Small-Scale Spatial Variability of Ozone in Boulder, Colorado

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ABSTRACT

Surface ozone (O$_3$) is detrimental and can pose several health problems to humans, such as increased number of and intensity of asthma attacks. Considering this, it is important that these ozone levels be monitored. While municipal air quality monitors are present in cities like Boulder, Colorado, these monitors often only consider regional-scale analysis, neglecting the variability of compounds, such as ozone or carbon monoxide, over smaller distances. Small-scale (approximately 1 kilometer) spatial variability in ozone is important because humans experience these small scales on a daily basis. Using low-cost air quality monitors (“pods”) developed at the University of Colorado-Boulder, we assessed small-scale spatial variability of surface ozone in Boulder, Colorado by placing clusters of 4-5 pods within ~1 km of each other at two sites in the city: South Boulder Creek and the University of Colorado-Boulder. Pods were left in their positions for one to two weeks allowing for observation of ozone trends. As hypothesized, higher ozone levels were detected during the afternoon hours. Also, the pod located closest to the roadway (Colorado 93) had the largest range of ozone data, which is consistent with its proximity to ozone precursor emission sources. Finally, it was determined that the differences in the pods’ ozone levels at South Boulder Creek were statistically significant implying that ozone levels do in fact vary over small spatial scales and should be monitored.

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1. Introduction

a. Health effects of ozone

Surface ozone levels have increased over the past decades, and they could keep rising to very dangerous levels in the United States (Vingarzan 2004). Excessive exposure to surface ozone can lead to health complications such as chest pain, coughing, throat irritation, congestion, and can also lead to reduced lung function (Environmental Protection Agency 2015b). This is one of the many different reasons the Environmental Protection Agency has set standards for ozone levels across the United States. In addition to adverse human health effects, ground ozone can also negatively affect local visibility and ecosystems (Musselman and Korfmancher 2014). Because exposure to ozone is a phenomenon that could threaten human health and the overall well-being of the population, it is important that ozone levels be studied and monitored.

b. Factors affecting ozone levels

There are two environmental aspects of our study, including the elevation and the time of the year when the sampling occurs, that led us to expect interesting results. First, with regard to elevation, Van Ooy and Carroll (1995) performed an ozone analysis from various sampling sites in the Sierra Nevada mountain range, and found increased ozone levels at higher elevation sites (i.e., ozone levels increase with increasing elevation level). Closer to the area of interest, Brodin, et al. (2010) also found that “background [ozone] is highest at the high-elevation sites” in their study of seasonal ozone behavior in the Colorado Front Range (background ozone is non-anthropogenically generated ozone). Considering these facts and that Boulder is situated more than a mile above sea level, this led to us to expect data depicting higher ozone levels than other places in the country.

Secondly, it is important to consider the time of year when sampling occurs. According to the Environmental Protection Agency (2014a), “Ozone is likely to reach unhealthy levels on hot sunny days in urban environments.” This can be attributed to the fact that more sunlight is readily available to assist NOx and volatile organic compound (VOC) reactions to generate more surface ozone. During the boreal summer months, Boulder experiences more sunlight and thus, can have more ozone created by that sunlight.

c. Studying small-scale spatial variability

It is essential that ozone be studied on small spatial scales because these scales are less studied and are important in understanding human exposure to surface ozone on a day-to-day basis. In several studies, the spatial scales studied are often regional or over the span of countries (Brodin, et al. 2010; Wang, et al. 2011). For example, in the city of Boulder, there are only three official air quality-monitoring stations, and only one is dedicated to measuring ozone. A map of these sites can be seen in Figure 1.
While the presence of the three monitoring sites in Boulder serve a purpose for regional analysis and comparison, a lack of municipal air quality sites fails to provide a picture of how ozone varies within the city. Due to this small-scale data gap in ozone, the Hannigan group, from the Environmental Sustainability section at the University of Colorado-Boulder’s Engineering Department, participated in the FRAPPE (Front Range Air Pollution and Photochemistry Experiment) field campaign during summer 2014. Their work involved comparing the ozone levels between different sites located within a 10x10 km grid cell.
Figure 2 highlights the Hannigan group’s work depicting ozone levels at two different sites within that 10x10 km grid cell. Between July 31 and August 3, and after August 9, differences as large as 20 parts per billion (ppb) between sites, which is significant, were observed, and ozone levels of this magnitude are statistically significant. Because these statistically significant differences were found in this small-scale study done by the Hannigan group, this is further motivation to study ozone variability on small spatial scales.

Our study focuses on scales smaller than those examined in Collier, et al. (2014) to truly observe the variability on the scales humans experience. Instead of studying variability in a 10x10 km grid cell, we are studying ozone variability over scales as large as 1 kilometer. Results from this study will lead to a better understanding of the impact small-scale spatial differences have on the ozone levels in Boulder, Colorado.

This paper will include all aspects of our study. Section 2 will shed light on our methods of collection and data analysis. Section 3 provides our results collected at South Boulder Creek. Section 4 will state our conclusions and examples of future work that can be done with our study.

2. Methods

All samples were collected using low-cost air quality monitors called UPods (“pods”) created at the University of Colorado-Boulder. Before collecting field data, pods were co-located with official reference instruments operated at each site, and the pod data was then normalized to reference data during calibration using linear regression. Field data was then collected from two different sites in Boulder, Colorado. After collection, all data were stored on each pod’s individual SD card. Time series analysis and statistical analysis were then performed on calibrated field data.
a. South Boulder Creek (SBC) (Site 1 – Rural)

Pods deployed at South Boulder Creek were co-located with the official reference instrument operated by the Colorado Department of Public Health and Environment at the same site from June 18-25, 2015. Field data was collected from June 29-July 11, 2015. Pods at this site were placed along a path from the reference station toward the trailhead. This arrangement allowed for compliance with site usage permissions and for pods to be within the range of power sources. As seen in Figure 3, there were four pods collecting field data at SBC.

