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Key Points:
- SoCAB maximum 1-hr NO_x and 24-hr $PM_{2.5}$ concentrations decreased 27% and 29%, respectively, between 19 March and 30 June of 2015–2019 and 2020
- The 8-hr daily maximum O_3 showed inconsistent changes across the basin during the COVID-19 associated decrease of atmospheric NO_x concentrations
- During a shift to a NO_x-limited regime, a better understanding of VOC emission sources is needed to improve air quality in the SoCAB

Supporting Information:
- Supporting Information S1

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Impacts of Traffic Reductions Associated With COVID-19 on Southern California Air Quality

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Abstract On 19 March 2020, California put in place Stay-At-Home orders to reduce the spread of SARS-CoV-2. As a result, decreases up to 50% in traffic occurred across the South Coast Air Basin (SoCAB). We report that, compared to the 19 March to 30 June period of the last 5 years, the 2020 concentrations of $PM_{2.5}$ and NO_x showed an overall reduction across the basin. O_3 concentrations decreased in the western part of the basin and generally increased in the downwind areas. The NO_x decline in 2020 (approximately 27% basin-wide) is in addition to ongoing declines over the last two decades (on average 4% less than the −6.8% per year afternoon NO_2 concentration decrease) and provides insight into how air quality may respond over the next few years of continued vehicular reductions. The modest changes in O_3 suggests additional mitigation will be necessary to comply with air quality standards.

Plain Language Summary On 19 March 2020, California put in place Stay-At-Home orders to reduce the spread of SARS-CoV-2. As a result, there was much less traffic in Southern California. Reduced traffic along with a month-long stretch of unusually rainy weather at the beginning of the lockdown led to significant reductions in $PM_{2.5}$ and NO_x levels across the basin. Concentrations of O_3, on the other hand, showed inconsistent changes across the basin. The response of O_3 to these large changes in nitrogen oxide concentrations suggests mitigation efforts beyond those associated with continuing vehicle emission reductions will be important to meet clean air goals.

1. Introduction

As restrictions were enacted to slow the spread of SARS-CoV-2, the virus that causes COVID-19, the decrease in human activity (traffic, industry, etc.) in major cities worldwide resulted in significant changes in air quality. Cities in China, Italy, Germany, and the United States have shown decreases in atmospheric nitrogen dioxide (NO_2) concentrations (Bauwens et al., 2020; Goldberg et al., 2020; Naeger & Murphy, 2020). In Pittsburgh, Pennsylvania, for example, significant decreases in concentrations of NO_2, carbon monoxide (CO), and fine particulate matter ($PM_{2.5}$) have been observed (Tanzer-Gruener et al., 2020). Los Angeles (LA), known for its car culture and multidecadal fight with air pollution (Parrish et al., 2016; Pollack et al., 2013), was reported to have some of the cleanest air in its history as a result of the sudden drop in traffic emissions (https://www.latimes.com/opinion/story/2020-04-22/coronavirus-is-making-it-clear-that-car-culture-is-its-own-kind-of-plague). For LA and the broader South Coast Air Basin (SoCAB), however, the COVID-19 restrictions coincided with precipitation at least 3 times the historical average (supporting information Figure S1). As the anomalously rainy period ended in the SoCAB, the levels of the secondary pollutant ozone (O_3) returned to values comparable to or exceeding those of previous years despite the sustained decrease in traffic flow (more than 20% below the values in January and February).

The influence of nitrogen oxide (NO_x) pollution in the SoCAB on air quality has been the subject of a decades-long study. Since the mid-twentieth century, NO_x in the SoCAB has been decreasing by roughly 3% per year on average (Parrish et al., 2016; Pollack et al., 2013). In the last decade, regulations of NO_x have been focused on reducing the emissions from heavy duty diesel vehicles (Final 2016 Air Quality Management Plan, 2016). Historically, reductions in weekend NO_x emissions have led to higher weekend O_3 levels. Higher weekend O_3 levels are the result of the combination of increased photochemical production of oxidant ($O_x = NO_2 + O_3$) from elevated OH levels due to the reduced loss of OH via its reaction with NO_2 and an increased fraction of O_x present as O_3 due to the reduced conversion to NO_2 via reaction with NO. This phenomenon is known as the "weekend effect." The weekend effect has been used to predict the effects of future NO_x emission reductions on air quality (Baidar et al., 2015). Changes in volatile organic compound (VOC) emissions do not generally scale with NO_x because these emissions are associated with many sectors (and include biogenic emissions). On-road vehicle VOC emissions are now thought to account for only about one fourth of the total emissions (CEPAM: 2016 SIP - Standard Emission Tool, 2019).

Both the weekend effect and the especially large reductions in vehicular emissions in 2020 provide evidence for the continuing efficacy of mobile fleet emissions reductions on air quality. Given the long-term trends in such emissions, the experience of spring 2020 provides a glimpse of what the air quality will look like approximately 5 years into the future of vehicle targeted emission reductions.

