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Intra-city variability of fine particulate matter during COVID-19 lockdown: A case study from Park City, Utah

Daniel L. Mendoza, PhD\textsuperscript{a,b,c,\*}, Tabitha M. Benney\textsuperscript{d}, Ryan Bares\textsuperscript{a}, Erik T. Crosman\textsuperscript{e}

\textsuperscript{a} Department of Atmospheric Sciences, University of Utah, 135 S 1460 E, Room 819, Salt Lake City, UT 84112, USA
\textsuperscript{b} Department of City & Metropolitan Planning, University of Utah, 375 S 1530 E, Suite 220, Salt Lake City, UT 84112, USA
\textsuperscript{c} University of Utah School of Medicine, Pulmonary Division, 26 N 1900 E, Salt Lake City, UT 84132, USA
\textsuperscript{d} Department of Political Science and Environmental Studies Program, University of Utah, 260 S Central Campus Drive, Salt Lake City, UT 84112, USA
\textsuperscript{e} Department of Life, Earth and Environmental Sciences, West Texas A&M University, Natural Sciences Building 324, Canyon, TX 79016, USA

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\textbf{ABSTRACT}

Urban air quality is a growing concern due a range of social, economic, and health impacts. Since the SARS-CoV-19 pandemic began in 2020, governments have produced a range of non-medical interventions (NMIs) (e.g. lockdowns, stay-at-home orders, mask mandates) to prevent the spread of COVID-19. A co-benefit of NMI implementation has been the measurable improvement in air quality in cities around the world. Using the lock-down policy of the COVID-19 pandemic as a natural experiment, we traced the changing emissions patterns produced under the pandemic in a mid-sized, high-altitude city to isolate the effects of human behavior on air pollution. We tracked air pollution over time periods reflecting the Pre-Lockdown, Lockdown, and Reopening stages, using high quality, research grade sensors in both commercial and residential areas to better understand how each setting may be uniquely impacted by pollution downturn events. Based on this approach, we found the commercial area of the city showed a greater decrease in air pollution than residential areas during the lockdown period, while both areas experienced a similar rebound post lockdown. The easing period following the lockdown did not lead to an immediate rebound in human activity and the air pollution increase associated with reopening, took place nearly two months after the lockdown period ended. We hypothesize that differences in heating needs, travel demands, and commercial activity, are responsible for the corresponding observed changes in the spatial distribution of pollutants over the study period. This research has implications for climate policy, low-carbon energy transitions, and may even impact local policy due to changing patterns in human exposure that could lead to important public health outcomes, if left unaddressed.

\textbf{1. Introduction}

Like many parts of the United States, poor air quality in Park City (PC), Utah is a significant concern for its residents. This high mountain city sees significant wintertime tourism since it is home to busy ski resorts and hosts the Sundance Film Festival. Synoptic scale high pressure systems paired with mountain topography can lead to extended episodes of atmospheric inversions which trap pollution, especially fine particulate matter (PM\textsubscript{2.5}), in the heavily populated, adjacent lower elevation Wasatch Front and Salt Lake Valley (SLV) (Lareau et al., 2013). The variability of pollution has been extensively studied in the SLV, but not the higher elevation mountain basins nearby like PC. Such basins are of interest because they are at a high enough elevation to experience more influence from free tropospheric air and have been comparatively understudied.

Urban air quality is a growing concern because air pollution has been found to impact a range of social and behavioral factors such as educational outcomes (Mendoza et al., 2020; Mullen et al., 2020), workforce productivity (Zivin and Neidell, 2013), and air quality is associated with a range of adverse health outcomes including asthma (McCreanor et al., 2007), chronic obstructive pulmonary disease (COPD) (DeVries et al., 2017), cardiovascular disease (Brunekreef et al., 2009), pneumonia (Pirozzi et al., 2018a), depression (Vert et al., 2017), and increased mortality (Liu et al., 2019; Vohra et al., 2021). Recent studies have shown that short term exposure and exposure to low levels of pollution, including “green” air quality (e.g. less than 12.1 g m\textsuperscript{-3}}
PM$_2.5$) are both detrimental to human health and increase the risk of mortality (Di et al., 2017), heart failure (Pope et al., 2008), pulmonary conditions (including childhood asthma) (McConnell et al., 2010; Pirozzi et al., 2018b), and several types of cancer (Krewski et al., 2009; Pun et al., 2017).

