LETTER

Mobility, nightlights and air pollution during the early phases of the SARS-CoV-2 pandemic

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Abstract

The SARS-CoV-2 pandemic dramatically shifted daily life in the United States during 2020. The release of high spatial and temporal resolution cell phone data presented a unique opportunity to study the correlation between mobility, electricity use, and tropospheric NO2. While many studies have identified trends of changes in air pollution in locations with reduced mobility due to Covid-19-related restrictions, these studies fall short of assessing whether these trends are statistically significant. Here we analyze if, and how much, mobility, nighttime light and NO2 concentrations correlate. We analyze seven geographically diverse metropolitan areas in the United States (Atlanta, Austin, Boston, Denver, Los Angeles, New York City, Phoenix) in the first half of 2020. Using statistical tests of significance, we find that there is a strong correlation between NO2 levels and nighttime light during February-July 2020 in all urban centers. Mobility and NO2 are correlated strongly in four of the seven urban areas investigated. Together, these results suggest that policies aimed at limiting anthropogenic emissions from fixed (power generation) and mobile (traffic) NO2 sources have an effect on air quality but additional factors should also be considered.

Introduction

In December of 2019, SARS-CoV-2 (‘Covid-19’) emerged as a public health threat in Wuhan, China and quickly grew into a global pandemic. In the absence of effective treatments or a vaccine, policy responses encouraging/mandating social distancing, school closures, and travel restrictions were the tools of choice for limiting the spread of the virus [1–4]. By mid-January, China had placed 5 cities in lockdown and instituted screening of people leaving Wuhan. China extended the Lunar New Year holiday (25 January 2020) to reduce travel and delayed the opening of schools and universities in the spring [5]. On 31 January 2020, the United States banned entry of all non-citizens who were in China in the previous 14 days [6]. One month later, a similar ban went into place for Iran, followed by limitations to travelers from the Schengen area [7]. On 11 March 2020, the World Health Organization declared the Covid-19 outbreak a global pandemic [8]. On 13 March 2020, the United States declared a national emergency [9]. Global air travel plummeted in March 2020, compared to the same periods in 2019, with notable declines in the earliest-hit countries and/or regions of Italy (−48%), Hong Kong (−77%), and China (−54%) [10]. By mid-March, 107 countries had implemented measures to close schools [2], imposed curfews and travel restrictions, and quarantines were widespread in many regions globally [11]. This period has been called the ‘anthropause’ [12, 13]. Several studies have shown possible reductions in air pollution in locations where local or state-level policies restricting movements and enforcing stay-at-home orders were put into place. City-level NOx emissions in East Asia were observed to decrease between 20%–50% during lockdown periods in February-April 2020 [14]. A study of emissions changes in the early phases of the pandemic (February 2020) in mainland China recorded reductions in NO2 exceeding 60% relative to the month before [15]. A global study investigated
36 cities and multiple global regions and found that reductions in air pollution were seen alongside mobility reductions [16]. Several studies and communiqués were published using data from early in the pandemic, highlighting the reductions in air pollution in several countries and exploring potential implications and causations. This includes health impacts related to Covid-19 [17], explanatory factors such as reductions in mobility [15, 18–22], and reductions in industrial activities including power production and shipping activities [14].

The degree to which anthropogenic sources drive air pollution, including tropospheric NO₂, is important because it determines how effective regulations to limit emissions can be even in business-as-usual conditions. The Covid-19 pandemic provided a unique opportunity to test the correlation between NO₂ and anthropogenic sources related to transportation and electricity production in urban environments. Archer et al (2020) [18] found that air quality and human mobility throughout the US trended in similar directions in April 2020 relative to the same month for the previous five years. Reductions in both mobility and air pollution were strongest in urban centers and large cities. Corpus-Mendoza et al (2021) [16] investigated the decreases in electricity demand, mobility and air quality indices globally for March–June 2020 for multiple cities and regions globally. Policies to reduce the spread of Covid-19 in different countries were assessed in the context of Google Mobility, hourly and daily electricity consumption, and Air Quality Data. However, the level of geographic assessment for each dataset varied. Ruan et al (2020) [23] created an online database collating data including electricity markets in the United States, weather data by location, mobile device location data, and satellite imaging. The stated purpose was to enable analysis of the impact of Covid-19 on the electricity sector in the United States by collating disparate data sources into usable inputs.