2. Methods and Data

Basin-wide air pollutant data (O_3, NO_2, NO_x, and $PM_{2.5}$) were obtained from the California Air Resources Board (CARB) Air Quality Data Query Tool (https://www.arb.ca.gov/aqmis2/aqdselect.php) (Figure 1). The 2020 air quality data are preliminary, unvalidated, and subject to change. Continuous measurements of $PM_{2.5}$ along with trace gas measurements of CO, SO_2, O_3, NO, NO_2, and NO_y were conducted at the Caltech campus by the Caltech air quality system (CITAQS) using Teledyne instrumentation (Text S1). While the regulatory NO_2 chemiluminescence measurements are known to include contributions from other nitrogen-containing species due to the non-selectivity of the molybdenum converter (Villena et al., 2012), the chemiluminescence data from the South Coast Air Quality Management District (South Coast AQMD) station in Pasadena (located approximately 400 m south of the CITAQS) agree within a few tenths of a ppb with the optical NO_2 measurements from the CITAQS. Remotely sensed CH_2O total column abundances are provided by the Total Carbon Column Observing Network (TCCON) site in Pasadena (Wunch et al., 2011). Temperature and precipitation data are taken from meteorological sensors located alongside the CH_2O measurement (https://tccon-weather.caltech.edu). Historical observations of temperature, relative humidity, and wind speed data across the basin were obtained from CARBs Meteorology Data Query Tool, and precipitation data were acquired from the National Oceanic and Atmospheric Administration (NOAA). The CITAQS, TCCON site, and meteorological station are all located in or on the Linde+Robinson Laboratory on the southwest corner of the Caltech campus roughly half a kilometer north of a regulatory air monitoring station in Pasadena, operated by the South Coast AQMD. Our analysis also makes use of O_3, NO_2, CH_2O, $PM_{2.5}$, and weather data from the 2010 CalNex campaign ground site also located on the Caltech campus (https://www.esrl.noaa.gov/csl/projects/calnex/). Basin-wide daily traffic counts were obtained from the Caltrans PeMS website (https://pems.dot.ca.gov/). TROPOMI tropospheric NO_2 columns are used for illustrative purposes in Figure 2 and follow suggested data quality guidelines (Veefkind et al., 2012).

In our analysis, we use the sum of NO_2 and O_3, also referred to as oxidant (O_x), CH_2O, and $PM_{2.5}$ as metrics of air quality. O_x is conserved with respect to the cycling of NO_2 photolysis to O_3 and NO, and O_3 reacting with NO to reform NO_2. This makes O_x measurements useful as a diagnostic of air chemistry since it is less sensitive to local effects on photochemistry (e.g., local NO emissions reacting with O_3 to form NO_2, or clouds changing the photolysis frequency of NO_2) and is instead driven by overall emissions, losses, and net photochemical O_x production. CH_2O is often used as a proxy for VOC reactivity, especially for the oxidation of small alkenes from both anthropogenic and biogenic sources (Pollack et al., 2012; Wolfe et al., 2016; Zhu et al., 2014). $PM_{2.5}$ is both directly emitted and produced within the atmosphere (secondary), with the latter generally being dominant in the SoCAB. Secondary production of $PM_{2.5}$ arises from NH_4, NO_3, and sulfate chemistry and the oxidation of gas-phase VOCs and is the main culprit for low visibility during smog events (Schiferl et al., 2014).

In sections 3.1 and 3.4, we only consider the air monitoring sites that were active through the entire 2015 to 2020 period. For NO_x and O_3, we consider sites that measure both of these parameters, while for $PM_{2.5}$ we consider data from all the sites with $PM_{2.5}$ measurements (Figure S2). In these sections, we report 24-hr $PM_{2.5}$, 8-hr daily maximum (DM) O_3, and 1-hr DM NO_x that have regulatory relevance.

In section 3.2, we use data from 13 sites in the basin that have measurements of both NO_2 and O_3 for the 2000 to 2020 period. In section 3.3, we focus on data from Pasadena only. In the above mentioned sections, we focus on data collected during the afternoon hours (12 p.m. to 4 p.m. local) since the afternoons are often the times with maximum values of O_3 or O_x and are therefore the most influential in terms of air quality reporting, such as O_3 exceedances (Figure S3). For an accurate comparison from year to year, we define the 19 March to 30 June window as the COVID-19 (or simply COVID) period for all comparisons.

