NOAA's Response to the Science Advisory Board Climate Working Group's 8 April 2020 Letter, "Opportunity for COVID-19-related Earth System monitoring and prediction efforts as a result of worldwide shelter in place/ stay at home policies."

Summary prepared by Gregory Frost (NOAA OAR) and Shobha Kondragunta (NOAA NESDIS)
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INTRODUCTION

In late 2019 a new coronavirus (SARS-CoV-2) emerged, causing the respiratory illness known as COVID-19. The resulting pandemic triggered a worldwide economic downturn in 2020 which reduced human-caused emissions of air pollutants and greenhouse gases.

As the pandemic swept across the planet in early April 2020, the NOAA Science Advisory Board's (SAB's) Climate Working Group (CWG) made several recommendations to NOAA scientists regarding research objectives related to COVID-19. While recognizing and endorsing the need for NOAA to protect its workforce and to continue to carry out its mission, the CWG suggested that NOAA consider the following actions in light of the opportunities presented by the pandemic:

1. *Assess "What can NOAA do?"* – NOAA should assess the feasibility of rapid response studies of the impact of COVID-19 "shelter-in-place" practices on atmospheric constituents and their effects on the radiation budget.
2. *Assess "What can NOAA organize?"* – NOAA should implement appropriate cross-agency and external organization to capture the impacts of COVID-19 "shelter-in-place" practices on our ability to predict the Earth System.
3. *Assess "How can NOAA help?"* – NOAA should collaborate with health and epidemiological agencies to assess whether these direct pollution and climate effects have quantifiable and predictive human health repercussions.

The actions suggested by the CWG were aimed at the following scientific objectives:

Objective 1. Observe, aggregate, and quantify the response of aerosols, radiatively active gases, and their radiative effects that have occurred in response to the pandemic-related decrease in transportation and manufacturing. This would require securing ongoing aerosol, atmospheric chemistry, and radiation monitoring from space and *in situ* networks. A rapid response to obtain these data is essential.

Objective 2. Bring together key modelling centers to explore and compare the impacts in their systems. This might involve initializing forecasts with COVID-era versus normal emissions to determine where the simulations diverge (or do not) from observations to evaluate our understanding of the atmosphere and Earth System and our predictive capabilities.

Objective 3. Collaborate with public health agencies and assess NOAA's environmental prediction capability in terms of forecasting favorable/unfavorable conditions for vector-borne diseases and in understanding the spreading mechanism of epidemic or pandemic (e.g., airborne disease) that may be (partially) attributed to physical environment changes (in temperature, humidity, airflow, aerosol, weather-climate pattern, etc.)

This response documents the efforts carried out by NOAA to meet these objectives. The first section summarizes research studies by NOAA scientists and their partners, highlighting the key accomplishments and findings of their work. Each summary point has a citation for a detailed report that can be found in the Supporting Material in the second section of this document.

SUMMARY OF NOAA EFFORTS ADDRESSING OBJECTIVE 1

NOAA scientists and their partners undertook an unprecedented effort to carry out wide-ranging observational and analysis studies immediately after the pandemic's lockdown period was initiated in March 2020. The goal of these studies was to document changes to trace gases and aerosols that impact air quality and climate forcing throughout the height of the pandemic lockdowns and as these restrictions were lifted. These observations provide foundational understanding of the pandemic's effects on human-caused emissions and their impacts on the environment and represent critical constraints on numerical models that seek to quantify the pandemic's effects on air quality and climate.

A summary of this work and its key findings include:

- Two field campaigns in Boulder, Colorado, organized by OAR's Chemical Sciences Laboratory (CSL) quantified the levels of a large number of reactive air pollutants, greenhouse gases, aerosols, and meteorological variables during the spring and summer of 2020. CSL scientists found decreases in ambient levels of many of air pollutants during spring 2020 when vehicle emissions were at a minimum. They observed more complex behavior in the levels of air pollutants during the following summer, when human-caused air pollution would typically reach a maximum. While human-caused emissions in summer 2020 were still below levels seen in previous years, wildfires in the Western U.S. were anomalously elevated. This dataset is providing an important constraint for a variety of model studies carried out by NOAA and other agencies to understand U.S. air quality changes during the pandemic. *[Brown et al.]*
- OAR's Air Resources Laboratory (ARL) carried out aircraft and ground-based measurements of reactive air pollutants and greenhouse gases in the Baltimore-Washington and New York City metropolitan areas during the spring and summer of 2020. OAR's Global Monitoring Laboratory (GML) led aircraft field sampling of carbon dioxide (CO_2), carbon monoxide (CO), and methane (CH_4) over the New York City, Boston, Philadelphia, and the Baltimore-Washington metro areas during spring of 2020 and compared these observations with similar aircraft sampling carried out in 2018. Analysis of the ARL and GML aircraft measurements placed constraints on pandemic-related decreases in emissions of CO_2 and CO from motor vehicles and other sources. ARL's analysis of their ground-based measurements of black carbon (i.e., soot) showed that heavy-duty diesel trucks emitted less black carbon during the pandemic, possibly as a result of reduced traffic jams compared with typical conditions. *[Ren and Luke; Lopez-Coto et al.]*

- During 2020, GML increased sampling of tropospheric ozone profiles from its stations in Boulder, Colorado, and Trinidad Head, California, and maintained regular sampling of surface ozone at 4 other baseline monitoring sites. NOAA's ozone observations, along with additional measurements from surface sites, vertical profiles, commercial aircraft, and lidar were analyzed by GML and CSL scientists, in collaboration with researchers in Europe. This team documented anomalously low concentrations of tropospheric ozone in 2020 relative to the long-term average trend of increasing ozone levels across the Northern and Southern Hemispheres. Subsequent modeling studies indicate that the 2020 tropospheric ozone declines are consistent with air pollutant emissions decreases across the Northern Hemisphere resulting from pandemic restrictions. *[Chang et al.]*
- CSL made regular lidar measurements of ozone vertical distributions in Boulder, Colorado, during spring 2020 and compared them to the group's ozone lidar observations during the same time period in previous years and to surface ozone observations made by regulatory agencies. The CSL team concludes that pandemic-related changes to emissions likely had only small impacts on springtime 2020 surface ozone levels in the Denver-Boulder area. *[Langford et al.]*
- The OAR Climate Program Office's Atmospheric Chemistry, Carbon Cycle and Climate (AC4) Program organized and supported intensive field measurements of air pollutants, greenhouse gases, and aerosols by a number of NOAA's academic partners in several urban areas in the continental U.S. and Canada. Like their NOAA colleagues, these AC4-funded investigators found profound decreases in air pollutant emissions and ambient concentrations during the springtime lockdown period and the persistence of these declines through the summer of 2020. *[Kopacz]*
- NESDIS scientists and their collaborators analyzed observations made by NOAA satellite instruments (VIIRS and OMPS) and those of its European partners (TROPOMI) and quantified pandemic-related changes to aerosol particulate matter (PM) and its precursors across the world. The NESDIS analysis found that PM levels decreased in 2020 relative to the business-as-usual conditions of 2019 in the U.S., western Europe, China and India. NESDIS demonstrated that the variability in PM across different countries and between major cities within each country could be explained by pandemic-related decreases to human-caused emissions of nitrogen oxides (NOx) and sulfur dioxide, both of which are precursors for PM, along with variations in dust and smoke from agricultural burning and wildfires. Through this analysis, NESDIS demonstrated the robustness of NOAA's satellite observational record to track changes in economic activity. *[Kondragunta et al.]*
- CSL produced a data archive and analyses of several key air pollutants observed by U.S. air quality monitoring networks, providing additional context for the field intensive datasets collected by NOAA scientists and their partners. *[Brown et al.]*
- CSL organized biweekly teleconferences in partnership with NASA and sessions at the American Geophysical Union Meetings in 2020 and 2021 to discuss the above-mentioned observations and analyses. *[Brown et al.]*
- CSL scientists, working with colleagues in Germany, carried out a review of over 150 peer-reviewed scientific papers that documented changes in emissions and ambient

levels of six key air pollutants during the period of greatest mobility restrictions around the world. *[Brown et al.]*

- Numerous peer-reviewed papers describing the above results are currently in preparation or have been published in scientific journals by NOAA scientists and their collaborators. *[Brown et al.; Ren and Luke; Chang et al.; Kopacz; Kondragunta et al.]*

SUMMARY OF NOAA EFFORTS ADDRESSING OBJECTIVE 2

NOAA scientists and their collaborators carried out a series of modeling studies documenting changes to emissions during the pandemic and describing the resulting impacts on ozone, particulate matter, and the Earth's radiative balance.

A summary of this work and its key findings include:

- CSL produced a set of near-real-time emissions inventories suitable for air quality modeling studies that represent the business-as-usual conditions of 2019 and the major perturbations to human-caused emissions during the 2020 pandemic period. CSL's near-real-time inventories are more up-to-date, and likely also more accurate, representations of U.S. emissions than the official regulatory inventories produced only every 3 years by the U.S. Environmental Protection Agency. CSL continues to update these inventories through the present time, and these datasets are used to drive a number of model analyses described below. *[Schnell et al.]*
- ARL and CSL analysis of CSL's near-real-time inventory for NOx, a key precursor of near-surface ozone and PM, showed that the pollutant decreased by up to 50% during the peak of the lockdown period from March to April of 2020. NOx emissions gradually returned to nearly pre-pandemic levels later in 2020. *[Schnell et al.; Campbell]*
- A numerical model similar to the one used for NOAA's operational air quality forecasts showed a variable response of continental U.S. near-surface ozone levels to pandemic-related NOx emissions changes in spring and summer 2020. This mix of near-surface ozone decreases and increases results from several factors, including the complex chemistry of ozone precursors, the dynamic nature of emissions changes as the pandemic progressed, and the emergence of wildfires in late summer 2020 as an additional source of emissions. *[Campbell]*
- OAR's Global Systems Laboratory (GSL) used CSL's near-real-time emissions for the 2020 pandemic period and for 2019 business-as-usual conditions as input to an experimental numerical model that simulated near-surface ozone and PM across a domain including North America, the Arctic, and parts of Europe, Asia, and South America. The GSL model simulations demonstrated that the pandemic-induced emissions reductions produced cumulative impacts on near-surface ozone and PM. Similar to ARL's findings, the GSL simulations showed both increases and decreases in near-surface ozone and PM in response to the pandemic-related emissions changes. *[Schnell et al.]*
- An inverse modeling analysis of airborne observations collected by ARL and GML over several Northeast US metropolitan areas before and during the pandemic demonstrated long-term declines in urban CO emissions that differed substantially from regulatory

inventory estimates. These analyses showed decreases in urban CO and CO_2 emissions in 2020 resulting from pandemic-related economic changes, while urban CH_4 emissions were not significantly impacted by the pandemic in comparison with previous years. *[Lopez-Coto et al.; Ren and Luke]*

- A team led by OAR's Geophysical Fluid Dynamics Laboratory (GFDL) investigated the impacts of the worldwide reduction in aerosol emissions resulting from the pandemic, using simulations with GFDL's state-of-the-art atmospheric model to separate the effects of meteorology and emissions. Pandemic-related emission reductions accounted for approximately one-third of the large, precipitous decrease in reflected sunlight that occurred when the sky was not covered by clouds over the East Asian Marginal Seas in March 2020. The remainder of the observed decrease in reflected clear-sky sunlight over this region was attributed to weather variability and long-term emission trends. *[Ming et al.]*
- Numerous peer-reviewed papers describing the above results are currently in preparation or have been published in scientific journals by NOAA scientists and their collaborators. *[Schnell et al.; Campbell; Ren and Luke; Lopez-Coto et al.; Ming et al.]*

SUMMARY OF NOAA EFFORTS ADDRESSING OBJECTIVE 3

Scientists supported by NOAA collaborated with researchers at health and epidemiological agencies to assess the extent that air pollution and climate have quantifiable and predictive human health repercussions, with the goal of improving predictive capabilities for vector-borne diseases like COVID-19.

A summary of this work and its key findings include:

- An interdisciplinary team of scientists from Princeton University, funded through NOAA GFDL's cooperative agreement with Princeton, and the National Institutes of Health used a climate-dependent epidemic model to simulate the pandemic, probing different scenarios based on what is known about the role seasonal variations have on the occurrence of similar viruses. In these simulations, climate became a mitigating factor only when large portions of the human population were immune or resistant to the virus. Their simulation accounting for the impact of control measures such as social distancing suggested that the longer these measures are in place and are able to slow the transmission of COVID-19, the more sensitive the virus becomes to warmer weather. *[Baker et al.]*
- Outbreaks of West Nile Virus (WNV), the leading cause of mosquito-borne disease in the continental U.S., are strongly influenced by environmental and atmospheric drivers. A small but important fraction of WNV infections result in the neuroinvasive form of the disease that can cause encephalitis, meningitis, and acute flaccid paralysis. A postdoctoral research working jointly with OAR GSL and the Centers for Disease Control (CDC) carried out 2 studies aimed at linking environmental/atmospheric and epidemiological science to improved prediction of vector-borne diseases like WNV and COVID-19. She first investigated the current use and value of weather/climate data in WNV predictions through the lens of the CDC's 2020 WNV Forecasting Challenge, in which various forecast predictions of the total county-level WNV neuroinvasive cases in

the continental US in 2020 were evaluated for accuracy and model characteristics and contextual factors were assessed. Based on her finding that a specific type of statistical model compared well with the predictions of more sophisticated forecast models, the postdoctoral researcher then explored the relationship between WNV neuroinvasive cases and near-surface temperature and precipitation conditions. Future directions of this specific project include quantifying the impact of environmental conditions on disease transmission potential and integration of NOAA weather forecasts into regional-scale early-warning predictions and short-term predictions on the sub-county scale. *[Holcomb et al.]*

- Peer-reviewed papers describing the above results are currently in preparation or have been published in scientific journals by these scientists. *[Baker et al.; Holcomb et al.]*

SUPPORTING MATERIAL

This section contains detailed reports describing research carried out by NOAA scientists and their collaborators to address each of the above objectives.

Pages	Authors	Title
7-13	Brown et al.	Research Activities in Response to Emissions Reductions Following the Onset of the COVID-19 Pandemic
14-17	Ren and Luke	NOAA/ARL's Measurements and Data Analyses during the COVID-19 Pandemic
18-19	Lopez-Coto et al.	East Coast Outflow – COVID (ECO-COVID) Aircraft Campaign
20-23	Chang et al.	NOAA CSL/GML/CIRES Research on COVD-19 Impacts on Tropospheric Ozone
24-25	Langford et al.	Analysis of surface ozone changes in the Denver-Boulder area during the COVID-19 lockdown
26-29	Kopacz	AC4 input on COVID-related research
30-41	Kondragunta et al.	Markers of Economic Activity in Satellite Data: COVID-19 Lockdown Impact on Air Quality
42-44	Campbell	Impacts of the COVID-19 economic slowdown on ozone pollution in the U.S.
45-49	Schnell et al.	Modeling studies of emissions and air quality forecasts during the pandemic period and comparisons to business-as-usual conditions
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52-53	Baker et al.	Susceptible Supply Limits the Role of Climate in the Early SARS-CoV-2/COVID-19 Pandemic
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Research Activities in Response to Emissions Reductions Following the Onset of the COVID-19 Pandemic

Steven Brown, Carsten Warneke, Jessica Gilman, Jeff Peischl, Ken Aikin, Matt Coggon, Ann Middlebrook, Mike Robinson, Chelsea Stockwell, Sunil Baidar, Drew Rollins (Tropospheric Chemistry Program, NOAA Chemical Sciences Laboratory (CSL); CIRES, University of Colorado)

The COVID-19 pandemic began in late 2019 and spread widely in the U.S. beginning in March of 2020. Public health measures intended to limit the spread of the disease in the U.S. and globally led to unprecedented emissions reductions. Several programs at NOAA CSL responded with research efforts to exploit this unique scientific opportunity to quantify the impacts of these reductions on atmospheric composition, air quality and climate at regional, continental and global scales. This report summarizes activities led by the Tropospheric Chemistry program at CSL, which occurred in collaboration with other CSL programs, NOAA laboratories and the external research community both nationally and internationally.

1. **The 2020 COVID-AQS Study**

Investigators from several CSL programs conducted two intensive field studies from the NOAA David Skaggs Research Center in Boulder, CO during calendar year 2020, collectively termed the COVID Air Quality Study (2020 COVID-AQS). The measurements took place at the Boulder laboratories since it was the only logistically feasible location where a campaign could take place in the midst of a pandemic. The first intensive period was March 30 – June 30, 2020, and coincided with the deepest reductions in mobility as measured by metrics such as google mobility or local traffic counts. The second intensive took place from July 21 – August 31, 2020, and was motivated by the recognition of ongoing emissions reductions during the photochemically active summer period. The second intensive coincided with a portion of the anomalously active fire season in western North America in late 2020.

The motivation for COVID-AQS was to understand the potential future of urban air quality that may result from continuing reductions in emissions of urban greenhouse gases (GHG), nitrogen oxides (NO_x), carbon monoxide (CO), and gasoline-related volatile organic compounds (VOCs). These shifts may cause other emission sectors, such as biomass burning, agriculture, biogenics, oil and gas production, and volatile chemical products (VCPs) to have a greater relative impact on air quality. Therefore, atmospheric composition changes during the COVID-19 outbreak may provide unique insight into a potential future in which decarbonization and emission reductions take place in U.S. cities to address climate change and mitigate poor air quality.

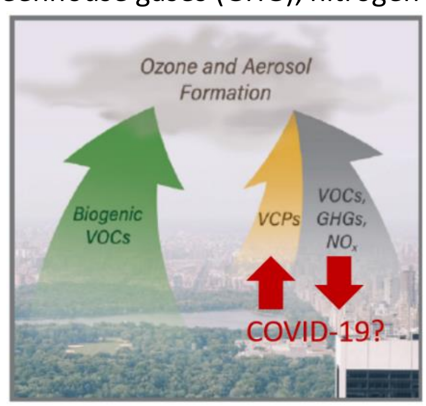


Table 1 below summarizes the measurements made during COVID-AQS from the DSRC. They include in-situ speciated VOCs, CO, NO_x, O_3, greenhouse gases, aerosol size distributions and speciated aerosol composition. In addition, a lidar instrument operated by the Atmospheric Remote Sensing program measured O_3 vertical distributions (described separately).