Emerging research also suggests that COVID-19 incidence rates may be associated with air pollution exposure (Sahoo et al., 2020), and that particulate matter may be responsible, at least in part, for the elevated spread of this and other diseases in urban areas (Becchetti et al., 2021; Sharma and Balyan, 2020). In fact, Gatti et al. (2020) discovered that in addition to social, economic, and health factors, air quality—especially particulate matter—was found to be one of the most important predictors of COVID-19 and its effects.

Since the SARS-CoV-19 pandemic began, governments have produced a range of non-medical interventions (NMI) (e.g., lockdowns, stay-at-home orders, mask mandates) to prevent the spread of COVID-19. A co-benefit of NMI implementation has been the measurable improvement in air quality in cities around the world (Rodríguez-Urrego and Rodríguez-Urrego, 2020). This has included a substantial drop in the concentration of primary pollutants (i.e., Nitrogen Oxides - NO, Carbon Monoxide - CO, Benzene, Toluene, Xylene - BTX, Non-Methane Hydrocarbons - NMHC, and Ammonia - NH$_3$) from March to June 2020 (Viteri et al., 2021). Even when a range of meteorological conditions are considered (Briz-Redón et al., 2021), the fifty most populous cities in the world experienced a 12% drop in air pollution on average (Rodríguez-Urrego and Rodríguez-Urrego, 2020), with some estimates ranging from 10 to 43% reductions in PM$_{2.5}$ even in unfavorable meteorological conditions (Sharma et al., 2020). If the resulting air quality improvements in the state of California alone persist for one year, it is estimated that 3970–8900 premature deaths could be prevented each year (Pan et al., 2020).

While a dramatic dip in emissions are expected worldwide due to pandemic-related disruptions to labor, transportation, and leisure time activities (Chung et al., 2020), the rare nature of pollution downturn events (i.e. the 2008 SARS-CoV-19 pandemic—“The Great Lockdown” or the 2008 Economic Crisis—“The Great Recession”) means that less is understood about how such events change the composition of air quality in a local setting or if such changes have important policy implications over the long-term (Mendoza et al., 2021). For instance, Long et al. (2018) show that even when adjusting for a range of controls, there is a unique and negative effect of the 2008 recession on pollution levels nationally in the United States, but what explains this pattern? Do all pollution downturn events lead to worse air quality after they rebound?

In late 2019, PC set out to establish an air quality baseline for the city. While extensive regulatory and research air quality data exists in the SLV and adjacent Wasatch Front, no similar studies on the air quality in PC existed before the 2019 baseline effort. The aim of the study was to analyze the fluctuations in local PM$_{2.5}$, and to begin to evaluate local air quality policies to understand their effectiveness. However, a month into the observation campaign, the COVID-19 pandemic began worldwide. This historic event presents a natural experiment with which to study changing emissions during periods of lockdown (Hooseini, 2020) and to better understand pollution downturn events. The global pandemic, for example, has temporarily slowed down emissions from the transportation sector, but is expected to drive up the use of heating and cooling in residential settings (Le et al., 2020) where energy efficiency and efforts to reduce building emissions has been least impactful (Narcowich et al., 2013). Likewise, it has yet to be determined if an air pollution rebound following the pandemic could lead to the accelerated transmission of COVID-19. Subsequently, pollution policies and goals may be shifting and quality research using recent and direct measurements is urgently needed to confirm and explain these changing patterns (Kuzemko et al., 2020).

This research has three main goals. Using the lockdown policy of the COVID-19 pandemic as a natural experiment (Klemes et al., 2020), our first aim is to trace the changing emissions patterns produced under the pandemic in a mid-sized, high altitude city in an effort to isolate the direct effects of lockdown policies on air pollution patterns. We also track pollution concentrations over various periods of policy implementation using high quality, research grade sensors to compare patterns found before, during, and after the lockdown period using direct measurements. The final goal of this research is to compare emissions levels in both commercial and residential settings over similar time periods of the pandemic to better understand how each setting may be uniquely impacted by pollution downturn events. Thus, we propose two hypotheses:

**Hypothesis 1.** The Lockdown period decreased air pollutant concentrations and the Easing and Reopening periods led to increased air pollution.

**Hypothesis 2.** The Lockdown period affected air pollutant levels in commercial and residential areas differently.

Based on these analyses, we aim to understand how energy policy may be impacted by the ongoing changes caused by the global pandemic, changing work patterns, and a global economic downturn in combination. As a result, this research has implications for climate policy, low-carbon energy transitions, and may even impact local policy due to changing patterns in human exposure that could lead to important public health outcomes, if left unaddressed (Rosenbloom and Markard, 2020).