Existing literature establishes that there is a measurable (although varying in magnitude) difference in month-to-month air pollution during the early phases of the pandemic. This is especially true in locations where measurable mobility reductions are also seen. A few studies and communiqués note that electricity consumption sees similar trends (e.g., [14, 16, 24–26]). Elvidge et al (2020) [27] and Straka et al (2021) [24] measure these changes of electricity using visible nighttime light as a proxy indicator in China and selected US metropolitan regions, respectively. Straka et al (2021) find that visible nighttime light, air pollution and a composite mobility index trend similarly across three US metropolitan regions. They find that reduction in mobility trended alongside improvements in air quality and lower energy usage, although no statistical significance testing is applied to the results.

In many studies, satellite data was used to assess air pollution including NO₂ levels [14, 15, 17–19, 21, 22, 24]. However, a limitation of the satellite data is that it is subject to obfuscation from clouds, instrumentation errors, and other factors. Therefore, it is advised that data is only used when aggregated over a sufficient time frame (at least one month) and should be analyzed only for pixels for which the data quality flag exceeds 0.75 [28]. Failure to do so can result in flawed analyses, a noted error in many early studies, especially across the United States. In some studies, there is no mention of whether a data quality flag was incorporated in the analysis [17, 18, 24] and, in others, the results are reported for a period of assessment under one month [14, 15, 19–21]. The Copernicus Programme noted that any studies not incorporating both of these guidelines may result in conclusions based on flawed data [28].

Two final limitations of existing work on this topic are that many investigate only the trends between two of the three drivers mentioned (e.g., mobility and pollution or mobility and electricity consumption) and, in all studies, the trend assessments fall short of statistical significance testing. Additionally, most are for 1–3 months’ time period, providing a very limited temporal snapshot of these observed trends.

The current study expands on existing work to assess if these trends hold both across a broader range of geographies (seven metropolitan areas) and temporal fetch (6 months). Further, we quantify the statistical significance of these findings. In this study, the seven urban regions considered span different geographies, climates, and policy responses to the Covid-19 pandemic, elucidating potential relationships between these factors. We avoid the limitations of many Covid-19-driven studies by following the recommendations for data application. This includes averaging daily data over a 30-day time period, using a six-month time fetch compared to a common baseline for each dataset, and ensuring quality, snow, stray light and other data corrections are properly accounted for [28–30]. We also aggregate visible nighttime light, NO₂ and mobility at a consistent spatial and temporal scale. When looking for correlations between these data, we normalize them to the same datum, a period from 3 January—6 February 2020 (‘January 2020’). This baseline was chosen because it is the only baseline provided for the mobility data and is therefore chosen as a common datum for each dataset being analyzed. This provides a consistent baseline for the statistical analysis. It is the same as multiplying the data by a constant and does not affect any of the inherent seasonal trends in mobility, nighttime light and NO₂ levels.
Methods

The changes in visible nighttime light (a proxy for electricity usage), mobility, and tropospheric NO₂ over six months, February-July 2020, were quantified for seven US metropolitan regions (Atlanta, Austin, Boston, Denver, Los Angeles, New York City, Phoenix). All data is normalized to January 2020, a common datum. All seven locations have international airports. For each dataset, the level of analysis was the county boundary [31], except for New York City, which includes the aggregated data from the counties of Kings, Queens, The Bronx and New York County to cover most of the metropolitan New York City region. Respectively, the counties used to bound the assessment of each data set are Los Angeles County (LA), Fulton County (Atlanta), Travis County (Austin), Denver County (Denver), Maricopa County (Phoenix), and Suffolk County (Boston). A survey of policy actions in each metropolitan region, and corresponding state where applicable, was generated. A Spearman’s rank correlation [32] was used to assess the relationship in each region between mobility and NO₂ concentrations, and visible nighttime light and NO₂ concentrations.