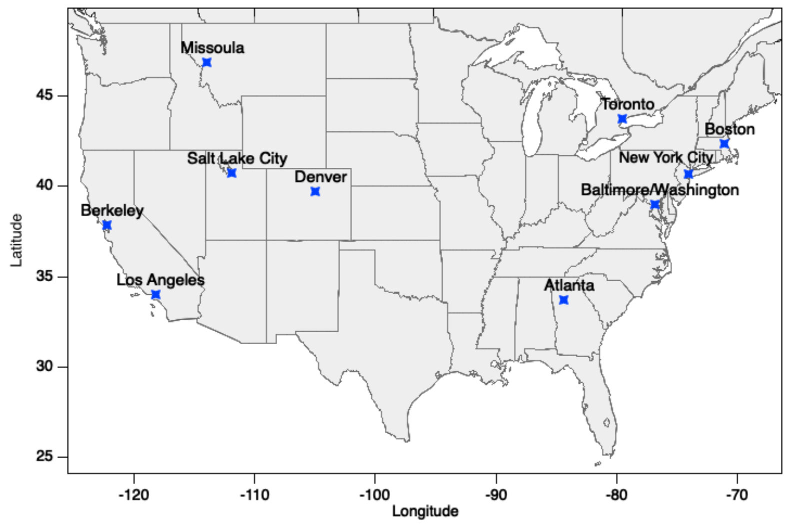
Table 1: COVID-AQS Measurements

Parameter	Instrument	Investigators
Speciated VOCs	Time of Flight Proton Transfer Reaction Mass Spectrometer (ToF PTRMS)	Carsten Warneke Matt Coggon Chelsea Stockwell
Speciated VOCs	Gas Chromatography – Mass Spectrometry (GC-MS)	Jessica Gilman Aaron Lamplugh
Nitrogen Oxides (NO_x**)**	Chemiluminescence monitor	Steve Brown Mike Robinson Delphine Farmer (CSU)
Nitrogen Oxides (NO_x**)**	Custom built LIF with photolytic converter for NO_2	Drew Rollins Pamela Rickley (ACCP)
Ozone	Commercial UV monitor	Raul Alvarez
Carbon Monoxide, Nitrous Oxide (CO, N_2O**)**	ICOS instrument	Jeff Peischl
Greenhouse gases (CO_2, CH_4**)**	Cavity ring down spectrometer	Jeff Peischl
Aerosol Size Distributions	Ultra High Sensitivity Aerosol Spectrometer (UHSAS)	Ann Middlebrook Chuck Brock (APP)
Speciated Aerosol Composition	Aerosol Mass Spectrometer (AMS)	Ann Middlebrook Jim Roberts Kathy Hayden (Environ Canada)
3-D Winds and Mixed Layer Height	Doppler Lidar	Sunil Baidar Alan Brewer (ARS)

The goals of COVID-AQS were as follows:
1. Source apportionment of in-situ VOC and satellite NO_x measurements to transportation and VCPs
2. Assessment of satellite NO_2 and formaldehyde columns over urban areas utilizing retrievals from OMPS on Suomi-NPP, Sentinel-5P TROPOMI, and Aura OMI satellite instruments (in collaboration with the Regional Chemical Modeling group, progress described elsewhere)
3. Comparison to extensive past CSL in situ measurements, including VOCs and O_3 and aerosol profiles
4. Updating CSL's U.S. air quality model with newly evaluated COVID-19 emissions (in collaboration with the Regional Chemical Modeling group, progress described elsewhere)
5. Archiving local and regional air quality monitoring data for measurement and model comparison
6. Doppler lidar wind and mixing height observations provide information on transport patterns and the depth of the volume that O_3 precursors are mixed into. In addition, spatially resolved, nearly horizontal, scanning data can be used to determine airmass trajectories for in-situ sensors, and evaluating model meteorology.

2. The COVID-AQS Network

NOAA CSL, in collaboration with the AC4 program, organized a set of nationwide measurements to complement the detailed measurements occurring in Colorado. The intent was to support efforts that would go well beyond routine air quality monitors to better understand detailed changes in emissions and chemistry that would quantify air quality changes during COVID. The map below shows the network, which included major urban areas across the U.S. Detailed measurements of speciated VOCs from either PTRMS or GC-MS instruments, similar to those in Boulder, were available in the Los Angeles Basin, Missoula MT, Atlanta GA, Toronto Ontario and the New York Region. Speciated aerosol composition was available in Atlanta, GA. Greenhouse gas monitoring networks were available in Berkeley, CA, Salt Lake City UT and the New York Region.

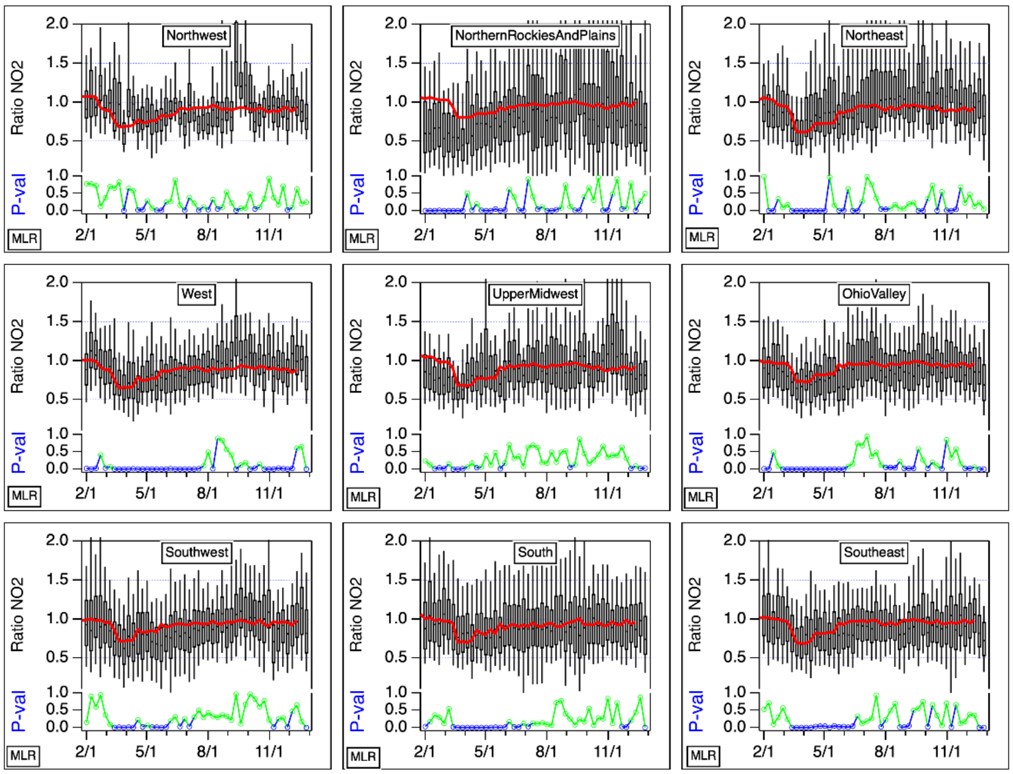


The AC4 program supported collaborators in this network. The list of investigators, their instruments, and scientific results will appear in a separate report from Monika Kopacz.

3. Nationwide COVID Data Archive

Ken Aikin at NOAA CSL compiled data throughout 2020 of four major pollutants from the U.S. air quality monitoring network, including NO_2, CO, O_3 and $PM_{2.5}$. These pollutants were then sorted into the continental U.S. air quality regions as defined (principally) by the EPA. Data for each site were then used to construct weekly averages throughout 2020 to assess changes that occurred with changing emissions. The 2020 data were then compared to historical data spanning either 5 or 10 years (i.e., 2010-2019 or 2015-2019). Historical data were fit to a series of meteorological and calendar variables (i.e., month of year, weekday vs weekend) to construct expected values for 2020. The figure below shows the result for NO_2 (similar plots are available in map format, and as a nationwide comparison). The grey points and bars show averages, together with box and whisker plots (10^{th}, 25^{th}, 50^{th}, 75^{th}, 90^{th} percentiles) showing the distributions of the ratio of the observed to predicted NO_2. The points at the bottom show the p-values and statistical significance, with blue points indicating a statistically significant deviation from the prediction. The overlaid red line shows the reduction in motor vehicle combustion emissions (the primary source of NO_2) from the FIVE inventory. Six of the regions show reductions in NO_2 that are significant and occur during the period of the largest predicted reduction from the inventory. Thee others (Northwest, Northern Rockies, Upper Midwest) show non-significant reductions, or reductions not coincident with the pandemic mobility changes. The Northwest region has very few monitors and so does not have statistics as robust as the others.

Data from this analysis are available to the collaborators in the nationwide network described above. Results of this analysis were presented at the fall 2020 AGU meeting and are currently in preparation for publication.

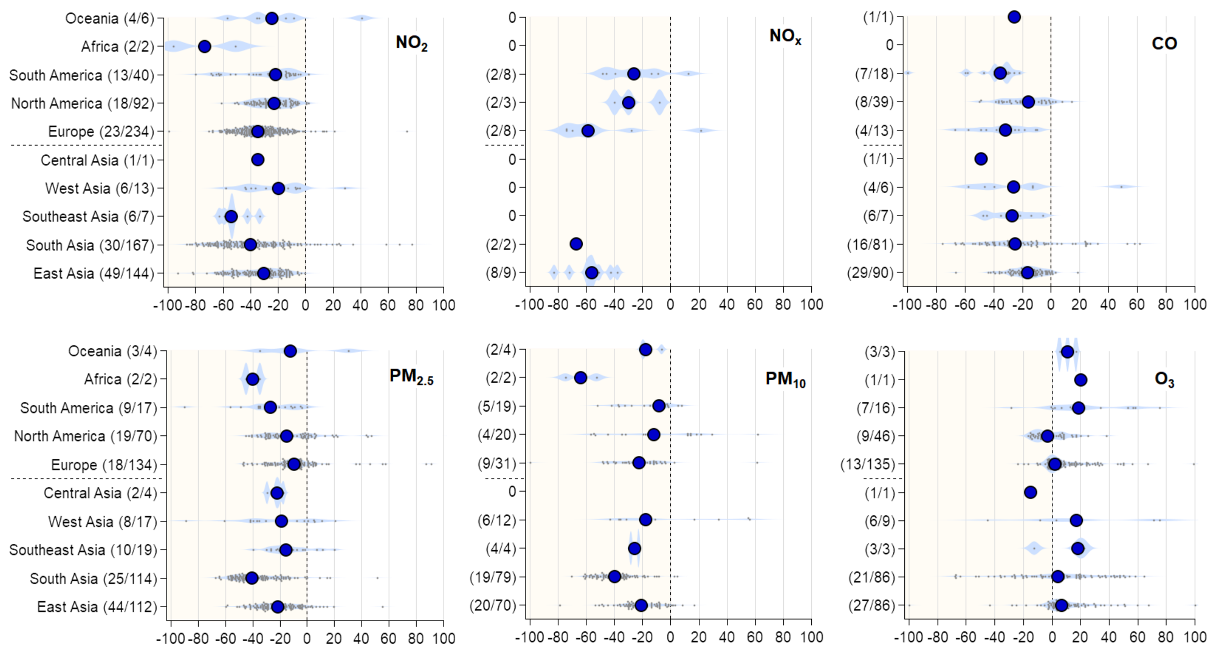


4. Review of Global COVID-19 Air Quality Impacts

As the pandemic and associated mobility restrictions evolved in 2020, it became clear that there was a large body of literature emerging that quantified the changes in various regions of the world. Indeed, within the first 7 months after the onset of the pandemic in early March in the U.S., there were already more than 150 peer-reviewed papers in the scientific literature. Investigators at NOAA CSL (led by Jessica Gilman, Steve Brown and Brian McDonald), in collaboration with a partner laboratory, the Forschungszentrum Jülich (FZJ), Germany, undertook a rapid review of this early literature. The goal of the review was twofold. First, to synthesize a first look at the data to discern emerging analysis of trends in major pollutants across all of the world's regions. And second, to critically assess these analyses, some of which were done very quickly after the beginning of the emissions reductions, to understand their quality and to make recommendations for best use of the data in future analyses.

The review paper, Gkatzelis *et al.*, was published in Elementa in early 2021. A key figure from that paper is shown below. It shows the distributions of ambient mixing ratio changes (bottom axis, in percent) for six major pollutants during the period of greatest mobility restriction in each region as determined by the global stringency index. The figure shows expected reductions in combustion related primary pollutants such as NO_x and CO, but increases in some regions in O_3 and decreases in most regions in $PM_{2.5}$.

CSL's partners at FZJ in Germany have established a database where further analyses of air quality and atmospheric composition from the COVID period can be submitted for inclusion in future reviews. The CSL web site contains a link to this database.



5. Conference Organization

NOAA CSL, in collaboration with the NOAA AC4 Program (Monika Kopacz) and the NASA Tropospheric Composition Program (Barry Lefer) organized a series of bi-weekly teleconferences from mid 2020 through 2021 to discuss emerging results from scientific analyses from the atmospheric composition changes during the COVID-19 pandemic.

Scientists at NOAA CSL and the Tropospheric Chemistry Program organized sessions at each of the AGU meetings following the COVID-19 pandemic, in fall of 2020 and 2021. These sessions and their organizers are listed below. Session, workshop and conference organization is anticipated in the future as further analysis of the atmospheric impacts of the COVID-19 pandemic enter the scientific literature.

Fall 2020 AGU meeting

Session Name: Air Quality during the COVID-19 Pandemic: Responses to Emissions Reductions and the Role of In Situ Data

Conveners: Jessica Gilman (NOAA CSL, USA), Steven Brown (NOAA CSL, USA), Armin Wisthaler (University of Oslo, Norway), Bin Yuan (Jinan University, China)

Fall 2021 AGU meeting

Session Name: COVID-19 Lockdowns: What Have We Learned About Air Pollution and Carbon Emissions from Local to Global Scale?

James Lee (National Center for Atmospheric Science, United Kingdom), Fei Lui (NASA Goddard, USA), Jessica Gilman (NOAA CSL, USA), Pieternel Levelt (KNMI, The Nethernlands)

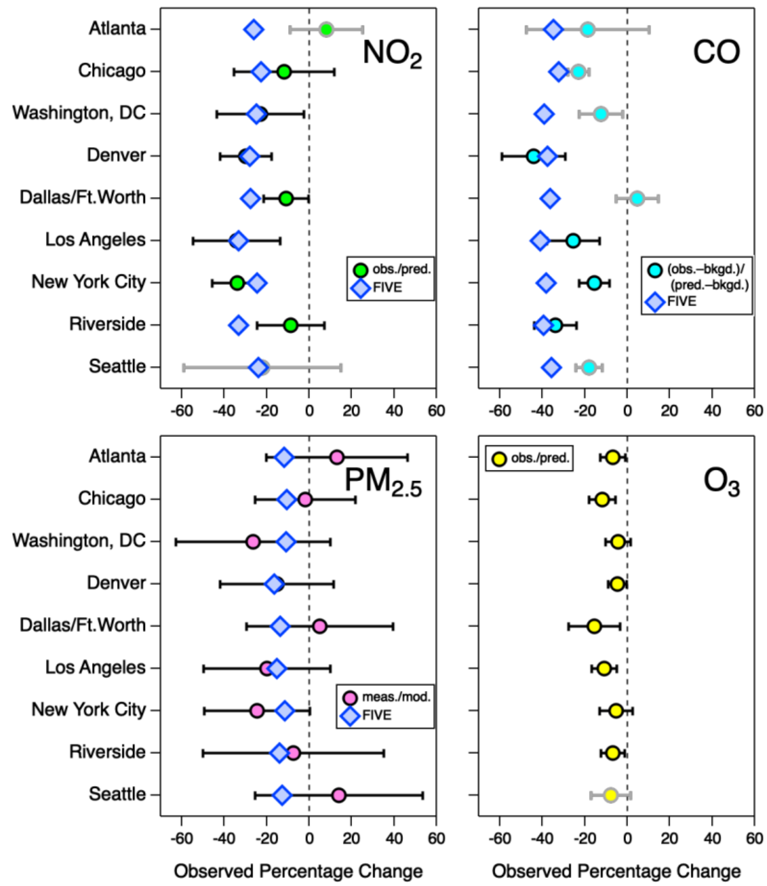
6. Analysis, Papers and Presentations

The Tropospheric Chemistry Program presented results from the COVID-AQS study and other activities listed above at the bi-weekly NOAA-NASA teleconferences as well as the two AGU meetings. First-author Tropospheric Chemistry presentations appear below.

- Fall AGU meeting 2020:
  - Ann Middlebrook: An Examination of the Impact of Local Shelter-in-Place Orders on Atmospheric Aerosol Mass and Chemical Composition in Boulder Colorado During the COVID-19 Pandemic
  - Aaron Lamplugh: COVID-AQS: A rapid response study to monitor air-quality impacts of COVID-19 in Boulder, CO
  - Ken Aikin: Discerning changes in primary and secondary pollutants due to COVID-19 amid natural variability and exceptional events by using monitoring network data
  - Jeff Peischl: A comparison of ambient measurements of NOX, CO,O3, and PM2.5 during the COVID-19 pandemic with a climatological multiple linear regression model for various U.S. cities
- Fall AGU meeting 2021:
  - Aaron Lamplugh: Positive matrix factorization analysis of VOC emissions in Boulder, CO during COVID-AQS 2020
  - Jeff Peischl: A comparison of ambient measurements of NO_x, CO, O_3 and $PM_{2.5}$ during the COVID-19 pandemic with a climatological multiple linear regression model for various U.S. cities

Several papers are currently in the preparation stage based on these analyses as well. These are associated with the presentations by Ken Aikin, Jeff Peischl, Aaron Lamplugh and Ann Middlebrook above. In addition, 2020 was an active fire season, and measurements taken during the second phase of COVID-AQS were heavily fire impacted, providing the potential for analysis of fire impacts on urban air quality. An analysis led by Matt Coggon and Pamela Rickly is using data from COVID-AQS to quantify fire impacts on urban ozone.

A figure from Peischl *et al.* is shown at right. This shows the percent change in four pollutants in nine U.S. cities during the strictest part of the lockdowns using a format similar to the Gkatzelis Elementa paper above. The methodology follows that of the data set from analysis shown above from Ken Aikin for the EPA regions. The circles show the ratio of observed to expected pollutant levels, while the diamonds show the change predicted from the FIVE emissions inventory.