3. Results and Discussion

3.1. The Confluence of Anomalous Weather and COVID-19 Restrictions

On 19 March 2020, the state of California enacted Stay-At-Home orders restricting all non-essential work in order to reduce the spread of COVID-19 (https://www.gov.ca.gov/wp-content/uploads/2020/03/3.19.20-attested-EO-N-33-20-COVID-19-HEALTH-ORDER.pdf). Eleven days before this order, on 8 March 2020, mobility and traffic started decreasing everywhere in the SoCAB (Figure 1c). By April, SoCAB traffic and mobility dropped to about 50% of the pre-COVID-19 period (January and February, 2020). SoCAB traffic counts slowly recovered from late April through early June and stabilized at about 80% of pre-COVID-19 levels by the end of June (Figure 1c) despite different phases of restrictions. While the traffic flow decreased in all areas of the basin, the average differences varied in different parts of the basin as the western and eastern areas have returned close to pre-COVID-19 values (Figure 1c, right panel). Concurrently, the air quality index (AQI) in the second half of March and beginning of April were consistently green, and SoCAB citizens enjoyed clean air with high visibility (Figures S4–S7). Naturally, this led to the association of the decrease in traffic with clean air and the condemnation of LA car culture as the culprit for bad air quality (https://www.latimes.com/opinion/story/2020-04-22/coronavirus-is-making-it-clear-that-car-culture-is-its-own-kind-of-plague).

The decrease in traffic and improvement in air quality was also coincident with frequent stormy conditions and above-normal amounts of rainfall. The rainfall in the basin in 2020 was well above that of the past decade with precipitation in March and April over 3 and 5 times the average values, respectively (Figure S1). Rainfall affects air quality by removing pollutants such as nitric acid and $PM_{2.5}$ from the air through wet deposition (Seinfeld & Pandis, 2006). In addition, rainy periods are associated with higher basin ventilation rates, decreasing pollution buildup in the basin. Figure 1b shows the basin-maximum concentrations of 8-hr DM O_3, 1-hr DM NO_x, and 24-hr $PM_{2.5}$ for the pre-COVID-19 and post-COVID-19 periods in 2020 along with the average values for 2015 to 2019 with the 2020 rainy days shaded in blue. During the rainy period in March and early April, temperatures dropped below the range observed over the previous 5 years (Figure S1). During this drop in temperature, the 1-hr DM NO_x and 24-hr $PM_{2.5}$ were consistently lower than the lower limits of the 2015 to 2019 range. The 8-hr DM O_3 concentrations were consistently at the lower end of the 2015 to 2019 range. After the rainy period, temperatures in late April and early May rose above historical values (Figure S1) and 8-hr DM concentrations of O_3 were highly elevated. In fact, in May 2020, SoCAB experienced 18 days of O_3 exceedance from the federal standard of 70 ppb—more than any other year from 2015 to 2019. The spike in O_3 concentrations outside the range of the 2015 to 2019 values in late April and early May is coincident with, and likely partially due to, a similar pattern of higher temperatures and lower wind speeds in the basin (Figures 1 and S1). This return to higher O_3 levels occurred although traffic remained at least 30% lower than pre-COVID levels. After May, however, the temperatures, wind speeds, and O_3 concentrations in the basin returned to values within the range of values observed in 2015–2019. NO_x concentrations remained equal to or lower than the previous 5 years, and, in June, $PM_{2.5}$ concentrations dropped lower than the lower end of the range of values from the past 5 years. To assess the impact of rainy days on the observed trends, a sensitivity test was carried out. When the rainy days are excluded from the analysis, the basin-maximum levels are comparable to the values for the entire window with only a 2.76%, 2.11%, and 0.64% difference between including rainy days and not for 24-hr $PM_{2.5}$, 8-hr DM O_3, and 1-hr DM NO_x, respectively (Figure S8).

The changes in 8-hr DM O_3 concentrations in 2020 were not consistent across the basin (Figure S9). Compared to the same months in 2015–2019, sites in the western part of the basin generally experienced lower 8-hr DM O_3 concentrations (up to 9 ppb or 22% reduction) while most of downwind areas experienced an overall increase (up to 8 ppb or 15% increase). The 24-hr $PM_{2.5}$ and 1-hr DM NO_x showed an overall decrease across the basin (10–45% and 13–40% reduction, respectively) (Figures S10 and S11). As discussed above, while the COVID-19 countermeasures altered pollutant concentrations in LA, the anomalous weather significantly contributed to the clean air observed in late March and early April.

3.2. Twenty Years of Reductions and COVID-19

In the context of the trends in air quality in the SoCAB over the past decade, the diverse response of secondary pollutants to the large drops in vehicular emissions during the COVID-19 period is not surprising. Over the past 20 years, vehicular emissions, particularly heavy-duty diesel trucks, have been targeted by regulation, and atmospheric concentrations of NO_x have decreased substantially (Final 2016 Air Quality

