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Effect of COVID-19 travel restrictions on Phoenix air quality after accounting for boundary layer variations

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ABSTRACT

Due to the global response to the COVID-19 pandemic, there have been a variety of policy responses that have produced a range of expected and unexpected effects on society and our surrounding environment. One widely reported result of the pandemic response is that travel restrictions have resulted in improvements in regional air quality. This study aims to determine the effect of COVID-19 related Stay at Home precautions on air quality in a metropolitan area. We specifically focus on CO, NO_2, and PM_{10} in Maricopa County (Phoenix), Arizona, as these all contribute to local air quality concerns. The role of meteorological parameters on ambient concentrations for these pollutants was investigated by using the local planetary boundary layer height (PBH) to account for vertical mixing. Across all three sites studied, there was no uniform decrease in either CO or NO_2, even when freeway traffic volume was down by ~35%. For PM_{10}, there was a significant decrease of ~45% seen at all the sites for the period most directly impacted by local Stay at Home restrictions compared to the past two years. This indicates that different pollutants have fundamentally different behavior in the local environment and suggests that these pollutants originate from different sources.

1. Introduction

In response to the 2020 COVID-19 outbreak, the state of Arizona issued a Public Health State of Emergency on March 11th, 2020 and over the following two weeks, closed down schools, canceled gatherings of ten or more people, mandated reduced business hours, and closed dine-in restaurants, culminating with a Stay at Home Order on March 31st (Ducey, 2020). During this first month of response to the COVID-19 pandemic, average weekly traffic volume in the Phoenix metropolitan area (Maricopa County) decreased by 35% and the miles traveled per person in Maricopa Country decreased by 31% (Zhang et al., 2020; MAG, 2020). Various local media outlets came to the conclusion that air quality was dramatically improved due to this reduction in travel demand with small caveats included, saying other factors could be causing the improvement (Whitman, 2020; Stone, 2020). Past mobile emissions investigations have studied the effect of taxi strikes and odd-even car trials on air quality, but these were on a limited spatial and temporal scale (Kumar et al., 2017; Norbeck et al., 1979). COVID-19 related Stay at Home order alterations of local mobile emission sources present a unique chance to elucidate how changes in anthropogenic emissions impact local air pollution.

This study focuses on three air pollutants, carbon monoxide (CO), nitrogen dioxide (NO_2), and particulate matter with an aerodynamic diameter ≤ 10 µm (PM_{10}). Both CO and NO_2 are precursors to ozone, for which Maricopa County is designated as a non-attainment area per the EPA (MCAQD, 2017a). Another danger of CO is that high concentrations in confined locations can lead to CO poisoning (Transportation Research Board and National Research Council, 2002). Additionally, Maricopa County is designated as an EPA non-attainment area for PM_{10}, which can cause lung damage among other adverse health effects when inhaled (MCAQD, 2017b). With the documented decrease in motor vehicles on the road, one would also expect to see a decrease in these pollutants as on-road mobile sources, such as passenger cars and trucks, account for 56% of Maricopa County CO emissions, 51% of Maricopa County NO_x emissions, and 34% of Maricopa County PM_{10} emissions. While mobile source emissions all contribute to some degree to the local air pollutant concentrations, the three pollutants are all produced in different ways. CO and NO_x are tailpipe emissions produced by incomplete combustion products and high temperature oxidation of atmospheric nitrogen, while PM_{10} is a combination of car wear, exhaust, and entrained road dust (Wallington et al., 2006). In fact, several recent studies have already observed reductions in pollutants in various parts of the world as an

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unintended result of their COVID-19 responses (Tanzer-Gruener et al., 2020; Zhao et al., 2020; Mohd Nadzir et al., 2020; Xu et al., 2020a, 2020b; Le et al., 2020).

However, when comparing pollutant levels from differing time periods, the impact of other influences must also be considered. Many of these pollutants experience seasonal variation throughout the year due to changing meteorological patterns as well as changing flux from natural sources (Antony Chen et al., 2001; Jain et al., 2020). Other recent studies have accounted for this seasonal variation by using a temporally-corrected historical median as their baseline value (Bekbulat et al., 2020). This study will evaluate how these pollutants are affected by meteorology, specifically the planetary boundary layer height (PBH). By normalizing for meteorological effects, a more accurate comparison between different time periods, such as before and during COVID-19 travel restrictions, will be used to evaluate the role of anthropogenic emissions on ambient air quality.