2. Materials and methods

Considering the increased uncertainty that a changing emissions system creates for adaptation planning and low carbon transition worldwide, pollution downturn and rebound events could be highly consequential. To address this, we use a physical exposure model that compares diurnally averaged fine particulate matter (PM$_{2.5}$) levels measured using research grade instrumentation with a high measurement frequency to study air quality downturn and extreme pollution events in an isolated, mountain setting. Through this approach, we aim to understand how emissions from commercial and residential settings are impacted by changing human behavior related to COVID-19 policies enacted at the onset of the pandemic in 2020. Quantifying and characterizing air quality over varying periods of policy implementation during the pandemic, gives us a unique opportunity to understand future air quality scenarios of policy importance and sheds light on how these changing patterns may impact energy policy at all levels of governance.

2.1. Case study: Park City, UT

Park City (PC), Utah is located 35 miles from the Utah state capital of Salt Lake City at elevations ranging between 2100 and 3000 meters above sea level (MASL). This high mountain city is home to several well-known ski resorts and an array of outdoor activities all year round, including the Sundance Film Festival. As a result, the local population is far outnumbered by the 600,000 tourists that visit the city each year. In 2019, the local population by census was 8375 people with a median age of 39.3 and a median household income of $111,000. The largest PC racial/ethnic groups are White (71.1%) followed by Hispanic (19.6%), and Asian (4.5%) (U.S. Census Bureau, 2020). For the same period, the median property value in the city was $1,035,300 and the median home is 2128 square feet in size. Since many properties in the area are for vacation purposes and generally not used year-round, the owner-occupied housing rate is only 63% (U.S. Census Bureau, 2020). According to the U.S. Department of Transportation, most families own two vehicles and individuals drive alone to work, with an average commute time of 18.8 min (Federal Highway Administration, 2017).
2.2. Instrumentation

This study deployed research-grade sensors, which have been shown to be comparable to regulatory grade instrumentation in accuracy and precision (Mendoza et al., 2019), and significantly more robust and reliable than commonly used low-cost or citizen science sensors (Bulot et al., 2020). We installed two Met One Instruments (Met One Instruments Inc., Grants Pass, OR 97526) ES-642 Remote Dust Monitors, with inlet sharp cut cyclones to measure PM$_{2.5}$, with a manufacturer’s stated uncertainty of 1 μg m$^{-3}$ (Met One Instruments, 2013) at both a commercial and residential site in PC.

The two sites are approximately 3.10 km apart and both sensors were installed outdoors. The commercial sensor was located in the city’s “Old Town” neighborhood, one of the busiest areas of the city (Fig. 1a). This site is surrounded by shops, galleries, restaurants, and bars, which mainly serve the local ski and tourism industry. The sensor was installed on top of the KPCW building (Fig. 1a) (40.64400° N, 111.49507° W, 1 Elevation 2156 MASL), and the roof is approximately 7 m above street level. The residential sensor was located at the PC Municipal Athletic & Recreation Center (MARC), which is within an established residential community (Fig. 1b) (40.67196° N, 111.50132° W, Elevation, 2055 MASL). PC is a fairly affluent area and the residential sector has larger lots and homes (Fig. 1b). Due to the mountainous terrain and property layout, on street parking is uncommon in the area.

Both sensor sites were optimally sited to avoid hyper-local influences and chosen for their potential to collect high quality and high frequency data. Data was stored locally by a Raspberry Pi 3 that recorded the incoming serial stream from the ES-642 via RS-232 communications at its native frequency of 10 s. Data was downloaded at monthly intervals and was expected to be used for policy evaluation and research purposes and to encourage efficient and actionable policy making in the short term.

2.3. Study period

This research encompasses the period spanning from February 3, 2020 through July 23, 2020. For our analysis, we break the data from each location into distinct periods identified by key inflection points in the lockdown policy (Table 1). Since, no localized air quality data exists for this area prior to December 2019, the “Pre-lockdown” period effectively serves as a baseline for the study as it captures normal mobility and business activity. The “Lockdown” period was a result of the Governor’s “Stay Safe, Stay Home” directive which started on March 16th and ended on April 30th. The Utah order was considered a partial order, since it was not enforceable under law. However, urban populations, in particular, took the recommendations seriously and a policy response similar to a full lockdown was observed in local traffic count and mobility data (Google LLC, 2021).