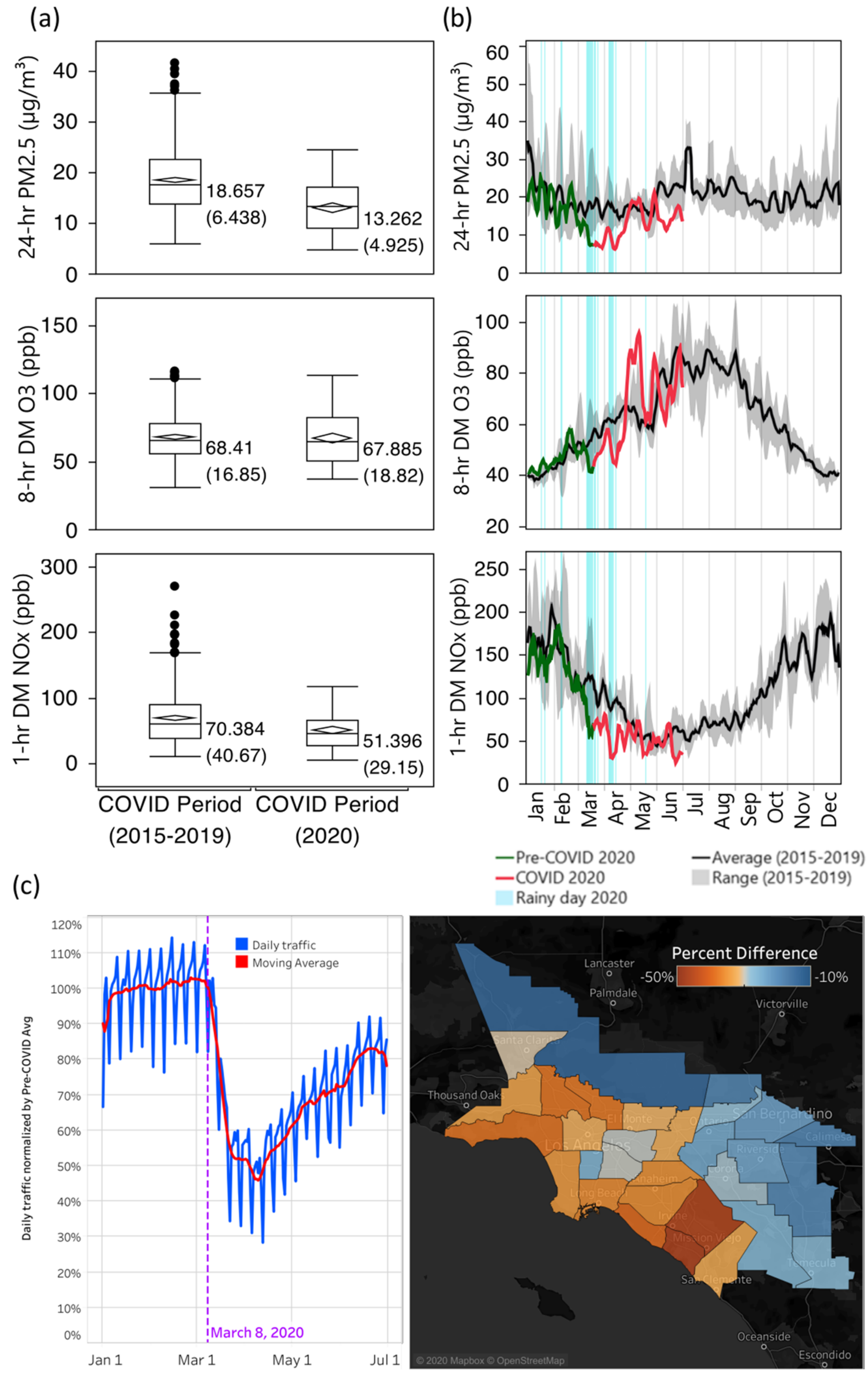

Figure 1. (a) Box plot of the basin-maximum 24-hr $PM_{2.5}$, 8-hr daily maximum O_3, and 1-hr daily maximum NO_x during the COVID-19 period (19 March to 30 June) in 2020 and in the past 5 years (2015–2019) in the South Coast Air Basin. Horizontal lines inside boxes denote median values, edges of box denote the 25th and 75th percentiles, and the whiskers denote ±1.5×IQR. Dots are data points >1.5×IQR. The confidence diamond in each box contains the mean and the upper and lower 95% of the mean. The means are reported to the right of the box plots with the standard deviation in parenthesis. (b) The 7-day moving average of basin-maximum 24-hr $PM_{2.5}$, 8-hr daily maximum O_3, and 1-hr daily maximum NO_x in 2020 and in the past 5 years in the South Coast Air Basin. (c) (left) Basin-wide daily average traffic flow deviation from January to February in percent is plotted with the 7-day moving average represented by the red line. (right) Average difference from January to February traffic levels for 19 March to 30 June period separated by the source/receptor area for the South Coast Air Basin.