For each of the three datasets considered, a rolling 30-day average was computed for every day between 15 February 2020–31 July 2020. Then, the resulting values were compared to a January 2020 (3 January 2020–6 February 2020) baseline:

$$\Delta V_{\text{pct}} = \frac{V_{\text{avgDAILY}} - V_{\text{avgJAN}}}{V_{\text{avgJAN}}}$$

Here, $\Delta V_{\text{pct}}$ is the change in percentage between each daily average value and the daily average January baseline. $V_{\text{avgDAILY}}$ is the daily average value for each day assessed using an evenly weighted, 30-day rolling average metric. $V_{\text{avgJAN}}$ is the average daily value for the January baseline. Note that while equation (1) gives $\Delta V_{\text{pct}}$ relative to the average in January 2020, this does not affect the correlations between time series data. Equation (1) is the same as $\Delta V_{\text{pct}} = c V_{\text{avgDAILY}} - 1$, where $c$ is a constant and the $-1$ is a DC shift for each time series data vector. Neither the constant, nor the DC shift affect the correlations between data vectors (i.e., mobility, NO₂, nighttime light).

The 30-day rolling average metric looks backwards over the previous 30 days and averages every daily value available within that timeframe. A daily average value is only computed when at least 15 days within that timeframe have available data. Data can be missing due to quality or other factors. The January baseline is comprised of daily data from 3 January 2020-6 February 2020, a range chosen by the mobility data. This was kept consistent across the pollution and nighttime light datasets to ensure identical time fetch comparisons.

Mobility

All mobility data was taken from Google [33], providing aggregated county-level daily data. A baseline value was provided by Google, defined as the ‘median value, for the corresponding day of the week, during the 5-week period from 3 January-6 February 2020’. This was used to create the ‘January 2020’ baseline value. Google provides six categories of mobility data from which an ‘out of home’ daily average value was computed by averaging rates of change from the baseline for transit stations, workplace, retail, and recreational locations.

NO₂

All available Tropomi Level 2 Nitrogen Dioxide (L2_NO₂) daily data products from the Sentinel-5P Data Hub from the Copernicus Programme for each metropolitan region was downloaded from the period of 3 January—31 July for 2020 [29]. Geographic coverage is approximately $3.5 \times 5.5$ km². All files have the WGS84 coordinate reference system (EPSG4326). Due to the longitudinal geographic diversity of the seven regions chosen, each metropolitan region has a slightly different ratio of degrees to meters conversion. Horizontal and vertical resolution conversions were done for all images based on the metropolitan region location [34].

Using the Geospatial Data Abstraction Library (GDAL) Virtual (.VRT) files, georeferenced geotiff images were produced from the original netCDF files and a quality image flag of $\geq 0.75$ was used as a threshold for filtering all NO₂ measurements [29, 35]. The quality flag omits pixels of questionable data quality. Each image was cropped to a county boundary for each metropolitan region using shapefiles to ensure only data points within the county boundaries were considered in the analysis. Each daily average value was created by averaging all pixels with data (pixels excluded for quality flag reasons are not included). This is done for each metropolitan region (January-July 2020) with daily values from 15 February-31 July calculated as the percent change relative a January 2020 baseline, equation (1).

Visible nighttime lights

Daily (nighttime) images for visible nighttime light were downloaded from the NASA Black Marble Product Suite for 3 January–31 July 2020. The data is corrected for lunar radiance and stray light, snow, bias, quality and gaps (product V2, gap-filled DNB_BRDF-Corrected nighttime lights) [30]. The nighttime light analysis was identical to the methodology described for the pollution data. First, each daily nighttime light image was cropped using a county shapefile, all pixels with data were averaged for each day, and an average daily value of
visible nighttime light was computed for each day. Then, the baseline daily average was calculated by averaging every day for which data was available in the period 3 January–6 February 2020. Finally, every day from 15 February–31 July 2020 was compared to the baseline using equation (1) to determine the daily percent change.