NOAA/ARL's Measurements and Data Analyses during the COVID-19 Pandemic

PIs: Xinrong Ren and Winston Luke, NOAA/ARL
Collaborators: NOAA/GML&CSL, NESDIS/STAR, UMD, NIST, MDE, and Stony Brook Univ.

In April 2020 in the wake of the COVID-19 pandemic and economic disruption, scientists at NOAA/ARL began to make aircraft and surface measurements of greenhouse gases (carbon dioxide (CO_2) and methane (CH_4)) and short-lived air pollutants to pursue the objective of "observe, aggregate, and quantify the response of aerosols, radiatively active gases, and their radiative effects that have occurred in response to the pandemic-related decrease in transportation and manufacturing". From April to August 2020, we conducted a total of 20 research flights over the Baltimore-Washington and New York City areas (Figure 1). In addition, we also deployed an instrument to measure CO_2 and CH_4 at the I-95 near-road site between Baltimore and Washington, DC in collaboration Maryland Department of Environment (MDE).

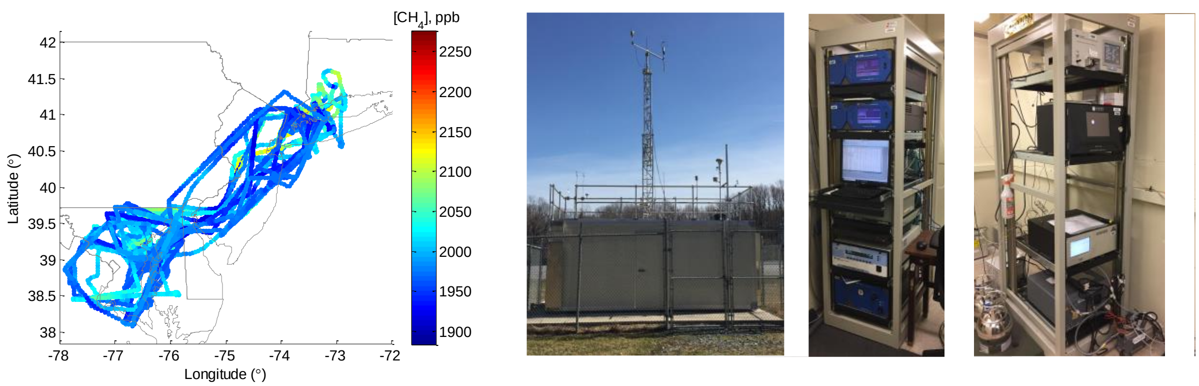


Figure 1. *Left:* flight tracks colored with observed methane for the 20 research flights conducted between April and August 2020. *Right:* some pictures showing the instrumentation at the I-95 near-road air quality monitoring site in Maryland where we deployed an Picarro analyzer to measure greenhouse gases.

We investigated the urban emissions of CO_2 and CO from the Balt-Wash area during the COVID-19 pandemic. We quantified the reductions in the emission of CO_2 and CO during the COVID-19 pandemic using the aircraft-based mass balance approach. Our mass balance estimates indicate that the mean CO_2 emission rate over the Balt-Wash area declined by about 32% in April and by 29% in May 2020, relative to the February mean. Our estimate of the mean CO emission rate declined by 37% in April and 30% in May, relative to the February mean (Figure 2) (*Ahn et al.*, in preparation). For both CO_2 and CO, the on-road transportation sector was determined to be the largest contributor to reduced emission rates in April 2020, followed by the residential/commercial/industrial (RCI) sector.

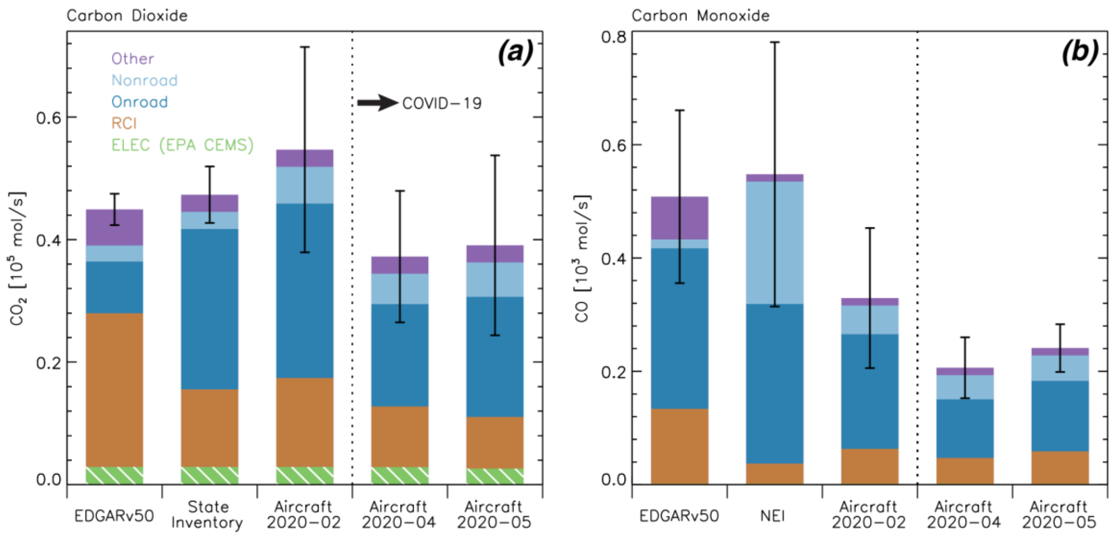


Figure 2. Emission rates of CO_2 (a) and CO (b) over the Baltimore-Washington, D.C. area. For each panel, the two leftmost estimates are based on bottom-up emission inventories (i.e., EDGARv50, the state of Maryland GHG inventory 2017, National Emissions Inventory 2017) and the three rightmost estimates are from the aircraft-based mass balance approach for February, April, and May 2020. The vertical dashed line distinguishes the time before (left to the dashed line) and after (right to the dashed line) the date when Maryland and D.C. governments first ordered the closure of recreational facilities to slow the spread of COVID-19. For the comparison of bottom-up and top-down emission estimates, bottom-up estimates are scaled to match the spatiotemporal footprint of aircraft observations. The error bar indicates 1σ uncertainty range assigned to each estimate. The bottom-up estimates are colored by major source sector as provided by each inventory. The aircraft top-down estimate of CO_2 and CO emissions during February 2020 are apportioned to major source sectors by relating observed emission reductions during COVID-19 pandemic to change in source sector activity-metrics such as traffic counts and natural gas.

We also analyze airborne measurements of atmospheric CO concentration from 70 flights conducted over six years (2015−2020) using an inverse model to quantify the CO emissions from the Washington, DC, and Baltimore metropolitan area. We found that CO emissions have been declining in the area at a rate of ≈−4.5% yr^{-1} since 2015 or ≈−3.1% yr^{-1} since 2016 (Lopez-Coto et al., 2022). Our results also show that the trend derived from the national emission inventory (NEI) agrees well with the observed trend, but that NEI daytime-adjusted emissions are about 50% larger than our estimated emissions. In 2020, measurements collected during the shutdown in activity related to the COVID-19 pandemic indicate a significant drop in CO emissions of 16% relative to the expected emissions trend from the previous years, or 23% relative to the mean of 2016 to February 2020 (Figure 3). Our results also indicate a larger reduction in April than in May. Last, we found that this reduction in CO emissions was driven mainly by a reduction in traffic.

The results from the I-95 near-road site highlight the significance of traffic flow on black carbon (BC) emissions from diesel trucks. Strong reductions in on-road vehicle counts in April 2020 relative to prior years resulted in the near-elimination of traffic jams and a 14% increase in the average vehicle speed. Significant improvements in traffic flow led to a ~27% decrease in both ΔBC/ΔCO and $\Delta BC/\Delta CO_2$ in April 2020 relative to prior Aprils (Hall et al., in preparation). The reduction of a factor of ~two in ΔBC/ΔCO, $\Delta BC/\Delta CO_2$, and the fraction of compression-ignited vehicles from weekdays to weekends is consistent with trucks as the dominant emitter of BC emissions. A likely explanation for the lower $\Delta BC/\Delta CO$ and $\Delta BC/\Delta CO_2$, and thus BC emission, in April 2020 is that diesel trucks emitted far less BC than under typical, congested traffic conditions with frequent acceleration. This suggests that elimination of traffic jams could reduce highway BC emissions from diesel trucks by ~70% (i.e., to ~30% of normal emissions). Further reductions in mobile BC emissions may be possible with diesel engine designs that reduce turbocharger lag. Assessing how air quality models perform given drastic changes in specific variables such as the number of on-road vehicles or stop-and-go traffic can help to improve the accuracy of future modeling endeavors.

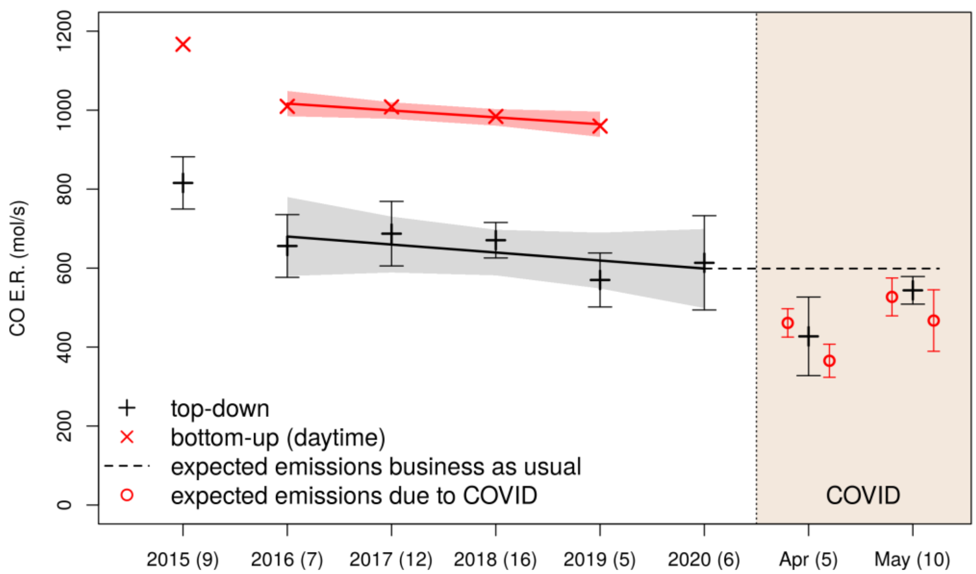


Figure 3. CO posterior (top-down) emissions rates for DC/Baltimore by year compared to EPA bottom-up estimates (scaled-up to represent daytime values) and annual trends. The COVID period is also shown separated between 16 - 30 April 2020 and 1 - 16 May 2020. The dashed line represents the expected emissions for 2020 extrapolated from the top-down trend and the red circles are expected emissions after accounting for mobile sector reductions (on-road only and on-road+non-road) due to mobility changes during the COVID lock-down using the extrapolated top-down trend as reference.

Peer-reviewed publication

Lopez-Coto, I., X. Ren, A. Karion, K. McKain, C. Sweeney, R. R. Dickerson, B. McDonald, D. Y. Ahn, R. J. Salawitch, H. He, P. B. Shepson, and J. R. Whetstone, Carbon monoxide emissions from the Washington, D.C. and Baltimore metropolitan area: Recent trend and COVID-19 anomaly detection, Environ Sci. Technol., 56(4), 2172-2180, 2022. doi: 10.1021/acs.est.1c06288.

Manuscriptions in preparation

Anh, D., X. Ren, P. Stratton, et al., Emissions of CO_2 and CO in the Baltimore, MD-Washington, D.C. area: Lessons learned from aircraft campaign during COVID-19 pandemic, in preparation, 2022.
Ren, X., A. Goodell, P. Stratton, H. Daley, R. Dickerson, et el., Methane and black carbon emissions from New York City metropolitan area during COVID-19 in 2020, in preparation, 2022.
Hall, D., X. Ren, R. Dickerson, et al., Response of near-road inferred vehicular emissions to changes in traffic patterns due to travel restrictions in the COVID-19 pandemic, in preparation, 2022.

East Coast Outflow – COVID (ECO-COVID) Aircraft Campaign

Israel Lopez-Coto, Colm Sweeney, Genevieve Plant, Kathryn McKain, Xinrong Ren, Anna Karion, Eric Kort, Brian McDonald, Sharon Gourdji, John B. Miller, Russell R. Dickerson, Paul B. Shepson, Geoffrey Roest, Kevin Gurney, Ariel Stein, James R. Whetstone

The Carbon Cycle Aircraft Program from NOAA's Global Monitoring Laboratory (GML) took advantage of an existing dataset and aircraft measurement capability to compare emissions of CO_2, CH_4 and CO from four large metropolitan regions in the Northeastern US (New York, Boston, Philadelphia and Baltimore/DC) before and during the shutdown precipitated by the initial COVID-19 outbreak during April/May of 2020. The first of two aircraft campaigns was performed in April and May of 2018 and consisted of 20 flights. The second campaign involved 28 flights in April and May of 2020 (Figure 1). Both campaigns consisted of taking in situ measurements of CO_2, CH_4 and CO in addition to winds, temperature and relative humidity. The measurements were performed both upwind and downwind of these metropolitan areas above and below the boundary layer to capture enhancements in CO_2, CH_4 and CO as a result of local emissions.

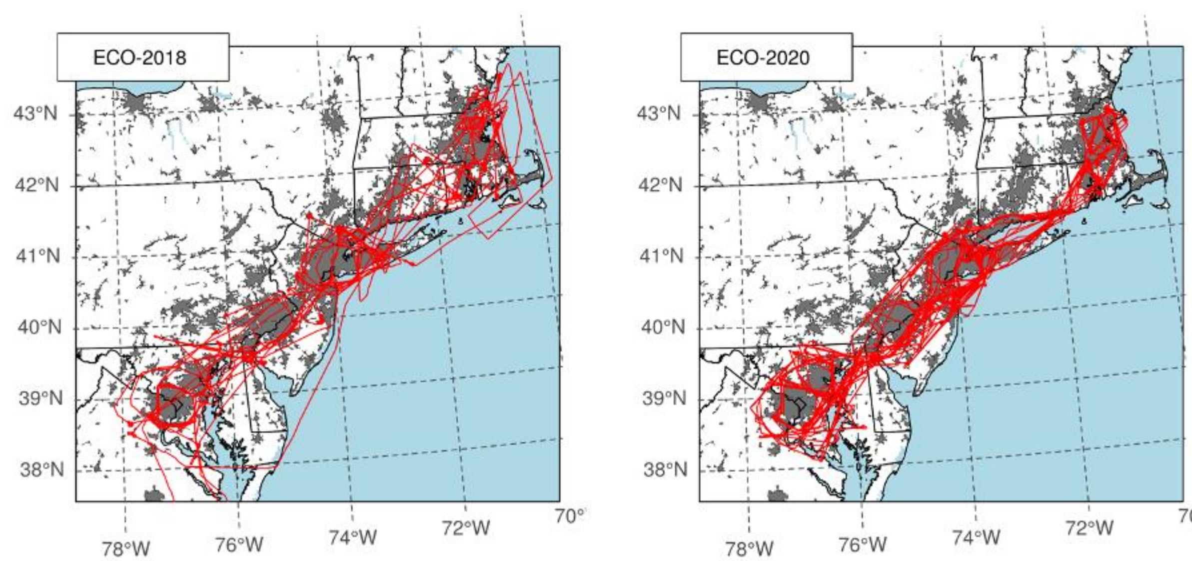


Figure 1. Flight tracks for NOAA Aircraft campaign in 2018 (20 flights 04/08/2018 – 05/12/2018) and 2020 (28 flights in 04/16/2020 – 05/16/2020).

The Aircraft measurements made during these East Coast Outflow (ECO) campaigns were then incorporated into an inverse analysis system using the NOAA HYSPLIT model and several different atmospheric transport models to calculate the surface influence of each aircraft measurement. The inversion system used to calculate emissions in these metropolitan regions was particularly unique in its ability to estimate upwind (background) concentrations of each flight as a part of a two-step process which used lower resolution transport models and prior estimates of CO_2, CH_4 and CO to optimize upwind concentrations. These upwind concentration estimates were incorporated into a higher resolution inverse modeling system to calculate the enhancements of each trace gas and the resulting flux from the metropolitan region of interest.

This analysis resulted in the following findings:

1) Systematic reductions in CO_2 and CO emissions for the four urban areas were observed in April 2020 compared to April 2018.

2) Signs of partial recovery were observed for the four urban areas in May 2020 with respect to April 2020.

3) The reductions in CO_2 is consistent with expected reductions due to traffic.

4) Methane emissions were not significantly different during the 2018 and 2020 campaigns

5) Biosphere emissions/uptake impacted the most southern cities and our methodology was able to account for it. However, further work needs to be done to see if we can learn anything more using C-14 of CO_2 given the uncertainty in the impact that biosphere has on CO_2 emissions.