2. Methods

2.1. Pollutant data

Hourly monitoring values of three pollutants, CO, NO_2, and PM_{10}, were obtained from the Maricopa County Department of Air Quality (MCDAQ) for the past three years from their Central Phoenix (ID: 040133002), West Phoenix (ID: 040130019), and Buckeye (ID: 040134011) sites, see Fig. 1. It should be noted that the 2020 data was obtained prior to the county's quality review. These sites were chosen because of their diverse locations representing urban core, suburban, and upwind rural monitoring locations, respectively. This raw data was then compiled into 24-h averages and divided into two time-frames, January 6th to March 6th, corresponding to the time before Arizona was significantly affected by COVID-19, and March 13th to April 8th, corresponding to the Public Health State of Emergency order initiated by the State of Arizona referred to as the pre-Stay at Home (pre-SAH) and Stay at Home (SAH) periods, respectively (Ducey, 2020). Data from 2020 during these time frames was compared to data from the same periods during 2019 and 2018 and analyzed for statistical significance (one-sided $p < 0.05$) using the Mann-Whitney U test assuming a normal approximation since $n > 20$. Emission inventory data for CO, NO_x, and PM_{10} was compiled from the MCDAQ 2017 Ozone and PM_{10} Periodic Emissions Inventory reports (MCDAQ, 2017a, MCDAQ, 2017b).

2.2. Planetary boundary layer height data

Planetary boundary layer height data from 2018 to 2020 was obtained from ERA5 Reanalysis hourly data downloaded from Copernicus Climate Change Service (CS3) (Copernicus Climate Change, 2020). Integrated Data Viewer (IDV) software from UCAR/Unidata was then used to convert the data file type and to select specific data corresponding to the air quality station locations with a resolution of $0.25° \times 0.25°$. This data was then compiled into 24-h averages for analysis.

3. Results

While pollutant levels are certainly impacted by anthropogenic emissions, they are also influenced by meteorological parameters such as horizontal wind speed, temperature, precipitation, and PBH (Miao and Liu, 2019; Wang et al., 2018). However, of these parameters, horizontal wind speed and PBH have the most direct influence on pollutant mixing, affecting their vertical and horizontal distribution. For this study, a linear regression model was used to show the effects of PBH and horizontal wind speed on pollutant levels as seen in Fig. 2 and S1 correlation plots. Although both PBH and horizontal wind speed are significantly correlated with CO concentration, the PBH already accounts for horizontal wind speed in its determination. As a result, PBH is more determinant on ambient CO and NO_2 levels than horizontal wind speed. Alternative meteorological factors were not considered because the PBH from the ERA5 reanalysis is calculated using parameters such as horizontal wind speed, temperature, and specific humidity.

In the Northern Hemisphere, the PBH experiences an annual cycle of increasing for the first half of the year, reaching a peak in June/July and then decreasing for the second half of the year, as a result of increasing solar radiation reaching the surface (Pal and Haeffelin, 2015; Seidel et al., 2012). This seasonality is evident at the Central Phoenix site as the PBH during the pre-SAH period (300 ± 200 m) is lower in 2020 compared to the SAH period (700 ± 200 m) ($p = 1.8 \cdot 10^{-8}$) as seen in Fig. 3. This trend is also present at the West Phoenix and Buckeye sites as seen in Figs. S2 and S3.

When looking at the year-to-year variation, the Central Phoenix PBH from 2020 (500 ± 300 m) is not significantly different from 2019 (600 ± 400 m) ($p = 0.19$) and 2018 (600 ± 300 m) ($p = 0.058$). This same trend is seen at the other two sites. Although there does not appear to be an annual variation in PBH, the seasonal variation in PBH affects the vertical mixing of all pollutants released to the atmosphere and will influence their measured concentration at ground surface level. When looking at the correlation coefficients between the pollutants' levels and