As illustrated in Table 1, we maintained a 6-week length uniformity across the study periods. The reopening period was divided into two 6-week phases because the first period (“Easing”) still had several restrictions on business re-openings, while the second phase (“Reopening”) was more representative of a return to a new status quo under the pandemic. Holidays, both federal and state, were excluded from the study and are listed in Table A1, Appendix A. The full study period hourly readings are shown in Fig. 2. Data recovery rates by site, and day of week are shown in Table 1.

While the seasonal effect of transitioning from the coldest part of winter during the Pre-Lockdown period should be taken into consideration, a sensitivity analysis was performed using only the last two weeks (March 2nd-15th, 2020) when meteorological conditions were similar to those experienced during the lockdown period, and the results were highly similar as when examining the full study period (February 3rd – March 15th, 2020). Thus, we chose identical length time periods in order to maintain as much uniformity in data availability as possible.

2.4. Meteorological data

The PC018 meteorological station located at Park City Mountain Resort (40.63207°N, 111.51211°W, Elevation 2483 MASL) is the closest observation site to PC. Temperature, relative humidity, wind speed, and precipitation data was retrieved for this site for the study period from MesoWest (Horel et al., 2002) and analyzed in the same manner as the observed PM$_{2.5}$ to study their potential impact on pollutant observations.

2.5. Data analysis

We aggregated all data to the hourly scale and type of day (e.g., weekdays and weekends). Using the median values for each study period, site, and day type, we compared the diurnal patterns and calculated the percent change across study periods. Finally, we performed t-tests to compare the PM$_{2.5}$ and meteorological variable percent change between study sites across the time periods. All data processing and analysis was done using R Version 3.6.3 software (R Core Team, 2019).

3. Results

3.1. Hypothesis 1: The lockdown period decreased air pollutant concentrations and the Easing and Reopening periods resulted in increased air pollution

During the Lockdown period, we expected overall PM$_{2.5}$ levels to decline, but how did it vary over different periods of the pandemic? Figs. 3 and 4 show the median hourly PM$_{2.5}$ readings for the Commercial and Residential sites, respectively, separated by weekdays and weekends. Because the Commercial site (Fig. 3) is located in the heart of downtown PC, the nightly evening dining and entertainment activity results in elevated pollution between 6pm and midnight in the Pre-lockdown period (blue line, Fig. 3). PC is a high elevation mountain basin which observes nocturnal stable layers that lower the mixing depth of the atmospheric boundary layer during the nighttime, potentially amplifying the observed PM$_{2.5}$ levels between 6pm and midnight.

It is clear that the Lockdown (red dash, Fig. 3) resulted in a marked decrease in pollution and even the Easing phase (grey dash, Fig. 3) did not return PM$_{2.5}$ to Pre-lockdown levels. It is only during the second reopening period when the evening peak starts to appear again, but at a much lower rate. This pattern is similar for both weekdays and weekends. The diurnal pattern of atmospheric stagnation observed, with mixing during the daytime, precludes a large impact of secondary PM$_{2.5}$ in the PC area is given in Section 4.2.

Similarly, Fig. 4 illustrates the Residential site, which shows a comparable decrease from the Pre-lockdown period (blue line, Fig. 4) to the Lockdown (red dash, Fig. 4) and Easing periods (grey dash, Fig. 4) as the Commercial site. A notable feature is the evening peak, starting at 6pm and ending around midnight, during the Pre-lockdown period for both weekdays and weekends. Many homes surrounding the Residential area have wood fireplaces, and on several occasions, while retrieving data at this site, the smell of burning wood was apparent. However, without the use of speciated particulate composition data, it is not possible to be certain that wood burning is directly affecting the signal. Another contributor to the evening pollutant rise is that residents may be returning home after evening activities in the downtown areas or...
outside of PC and this could be capturing vehicular traffic. Although the peak is lower during the weekends, it is a proportionately similar increase over the daylight hour readings as during the week. The reopening period showed a proportionately larger increase in PM$_{2.5}$ readings compared to the Commercial site (Fig. 4).

Table 2 lists the median pollutant concentrations for each of the study time periods measured at each location, disaggregated by type of day (all days, weekdays, and weekends). For the Commercial site, weekends always read lower than weekdays, while this was only true for the Pre-lockdown and Reopening periods at the Residential site. The Commercial site recorded higher values than those observed at the Residential location during the Pre-lockdown and Lockdown periods, but lower values during the subsequent periods.