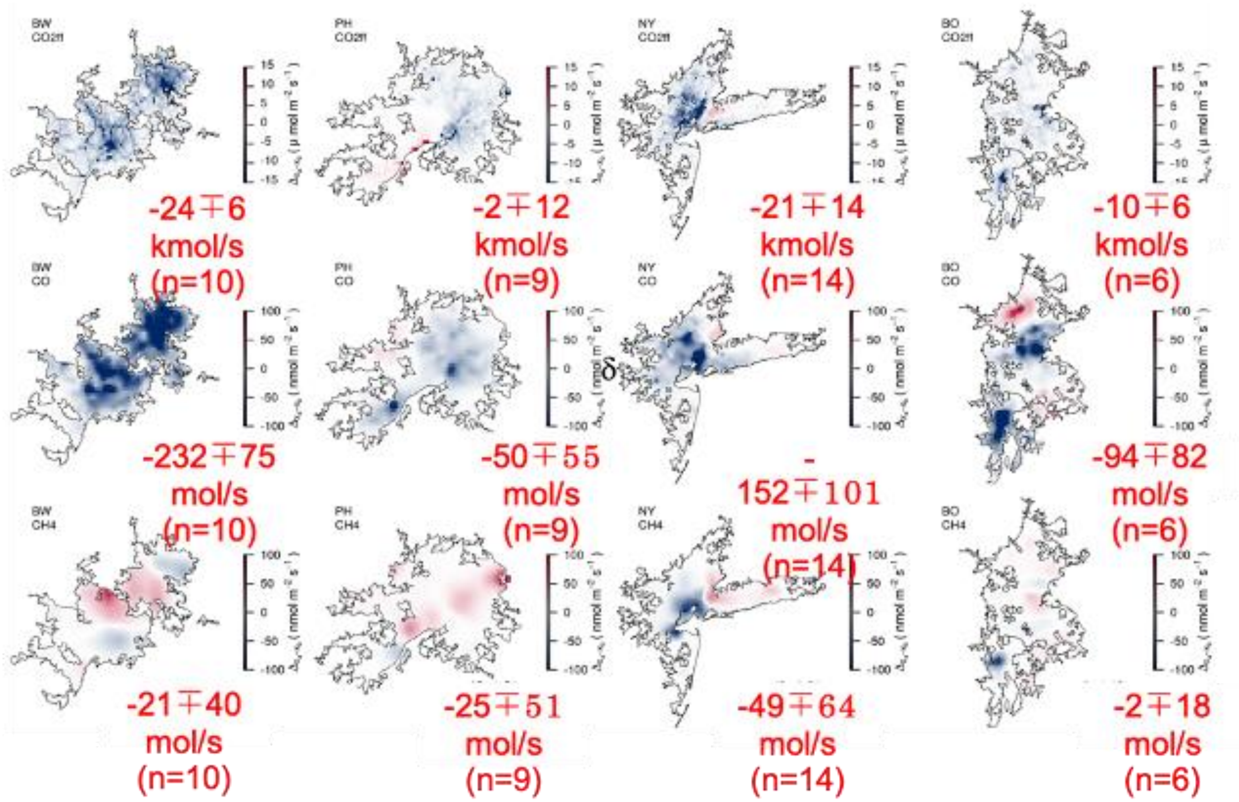


Figure 2. Emission differences (2020-2018) between April 2018 and 2020 for CO_2, CH_4 and CO. Top row is the estimated difference in fossil fuel CO_2 (total CO_2 emissions – CO_2 biospheric emissions). Middle row shows CO emission differences and the lower row shows CH_4 emission differences.

NOAA CSL/GML/CIRES Research on COVID-19 Impacts on Tropospheric Ozone

K.-L. Chang[1,2], O. R. Cooper[1,2], P. Cullis[1,3], Peter Effertz[1,3], A. Gaudel[1,2], B. J. Johnson[3] and I. Petropavlovskikh[1,3]
[1]Cooperative Institute for Research in Environmental Sciences, University of Colorado Boulder, USA
[2]NOAA Chemical Sciences Laboratory, Boulder, USA
[3]NOAA Global Monitoring Laboratory, Boulder, CO, USA

In late 2019 a new coronavirus (SARS-CoV-2) emerged, causing the respiratory illness known as COVID-19. The resulting COVID-19 pandemic triggered a worldwide economic downturn in 2020 which reduced emissions of air pollutants and greenhouse gases. At the beginning of the pandemic the NOAA Science Advisory Board's (SAB's) Climate Working Group made several recommendations to NOAA scientists regarding research objectives related to COVID-19. One of these objectives had particular relevance to current research conducted by NOAA CSL, NOAA GML and affiliated scientists with the Cooperative Institute for Research in Environmental Sciences (CIRES) at the University of Colorado Boulder:

> *Observe, aggregate, and quantify the response of aerosols, radiatively active gases, and their radiative effects that have occurred in response to the pandemic-related decrease in transportation and manufacturing. This would require securing ongoing aerosol, atmospheric chemistry, and radiation monitoring from space and in situ networks. A rapid response to obtain these data is essential.*

Recognizing the potential impact of emissions reductions on tropospheric ozone, an air pollutant and radiatively active trace gas, NOAA GML immediately arranged for enhanced sampling of vertical tropospheric ozone profiles from the laboratory's monitoring sites of Boulder, Colorado and Trinidad Head, California. These sites are key locations for monitoring ozone fluctuations above western North America, with a particular focus on understanding the impacts of changing Asian emissions on ozone above North America. This effort led to a doubling of ozone profile sampling above both sites in April-May 2020 and 2021, to focus on the time of year when air mass transport from Asia to North America is most efficient.

In addition to the enhanced vertical profiling, the GML baseline observations at several high-elevation sites in the western US (i.e. Mount Bachelor, OR; Niwot Ridge C1 and Tundra stations, CO) and at Mauna Loa Observatory, Hawaii, continued to operate and record ozone variability in 2020 and 2021 to capture COVID19-related anomalies in polluted air masses originating in Asia. During 2020-2021, several instruments stopped collecting data, requiring special efforts to restart observations during the pandemic. To assure the continuity and quality of observations, automated power supplies were installed at several stations and the surface ozone analyzers were calibrated against the NIST-referenced instrument at NOAA/GML. The climatology for surface ozone records was developed in 2021 (Peter Effertz of GML, publication in preparation) to provide a reference for detecting anomalies in the baseline ozone levels influenced by the COVID19 economic slowdown. All ozonesonde and surface ozone records are accessible from the GML archive (https://gml.noaa.gov/aftp/data/ozwv/).

The enhanced ozone profiles directly contributed to the success of two new publications on Northern Hemisphere ozone anomalies in 2020. *Steinbrecht et al.* [2021] coordinated an international effort to rapidly analyse and publish a study in early 2021 that clearly showed a decrease in tropospheric ozone (1-8 km altitude), from April to August, that was on average 7% (~ 4ppbv) below the 2000–2020 climatological mean. Such low ozone, over several months, and at so many stations (34 stations across the Northern Hemisphere, and 5 in the Southern Hemisphere, with observations from ozonesondes, LIDAR and FTIR instruments), had not been observed in any previous year since at least 2000. Independent modelling studies indicate the observed ozone decreases were consistent with the observed and estimated decreases in air pollution emissions across the Northern Hemisphere in 2020. These findings received attention from several press outlets worldwide, and were highlighted in WMO's new Air Quality and Climate Bulletin [WMO, 2021].

A follow-up study by *Chang et al.* [2022] focused on the ozone decreases above Europe and western North America, combining all available ozonesonde, LIDAR and commercial aircraft observations to provide a detailed understanding of the ozone anomalies throughout the entire year of 2020 and to quantify their impact on long-term ozone trends (Figure 1). The negative ozone anomalies were strongest in July (-7.5% above Europe), indicating a clear link to reduced photochemical ozone production. In addition, the 2020 anomalies weakened the positive trend in ozone above western North America and Europe that had been observed for the period 1994-2019 (Figure 2). This paper received an Editor's Highlight in AGU's Eos.org, an honor bestowed on fewer than 2 percent of papers published by AGU: https://eos.org/editor-highlights/air-pollution-was-reduced-during-the-covid-19-pandemic

Acknowledgments: This work was supported in part by the NOAA Cooperative Agreement with CIRES, NA17OAR4320101.

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Steinbrecht, Wolfgang, Dagmar Kubistin, Christian Plass-Dülmer, Jonathan Davies, David W. Tarasick, Peter von der Gathen, Holger Deckelmann, Nis Jepsen, Rigel Kivi, Norrie Lyall, Matthias Palm, Justus Notholt, Bogumil Kois, Peter Oelsner, Marc Allaart, Ankie Piters, Michael Gill, Roeland Van Malderen, Andy W. Delcloo, Ralf Sussmann, Emmanuel Mahieu, Christian Servais, Gonzague Romanens, Rene Stübi, Gerard Ancellet, Sophie Godin-Beekmann, Shoma Yamanouchi, Kimberly Strong, **Bryan Johnson, Patrick Cullis, Irina Petropavlovskikh**, James W. Hannigan, Jose-Luis Hernandez, Ana Diaz Rodriguez, Tatsumi

Nakano, Fernando Chouza, Thierry Leblanc, Carlos Torres, Omaira Garcia, Amelie N. Röhling, Matthias Schneider, Thomas Blumenstock, Matt Tully, Clare Paton-Walsh, Nicholas Jones, Richard Querel, Susan Strahan, Ryan M. Stauffer, Anne M. Thompson, Antje Inness, Richard Engelen, **Kai-Lan Chang, Owen R. Cooper** (2021), COVID-19 Crisis Reduces Free Tropospheric Ozone Across the Northern Hemisphere, *Geophysical Research Letters, 48*, e2020GL091987. https://doi.org/10.1029/2020GL091987

WMO Air Quality and Climate Bulletin, No. 1, September 3, 2021; Editors: **O. R. Cooper**, R. S. Sokhi, J. M. Nicely, G. Carmichael, A. Darmenov, P. Laj and J. Liggio; a publication of the World Meteorological Organization, https://library.wmo.int/index.php?lvl=notice_display&id=21942#.YTIzN99MG70

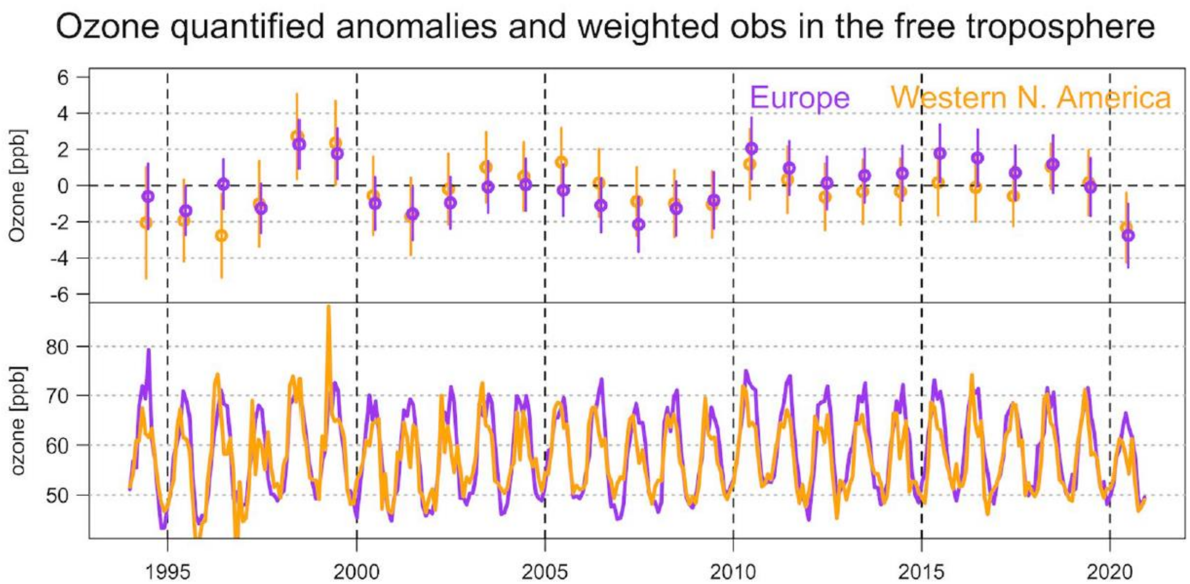


Figure 1. Quantified annual ozone mean anomalies (with 2-sigma intervals) and uncertainty weighted time series in the free troposphere (700-300 hPa) above Europe and western North America (Figure 9 from Chang et al., 2022).

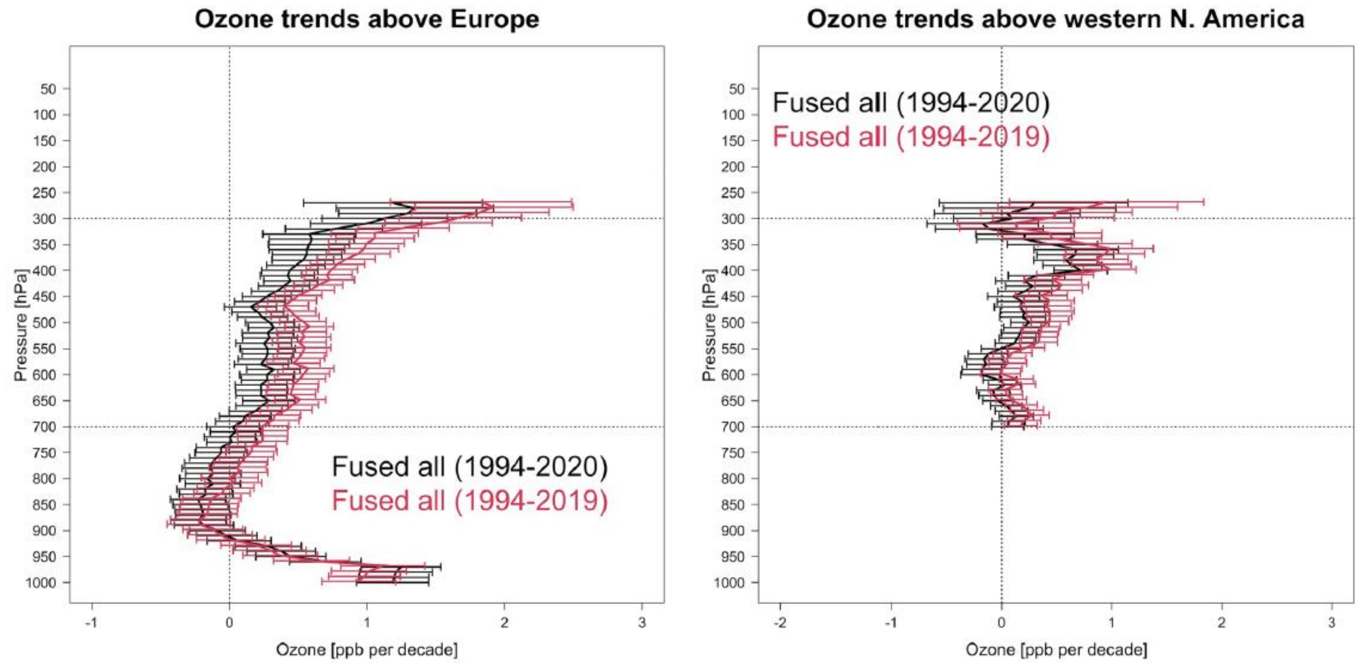


Figure 2. Profiles of ozone mean trends above Europe and western North America (in units of ppbv/decade) derived from the final fused product over 1994–2019 and 1994–2020 (Figure 8 from Chang et al., 2022).

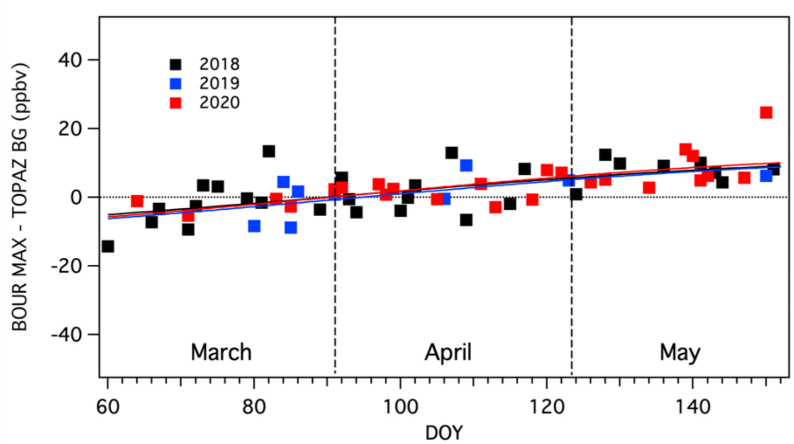
Analysis of surface ozone changes in the Denver-Boulder area during the COVID-19 lockdown

Andrew Langford, et al., NOAA OAR Chemical Sciences Laboratory (CSL)

The NOAA CSL Atmospheric Remote Sensing (ARS) group operated the TOPAZ and Doppler lidars from the Boulder DSRC campus several times per week during the height of the COVID-19 lockdown (March, April, and May of 2020). We used these measurements in conjunction with those made during the same time period in 2018 and 2019 (Table 1) and nearby regulatory O_3 measurements to quantify COVID-19 related changes in boundary layer and lower tropospheric O_3 above the Denver-Boulder area.

	2018			2019			2020		
	Mar	Apr	May	Mar	Apr	May	Mar	Apr	May
Days	11	11	10	6	8	4	7	10	11
Profiles	507	640	557	267	196	144	267	436	575
Avg. run (hours)	6.2	7.8	7.4	5.9	3.2	4.8	5.1	5.8	7.0

To do this, we first used the lower tropospheric TOPAZ measurement to derive representative daily background O_3 concentrations, and then used these background values to isolate the local and regional contribution to the maximum daily 8-h average (MDA8) O_3 measured by the regulatory monitor located 7.3 km to the NE at the Boulder Reservoir. This record was then filtered to account for the interannual variability of background O_3, and days influenced by stratospheric intrusions or other anomalous meteorological events were removed from the record. Figure 1 plots the local and regional contributions to MDA8 O_3 that remain. Sinusoidal fits (annual variation) of the three annual time series (solid lines) appear very similar.



This analysis shows that surface O_3 was dominated by the free tropospheric background over most of the lockdown period, with net surface destruction of O_3 at the beginning of March, and a regional photochemical contribution roughly 15% of the background at the end of May. The relatively small contribution of local and regional photochemistry in springtime means that reduction in NO_x caused by the lockdown had very little impact on surface concentrations. From the differences in the three sinusoidal fits, we estimate that any associated change to MDA8 O_3 in the Denver-Boulder area was less than 2 ppbv.