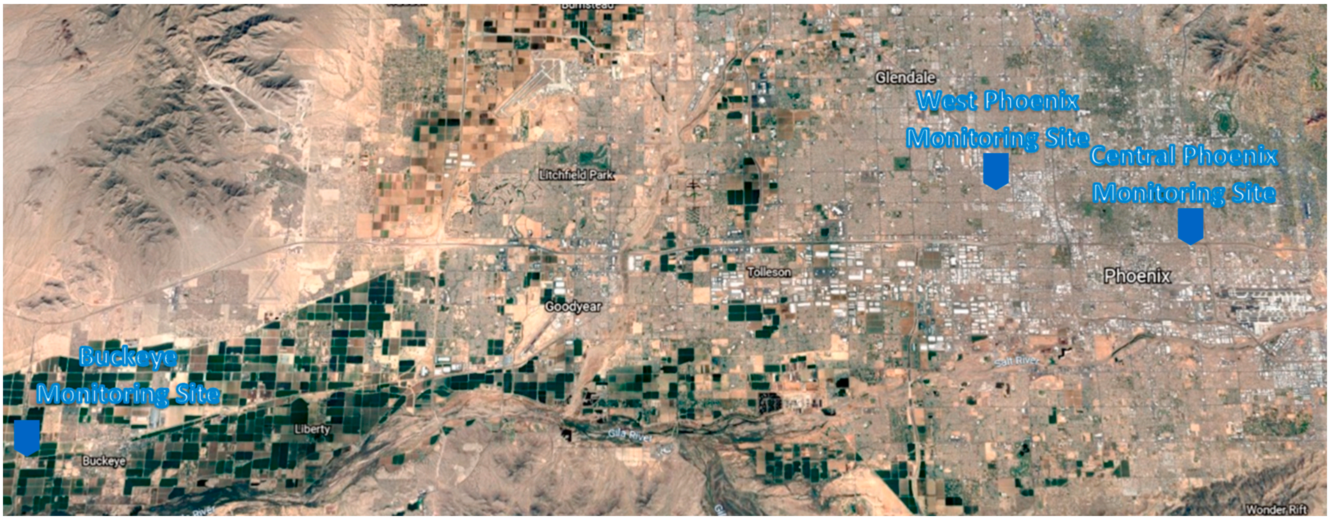

Fig. 1. Map of the Phoenix metropolitan area showing the MCDAQ Air Monitoring Stations for Central Phoenix, West Phoenix, and Buckeye.

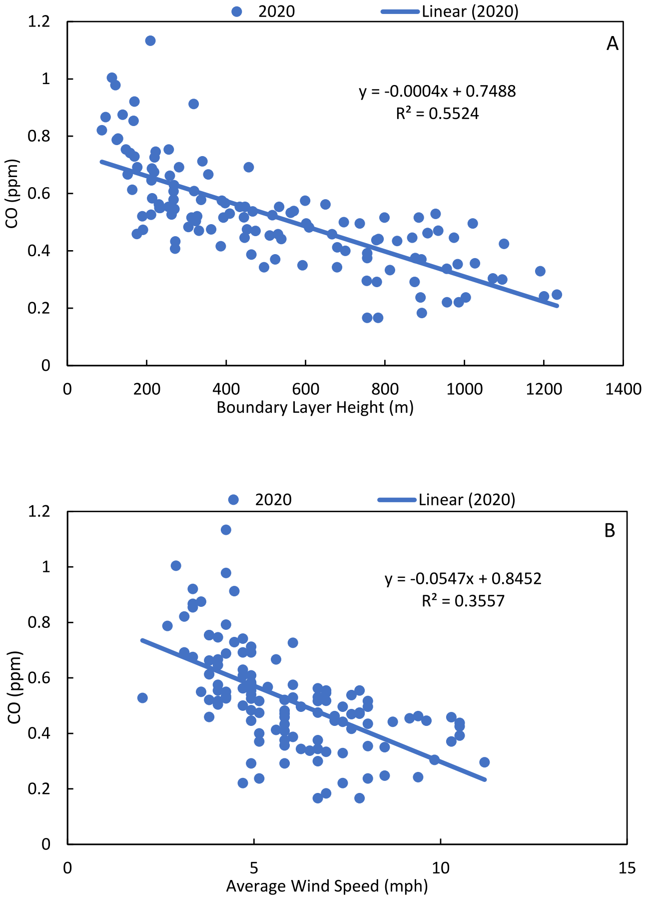

Fig. 2. CO concentrations from the Central Phoenix site plotted against planetary boundary layer height (A) and average wind speed taken at Phoenix Sky Harbor Airport (B). For 2020 the correlation coefficient between CO and PBH is -0.74 ($p = 1{\cdot}10^{-23}$) and between CO and wind speed it is -0.60 ($p = 1{\cdot}10^{-13}$).