3.2. Hypothesis 2: The lockdown period affected pollutant levels in commercial and residential areas differently

Table 3 shows the percent differences in median pollutant concentrations recorded by each site across comparison periods by day of week type. All results for weekdays were statistically significant showing that pollution during workdays varied across the time periods. The Lockdown to Easing transition was the least significant in terms of pollutant concentration variability and this can be attributed to a slow recovery from the lockdown. Furthermore, the Residential weekend patterns showed little change from the Pre-lockdown through the Lockdown and Easing time periods, likely due to the residential nature of the neighborhood with little impact on the residents’ behavior.

Table 4 compares the difference in median pollutant concentration change across time periods for the two measurement sites. This analysis aims to clarify whether the Commercial and Residential areas showed different pollutant gradients across time periods when compared. Only three results were found to be statistically significant in this analysis.

The first was the Pre-Lockdown to Lockdown differences during the weekends. Tables 3 and 4 show that the Residential site observed no difference during those two time periods, while the Commercial site showed a drop of 36%. This suggests that the commercial area showed a relevant decline in emissions during the lockdown policy period, but this same impact was not found in the residential area. Therefore, the lockdown policy reduced pollutant concentrations in the commercial area more than the residential one. Another statistically significant difference was during the weekdays for the Lockdown to Reopening time periods. In this case, the Residential site showed a higher rate of pollution increase over the policy periods. This suggests that the residential area had a significant increase in pollution, while the commercial areas did not experience a rebound yet. The last statistically significant difference was during the weekends for the Pre-Lockdown to Reopening periods. For this time period the growth in air pollution at the Residential site was nearly an order of magnitude larger than at the Commercial site. Despite this, overall emissions remained low when aggregated, which could obfuscate these findings and lead to higher-than-expected levels of human exposure.

3.3. Meteorological observations

Analysis of meteorological variables of wind, temperature, and precipitation (Figures B.1-B.7 and Tables B.1-2) show the following

Fig. 1. Location of air quality sensors (yellow circle): a) Commercial and b) Residential. Maps courtesy of Google Maps. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

| Study Period | Dates (2020) | Commercial | Residential |
|--------------|--------------|------------|-------------|
|              | Weekday | Weekend | Weekday | Weekend |
| Pre-Lockdown | Feb. 3 – Mar. 15 | 0 (100%) | 0 (100%) | 0 (100%) | 0 (100%) |
| Lockdown | Mar. 16 – Apr. 26 | 83 (88.47%) | 48 (83.33%) | 83 (88.47%) | 48 (83.33%) |
| Easing | May 1 – Jun. 11 | 63 (91.25%) | 48 (83.33%) | 63 (91.25%) | 48 (83.33%) |
| Reopening | Jun. 12 – Jul. 23 | 0 (100%) | 0 (100%) | 0 (100%) | 0 (100%) |
expected seasonal trends, with increases in air temperatures and decreases in humidity and rainfall as spring transitioned into the summer season. Winds were relatively weak on average throughout the study period (Figures B.3 and B.7). The ability to analyze the impacts of meteorological conditions, as presented in Appendix B, on the variability of pollution during this study is limited by a lack of vertical profiles of temperature (and hence stability) and winds (transport).

4. Discussion

4.1. Findings

Under the Lockdown, we expect overall emissions to decline and that did occur in the Commercial area consistently across all periods of the study. Even by the end of the study period, emissions levels have not returned to pre-pandemic levels. In contrast, the Residential area showed this effect in the earlier stages of the pandemic only. With the exception of weekday evenings, which are highly regulated by bar and restaurant curfews, the residential areas only showed a decline in

Fig. 2. Hourly PM$_{2.5}$ readings for the a) Commercial and b) Residential sites for the full study period, showing individual time periods.
emissions in the Lockdown and Easing periods but have already returned to Pre-lockdown emissions levels. Although meteorological conditions may have an effect on the observed decrease during the Lockdown period, a return to Pre-Lockdown levels during the Reopening period shows that the impact of climatic variables is second-order in comparison to changes in emissions, as warming summertime temperatures and weaker nocturnal inversions in the summertime would have resulted in lower Reopening period air pollution levels if meteorological factors were dominant (Section 4.2). In addition to differences between the Commercial and Residential sites across the policy periods, we found statistically significant differences by hour between the locations. This suggests daily differences in emissions peaks between commercial and residential areas. Finally, these findings demonstrated changing patterns across the study periods within each site. Thus, as a result of changing human behavior, emissions peaks and valleys were quantitatively different for the commercial and residential sites across and within similar time periods and this varied uniquely for commercial and residential locations. These findings suggest some key implications.