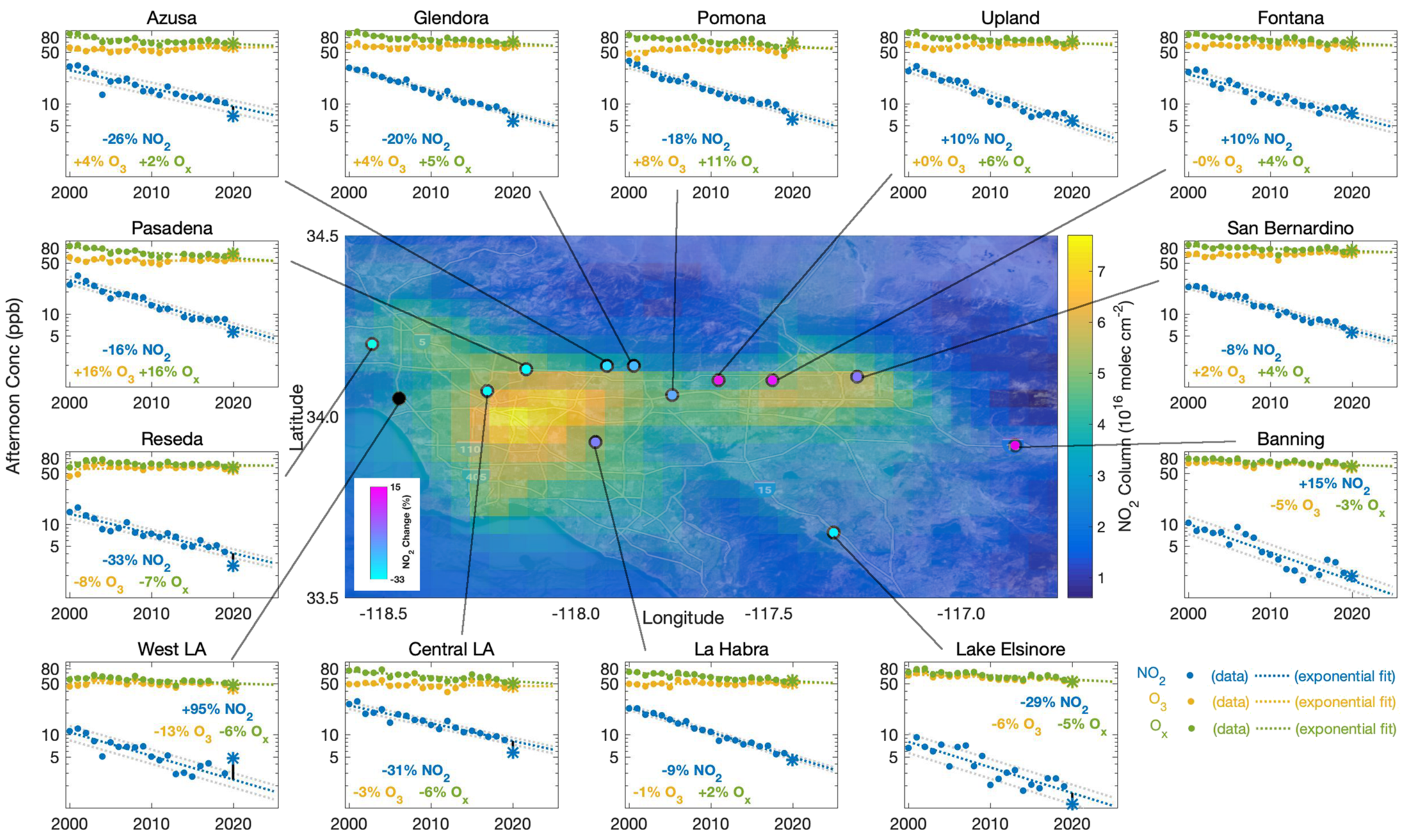

Figure 2. (middle panel) Map of the tropospheric NO_2 column as measured by the TROPOMI instrument for the 19 March to 30 June 2020 period with color indicated by the bar to the right of the map. The locations of each air quality monitoring site are denoted by circles color coded (excluding the West LA site) by the difference between the 2020 afternoon NO_2 values and the value expected by the 2000 to 2019 trend in afternoon NO_2 in percent. (surrounding panels) Time series plots of NO_2, O_3, and O_x in ppb for each site for the 19 March to 30 June period from 2000 to 2020. The dotted lines show the exponential fit for each species. The gray dotted lines represent the standard deviation of the residuals between the measured values of NO_2 and the fit. Values for 2020 are represented by asterisks. The difference between the average afternoon values of NO_2, O_3, and O_x in our analysis period in 2020 and the long-term trend is noted within each individual plot in percent.

Management Plan, 2016). Figure 2 shows the changes in afternoon concentrations of NO_2, O_3, and O_x in sites across the basin since 2000 around a map of tropospheric NO_2 column concentrations for COVID-19 period in 2020 from the TROPOMI instrument. While the 1-hr DM NO_x and 8-hr DM O_3 concentrations have regulatory relevance, the afternoon (i.e., 12:00 to 16:00) values of air pollutants used below are more closely related to the photochemical interactions occurring at peak O_x values.