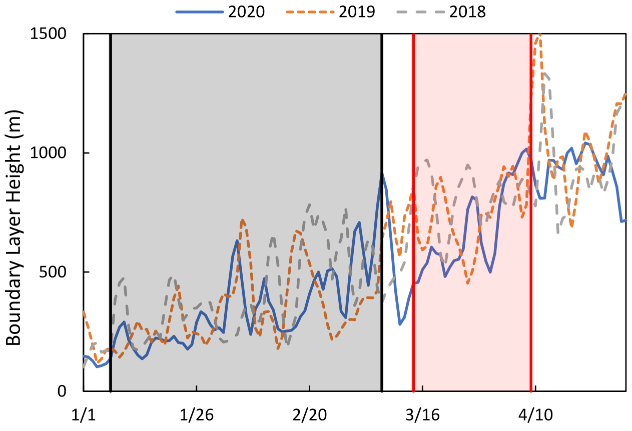

Fig. 3. Central Phoenix boundary layer height for 2020, 2019, and 2018. The gray shaded area represents the pre-SAH period and the red shaded area represents the SAH period. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

PBH at Central Phoenix in 2020, CO and NO_2 had significant correlation coefficients of -0.74 ($p = 1{\cdot}10^{-23}$) and -0.70 ($p = 3{\cdot}10^{-20}$) respectively, while PM_{10} and PBH were not significantly correlated. Therefore, when comparing pollutant levels of different time periods, the CO and NO_2 concentrations were normalized to the PBH by dividing concentration by PBH. The effects of this normalization on CO and NO_2 for Central Phoenix are seen in Fig. 4, while the unaltered PM_{10} can be found in Fig. S4.

With a decrease in traffic volume during the 2020 SAH period, one would expect a corresponding decrease in pollutant emissions. However, when boundary layer height is considered, there was no significant decrease in CO for all three sites during the SAH period compared to the past two years. The average daily CO normalized concentrations for Buckeye, West Phoenix, and Central Phoenix for the 2020 pre-SAH period were higher than those from the 2020 SAH period, as seen in Table 1, S1, and S2. Looking at these numbers, it appears that the PBH normalized CO concentration did decrease during the SAH period relative to the pre-SAH period in 2020; however, when compared to the same period for the past two years this trend is also present, as seen in Figs. 4C and 5A. Compared to 2019, the 2020 normalized CO concentration during the SAH period decreased by 3.1% and 3.5% for West Phoenix and Buckeye, and significantly increased by 58% for Central Phoenix. Compared to 2018, the 2020 normalized CO concentration during the SAH increased by 15% for West Phoenix, decreased by 8.4% for Buckeye, and significantly increased by 58% for Central Phoenix.

When analyzing the NO_2 concentrations normalized by boundary layer height, only West Phoenix experienced a significant decrease during the SAH period in 2020 compared to 2019; however, that same improvement in air quality was not observed relative to 2018. The average daily NO_2 normalized concentrations for Buckeye, West Phoenix, and Central Phoenix for the 2020 pre-SAH period were higher than those from the 2020 SAH period, as seen in Table 1, S1, and S2. While the normalized NO_2 concentrations during the SAH period do decrease compared to the pre-SAH period, this same trend is also observed in 2019 and 2018 as shown in Figs. 4B and 5B. Comparing the 2020 SAH period to the 2019 SAH period, the normalized NO_2 concentration at Buckeye decreased by 12%, significantly decreased at West Phoenix by 31%, and decreased by 15% at Central Phoenix. Looking at the 2018 SAH period, Buckeye normalized NO_2 decreased by 9.5%, West Phoenix by 28%, and Central Phoenix by 5.8%. While the normalized NO_2 during the 2020 SAH period is lower than prior years it is not a significant difference, except for West Phoenix compared to 2019.