AC4 input on COVID-related research

Monika Kopacz (NOAA OAR Climate Program Office, Atmospheric Chemistry, Carbon Cycle and Climate (AC4) Program)

Three AC4 projects (5 PIs) were funded to take measurements of drastic changes in atmospheric composition during the lockdown in spring 2020 and subsequent reopening in summer 2020 in New York City, Atlanta and Los Angeles. Subsequently, eight 2-year AC4 projects were started at the end of FY2020 to analyze data that those and other PIs could obtain across the country. The measurements included NOx, ozone, VOCs, aerosols and greenhouse gases from ground sites, mostly in urban areas. Most of the research consistent of short duration deployment of research grade instruments, but low-cost sensors and long-term monitoring sites were also included in the projects. Overall, all investigators found a profound decrease in emissions during April and May, which often persisted through the summer and beyond. Analysis of subsequent months (Fall 2021 and later) is ongoing. Below is a list of projects and a set of short reports on activities and findings so far:

#	Investigators	Project title	Institution(s)	Funding amount
1	Baek, Bok Haeng; Yang, Kai	Developing an enhanced bottom-up and top-down emissions inventories over the U.S. during the pandemic outbreaks by satellite data and chemical transport model	George Mason University, University of Maryland	$399,883
2	Barsanti, Kelley; Blake, Donald	Using Observations of Gaseous Compounds in the LA Basin during COVID-19 to Elucidate Sources and Atmospheric Processes Affecting Urban Air Quality	UC Riverside, UC Irvine	$385,858
3	Commane, Roisin; Hutyra, Lucy; Wofsy, Steve	Understanding methane changes in cities affected by COVID-19 shutdowns	Columbia U, Boston U, Harvard U	$397,394
4	Davis, Kenneth; Turnbull, Jocelyn; Weiss, Ray; Lin, John; Gurney, Kevin	COVID impact on urban GHG emissions: A multi-city investigation	Penn State U; U of Colorado; UC San Diego; U of Utah, Northern Arizona U	$400,000
5	Hu, Lei; Miller, Scot	Quantifying the impacts of COVID-19 on U.S. national and regional non-CO2 greenhouse gas emissions from atmospheric observations	U of Colorado; Johns Hopkins U	$399,845
6	Mitchell, Logan	Tracking impacts of COVID-19 lockdowns & recovery on urban atmospheric composition at neighborhood scales with public-transit based measurements	U of Utah	$399,904

7	Ng, Nga Lee (Sally)	Changes in Aerosol Loading and Composition in Atlanta Driven by Changes in Anthropogenic Emissions during the COVID-19 Pandemic	Georgia Tech	$393,915
8	Wennberg, Paul	Changes in Air Quality in Los Angeles Associated with COVID-19 'Safer-at-Home' Traffic Reductions	CalTech	$398,462

Bok et al. project
A close interagency (NOAA/EPA/DOT) collaboration has begun with regular meetings to exchange information on emissions inventory updates that reflect the sudden drop in emissions in spring 2020. The PIs have developed accurate emission factors (based on data that was available) that can be incorporated in EPA (NEI) emission inventory for on road traffic.

Barsanti et al. project
From mid-April to mid-July 2020, the PIs collected samples of volatile organic compounds (VOCs) in Pasadena, CA, in collaboration with Donald Blake at UC Irvine and Paul Wennberg and John Seinfeld at Caltech. We published a manuscript in ACS (https://pubs.acs.org/doi/abs/10.1021/acsearthspacechem.1c00248) reporting the concentrations of ~150 compounds and concluding that relative to 2010, there has been a significant increase in: 1) the contribution of off-road/other sectors to mobile source emissions, and 2) OH exposure. Analysis is ongoing, with the goal of better link between atmospheric composition and chemistry, and changes in anthropogenic activity during these months.

Commane and Mak project
The PIs made observations of CO2/CH4/CO (Commane) and VOCs (using a PTR-ToF-MS; Mak) at an urban site in Harlem, NYC through the COVID shutdown into summer 2020. Manuscripts based on this data are being prepared. They found that CO reductions were much less than expected from traffic changes and point to incorrect sources in the inventories. They observed large changes in VOC species associated with population and vehicle emissions but did not see much change in other species. PIs' modeling work for these papers has also a key component in a study of total column and in situ NOx that found that NOx emissions changes could be explained by the observed changes in traffic and power plant use (Tzortiou et al., 2022).

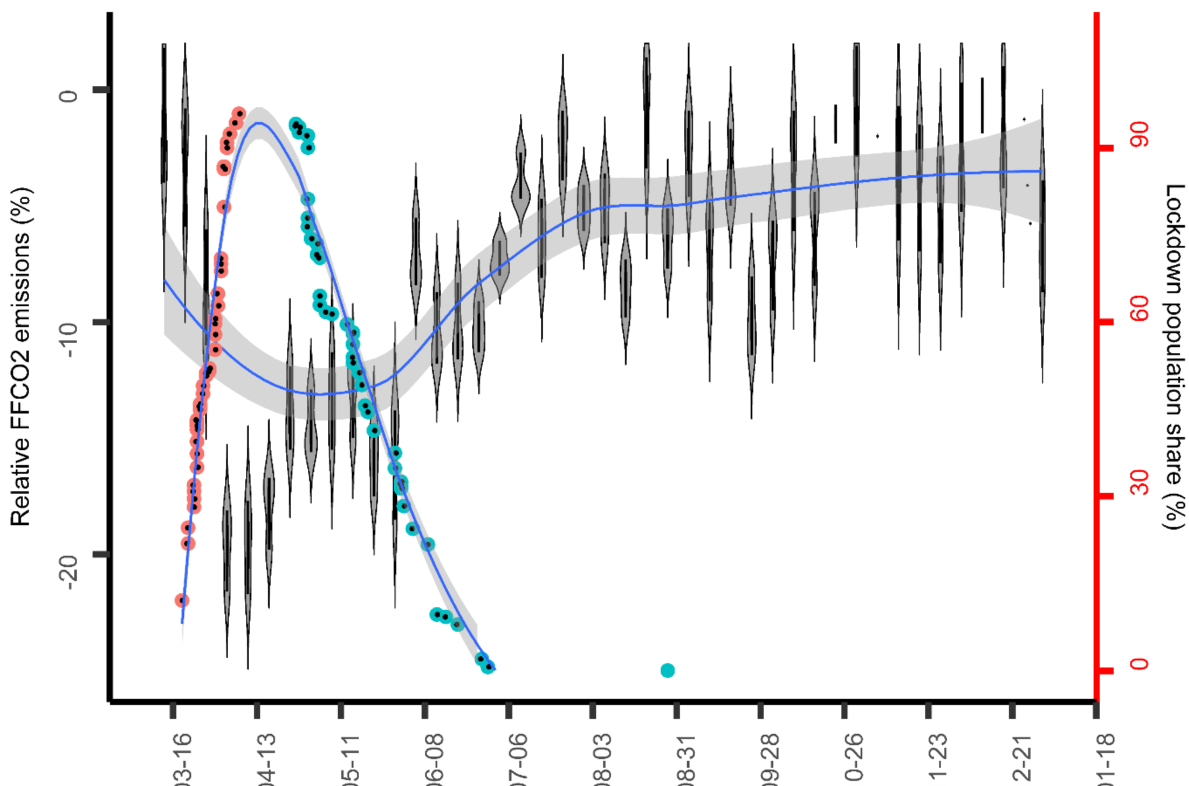
Citation:
Tzortziou, M., Kwong, C. F., Goldberg, D., Schiferl, L., Commane, R., Abuhassan, N., Szykman, J. J., and Valin, L. C.: Declines and peaks in NO2 pollution during the multiple waves of the COVID-19 pandemic in the New York metropolitan area, Atmos. Chem. Phys., 22, 2399–2417, https://doi.org/10.5194/acp-22-2399-2022, 2022.

Davis et al. project
The PIs continued their multi-year measurements of GHGs in 6 urban areas across US and Canada (Boston, Indianapolis, Northeast Corridor, Salt Lake City, Los Angeles and Toronto) and analyzed the effect of lockdowns on atmospheric concentrations. The measurements showed

decreases in CO2 and CO metrics during the lockdown period in all cities for all metrics, while changes in the CH4 metrics were variable across cities and not statistically significant. Traffic decreases in 2020 compared to previous years were statistically significant, whereas changes in meteorology and biology were not, implying that decreases in the CO2 and CO metrics were related to reduced emissions from traffic.

Gurney et al. project

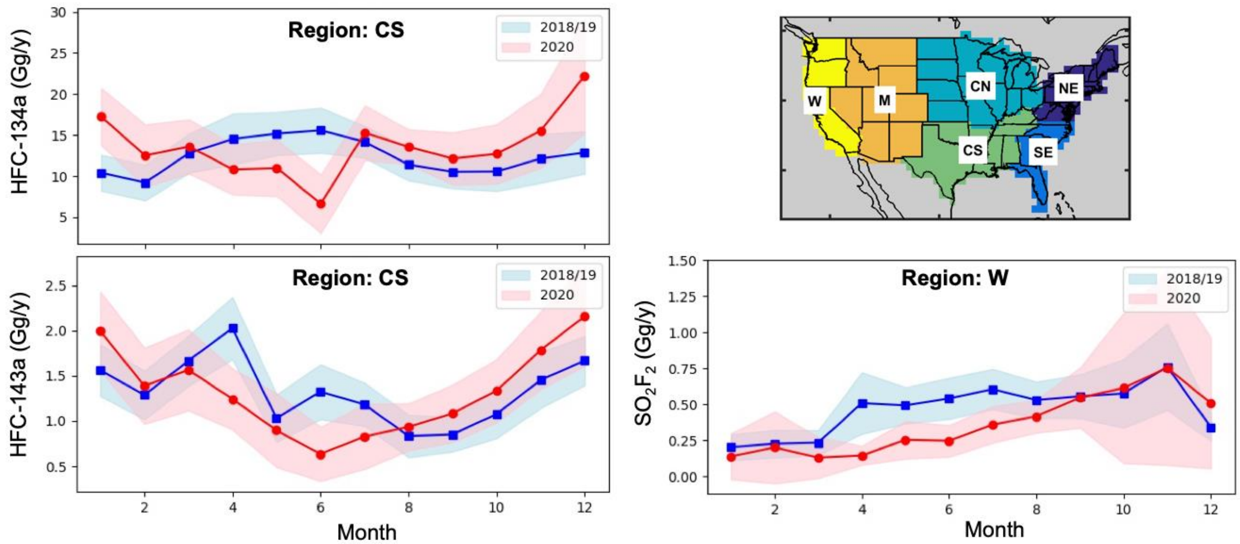
US fossil fuel CO2 emissions experienced unprecedented declines during 2020 COVID-19 lockdown orders. With a new real-time emissions data product, Vulcan-NRT, we find that total US emissions reached a maximum departure of -15.6% during the months of April and May. This decline was seen in all economic sectors except for commercial surface transportation and natural gas consumption in the residential and commercial sectors. Aviation saw the largest April/May decline of -59.7%. By early 2021, emissions had rebounded to pre-COVID levels. Comparison to two real-time global CO2 emissions studies that primarily rely on indirect proxy metrics for emissions, shows large disagreements in specific sectors raising questions about the use of indirect proxies as a substitute for fuel consumption statistics.



Weekly total $FFCO_2$ emissions in the U.S. relative to detrended long-term (2005-2019) median values (left axis) with long-term ensemble distribution (violin symbols). The gray shading represents the locally weighted scatterplot smoothing (LOESS) curve. LOESS was used to depict the non-linear change of the weekly median values of the relative emissions as a function of 'date'. Share of U.S. population (right-axis) included in the initiation of state-scale lockdown orders (red) and the end of the state-scale lockdown orders (light blue) with LOESS curve (Lockdown population share (%) ~ date) plotted to highlight the non-linear increase and decline trend of lockdown population as a function of time.

Hu et al. project

This project uses the NOAA long-term atmospheric observations, in combination with airborne campaigns and space-based greenhouse gas (GHG) observations, to quantify the COVID-19 impacts on U.S. national and regional emissions of non-CO2 GHGs. Preliminary, atmospheric observation-based emission estimates show a noticeable reduction in GHG emissions from mobile air conditioning (HFC-134a) and commercial refrigeration (HFC-143a) in the central south region of the US and from the fumigation uses (SO2F2) in the western states (see the figure attached).



Ng et al. project

PIs deployed an extensive set of instrumentation to track atmospheric composition in Atlanta from April through December 2020. The instruments deployed included a High-Resolution Time-of-Flight Aerosol Mass Spectrometer (HR-ToF-AMS), an Aerosol Chemical Speciation Monitor (ACSM), a Scanning Mobility Particle Sizer (SMPS), a Proton-Transfer-Reaction Time-of-Flight Mass Spectrometer (PTR-ToF-MS), a High-Resolution Time-of-Flight Chemical Ionization Mass Spectrometer fitted with a Filter Inlet for Gases and Aerosols (FIGAERO HR-ToF-CIMS), ozone and NOx monitors, as well as low-cost air quality sensors. We have conducted source apportionment analysis to investigate the sources and properties of different organic aerosol subtypes and their response to the emission changes during the pandemic. In particular, we observed changes to anthropogenic factors such as cooking organic aerosols (COA) and reductions in more-oxidized oxygenated organic aerosols (MO-OOA), possibly linked to reductions in nitrogen oxides (NOx). Source apportionment of PTR-measured VOCs shows delineation of anthropogenic VOCs into traffic, cooking/biomass burning, and nontraditional source sectors, with volatile chemical products contributing to a significant fraction of total VOCs during the winter. In addition, comparison of research-grade and low-cost sensor data demonstrated that low-cost sensors can be used for in-depth source apportionment studies even in an urban environment with complex aerosol sources and processing (Yang et al., ES&T, in press).

Markers of Economic Activity in Satellite Data: COVID-19 Lockdown Impact on Air Quality

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Summary. The COVID-19 pandemic provided an opportunity for the scientific community to study the influence of changes in economic activity on anthropogenic emissions that lead to harmful pollution and determine if those changes can be detected in satellite data. Nitrogen dioxide (NO_2) emissions, primarily from the transportation sector, dropped during the lockdown period and those reductions impacted secondary aerosol formation. Nine years of Suomi National Polar-orbiting Partnership Visible Infrared Imaging Radiometer Suite (SNPP VIIRS) of aerosol optical depth (AOD) product were reprocessed using calibrated radiances to remove long-term trend and seasonality in AOD data prior to computing the differences in AOD between 2020 (COVID-19) and 2019 (business as usual). AODs decreased by 10%, 13%, 21%, and 14% in United States (US), India, western Europe, and China respectively. Large AOD changes, up to 50%, were observed in parts of China where stringency index was higher and pollution levels are generally larger than in the western Europe or the US. Beijing and its surrounding regions in the northeast China are generally under the influence of industrial emissions dominated by sulfur dioxide (SO_2) and dust transport due to which no significant decreases in AOD were noticed. In southern China, gains of improved air quality due to reduced NO_2 emissions were offset by emissions of aerosols and aerosol precursors from fires; in cities such as Nanning, Guiyang, and Kunming that were in downwind region of fires, transported smoke increased AODs by up to 38%. In Taiwan, increased AODs up to 42% were observed during the pandemic due to the policy of isolation rather than the lockdown as the main method to combat the spread of COVID-19 virus. Elsewhere in the world, despite being top NO_x emitting cities, Madrid and Seattle had a 5% increase in AODs; this is attributed to increased background NO_2 in the troposphere. Overall, in 37 out of 47 cities that were identified as top NO_x emitters from their transportation sector, AODs decreased due to reduced emissions. The AOD changes detected were twenty times higher than the product uncertainty (a global average of 0.02) rendering the data reliable to track changes in economic activity.

1. **Introduction**

Lockdown measures related to the novel coronavirus 2019 (COVID-19) spawned a host of press releases, news articles, seminars, and workshops in the mainstream media on the connections between reduced human activity and improved air quality. As the virus spread from China to other parts of the world, various countries started imposing lockdown measures one by one. These lockdowns were soon followed by reports of improved air quality, which was also observed by satellites, and offered a rare opportunity for air quality researchers to showcase their measurements and models. **For NOAA's COVID-19 project that was initiated in April 2020 as a joint NESDIS-OAR-NWS[1] effort, one of the objectives was to observe,**

[1] NESDIS: National Environmental Satellite Data and Information Service; OAR: Oceanic and Atmospheric Research; NWS: National Weather Service

aggregate, and quantify the response of aerosols and radiatively active gases, and their radiative effects, that occurred in response to the pandemic-related decreases in transportation and manufacturing. The project work reported here started with an objective to investigate the impact of lockdowns on nitrogen dioxide (NO_2) and aerosol optical depth (AOD, which is a proxy for surface $PM_{2.5}$ - particulate matter in µg/m^3 for particles smaller than 2.5 µm in median diameter) across the globe as observed by NOAA satellites. Changes in $PM_{2.5}$ along with its precursor trace gases, such as nitrogen dioxide (NO_2) and volatile organic compounds (VOCs), were expected because emissions from cars and trucks (transportation sector) decreased during lockdowns due to reduced human activity associated with remote work, etc. Though industrial activities also decreased, the reduction in emissions from the transportation sector was precipitous.

We explored regional NO_2 and AOD changes in 2020 during the lockdown time periods compared to 2019 in China, India, Europe, and United States (US). We also looked at individual urban areas that are top 5% NO_2 emitters as identified by the Community Emissions Data System (CEDS). We processed/reprocessed Suomi NPP Visible Infrared Imaging Radiometer Suite (VIIRS) and NOAA-20 Ozone Mapping and Profiler Suite (OMPS) radiances with consistent AOD and NO_2 retrieval algorithms, respectively, to create a reference dataset to compare against 2020. NOAA-20 OMPS was used in this study because of its higher spatial resolution of 17 × 13 km^2 at nadir, improved over the SNPP OMPS nadir resolution of 50 × 50 km^2. The nine years of SNPP VIIRS AOD reprocessing work was carried out on the Amazon Web Services Cloud environment, and the reprocessed AOD data were validated by comparison against the global ground-based Sun photometer network to determine performance metrics. The reprocessing of NOAA-20 OMPS NO_2 was carried out at the University of Maryland, and the reprocessed OMPS NO_2 data were validated by comparing the retrievals to data from the ground-based Pandora network in the eastern United States. In this report, we summarize the findings on the impact of COVID-19 lockdowns on AOD and tropospheric column NO_2 (tropNO_2).

2. COVID-19 Impact

2.1. Tropospheric Column NO_2 (tropNO_2)

The impact of COVID-19 lockdowns on tropNO_2 was studied using both Sentinel-5P Tropospheric Monitoring Instrument (TROPOMI) and OMPS data. In the US, estimates based on fuel sales on-road NO_2emissions from light and heavy-duty vehicles decreased by 9%–19% between February and March, at the onset of the lockdown period, which began in the middle of March for most of the country; between March and April, when lockdown measures were most stringent, on-road NO_2 emissions dropped further by 8%–31% (Harkins et al., 2021). These precipitous drops in NO_x emissions on monthly timescales correlated well (r = 0.75) with TROPOMI tropNO_2. Furthermore, decreases in TROPOMI tropNO_2 across the US for 2020 compared to 2019 correlated well with the decreases in on-road NO_x emissions (r = 0.68) but correlated weakly with decreases in emissions from power plants (r = 0.35).