4.2. Meteorology

While the impact of meteorology cannot be quantified using limited observations, the sudden changes in air pollution observed between the adjacent study periods are clearly due to changes in emissions, as
son and result in pollution accumulating in a deep stable layer, such as over a valley, an adjacent basin at a similar elevation just to the south of PC, the shallow boundary-layers that form in elevated mountain basins such as the PC or SLV. In addition, a notable increase in PM$_{2.5}$ was observed during the summertime reopening period. If meteorological forcing were a large factor, the increases in PM$_{2.5}$ signatures observed during the reopening period during the summer of 2021 would have been less.

The diurnal cold air pools observed in PC also are expected to result in less secondary PM$_{2.5}$ formation than observed in the persistent cold-air pools that dominate lower elevation basins. In the adjacent SLV, it has been found that secondary PM$_{2.5}$, mainly in the form of ammonium nitrate (Kuprov et al., 2014), is the dominant fine particulate species, whereas during the non-inversion (stagnation) periods, the relative amount of secondary PM$_{2.5}$ (ammonium nitrate) to primary fine particulate pollution was about half that observed during stagnation periods. Thus, because of a lack of extended persistent cold-air pool stagnation episodes at this high elevation location, we hypothesize that secondary PM$_{2.5}$ species are likely not dominant in the PC area, but actual measurements would be needed to verify this hypothesis.

### 4.3. Implications

The notion that our day-to-day behavior has changed due to the pandemic, and this in turn has caused a corresponding change in the spatial distribution of pollutants, suggests a range of implications. First, it is widely accepted that cities have consequential emissions exposure effects that vary distinctly by neighborhood, but emissions reporting is generally aggregated to the city level (Giani et al., 2020). Nuances, like those presented here, can be missed as a result. In addition, due to the cost of research grade instrumentation, much of the research in this area uses modeling and estimation techniques to report emissions levels. While this is a useful, cost saving technique for monitoring and research purposes, changing pollution patterns in larger downturn events requires increased granularity due to the foundational nature of this work. For instance, if residential areas continue to have higher levels of pollution exposure following the pandemic, policy will need to be designed to adapt to this changing profile of human pollution exposure, which could be consequential. Such findings are highly relevant to researchers and policy makers alike due to the potential public health related impacts from increased pollution exposure, especially since minorities and low income communities are already disproportionately impacted by these effects (Bell and Ebisu, 2012). Calls for direct, high-quality air quality measurement could be warranted as a result.

Second, this research has implications for energy policy at all levels of governance. At the local level, research on changing air pollution patterns is necessary for a variety of reasons. It is needed to understand whether PM$_{2.5}$ concentrations reach levels of concern for residents, workers, and tourists, each with their particular social, economic, political consequences. Therefore, this research may have relevant implications for mapping local emissions exposure and resulting human health impacts. At the state and national level, these findings also have implications for energy policy at all levels of governance.

### Table 2

| Time Period       | Commercial | Residential |
|-------------------|------------|------------|
|                   | Weekdays   | Weekends   |
|                   | Weekdays   | Weekends   |
| Pre-lockdown      | 2.40       | 1.95       | 2.35       | 1.40       |
| (1.85–3.25)       | (1.35–2.30)| (1.80–3.15)| (0.95–2.40)|            |
| Lockdown          | 1.30       | 1.30       | 1.23       | 1.33       |
| (1.05–1.70)       | (0.90–2.15)| (1.00–1.55)| (1.05–2.00)|            |
| Easing            | 1.38       | 1.13       | 1.40       | 1.58       |
| (1.10–2.05)       | (0.80–1.90)| (1.00–1.95)| (0.50–2.60)|            |
| Reopening         | 2.20       | 2.13       | 2.30       | 2.20       |
| (1.50–2.80)       | (1.20–3.00)| (1.55–3.10)| (1.00–4.75)|            |

### Table 3

| Time Period       | Commercial | Residential |
|-------------------|------------|------------|
|                   | Weekdays   | Weekends   |
|                   | Weekdays   | Weekends   |
| Pre-Lockdown to   | 47         | 36         | 49         | 0          |
| Lockdown          | (8.24e-05)| (4.78e-04)| (8.86e-05)| (6.655)    |
| Lockdown to       | 12         | 8          | 13         | 2          |
| Easing            | (2.36e-02)*| (0.568)    | (2.67e-02)*| (0.908)    |
| Lockdown to       | 70         | 70         | 65         | 67         |
| Reopening         | (1.17e-09)| (3.00e-08)| (2.31e-11)| (6.31e-08)|            |
| Pre-Lockdown to   | 6          | 8          | 7          | 67         |
| Reopening         | (5.42e-02)| (0.441)    | (0.140)    | (1.35e-09)|            |