PM_{10} presents a different story, as all sites experienced a significant decrease during the 2020 SAH period compared to prior years, shown in Table 1, S1, and S2. Compared to the 2019 SAH period, the 2020 Buckeye SAH period experienced a significant decrease of 39%, West Phoenix a significant decrease of 36%, and Central Phoenix a significant decrease of 34%. Compared to the 2018 SAH period, the 2020 Buckeye SAH period experienced a significant decrease of 62%, West Phoenix a significant decrease of 62%, and Central Phoenix a significant decrease of 40%. These decreases are unique for the 2020 SAH period compared to the 2019 pre-SAH and greater than the decreases observed in the 2018 pre-SAH period. Looking at Fig. 5C, 2020 is the only year where a decrease in PM_{10} is present at all three sites. Additionally, this decrease from pre-SAH to SAH is larger than the previous two years across all sites.

4. Discussion

The presented results were further analyzed to determine whether the observations were related to the COVID-19 shutdown or other events. The increase in normalized CO for Central Phoenix in 2020 compared to 2019 and 2018 does not appear to be related to COVID-19 associated events, as this increase was also present in the pre-SAH period, which can be seen in Fig. 4C. While reported freeway traffic volume did decrease in Maricopa County, ambient air quality data shows no significant corresponding decrease in CO unique to 2020 at the Central Phoenix site (MAG, 2020). Additionally, no other local site or pollutant experienced such an increase compared to 2019 during both the pre-SAH and SAH period, suggesting that the CO is a result of a

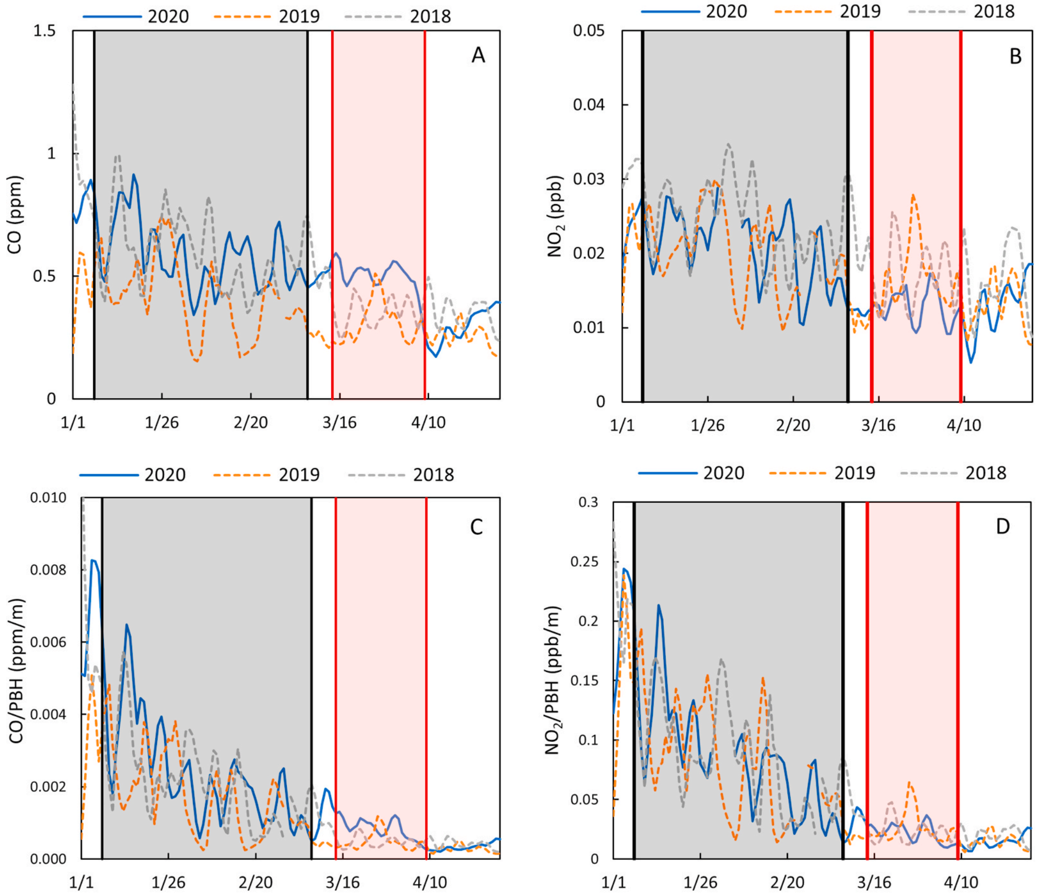

Fig. 4. Central Phoenix CO and NO_2 concentrations (A & B) and CO and NO_2 concentrations adjusted for boundary layer height (C & D) for 2020, 2019, and 2018. The gray shaded area represents the pre-SAH period and the red shaded area represents the SAH period. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 1
Central Phoenix mean and range of daily pollutant concentrations during the pre-SAH and SAH time periods for 2020, 2019, and 2018.