Over the 2000 to 2019 period, the afternoon NO_2 concentrations have been decreasing at rates between 4.90% and 9.08% per year across the basin (Table S1). The trends reported here are larger than described elsewhere due to the use of afternoon values instead of the data from the entire day (Jiang et al., 2018; Parrish et al., 2016; Pollack et al., 2013). In terms of O_x, the decreases in NO_2 concentrations have been partially offset by increases in O_3 concentrations due to the nonlinear relationship between NO_2 and O_3 (Fujita et al., 2016). The trends in afternoon O_3 concentrations vary in different parts of the basin, from decreases of 0.87% to increases of 0.64% per year, while afternoon O_x concentrations have decreased by between 0.39% and 1.53% per year across the basin.

COVID-19 traffic reductions led to an overall drop in atmospheric NO_2 concentrations in LA similar to those seen in other major cities around the world (Bauwens et al., 2020; Goldberg et al., 2020; Le et al., 2020; Naeger & Murphy, 2020; Tanzer-Gruener et al., 2020). Depending on the location in the basin, afternoon NO_2 concentrations for 2020 were up to 33% lower than those expected using the trend between 2000 and 2019; in several remote locations, NO_2 levels were actually larger than expected in 2020 (Table S1). For example, COVID period afternoon NO_2 values in Reseda in 2020 were even lower than the expected 5.7% yearly decrease by 33% or 1.3 ppb. Changes in afternoon O_3 are modest and of both signs (decreases of up to 13% or 6.5 ppb and increases as large as 16% or 8.6 pbb). Half of the sites (West LA, Pasadena, Azusa, Glendora, Pomona, Banning, and San Bernardino) have anomalies of opposite sign (a positive NO_2 anomaly and a negative O_3 anomaly or vice versa) as is expected in a NO_x-saturated atmosphere. The other half of the sites (Reseda, central LA, La Habra, Upland, Fontana, and Lake Elsinore) show little O_3 anomaly at all or have O_3 and NO_2 anomalies with the same sign suggesting that they may be in NO_x-insensitive or even NO_x-limited photochemical regimes in 2020. Each site in the SoCAB is influenced by accumulation and photochemical processing of the upwind pollutants, local emissions, and average meteorology (Baidar et al., 2015; Wagner et al., 2012). The combination of these factors has led to historically larger O_3, and often lower NO_2, concentrations in the northeast parts of the basin. It is no surprise then that the sites exhibiting NO_x-insensitive or NO_x-limited behavior are downwind or outside the most heavily NO_x polluted areas of the basin (Figure 2). The central LA site is an exception with negative 2020 anomalies in both NO_2 and O_3 despite being close to the maximum in tropospheric NO_2 columns but also experienced one of the largest NO_2 anomalies, possibly triggering this NO_x-limited response.

The measurement site in West LA shows significantly larger afternoon NO_2 values in 2020 compared to the fit (95% or 2.5 ppb increase), but the decreases in 1-hr DM NO_x from the 2015–2019 to the 2020 COVID period shown in Figure S10 suggest that there may be a significant shift in time-of-day emission patterns near this site. The variations in NO_2 in the basin are independent of the analysis period. For example, when using the period after the anomalous rain in 2020 (19 April to 30 June), the range of deviations in afternoon NO_2 concentrations is between −34% and 176% (−1.9 and 3.7 ppb) with the West LA site responsible for the upper value of this range (Table S1).

At this time, we have fewer constraints on how VOC emissions have changed in 2020. Formaldehyde columns measured in Pasadena, however, provide some clues. CH_2O is formed within the atmosphere from the photo-oxidative degradation of hydrocarbons. Major CH_2O loss pathways are photolysis and reaction with OH radical. Assuming daytime $[OH] = 4 \times 10^6$ molecules cm^{-3} (Griffith et al., 2016), and $j_{HCHO} = 5.3 \times 10^{-5}\ s^{-1}$ (noontime values scaled by 0.7), we estimate a daytime photochemical lifetime of 3.2 hr for CH_2O, with photolysis accounting for about 60% of the loss. Thus, we expect the abundance of CH_2O to be quite sensitive to the oxidation rate of VOC. Afternoon column CH_2O measurements in Pasadena exhibited a 10% decrease in the COVID-19 period in 2020 ($1.25 \pm 0.53 \times 10^{16}$ molecules cm^{-2}) from the COVID-19 period between 2015 and 2019 ($1.37 \pm 0.35 \times 10^{16}$ molecules cm^{-2}) (Figure S12). The changes in CH_2O column abundance are consistent with what would be expected from the 30% decline in vehicular emissions assuming such emissions account for one fourth of the total. Since Pasadena exhibited NO_x-saturated behavior, the increase in O_3 in 2020 from the reduction of NO_2 may have been muted by the observed 10% decrease, so far as CH_2O is effective as a proxy of VOC emissions. Changes in VOCs around the basin may have similar corresponding effects on the local chemistry shown in Figure 2 and Table S1.