The red pod (D7) was located closest to the roadway and trailhead parking lot, and this pod’s ozone levels were expected to be affected by the proximity to the roadway emissions. The blue and black pods (D5 and D4, respectively) are situated furthest west in this map. The black pod was located at the reference station, while the blue pod was situated a few meters west in the trees. Because of this small spatial difference between the two pods, the ozone levels detected were expected to be relatively similar. However, the blue pod’s presence in the trees could result in decreased ozone levels due to the presence of vegetation. Lastly, the green pod served as a midpoint between the red pod and the blue and black pods.

b. University of Colorado-Boulder

Pods deployed at the University of Colorado-Boulder were co-located with the reference instrument at the Boulder Atmospheric Observatory in Erie, Colorado from June 11-18, 2015. Field data was collected at the campus from June 23-July 13, 2015.
Figure 4 shows the distribution of pods on the University of Colorado-Boulder campus while collecting field data. There were four pods deployed at the campus. In numerical order, pods were located at the Continuing Education building, the Geography building, the Chemistry building, and the University Memorial Center. While data was collected on the campus, the results and conclusions in this paper solely focused on data collected at South Boulder Creek due to issues encountered during the calibration of the campus pods.

3. Results and Discussion

a. Co-location/Calibration

Calibration is an important process because these pods can be affected by environmental conditions (i.e., temperature and humidity), and there may be differences in the behavior from sensor to sensor. Figures 5-8 show the calibration graphs for each of the four pods co-located (and then used for field data) at South Boulder Creek. Reference data are represented with a blue line on each graph, while the respective pod’s data are represented with a red line. Lastly, the green shading around the data lines indicate that 95% of the data is expected to lie within this range (i.e. the 95% confidence interval).
Figure 5 (D4): $R^2 = 0.84$, RMSE = 5 ppb

Figure 6 (D5): $R^2 = 0.82$, RMSE = 5.1 ppb
Figure 7 (DB): $R^2 = .95$, RMSE = 3.5 ppb

Figure 8 (D7): $R^2 = .74$, RMSE = 8.5 ppb
To determine the quality of a calibration, two statistics are considered: the coefficient of determination ($R^2$), which indicates how well the regression equation fits the data, and the root mean squared error (RMSE), which shows the average distances between the regression line and the data points. Anticipated values of the coefficient of determination are .8 or above, while anticipated values of the root mean squared error are 5 ppb or below. Three of the four pods performed particularly well in terms of calibration, while one pod (D7 – closest to the road for field data) did not perform as well, as seen in Figure 8. Despite D7’s values being different from the anticipated values, its data need not be disregarded. Pod D7’s differences in coefficient of determination and root mean squared error values could be attributed to the quality of the sensor or other technical difficulties.

b. Time Series

![Figure 9: Time series depicting data collected at South Boulder Creek from June 29-July 11](image)

The diurnal cycles can be seen in the oscillations depicted on the time series in Figure 9. This is consistent with what is expected as higher ozone levels are observed in the afternoon, due to increased sunlight. We would expect the trends to be the same between the pods, especially since they are located very close together. However, the differences in concentrations at a particular time (e.g., on 7/7) provide a nice example of the small-scale variability we are investigating herein.

c. Box plots

In Figure 10, four box plots represent each of the four pod data sets. The notches, the vertical spaces on either side of each median (depicted by the red bars on each data set), do not
overlap between data sets. When this occurs, we can assume with 95% confidence that the data sets’ medians are different and that the data sets differences’ are statistically significant.

![Ozone Levels for Pods at South Boulder Creek](Image)

**Figure 10: Box plots representing pod data sets from South Boulder Creek; pods’ orientation from left to right on x-axis represent the pods’ orientation from east to west at SBC**

First, pod D5 (located in the trees) had lower maximum and minimum values than pod D4 (located at the reference station), as expected. However, the median for D5 was higher than D4’s median. As the presence of vegetation was considered the only difference between the two pod settings, it appears to have an impact, but other variables may be contributing to the results seen for D5 and D4.

Pod DB was the pod located between the vegetation and the roadway. This pod had the smallest range of data, which may be due to the fact that this pod was detecting ozone created by roadway emissions, but may also have had ozone being taken from it by vegetation. This pod also possessed many outliers on the upper end, possibly suggesting that the roadway emissions had more of an impact on the data than the vegetation did.
Lastly, pod D7 had the largest spread of data. This is expected, as it was located closest to the roadway. Because the roadway emissions were readily available to assist in the generation of ozone, D7 detected the highest levels of ozone. However, in the absence of those roadway emissions, one could surmise that D7 would also have a very small lower bound.

4. Conclusions and Future Work

After considering our results, we conclude that the differences between the pod data sets are statistically significant. Therefore, the small-scale spatial differences are shown to be important in observing ozone levels. We also conclude that vegetation has an effect on ozone levels in Boulder, but future work is needed in order to determine the extent of its effect. Future work also includes determining causes of ozone variability over small spatial scales and performing more statistical analysis (such as significance testing). Future work will also compare the University of Colorado-Boulder campus data to South Boulder Creek’s in order to determine and understand differences in variability between urban and rural settings. Lastly, the data collected and reported on herein will be compared to the Environmental Protection Agency’s ozone standards in order to determine whether ozone levels are harmful to human health.

5. Acknowledgements

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