		Pre-SAH			SAH		
		CO/BLH (ppm/m)	NO_2/BLH (ppb/m)	PM_{10} (μg/m^3)	CO/BLH (ppm/m)	NO_2/BLH (ppb/m)	PM_{10} (μg/m^3)
2020	Mean	0.0025	0.088	29.3	0.0009	0.022	21.3
	Range	0.0004–0.0090	0.011–0.284	7.1–79.9	0.0003–0.0017	0.006–0.050	6.9–35.6
2019	Mean	0.0018	0.0849	25.2	0.0005	0.026	30.0
	Range	0.0001–0.0077	0.008–0.274	6.6–48.9	0.0001–0.0017	0.005–0.091	13.4–54.0
2018	Mean	0.0022	0.088	34.8	0.0005	0.024	32.0
	Range	0.0002–0.0060	0.009–0.284	10.5–118.5	0.0002–0.0011	0.006–0.057	16.7–47.4

localized emission source that does not emit excessive amounts of NO_2 or PM_{10}. Local emission inventories (MCDAQ, 2017a, MCDAQ, 2017b) were used to determine what types of sources with high CO:NO_x:PM_{10} ratios existed besides traditional mobile sources. Sources of CO not expected in urban settings, such as wildfires and recreational vehicles, were ruled out with the remaining options including commercial non-road mobile sources, and lawn and garden non-road mobile sources. During the 2020 Pre-SAH period CO levels at West Phoenix were significantly lower than 2019 and 2018 but then return to the historical levels during the SAH period. However, the 2020 CO decrease from pre-SAH to SAH at the site remains on par with the decreases seen in 2019 and 2018 as demonstrated in Fig. 5A.

Compared to the Central Phoenix and Buckeye sites, which are near major roadways that serve as part of the regional transportation network, the West Phoenix site is a residential area that perhaps saw a greater decrease in large diesel vehicle traffic relative to sites closer to major roadways. This could explain why a decrease in NO_2 was observed but no significant decrease in CO, as diesel trucks account for 21% of Maricopa County's NO_x emissions but only 6% of its CO emissions. While the West Phoenix site did experience a significant decrease in NO_2, there was no decrease at the other two sites. This is consistent with the contribution of diesel vehicles, traveling on major transportation corridors, to ambient NO_2 levels as the average weekday heavy truck volume for Maricopa County freeways only decreased by 5% during the SAH period (MAG, 2020).

Looking at the overall NO_2 and CO trends, a large decrease in these pollutants unique to COVID-19 across all 3 sites was not detected. One possible explanation is that while the local community did decrease work related travel (decrease of 24% during SAH compared to pre-SAH), the decrease in non-work trips (decrease of 13%), such as trips to the grocery store, was not as large (Zhang et al., 2020). This is consistent with the observed trend in air quality, reflecting that while the freeway