### Table 4

| Time Period       | Commercial vs. Residential |
|-------------------|---------------------------|
|                   | Weekdays | Weekends |
| Pre-lockdown to   | 0.846    | 2.09e-08***|
| Lockdown to       | 0.716    | 0.216    |
| Easing            | 2.27e-02*| 0.241    |
| Reopening         | 0.266    | 2.75e-07***|
policies will increasingly be valued for the role they play in the low-carbon transition process, but will be plagued with technical, political, and economic challenges that will lead to uncertainty. Subsequently, academics and policy makers alike must develop the necessary skills to monitor, evaluate, and take action to resolve these concerns if policy solutions are to be robust and take a range of scenarios into consideration. Where cutting edge research is incorporated into policy and planning around energy, greater resiliency and cost savings will likely result. However, outdated, estimated, or aggregated information about baseline emissions patterns could also lead to policies that are ineffective, costly, and less resilient.

4.4. Limitations

This research has four primary limitations. The first is that during the Lockdown period, street traffic in residential areas was not completely eliminated, while the downtown area of Old Town (Commercial) was mostly closed down and street traffic was nearly non-existent. While we are unable to account for this variation, overall, emissions associated with transportation were significantly reduced in both locations.

The second limitation of this study is that no detailed meteorological observations exist to analyze during this study in the area of interest. However, we discussed in Section 4.2 why atmospheric variability had a second-order impact on the study outcomes. The frequency of wood burning may have changed due to temperature and weather patterns, rather than the Lockdown, but accounting for this was beyond the scope of this study.

A third limitation of this work is that the changing patterns in human behavior found in this study are only assumed, they are not measured directly. Thus, assumptions about human behaviors and their role in changing particulate matter concentration during the different periods pre- and post-lockdown will need to be confirmed and additional research in this area will be required to confirm these findings.

The fourth limitation of this work is that seasonality effects caused particulate matter levels in PC to naturally decrease over the course of the study period. Thus, there is a possibility that the later study periods would naturally have lower pollutant levels. Despite these limitations, this research should be considered novel for tracing the general patterns at greater levels of granularity to see what forms actually emerge. These findings should be considered foundational and future research will be needed to identify the impacts of increased residential building use in future energy scenarios – either during low carbon transitions or in climate resiliency planning.

4.5. Future research

Understanding the impact of human behavior on local emissions patterns is of growing interest and real time measurement using research grade sensors has proved to be a valuable tool for studying this phenomenon. Despite this, further research on how air quality measurements can contribute to our understanding of human health and well-being are still needed. For example, this study focused on PM$_{2.5}$ but ozone is also a significant concern in PC (Arens and Harper, 2012) and other key emissions may also matter. Research to untangle the meteorological effects of diurnal cold air pools on seasonal trends in pollution in areas such as PC is a suggested topic of future work. In addition, building the capacity and the baseline detail to map the changing pollution landscape across a range of urban context is essential as people from all industries work increasingly from home. Future research is essential in this area to map a more complete range of urban settings. Finally, making progress in this area will require more than just technical advancements. Better strategies are also needed to affect behavior. This might include research on policies that ensure safer shared mobility, higher adoption of telecommuting, automation in the freight sector, and cleaner energy transition (Pan et al., 2020).

5. Conclusions

As this research has illustrated, the dramatic dip in emissions caused by disruptions in human behavior around work, transportation, and leisure time activities, along with the rare nature of pollution downturn events, means that less is understood about how such events change the composition of air quality in a local setting or if such changes have important policy implications over the long-term. To address this, we studied how local PM$_{2.5}$ was impacted during pollution downturn events in a residential and commercial settings. By using the lockdown policy of the COVID-19 pandemic as a natural experiment, we traced the changing emissions patterns produced during the pandemic in a secluded, mid-sized city. Based on these efforts, we found patterns of change in human behavior and a corresponding change in the spatial distribution of pollutants that resulted in an effort to isolate the direct effects of human behavior on air pollution patterns.