3.3. The Correlation of Air Quality and Temperature

There is a strong correlation between air pollution levels and temperature in LA (Figure 3). Such correlations are well documented and have been used to analyze changes in emissions and photochemical regimes elsewhere (Baidar et al., 2015; Geddes et al., 2009; Pusede et al., 2014, 2015). In the SoCAB, hot, sunny days result in faster rates of photochemistry from the combination of increases in sunlight, increased biogenic and evaporative emissions, increases in many temperature-dependent rate coefficients, and metrological differences due to a shallower mixed layer that traps pollutants closer to the surface. While NO_x emissions have been shown to be largely independent of temperature, VOC emissions are known to increase with temperature due to enhanced evaporation and increased biogenic emissions (Final 2016 Air Quality Management Plan, 2016; McDonald et al., 2018; Pusede et al., 2015). Here, we illustrate the correlation of air quality with temperature using measurements in Pasadena made in 2010 and 2020.

Figure 3 shows afternoon values of O_x, CH_2O, and $PM_{2.5}$ plotted against temperature during CalNex in 2010 (May through July 2010) and for data from the 19 March to 30 June period from the South Coast AQMD station in Pasadena, CITAQS, or the Caltech TCCON instrument. Afternoon temperatures in Pasadena were slightly cooler in 2020 (by 0.22°C on average) than in the 2015–2019 COVID periods (Figure S13). There is little change in the values of O_x or its relationship to temperature. Likewise, the relationship of O_3 to temperature is consistent over the same period (Figure S14). $PM_{2.5}$ has, however, decreased. Although the overall concentration of O_x is decreasing, it is doing so slowly and following the same relationship with respect to temperature as observed over the last 5 to 10 years so that it is not readily apparent in Figure 3.

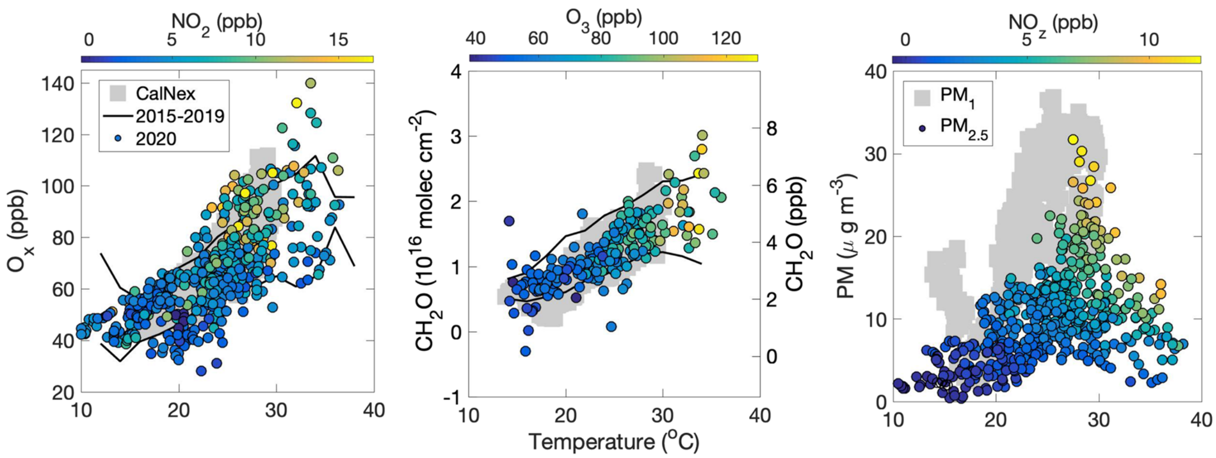

Figure 3. (left) Hourly afternoon COVID period O_x concentrations are plotted against temperature and color coded by NO_2, all in ppb. The gray boxes are CalNex O_x concentrations in ppb. (middle) Hourly afternoon COVID period CH_2O column abundances, in molecules per square centimeter, are plotted against temperature and color coded by O_3. The gray boxes are CalNex CH_2O concentrations in ppb and follow the right *y* axis. (right) Afternoon COVID period $PM_{2.5}$ concentrations are plotted against temperature and are color coded by NO_z. The gray boxes are PM_1 concentrations from CalNex measurements. All data shown here are from Pasadena. In the left and middle panels, the upper and lower black lines are the 10% and 90% quantile values for the COVID period from 2015 to 2019 values, respectively.

CH_2O column amounts have been consistent over the past 5 years with a clear dependence on temperature that remains in 2020 despite lower observed values. While the mechanisms leading to the formation of $PM_{2.5}$ are more complicated than the reactions that lead to the formation of NO_2, O_3, and CH_2O, Figure 3shows that $PM_{2.5}$ is correlated to temperature, particularly for temperatures comparable with the CalNex measurements (10–30°C), and that variations in $PM_{2.5}$ across the temperature range are correlated with variations in NO_x oxidation products (NO_z). By definition PM_1 concentrations are at most equal to $PM_{2.5}$ values so that Figure 3 shows $PM_{2.5}$ concentrations have decreased since CalNex measurements of PM_1 in 2010.