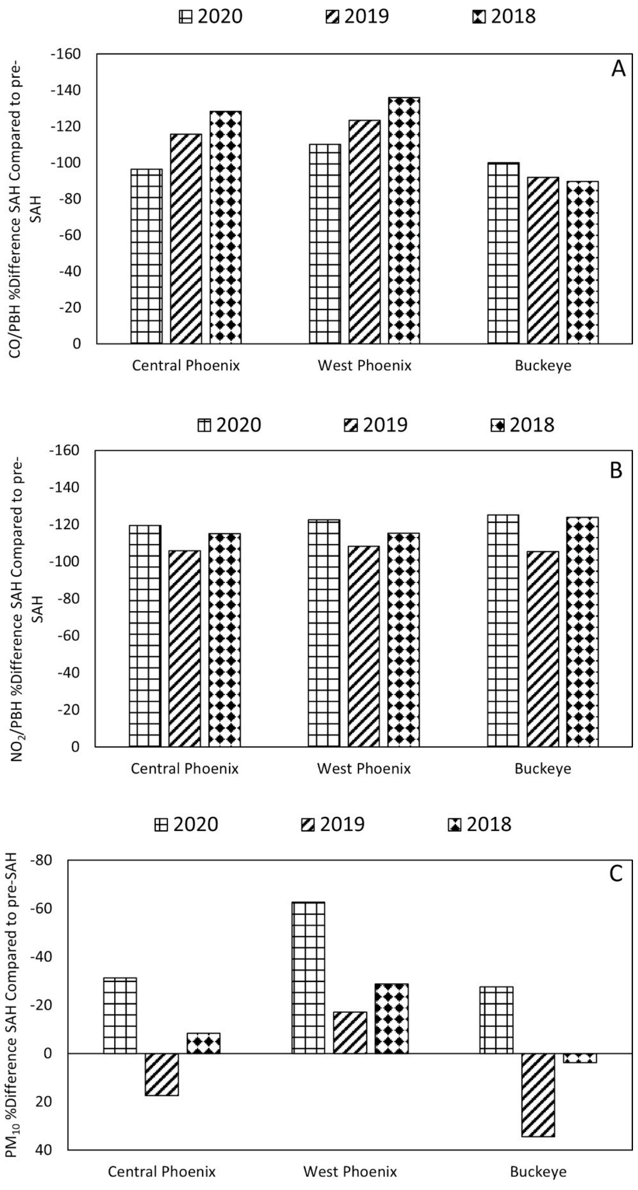

Fig. 5. Percent difference of the SAH period compared to pre-SAH normalized CO (A), normalized NO_2 (B), and PM_{10} (C) for 2020, 2019, and 2018 for all three sites.

traffic volume was down because people were not traveling long distances to work, they were still using their cars for shorter distance local trips. Therefore, people were still starting their cars which contributes to NO_x and CO emissions as the catalytic converter is at lowest efficiency when starting (Xue and Ho, 2000). Furthermore, NO_x and CO emissions from ignition, idling, and street driving account for more than double the emissions coming from interstates and highways (MCAQD, 2017a). Our data indicates that while some traffic did decrease, there was not a uniform decrease across all traffic trips that might have resulted in significantly lower CO or NO_2 concentrations city-wide.

However, a different trend was observed with PM_{10} as it has slightly different emission sources than CO and NO_2. With 2020 PM_{10} concentrations at all three sites decreasing significantly compared to prior years for the SAH period, this points to a regional decrease in a major emission source for PM_{10}. Additionally, compared to the past two years 2020 was the only year where all three sites experienced a significant decrease in PM_{10} during the SAH period compared to the pre-SAH period. Compared to 2019, the 2020 daily average PM_{10} concentration across all three sites decreased by ~36% and by ~55% compared to 2018. On-road mobile PM_{10} emissions are a combination of tire and brake wear, exhaust, and re-entrained road dust that is more related to the number of miles traveled, as opposed to CO and NO_2 which are more related to automobile tailpipes and startup. With on-road mobile sources accounting for 34% of Maricopa County's PM_{10} emissions and the county experiencing a 35% decrease in traffic volume and a 31% decrease in miles per person during the SAH period, it appears that COVID-19 travel restrictions are the primary driver to significantly lower PM_{10} concentrations (MCDAQ, 2017b; MAG, 2020). This conclusion highlights the importance of utilizing several sites to determine whether changes in air quality are due to local or regional impacting factors.

5. Conclusion

Local responses to the global COVID-19 pandemic have provided a unique opportunity for the study of significant anthropogenic upheaval on air quality. As a result of the Stay at Home order, Maricopa County freeways experienced a significant decrease in traffic volume; however, there was no corresponding consensus decrease seen in CO and NO_2 after accounting for PBH at the three sites compared to the past two years. In fact, there was a significant increase in CO at the Central Phoenix site compared to 2019 that does not appear to be associated with COVID-19 related events. There was a significant decrease observed in PM_{10} at all the sites. These findings imply that decreases in freeway travel do not necessarily imply decreases in tailpipe emissions, as people are still traveling on local roadways during the Stay at Home order. Applied more generally, these results demonstrate the need to account for annual variations in mixing by using the planetary boundary layer height when examining year to year changes in pollutant levels. By examining several local sites, we were able to show the air quality disparity that exists at a small scale and the importance of local emission sources. Therefore, even when there are less global and regional emissions, specific areas could still be experiencing normal or increased pollutant levels.

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. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.aeaoa.2021.100105.

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