Policy
For each metropolitan region, data were collated for state and city emergency orders, restrictions on gatherings and business operations and other resources for the initial months of the pandemic. The result is a summary of Covid-19-related actions taken for each metropolitan region, the type of action, and the date[s] for which they were implemented. The types of action are broadly summarized to reflect the types of orders issued and, where possible, to align with the available mobility dataset used to contextualize the results of this study. A full set of policy dates reviewed for each metropolitan region can be found in Table 1. The policy analysis includes the dates, authority and issuing body for the following actions: Declaration of a state of emergency, the closure of schools, restrictions on gatherings, ban on dine-in for restaurants, restrictions on businesses, and the issuing of stay-at-home orders. While impossible to specifically compare orders across geographies, these provide a context for the breadth and timing of mobility restrictions by location.

Results
Figure 1 shows 30-day moving averages for changes in mobility, NO$_2$ and visible nighttime light from February to July of 2020 relative to the average for January baseline for the seven urban regions considered. Figure 1(A) shows that pollution sees little change in early March 2020 (the daily value shown is the average of the previous...
30 days), with increasing changes over the time fetches of late March, April, and early May. Monthly mobility results show that all locations begin to see decreases from early March and reach a minimum in late mid-April. The daily values are the average of the previous 30 days, meaning that the mid-April daily data is the average of the first full month of pandemic restrictions. This aligns with the introduction of restrictions on gatherings, businesses, school closures, and stay at home orders, table 1. The changes in nighttime light, a proxy for electricity use, show consistent reduction trends in each region, although the magnitude varies by location.

Figure 1(B) show clear differences in the degree to which mobility changed in specific metro regions. State and local policy directives may have influenced this, table 1. In all regions, a declaration of emergency was the first action taken, as this allows city, county and/or state authorities to mobilize resources, create new administrative committees, expedite distribution of funding and expand the city/state powers deemed necessary...
for emergency response actions. Los Angeles and New York City were the first of the seven regions analyzed to declare restrictions on gatherings (12 March 2020) [36–44]. In some locations, such as Phoenix, the restrictions were ‘encouraged’ based on Center for Disease Control guidelines [45], while others, such as New York City were more directly mandated (‘shall be cancelled or postponed’) [39, 46]. Stay-at-home orders were also issued in various forms from every metropolitan region throughout March. Phoenix was again the last metropolitan region to issue the orders (30 March) [47–49] while Los Angeles was the first (19 March) [37, 50], closely followed by New York City (22 March) [51–54].

Table 2 shows the statistical significance of these trends for each dataset and region using a Spearman’s rank correlation. Mobility and NO2 show a consistently strong correlation across four of the seven of the urban regions considered (Austin, Boston, Los Angeles, and Phoenix). Nighttime lights and NO2 show statistically significant correlations across all cities for the assessed six-month period. This indicates that pollution changes are statistically significantly correlated with mobility changes and changes in visible nighttime light, a proxy for electricity use. Three cities (New York City, Denver and Atlanta) showed lower correlation (not statistically significant) between pollution and mobility over the timeframe analyzed. However, of the cities studied, these locations host very large international airports with the top traffic among United States air traffic and of all locations assessed. Therefore, additional confounding contributions to air pollution may play greater roles than in other locations. For example, only 28% of NO2 emissions in New York City are from vehicles, with fixed sources dominating. The weak correlation is not unexpected as a result [55].

### Discussion

The Covid-19 pandemic had a major effect on normal activities during 2020. The release of high spatial and temporal resolution cell phone data presented a unique opportunity to study the correlation between mobility, electricity use and tropospheric NO2. The current study investigates the first 5 months of the Covid-19 pandemic (March to July) in the United States. This time fetch covers the most severe early pandemic-related restrictions but captures only a snapshot of the overall timeframe of the pandemic (still ongoing at the submission of this manuscript). Data presented in this study were 2020 rolling daily averages (relative to the January 2020 baseline). A different approach would have been to normalize the time series data to their respective monthly averages from 2019. However, no mobility data was available for 2019, making a comparison of the three datasets to an equal datum of prior years impossible.