We tracked pollutant concentrations over varying periods using high quality, research grade sensors to compare patterns found before, during, and after the lockdown period using direct measurements. The goal here was to compare pollutant levels in both commercial and residential settings over similar time periods of the pandemic to better understand how each setting may be uniquely impacted by pollution downturn events. Under the Lockdown period, PM$_{2.5}$ pollution declined in both residential and commercial areas of the city. The commercial area showed a greater decrease of air pollution than residential but experienced a similar rebound post lockdown. The restriction easing period did not lead to an immediate rebound in human activity and the pollution increase, associated with reopening, took place nearly two months after the lockdown period ended. These findings illustrate the usefulness of this approach and help show how energy policy may be impacted by the ongoing changes caused by the global pandemic, changing work patterns, and a global economic downturn in combination. As a result, this research has implications for climate policy, low-carbon energy transitions, and may even impact local policy due to changing patterns in human exposure that could lead to important public health outcomes, if left unaddressed.

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Credit author statement

Daniel L. Mendoza: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Resources, Data Curation, Writing – Original Draft, Writing – Review & Editing, Visualization, Funding Acquisition. Tabitha M. Benney: Conceptualization, Methodology, Formal analysis, Writing – Original Draft, Writing – Review & Editing. Ryan Bares: Methodology, Validation, Writing – Original Draft, Writing – Review & Editing. Erik T. Crosman: Methodology, Validation, Writing – Original Draft, Writing – Review & Editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A

Table A.1
Excluded days from the study due to being federal or state holidays.

| Excluded Holidays                        | Date(s)                      | Study Period  |
|------------------------------------------|------------------------------|---------------|
| Washington and Lincoln Birthday          | February 17, 2020 (Monday)   | Pre-Lockdown  |
| Memorial Day                             | May 25, 2020 (Monday)        | Easing        |
| Fourth of July (weekend)                 | July 3–5, 2020 (Friday-Sunday)| Reopening     |

Appendix B

Table B.1
Median meteorological values for each time period.

| Time Period      | Temperature (°C) | Relative Humidity (%) | Wind Speed (m/s) |
|------------------|------------------|-----------------------|------------------|
| Pre-Lockdown     | -3.11            | 62.55                 | 1.24             |
| Lockdown         | 0.30             | 60.71                 | 1.41             |
| Easing           | 8.52             | 43.14                 | 1.71             |
| Reopening        | 16.94            | 33.74                 | 1.33             |

Table B.2
Percent difference (%) in median meteorological values for each comparison time period with p-value in parentheses. For statistically significant results: * = p ≤ 0.05; ** = p ≤ 0.001.

| Time Period                  | Temperature | Relative Humidity | Wind Speed |
|------------------------------|-------------|-------------------|------------|
| Pre-Lockdown to Lockdown     | 1 (2.03e-10)*** | -6 (6.72e-02)     | 13 (5.44e-02) |
| Lockdown to Easing           | 3 (1.80e-17)*** | -30 (4.40e-11)*** | 26 (3.19e-02)* |
| Lockdown to Reopening        | 6 (2.53e-27)*** | -46 (8.68e-18)*** | 1 (0.900)    |
| Pre-Lockdown to Reopening    | 8 (9.32e-25)*** | -47 (2.26e-27)*** | 16 (0.123)   |

Fig. B.1. Time Series of 2-m air temperature at the PC018 meteorological site located at Park City Mountain Resort. Location 40.63207 N, 111.51211 W, Elevation 2483 MASL.
Fig. B.2. Time Series of 2-m relative humidity at the PC018 meteorological site located at Park City Mountain Resort. Location 40.63207 N, 111.51211 W, Elevation 2483 MASL.

Fig. B.3. Time Series of 10-m wind speed (m s\(^{-1}\)) at the PC018 meteorological site located at Park City Mountain Resort. Location 40.63207 N, 111.51211 W, Elevation 2483 MASL.

Fig. B.4. Time Series of daily precipitation (mm) at the PC018 meteorological site located at Park City Mountain Resort. Location 40.63207 N, 111.51211 W, Elevation 2483 MASL.
Fig. B.5. Mean diurnal temperatures at the PC018 meteorological site located at Park City Mountain Resort for the 4 study periods. Location 40.63207 N, 111.51211 W, Elevation 2483 MASL.

Fig. B.6. Mean diurnal relative humidity at the PC018 meteorological site located at Park City Mountain Resort for the 4 study periods. Location 40.63207 N, 111.51211 W, Elevation 2483 MASL.
Fig. B.7. Mean diurnal wind speed at the PC018 meteorological site located at Park City Mountain Resort for the 4 study periods. Location 40.63207 N, 111.51211 W, Elevation 2483 MASL.

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