Elsewhere in China, Observations from NOAA-20 OMPS revealed a 20%–40% decline in regional tropNO_2 in January-April 2020, due to the COVID-19 lockdown, compared to 2021 (Figure 1). Note that 2020 vs. 2021 was used for NOAA-20 OMPS analysis because of instrument changes that occurred in 2019. Figure 1 shows a visual comparison of OMPS-observed tropNO_2 over China before and after the lockdown in 2020 (a-e) and over the same period in 2021 (f-j), with indications of the Chinese New Year holiday (CNY, by red lantern, top left) and of the lockdown period (by padlock, bottom right). In 2021, OMPS observed large winter tropNO_2 abundances (Figure 1f-g), followed by a drop during CNY (Figure 1h). Declining tropNO_2 values during CNY is a typical phenomenon observed every year because most Chinese factories shut down for the holiday and traffic volumes decrease, resulting in a decrease in fuel consumption and thus NO_x emissions. A rebound of tropNO_2 is usually observed immediately after CNY, marking the end of the 7-day CNY holiday when people return to work (Figure 1i). Note that the tropNO_2 rebound after CNY is much lower than its January peak, due to seasonality caused by the shorter NO_2 lifetime in the warmer season. In 2020, since the initial lockdown phase was coincident with the CNY holiday, NO_x emissions curtailed significantly, and NOAA-20 OMPS observations indicate a steep drop in tropNO_2, decreasing a factor of 2 or more in most Chinese cities (Figure 1b). The average NO_2 reduction in 2020 over China is 35% from "before" (Figure 1a) to "after" (Figure 1b), while a reduction of 15% in over the same period in 2021 is observed. This difference suggests that the observed reduction in 2020 far exceeds the typical CNY holiday-related reduction. In addition, unlike during typical years with a clear tropNO_2 reduction during CNY and a quick increase after CNY, tropNO_2 did not bounce back after the week of the 2020 CNY holiday (Figure 1c). In fact, tropNO2 remained low for several weeks during the strict COVID-19 quarantine in China (31 Jan – 17 Feb 2020), after which tropNO_2 gradually recovered, reflecting the return of economic activities and NO_x emissions (Figure 1d-e).

In the US, for which unemployment records are available, at the height of lockdown-related unemployment in the second quarter of 2020, TROPOMI tropNO_2 decreased at the rate of 0.8 μmoles/m^2 per unit percentage increase in the unemployment rate (Figure 2, adapted from Kondragunta et al., 2021). Because of the lockdown measures and work from home policies for the majority of the workplaces in the US, the service industry suffered and the unemployment rate rose. The US unemployment rate increased from about 4.4% in March to 14.7% in April during the first phase of lockdowns. The unemployment rate nationwide improved as lockdowns were lifted, but certain parts of the country continued to experience a very high unemployment rate throughout 2020 (Figure 2). Among the employed, 28% of employees were still working from home as of November, indicating that below normal NO_x emissions data are to be expected. The correlation between unemployment rate and tropNO_2 for metropolitan areas with a pre-pandemic civilian labor force greater than 2 million is negative for the second and third quarters (the regression line shown in Figure 2 is for second quarter data). The unemployment rate combined with telework policies contributed to reduced NO_x emissions and thus lower tropNO_2 values across the US. This result is similar to the positive correlation between Gross Domestic Product (GDP) and tropNO_2 reported by Keller et al (2020). For reasons unknown, cities such as Phoenix, AZ, Minneapolis, MN, Dallas and Houston, TX, and Chicago, IL showed no change or a slight increase in tropNO_2 in 2020 compared to 2019, though the unemployment rate in 2020 was much higher compared to 2019. Keller et al. (2020) do not report these outliers because their analysis is for all developing countries around the world and is not granular at the city level like our analysis. Despite the lifting of lockdown measures, parts of the US continued to have ~20% below normal on-road NO_x emissions. To achieve this new normal urban air quality in the US, continuing remote work policies that do not impede economic growth may become one of the many options in the future.

2.2. AOD

Unlike NO_2, aerosols are long lived and are transported long distances. Therefore, to analyze the impact of COVID-19 lockdowns on particulate pollution, we had to remove from satellite AOD the contribution of aerosols from natural sources, such as smoke from fires. We developed two methods, both involving the use of tropNO_2, to remove the contribution of biomass burning in VIIRS AOD data. Prior to applying our screening methods, we calculated background tropNO_2 using TROPOMI data, which was found to be ~16 µmoles/m^2 (Kondragunta et al., 2021); this background value was subtracted from daily TROPOMI tropNO_2 data to isolate clusters of elevated tropNO_2 values. In the first method, we filtered the AOD data based on the tropNO_2/AOD ratio with a threshold of 200 (the ratios vary from 0 to 2000); when urban/industrial regions have poor air quality, both tropNO_2 and AOD are high, whereas when transported smoke reaches an urban region, tropNO_2 is low but AOD is high. In the second method, we looked at tropNO_2 and AOD changes to see if they co-increased or co-decreased between 2020 and 2019, and filtered AOD data based on absolute changes in tropNO_2 greater than 5 µmoles/m^2. Though both methods screened AOD data for transported smoke consistently, results shown in this report are from the second method. The differences in tropNO_2 and AOD between 2020 and 2019 due to meteorology were minimized by averaging the data for the duration of the lockdown period (approximately a month or longer). Kondragunta et al. (2021) showed that when looking for signatures of emissions changes in satellite observations from one year to another, averaging the data over 30 days or more will minimize the influence of meteorology.

2.2.1. **Time Series Analysis for AOD Trends**

Year to year changes in AOD can occur for four reasons: (1) meteorological variability, (2) variability in fires and dust storms, (3) long-term trend due to pollution control strategies, and (4) sudden unexpected changes due to events such as lockdowns. After applying our method (Section 2.1) to screen for the influence of smoke in AOD and identifying areas of high tropNO_2 and AOD, we identified eight cities in the US, six cities in western Europe, 21 cities in China, and eight cities in India that experienced a drop in AOD. We also confirmed that these mega cities are under the influence of high NOx emissions from the transportation sector by analyzing the 2019 CEDS (McDuffie et al., 2020; Hoesly et al., 2018). For these regions, we conducted time series analyses to remove the long-term trends. Instead of the traditional least-squares fit analysis to identify long-term trends in time series data, we used the Theil-Sen slope method and determined the significance of the derived trends using the Mann-Kendall test (Thiel, 1950; Sen, 1968). This method is insensitive to outliers and is significantly more accurate than the least squares method. Finally, in reporting AOD changes due to lockdowns in 2020 compared to 2019, we accounted for the long-term trends.

2.2.2. **Magnitude of Impact on AOD**

Figure 3 shows VIIRS AOD changes ($\Delta AOD_{2020\text{-}2019}$) identified due to changes in emissions between 2020 and 2019 for China, India, western Europe, and the US; lockdown periods were different for these four different regions. Lockdown occurred in China from 23 January to 08 April, in India from 25 March to 7 June, in Europe it varied from country to country but in general was from 09 March to 04 July, and in the US from 19 March to 15 June. Of the four regions investigated, the largest reductions were observed in China, because China's AOD levels are the highest in the world; China's particulate pollution is four times higher than in the US. The lockdown areas of Hubei province, including the Wuhan area where the pandemic started, and other provinces resulted in $\Delta AOD_{2020\text{-}2019\ change}$ up to 0.2 over two months. During the most stringent portion of the lockdown, from 10 to 25 February, the $\Delta AOD_{2020\text{-}2019}$ values changed by up to 0.5, which is quite significant; for an optical depth of unity, a 0.5 change in AOD corresponds to a change of 50%.

There are some regions with an increase in $\Delta AOD_{2020\text{-}2019}$ in China and India. Increasing AOD is associated with smoke from fires; analysis of SNPP VIIRS fire detections and fire radiative power (FRP) shows distinct correlations with elevated levels of fire intensity in regions where the increase in $\Delta AOD_{2020\text{-}2019}$ was observed. Figure 4 shows the difference in VIIRS smoke fraction between 2020 and 2019. The smoke fraction in 2020 was quite strong and partially offset the gains from lockdowns, especially in urban areas closer to areas with fires. Though cities such as Chengdu, Chongqing, Guiyang, Kunming, and Nanning are among the top 5% NOx emitting cities, $\Delta AOD_{2020\text{-}2019}$ values increased due to their proximity to intense burning in Southeast Asia and were under the influence of transported smoke. These increases are not associated with unaccounted meteorological differences between 2020 and 2019 in our analysis, as Hammer et al. (2021) showed no such increases due to meteorology in their model simulations. The increase in $\Delta AOD_{2020\text{-}2019}$ northeast of Beijing, however, does not correspond to an increase in fire activity between the two years. Other studies that used model analysis attributed the increase in $\Delta AOD_{2020\text{-}2019}$ in that region to sulfate and organic aerosols (Miyazaki et al., 2020; Hammer et al., 2021). It is important to note that this region is not a significant source for NOx emissions according to the CEDS database (Hoesly et al., 2018), and reductions in AOD due to the lockdown were not expected in this region.

Figure 5 shows the impact of AOD in various cities/urban areas that are top 5% NOx emitters. Of the 21 cities analyzed in China, only four cities showed an increase in AOD. All other cities showed a decrease in AOD up to 25%, with a mean overall decrease of 14%. Beijing experienced no change, as it is outside of the Hubei province, where lockdown measures were not as stringent as inside the province. Taiwan did not impose any lockdown measures but went into an isolation, due to which neither AOD nor tropNO_2 decreased. In the Contiguous United States (CONUS), the overall decrease in AOD was ~9%, with highest decrease observed in the capital city of Washington, DC. The Seattle area observed a small increase in AOD due to an increase in tropNO_2; Kondragunta et al. (2021) and Qu et al. (2021) showed that background tropNO_2 has been increasing in the Pacific Northwest. India showed an average AOD decrease of 13% and is consistent with findings observed in China. Smoke from fires increased AOD in parts of India despite the lockdown, but overall, with the smoke impact removed from the AOD data, we are able to show that NOx and primary particulate emissions reductions, predominantly from the transportation sector, reduced AOD. Europe, similar to the US, has reduced particulate pollution in general compared to Asia. Cities in Europe dominated by NOx emissions showed a 25% decrease in AOD except Madrid; the overall decrease in AOD in western Europe is 21%.

2.2.3. **VIIRS Day/Night Band (DNB)**

In the early stages of the pandemic, social distancing measures, such as lockdown restrictions, were applied in a non-uniform way across the world to reduce the spread of the virus. While such restrictions contributed to flattening the curve in places like Italy, Germany, and South

Korea, it plunged the economy in the United States to a level of recession not seen since WWII, while also improving air quality due to the reduced mobility. Using daily Earth observation data (Day/Night Band (DNB) from the National Oceanic and Atmospheric Administration Suomi-NPP and NO_2 measurements from the TROPOspheric Monitoring Instrument TROPOMI) along with monthly averaged cell phone derived mobility data, we examined the economic and environmental impacts of lockdowns in Los Angeles, California; Chicago, Illinois; Washington DC from February to April 2020—encompassing the most profound shutdown measures taken in the U.S. The analysis revealed that the reduction in mobility involved two major observable impacts: (i) improved air quality (a reduction in NO_2 and $PM_{2.5}$ concentration), but (ii) reduced economic activity (a decrease in energy consumption as measured by the radiance from the DNB data) that impacted on gross domestic product, poverty levels, and the unemployment rate. With the continuing rise of COVID-19 cases and declining economic conditions, such knowledge can be combined with unemployment and demographic data to develop policies and strategies for the safe reopening of the economy while preserving our environment and protecting vulnerable populations susceptible to COVID-19 infection (Straka et al., 2020).

3. Conclusions

The COVID-19 pandemic provided an opportunity for the scientific community to study the influence of changes in economic activity on anthropogenic emissions that lead to harmful pollution and determine if those changes can be detected in satellite data. NO_2 emissions, primarily from the transportation sector, dropped during the lockdown period and those reductions were detected in tropNO_2 observed by S5P TROPOMI and NOAA-20 OMPS. The tropNO_2 reductions seen in satellite data correlated well with changes in NOx emissions across the US. Similarly, changes in AOD during the lockdown periods, from 9% to 25% observed in urban areas, are attributed to changes in NO_2 emissions. In certain areas, gains of improved air quality were offset by emissions of aerosols and aerosol precursors from fires. Other reasons of increased pollution in 2020 compared to 2019 include implementing isolation instead of a lockdown as the main method to combat the spread of COVID-19 virus. Given this context, unemployment rate in the US, which is a good indicator of economic activity, correlated well with the decreases observed in tropNO_2 and provided corroborating evidence that satellite data can be used as markers of changes in economic activity.

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4. Relevant Publications

Kondragunta, S., Wei, Z., McDonald, B. C., Goldberg, D. L., & Tong, D. Q. (2021). COVID-19 induced fingerprints of a new normal urban air quality in the United States. *Journal of Geophysical Research: Atmospheres*, 126, e2021JD034797. https://doi.org/10.1029/2021JD034797

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Kondragunta, S., Wei, Z., McDonald, B. C., Goldberg, D. L., & Tong, D. Q. (2021). COVID-19 induced fingerprints of a new normal urban air quality in the United States. *Journal of Geophysical Research: Atmospheres*, 126, e2021JD034797. https://doi.org/10.1029/2021JD034797

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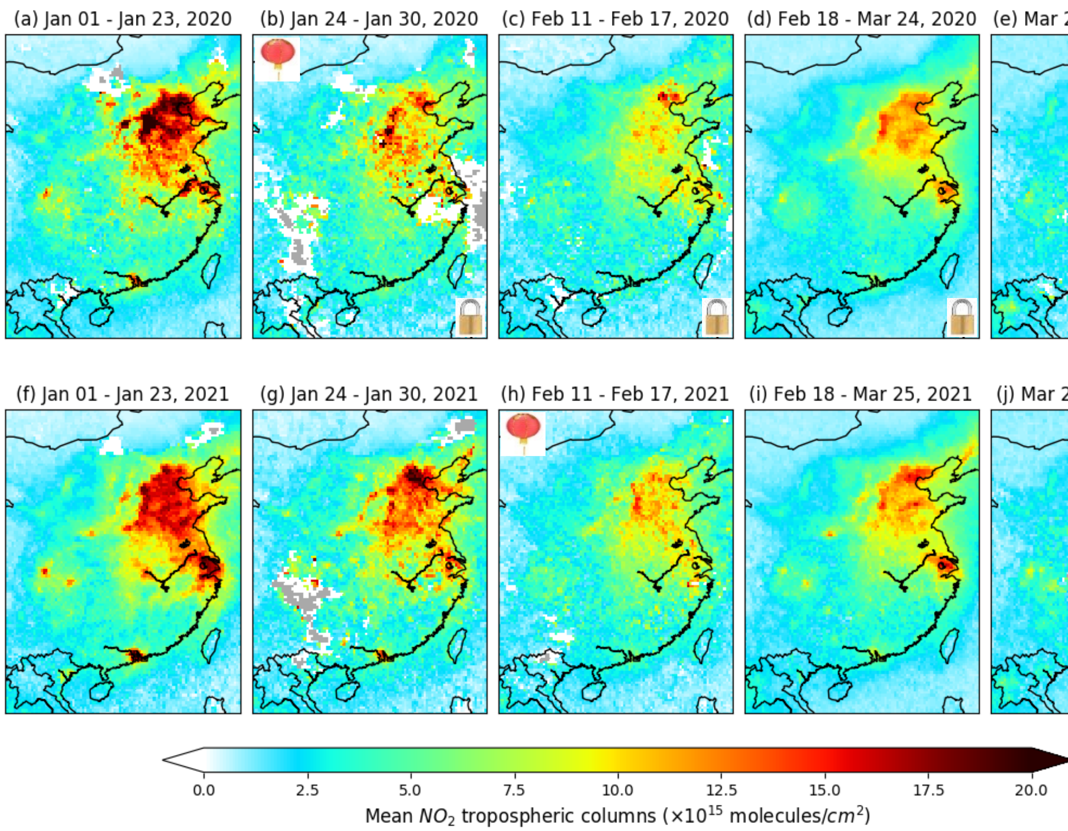

Figure 1: NOAA-20 OMPS mean NO_2 maps for different time periods in 2020 (top row) compared to the same time periods in 2021 (bottom row).

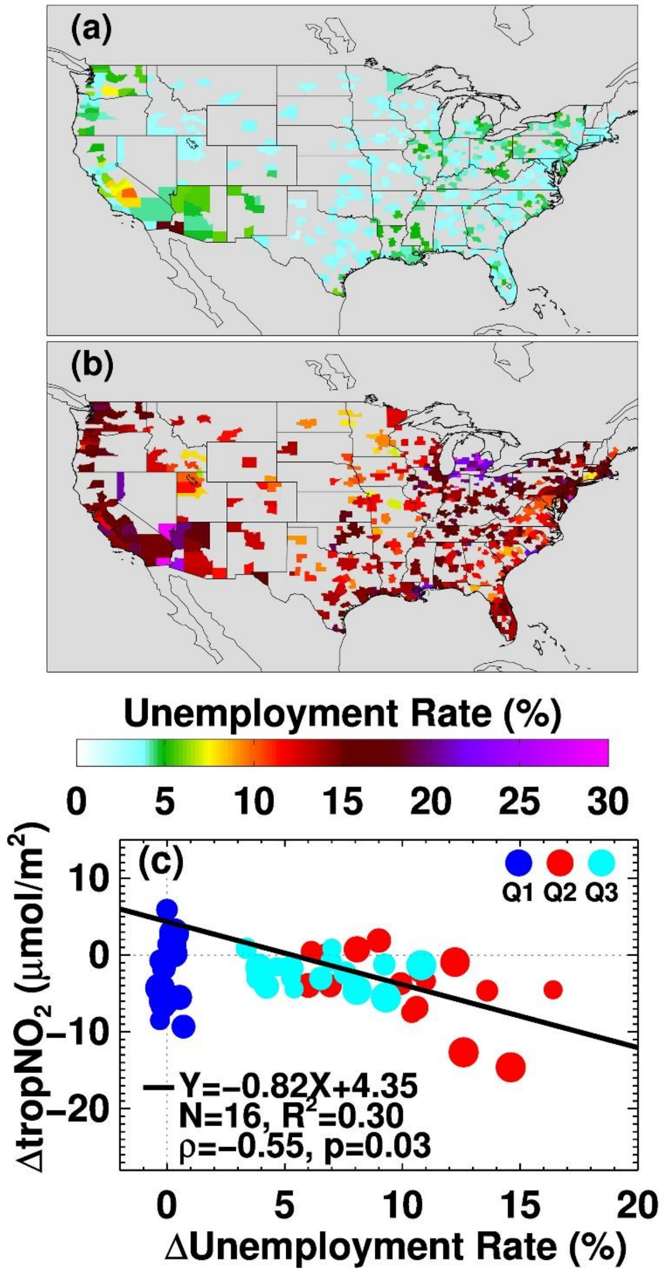

Figure 2: The impact of COVID-19 lockdown on the unemployment rate in metropolitan areas and tropNO_2. (a) Unemployment rate in April 2019, (b) Unemployment rate in April 2020, and (c) Correlation between increase in unemployment between 2019 and 2020 and tropNO_2 changes. Only data for metropolitan areas where the civilian labor force in 2019 was greater than 2 million are shown in the correlation plot. In the first quarter (Q01), unemployment changes are close to zero as pandemic impact did not begin until late March. Strong negative correlation is observed for the second (Q02) and third (Q03) quarters. The solid black line is the fit to the second quarter data.