As NO_x decreases in a NO_x-saturated photochemical regime, OH concentrations increase, and therefore the rate at which VOCs are oxidized also will increase. Thus, even if VOC emissions decrease the net photochemistry will not necessarily change. CH_2O concentrations can provide a measure of this net VOC photochemistry. In Pasadena, the increase of O_3 and decrease in CH_2O compared to the last 5 years suggests, therefore, that NO_x reductions have not yet reached the point where the net photochemistry has slowed significantly outside of temperature driven variations. The continued temperature dependence over the past decade in Pasadena suggests that the O_x in similarly NO_x-saturated areas of the basin will continue to be driven by meteorology along with changes in emissions and that the reductions in NO_x concentrations from COVID-19 countermeasures have not outpaced the effects of meteorology on the production of O_x. It should be noted that the CH_2O measurements from CalNex shown in Figure 3 were in situ and therefore are not directly comparable to the column CH_2O observations but still demonstrate the same temperature dependence.

In summary, while absolute concentrations of O_x have slightly decreased over the last decade, the temperature dependences of O_x, CH_2O, and $PM_{2.5}$ have remained similar over the past 5 years and to CalNex-2010 observations, despite substantial reductions in NO_x emissions (Final 2016 Air Quality Management Plan, 2016). The consistency of pollutant concentrations and patterns with respect to temperature in 2020 despite significant reductions in vehicular emissions during COVID-19 countermeasures emphasizes the influence of weather on air quality (especially during years with consistently record-breaking temperatures) and the need for other, concurrent approaches to reducing O_x in combination with vehicular emissions reductions.

3.4. 2020 Air Quality as a Glimpse of the Future

In the same way that changes in air quality between the weekend and week days have provided insight into the role of truck emissions (Baidar et al., 2015), the broader traffic reductions associated with COVID-19 provide insight into expected air quality changes over the next 5 years, assuming the continuation of the long-term trends of reductions in vehicular emissions. On most weekends in the SoCAB, the reduction in NO_x emissions from heavy duty diesel trucks reduces morning O_3 titration and increases O_3 production efficiency, leading to an overall increase in O_3 concentrations (the so-called NO_x disbenefit). While the magnitude of the weekend reduction in 1-hr DM NO_x varies from site to site, most of the sites across the basin showed a larger percentage reduction (5–30%) of 1-hr DM NO_x from the weekends to the weekdays between the 2015 to 2019 and 2020 COVID-19 period which would theoretically enhance the O_3 weekend effect (Figure S15). However, the weekend to weekday differences in 8-hr DM O_3 have decreased across the basin (Figure S16). In fact, some of the sites (mostly located in downwind areas of the basin such as Pasadena, Mira Loma, and Rubidoux) show lower 8-hr DM O_3 on weekends compared to weekdays during the 2020 COVID period, suggesting that in some areas of the basin we may finally be approaching NO_x emission levels that slow photochemistry. On the other hand, the consistency of O_x values despite the substantial NO_x reduction suggests that the western portion of the basin is still NO_x-saturated (Baidar et al., 2015; Fujita et al., 2016; Pollack et al., 2012; Wolff et al., 2013).

The lack of improvement in O_x levels in 2020 is consistent with the pattern observed over the past decade in the basin (Figure 3). Only under exceptionally low vehicular emissions (e.g., weekends during April and May 2020), are there now glimmers of hope that oxidant levels will begin to decline. Thus, these data suggest that a broader focus on reducing VOC emissions (in combination with the current focus on NO_x reductions) will be needed to attain air quality standards basin-wide. As VOC emissions from light duty vehicles are now thought to be a minority of the total VOC emissions (McDonald et al., 2018), reductions in VOC emissions will need to come primarily from area and non-mobile sources such as solvent use, paints, cleaners, gardening equipment, and the oil/gas sector. To the extent that biogenic emissions are important, replacing high-VOC emitting trees species would also be helpful.

Data Availability Statement

Data from the CITAQS are available by request and will be available online to the public in the near future. All data from the AQMD sites are available through the California Air Resources Board Air Quality Data Query Tool (https://www.arb.ca.gov/aqmis2/aqdselect.php). Data from the CalNex campaign are available online (https://www.esrl.noaa.gov/csl/projects/calnex/). TROPOMI data used in this research are available through the Sentinel-5P Data Hub (https://s5phub.copernicus.eu/). Traffic data used here are available through the Caltrans PeMS program (https://pems.dot.ca.gov/). Weather data are available online or by contacting the corresponding author (https://tccon-weather.caltech.edu/).

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