 UTC 10 February 20116. (E) Plan view of helicopter PM_{2.5} (represented by circles, in $\mu\text{g m}^{-3}$ according to color scale) from the real-time website for the period in (D). (F) vertical profile of PM_{2.5} data and potential temperature (K, red line) shown in (D) and (E).). Potential temperature derived from nearby rawinsonde observations.

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