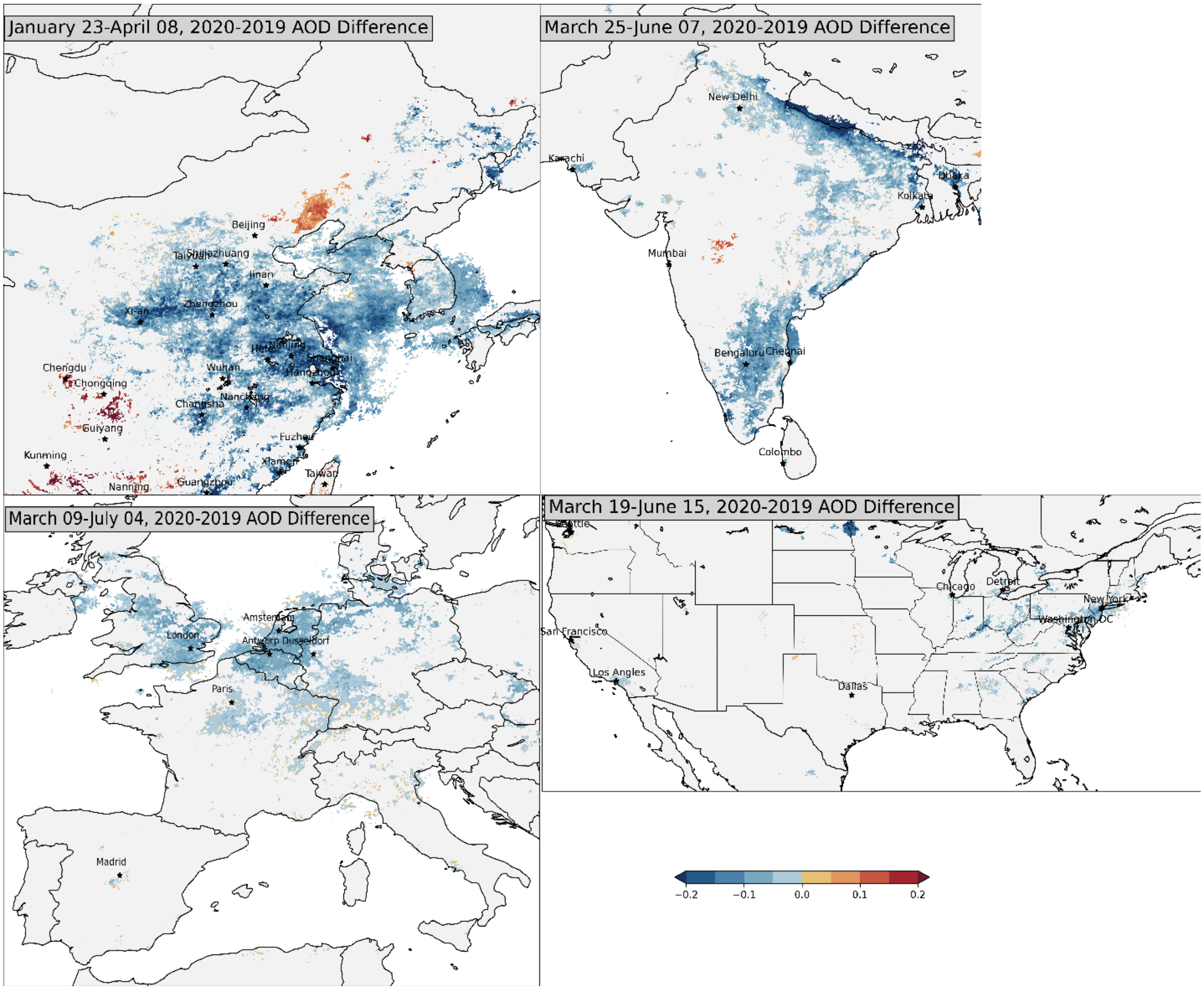

Figure 3: VIIRS AOD changes ($\Delta AOD_{2020\text{-}2019}$) identified due to changes in emissions between 2020 and 2019 for China (top left), India (top right), western Europe (bottom left), and the United States (bottom right).

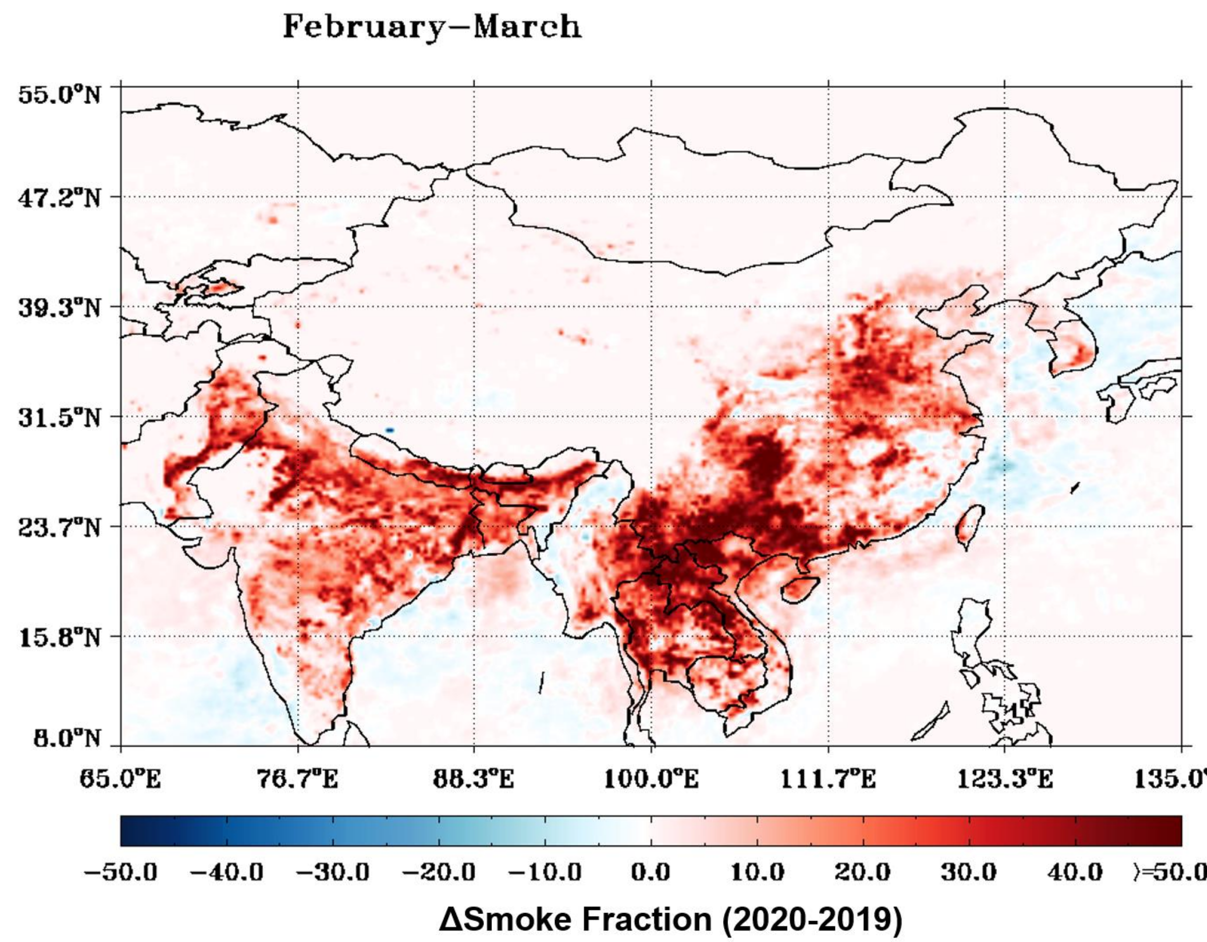

Figure 4: SNPP VIIRS smoke fraction difference between 2020 and 2019, indicating fairly significant smoke was present in the atmosphere.

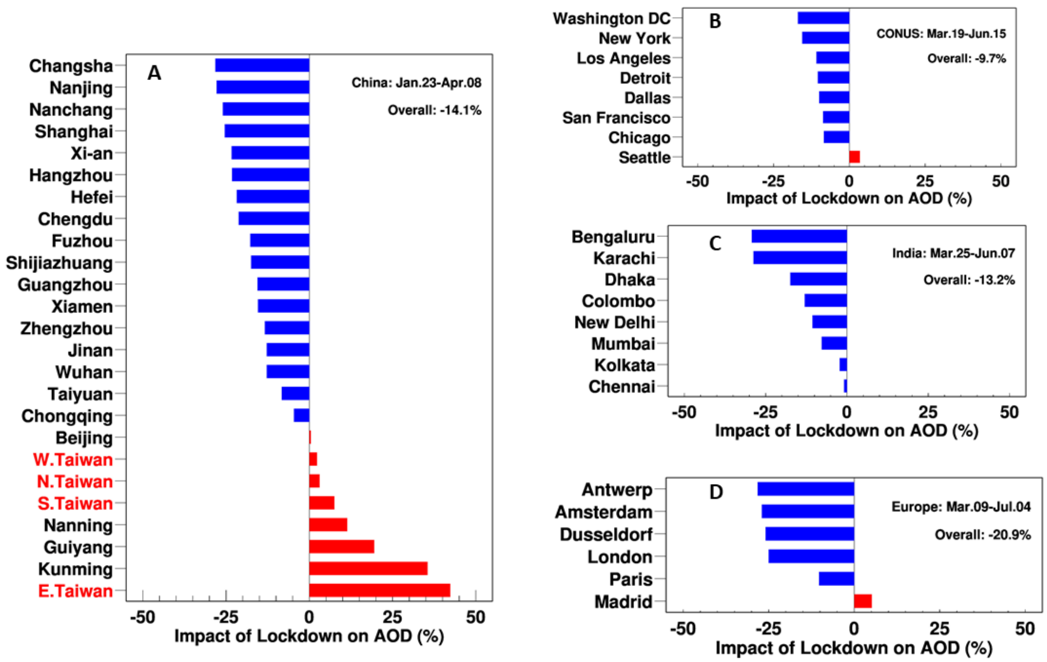

Figure 5: Impact of lockdown on AOD for different cities in (A) China, (B) Contiguous United States, (C) India, and (D) Europe. Cities highlighted in red are regions where AOD increased due to transported smoke, except in Taiwan where lockdowns were not imposed.

Impacts of the COVID-19 economic slowdown on ozone pollution in the U.S.

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The global confinement due to rising COVID-19 cases, in particular, travel restrictions and quarantining shelter-in-place orders are associated with significant decreases in surface transportation activity by about 50% globally. Consequently, the COVID-19 economic slowdown led to a "natural air pollution control experiment" due to widespread anthropogenic emissions reductions for atmospheric pollutants and their precursor gasses, such as decreased oxides of nitrogen ($NO_x = NO + NO_2$) emissions of up to ~ 50%. The COVID-19 impacts on air pollution occurred on a scale impossible to reproduce outside of such a global health emergency.

Motivated by the apparent COVID-19 related near-surface ozone (O_3) variability in different global regions and in portions of the U.S., we investigated the regional differences in the impact of COVID-19 lockdowns on O_3 formation across the U.S. Our study combined the use of both ground and satellite-based observations of NO_2 to infer changes in precursor emissions due to the COVID-19 economic slowdown, and then used the derived emission changes and a chemical transport model to quantify the related changes in O_3 concentrations across the entire contiguous U.S. Here we focused on O_3 as an indicator of pollution changes due to the COVID-19 economic slowdown in the U.S. because 1) changes in traffic NO_x emissions strongly impact O_3 formation, 2) O_3 is the dominating pollutant contributing to non-attainment zones in the warm summer months, and 3) because O_3 has well-defined health impacts.

The results of our study (Campbell et al., 2021) indicated that by mid-May, ground level ozone had not fallen in parallel with decreasing NO_x levels across much of the country. During the peak of the lockdown from March to April of 2020, reduced emissions led to widespread ozone decreases, though there are notable increases in some urban areas (e.g. New York's Long Island Sound). At the peak of the ozone season from July to August some regions showed widespread increases in ozone, which is partly attributable to shifts in vehicle fleets and relaxed mobility restrictions in some states. From an additional collaborative study (Qu et al., 2021), we also found that the use of satellite NO_2 retrievals to infer NO_x emissions changes during the COVID-19 economic slowdown become more limited in the summer due to a large background contribution to the NO_2 column, which are potentially attributable to wildfires.

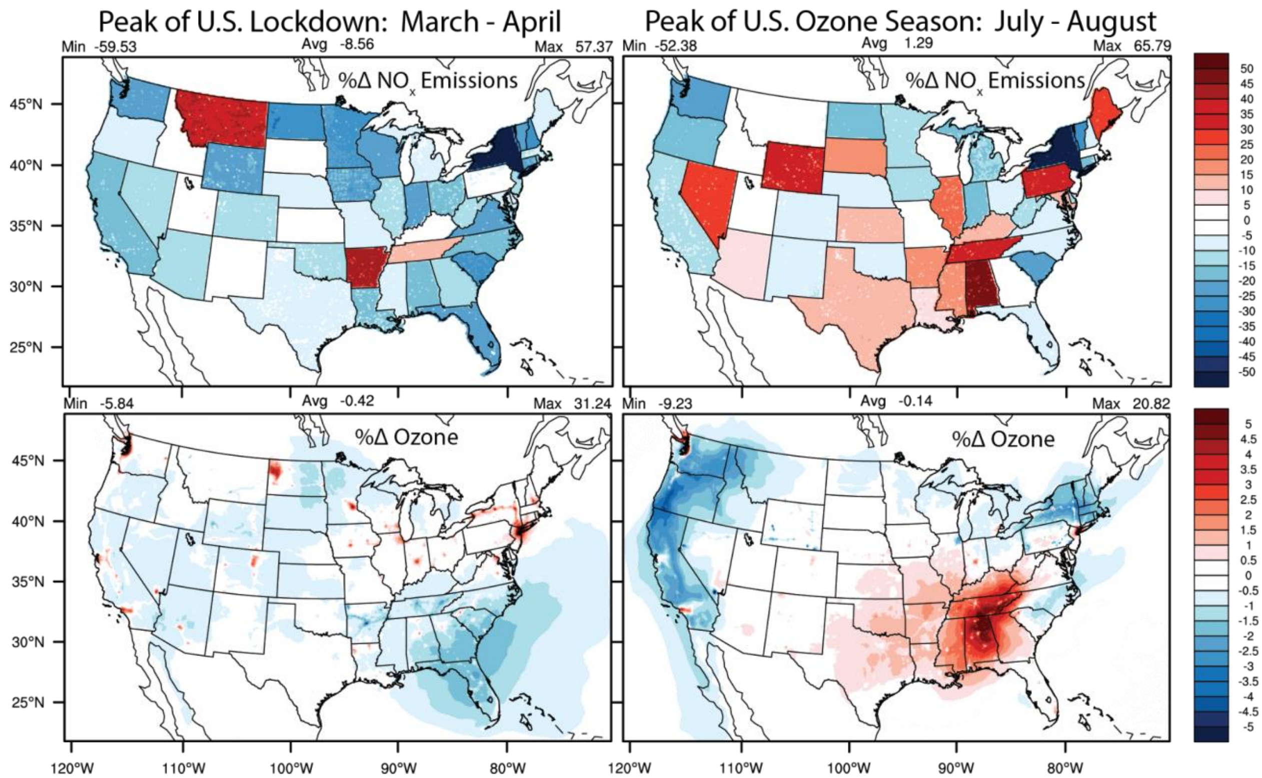

Image Caption: During the peak of the lockdown and reduced mobility and traffic in the U.S. for March – April (on the left), there are widespread NO_x emissions decreases, which leads to widespread ozone decreases in rural regions, but local increases in some urban regions. Later during the peak of the warmer, ozone season in the U.S. for July – August (on the right), there are more widespread NO_x emissions increases in some regions (e.g., south-southeast), which leads to more widespread ozone increase across the U.S. Image adapted from Figure 2 and Figure 6 of Campbell et al. (2021).

Related Presentations

Campbell, P. C., Impacts of the COVID-19 Economic Slowdown on Ozone Pollution in the U.S., 2021 NOAA-OAR Senior Management Meeting (January 11, 2021): https://docs.google.com/presentation/d/1ycuh31REpw9vKXKqhdz4WO0RBMubuxw2XGIJQlZpDcs/edit?usp=sharing

Zhen, Q., D. J. Jacob, R. F. Silvern, V. Shah, P. C. Campbell, L. C. Valin, and L. T. Murray. Responses of satellite and surface NO_2 observations to US NO_x emission reductions during the COVID19 shutdown. 2021 American Meteorological Society Annual Meeting (January 10-15, 2021): https://scholar.harvard.edu/files/zhenqu/files/ams_qu_v1.0.pdf

Related Publications

Campbell, P. C., D. Tong, Y. Tang, B. Baker, P. Lee, R. Saylor, A. Stein, S. Ma, and L. Lamsal (2021). Impacts of the COVID-19 Economic Slowdown on Ozone Pollution in the U.S. Atmospheric Environment, https://doi.org/10.1016/j.atmosenv.2021.118713.