The combustion of fossil fuels is a major source of NO2 in the United States and is a major contributor to air pollution. Peak concentrations occur in January and February over most of the contiguous United States and drop into summer [56, 57]. Regulations to improve air quality have significantly reduced emissions [58]. However, top-down satellite measurements have also shown that tropospheric NO2 has not dropped as rapidly as would be expected from bottom-up estimates. This suggests that the relative contribution of other sources of NO2 may not be declining as quickly as those coming from on-road vehicles and coal plant retirements [59]. Zhang et al (2003) [60] showed that lightning has a significant effect on total tropospheric NO2 concentrations, particularly during the summer months, and is the dominant source between 5 km–10 km elevation. However, the analysis presented here shows a very strong correlation between mobility and NO2 in four of the seven urban centers studied. The correlation of nighttime lights (a proxy for electricity consumption) is statistically significant in all seven urban centers. Together, this shows that anthropogenic activity remains a potential driver for NO2 emissions.

While quantifying policy responses across geographies was not feasible in this study, the dates and scope of orders related to stay-at-home restrictions were seen to vary by region. Boston and New York City saw some of the earliest and most strict responses to Covid-19 at the city, county, and state levels, with resulting changes in mobility of more than ~60% compared to the January baseline. In contrast, Phoenix had less strict mobility responses to Covid-19, and the resulting mobility changes, while notable, were far less drastic at approximately ~40% at similar times. For these same locations, the reduction in pollution was higher in New York City and Boston compared to Phoenix. Boston saw the greatest changes in mobility and nighttime light of the seven regions studied, with consistent (although not the largest) changes in pollution from February-July. Phoenix saw the lowest change in

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**Table 2.** Spearman’s Rank correlation between mobility, visible nighttime light, and NO2. The table shows the correlation between visible nighttime light (NTL) and NO2 as well as correlation between NO2 and Mobility along with corresponding p-values.

| Metropolitan Region | Dataset 1 | Dataset 2 | Dataset 3 |
|---------------------|-----------|-----------|-----------|
|                     | AUS | BOS | DEN | LA | NYC | PHO |
| P-Value | P-Value | P-Value | P-Value | P-Value | P-Value | P-Value |
| NTL NO2 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 |
| NO2 Mobility | 0.65 | <0.01 | <0.01 | 0.48 | <0.01 | 0.83 | <0.01 |
mobility, with Los Angeles and Atlanta showing smaller changes when compared to the remaining cities, especially New York City and Boston. Both Boston and New York City have public transportation networks exceeding those of the other regions, which may impact the trends seen in mobility changes.

There are several limitations with the current work. While the correlation between nighttime light, mobility and tropospheric NO2 is established, this does not equal causation. More work needs to be done to understand why a statistically significant correlation between mobility and NO2 is absent in New York City, Denver over the entire time period analyzed. Another limitation is that the present study was done considering time series data in 2020 alone. Additional data from other years would be of value in establishing the statistical fluctuation in NO2 in particular. While this would not change the significance of the correlations found here, it would provide a measure of how much of the observed NO2 changes in 2020 were driven by the pandemic. A lack of mobility data limited this option.

Conclusions

Multiple studies, including city, national and regional-level analyses, have shown that changes in mobility occurring during the early phases of the pandemic have trended alongside changes in air pollution, including NO2. Some studies have identified similar trends in electricity consumption. In this study, we assess the correlation between mobility, nighttime light and tropospheric NO2. We use an expanded temporal stretch of analysis (6 months) and quantifying whether these trends are statistically significant using Spearman’s Rank Correlation. Our findings show that the observed trends between mobility and NO2 are statistically significant in four out of seven of the regions investigated, and in all regions for visible nighttime light and NO2. The strength of the correlations varies by geography, with the largest changes generally found in metropolitan regions where more strict policies were implemented earlier. Tropospheric NO2 has both natural sources (e.g. lightning) and anthropogenic ones, in particular emissions from mobile, agricultural, and fixed sources. These all have seasonal variations. However, normal patterns of mobility were significantly disrupted during the first half of 2020. Despite this, there is still a strong correlation in 4 urban centers between mobility and NO2 and there is a strong correlation between nighttime light (a proxy for electricity consumption) and NO2 in all urban centers.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

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