Qu, Z., D. J. Jacob, R. F. Silvern, V. Shah, P. C. Campbell, L. C. Valin, and L. T. Murray (2021). US COVID-19 shutdown shows importance of background NO_2 in inferring nitrogen oxide (NO_x) emissions from satellite NO_2 observations. Geophysical Research Letters, https://doi.org/10.1029/2021GL092783.

Modeling studies of emissions and air quality forecasts during the pandemic period and comparisons to business-as-usual conditions

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The COVID-19 lockdowns and associated restrictions caused dramatic changes to many anthropogenic emission sectors. For example, at the height of the lockdowns in April/May 2020, passenger and light-duty vehicle mileage was reduced by 50% compared to the previous year; by August, passenger travel was still 10-20% below 2019 levels (Figure 1a). Changes were also found in diesel sales, which power the heavy-duty truck fleet in the US (Figure 1b). The emissions were developed using fuel-use based inventories, namely the Fuel-Based Inventory of Vehicle Emissions (FIVE) and published in *Environmental Research Letters* (Harkins, 2021). Fuel-based methodologies are well-suited to capture rapid variations in their respective sectors as these data are publicly available from the US Department of Energy on a near real-time basis. The NOAA Chemical Sciences Laboratory (CSL) was able to combine this information on fuel activity with co-emitted air pollutant emission factors to develop gridded emission inventories for air quality models (Figure 1c). A subset of these emissions were also compared with trends in TROPOMI NO2 data (Kondragunta et al., 2021).

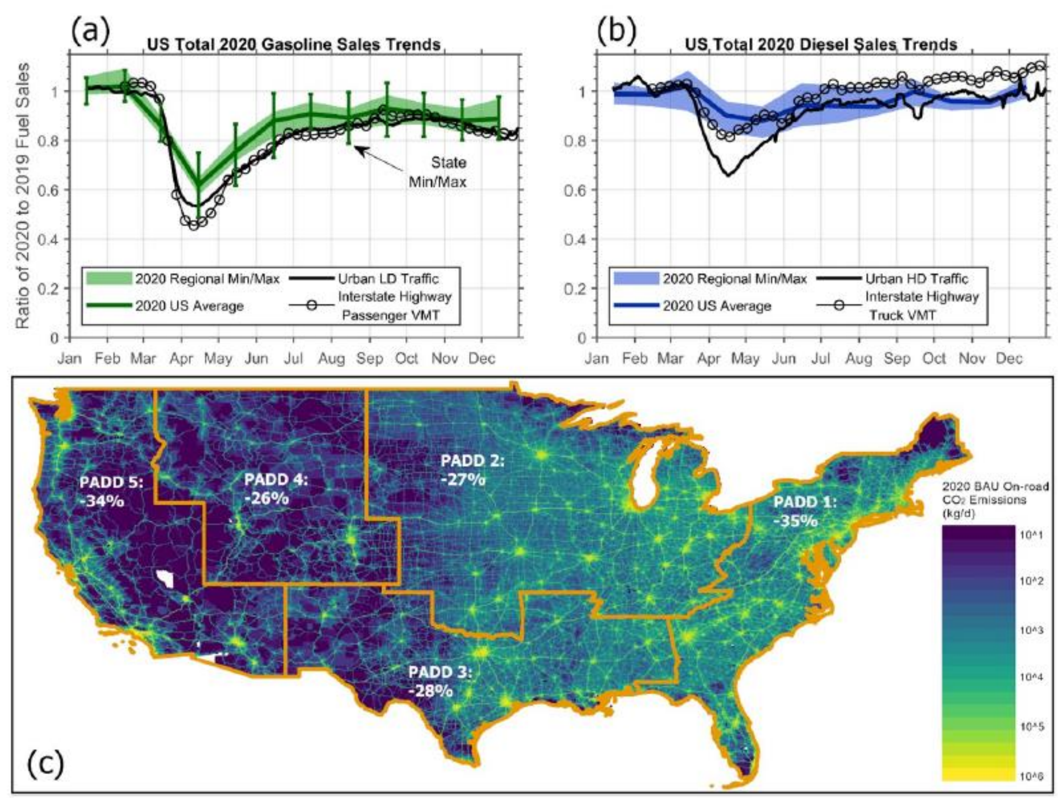

Figure 1. Ratio of 2020 versus 2019 (a) gasoline and (b) diesel fuel sales by month. (c) Reduction in on-road CO_2 emissions in April 2020 versus business-as-usual at 4 km × 4 km resolution and summarized by PADD region (Harkins et al., *Environ. Res. Lett.* 2021).

Developing near real-time transportation emissions was important because they contribute roughly half of the budget of nitrogen oxide (NO_X)– a key precursor species for both surface ozone (O_3) and fine particulate matter ($PM_{2.5}$) – and a shift in these criteria pollutants was also expected. The emissions used in real-time air quality forecasts are typically developed for an earlier year's 'business-as-usual' (BAU) scenario, which themselves are often several years out of date. For example, in early 2020, the most recent version of the EPA's National Emission Inventory (NEI), which forms the basis for many model's emissions over the U.S. was representative of the year 2017. Follow-on work by NOAA CSL has expanded on Harkins et al. to account for COVID-19 impacts on industrial activity, consumer product sales, oil and gas development in constructing a comprehensive emission dataset that reflect changes due to COVID-19 in addition to a 2020 BAU dataset. These comprehensive emissions are currently being updated on a near real-time basis through each month of 2021 and evaluated with satellite data in the Weather Research Forecasting with Chemistry (WRF-Chem) model. Several presentations by NOAA CSL scientists have been made, including at the 2021 AGU Fall Meeting, 2022 American Meteorological Society, and other international and domestic meetings.

The Global Sciences Laboratory (GSL) at NOAA ESRL then began using these emissions to drive an experimental forecast model, the Rapid-Refresh model coupled to chemistry (RAP-Chem). RAP-Chem is based on the Rapid-Refresh or RAP, a continental-scale NOAA hourly-updated assimilation/modeling system that went operational in December 2020. The chemistry component of the model uses packages developed within the framework of the Weather Research and Forecasting model coupled to Chemistry (WRF-Chem). RAP-Chem has a resolution of ~13 km and covers all of North America, Alaska, Hawaii, the northern tip of South America, and parts of Europe and East Asia. RAP-Chem uses the RAP input and boundary conditions which have undergone extensive data assimilation. The initial forecast was run once per day, initialized at 06Z with a lead time of 48 hours. RAP-Chem also ingests daily satellite measurements of fire radiative power (FRP) similarly to the RAP-Smoke and HRRR-Smoke models, except RAP-Chem estimates emissions of both gases and aerosols from wildfire FRP rather than only a single $PM_{2.5}$ tracer. Like RAP- and HRRR-Smoke, RAP-Chem accounts for the scattering and absorption of radiation by aerosols, but utilizes Mie-calculated properties that depends on aerosol composition and size as opposed to generic prescribed properties. Because of the large model domain, the chemical mechanism chosen was a reduced carbon bond mechanism based on and expanded from the carbon bond mechanism version 4 and consists of only 85 species for all gases and aerosols and less than 100 gas-phase and photolytic reactions. This can be compared to the current mechanism in the National Air Quality Forecasting Capability (NAQFC) with 200+ chemical species and 300+ reactions. The forecast began running in August 2020, with plots of key weather and chemistry species published online for each forecast (https://rapidrefresh.noaa.gov/RAPchem/).

While RAP-Chem was the only known air quality forecast operating with COVD-19-adjusted emissions during the pandemic, quantifying how those emission reductions impacted atmospheric composition (and weather) required running a simultaneous forecast that utilizes BAU emissions. Initially, two simultaneous forecasts were run – one with COVID-adjusted emissions and one with BAU emissions - but the computational overhead (e.g., ~200K core-hours/month for one 48-h forecast per day) soon proved too burdensome such that the priority of the forecast in the supercomputer queue was reduced enough that many forecasts sat idle for longer than they may have been useful. Instead, retrospective forecasts during specific periods using BAU emissions were run outside of real-time and compared with the experimental forecast using the COVID-adjusted emissions.

Figure 2 shows one such retrospective forecast example over a four-day period in August 2020 and the associated reductions in surface O_3 during the period. Importantly, the example demonstrates the impact of the emission reductions accumulating over the four-day period. In general, we found that COVID-19 induced emission reductions resulted in moderate (1-5 ppb) reductions in surface O_3 over most of the U.S., with the largest reductions southern California, the Midwest, and the northeast urban corridor. There were locations that showed increases however, generally in regions considered to be 'NO_X-saturated' such as the model pixel containing the Los Angeles urban core. $PM_{2.5}$ changes were more complicated than ozone. Overall, decreases were small, and mostly concentrated to the Midwest and east coast, though reductions in one $PM_{2.5}$ component may have been offset by another. For the time periods evaluated (mid-summer), total $PM_{2.5}$ mostly decreases –nitrates decreased due to reduced NO_X emissions, and sulfates and secondary organic aerosols also decreased likely due to reduced precursor emissions combined with reductions in oxidants. Changes in the highest levels of O_3 and $PM_{2.5}$ were about twice as large as changes in the mean, but much more variable.

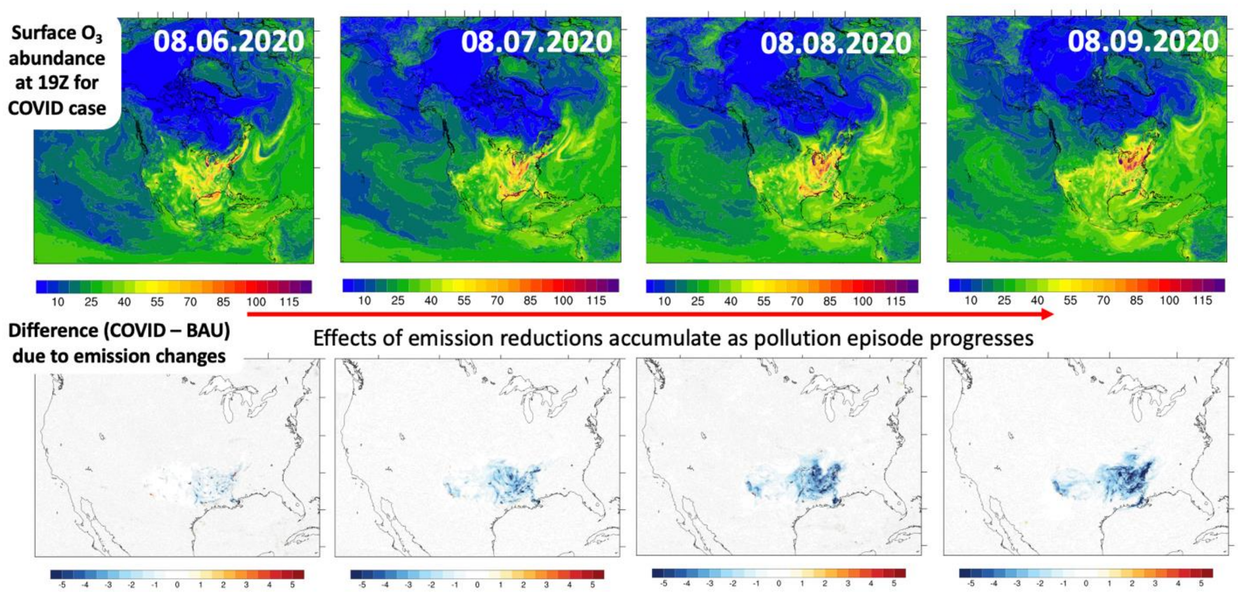

Figure 2. (top) RAP-Chem simulated surface ozone (O_3, ppb) at 19Z for four days (6-9 August 2020) using COVID-19-adjusted emissions. (bottom) Difference (COVID minus BAU, ppb) in surface O_3 for an identical simulation using business-as-usual emissions and zoomed over CONUS. Forecasts are initialized at 18Z using the previous days forecasted chemical abundances.

Highlights of the RAP-Chem forecast using the COVID-19 adjusted emissions were presented orally at the 2021 American Meteorological Society Annual Meeting, and at the 2020 AGU Fall Meeting in two different sessions - one in a regularly scheduled session focusing on COVID-19 emission changes and additionally as invited talk in a special session dedicated specifically to COVID-19 emissions. The RAP-Chem experimental forecast has continued running since August 2020 with no immediate plans of ending. At present, the model uses BAU emissions and has undergone significant and consistent developments since the original version.

Related Publications

Harkins, C., et al. (2021). "A fuel-based method for updating mobile source emissions during the COVID-19 pandemic." Environmental Research Letters **16**.

Kondragunta, S., et al. (2021). "COVID-19 Induced Fingerprints of a New Normal Urban Air Quality in the United States." Journal of Geophysical Research-Atmospheres **126**(17).

Related Presentations

He, J, et al. (2022). Investigating the emission changes over the United States during the COVID-19 pandemic, American Meteorological Society Annual Meeting, Houston, TX (oral). https://ams.confex.com/ams/102ANNUAL/meetingapp.cgi/Paper/395648

McDonald, B.C., et al. (2021). Developing near real-time emissions over the US during the COVID-19 pandemic, *American Geophysical Union Fall Meeting*, New Orleans, LA (oral). https://agu.confex.com/agu/fm21/meetingapp.cgi/Paper/924590

McDonald, B.C., et al. (2021). Developing near real-time emissions over the US during the COVID-19 pandemic, *10th International Workshop on Air Quality Forecasting*, remote (oral). https://congresos.cuaieed.unam.mx/event/5/book-of-abstracts.pdf

He, J. et al. (2021). Modeling COVID Perturbation on Urban Emissions over the US, *10th International Workshop on Air Quality Forecasting*, remote (oral). https://congresos.cuaieed.unam.mx/event/5/book-of-abstracts.pdf

Guevara, M., B.C. McDonald, T. Doumbia (2020). Quantifying COVID-19 transportation emission reductions: European, US, and global perspectives. *IGAC/AMIGO Workshop*, remote (oral). https://www2.acom.ucar.edu/sites/default/files/workshop/AMIGO-COVID_Guevara_McDonald.pdf

McDonald, B.C., et al. (2020). COVID-Air Quality Study: U.S. Urban Air Quality during the COVID-19 Outbreak and Future Implications. *NASA Interagency COVID-AQ Meeting*, remote (oral).

McDonald, B.C., et al. (2020). Quantifying Mobile Source Nitrogen Oxides Emissions during the COVID-19 Pandemic. *Global Monitoring Annual Conference*, remote (oral). https://gml.noaa.gov/publications/annual_meetings/2020/2020%20eGMAC%20July10%20Regional%20Abstracts.pdf

McDonald, B.C., et al. (2020). COVID-19: Near Real-time Emissions Adjustments for Air Quality Forecasting and Long-Term Impact Analyses. *NOAA & Copernicus CAMS COVID-19 Workshop*, remote (oral).

Schnell, J. L., What have we learned about air quality forecasting using COVID-19 adjusted Emissions? 2020 American Geophysical Union Fall Meeting, December 3, 2020. https://agu.confex.com/agu/fm20/meetingapp.cgi/Session/105086.

Schnell, J. L., R. Ahmadov, G. J. Frost, S. A. McKeen, B. C. McDonald, M. Bela, E. James, R. Schwantes, K. Y. Wong, G. Grell. Characterizing the air quality impact of COVID-19 emission reductions through experimental forecasts with the Rapid-Refresh model coupled to chemistry (RAP-Chem). 2020 American Geophysical Union Fall Meeting, December 9, 2020, https://ui.adsabs.harvard.edu/abs/2020AGUFMA079...01S/abstract.

Schnell, J. L., R. Ahmadov, G. A. Grell, E. James, C. R. Alexander, K. Y. Wong, G. Frost, S. A. Mckeen, B. C. McDonald, M. M. Bela, R. Schwantes, J. B. Olson, G. Pereira, S. R. Freitas, I. A. Csiszar, M. Tsidulko. The impact of anthropogenic emissions, wildfires, and heat waves on US air quality during the summer of 2020. 2021 American Meteorological Society Annual Meeting January 13, 2021. https://ams.confex.com/ams/101ANNUAL/meetingapp.cgi/Paper/384613.

Assessing the influence of COVID-19 on Earth's radiative balance

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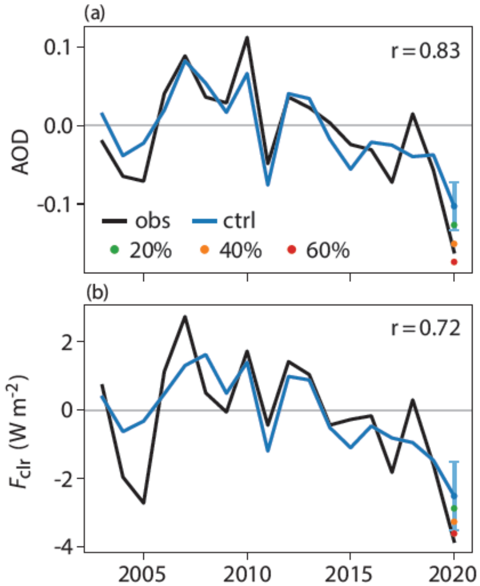
The authors investigated the impacts of the worldwide reduction in aerosol emissions resulting from the COVID-19 pandemic, using simulations with GFDL's AM4.0 model to separate the effects of meteorology and emissions. Pandemic-related emission reductions account for approximately one-third of the large, precipitous decrease in solar clear-sky reflection (when the sky is not covered by clouds) over the East Asian Marginal Seas in March 2020. The remainder of the observed decrease can be attributed to weather variability and long-term emission trends. By contrast, no robust signal is identified in the negative anomaly in solar all-sky reflection. The presence of clouds makes it harder to detect any signal from COVID.
This study looked at the underlying mechanisms of the large, precipitous decrease in solar clear-sky reflection over the East Asian Marginal Seas in March 2020, using satellite observations and model simulations. AM4.0 is skillful at reproducing the observed interannual variations in solar all-sky reflection, under both clear and cloudy-sky conditions. This allowed the scientists to distinguish forced signal from weather variability, a prerequisite for interpreting observations.

The COVID-19 pandemic provides an opportunity for evaluating the model representation of the aerosol-cloud-radiation interactions, a major source of uncertainty in global weather and climate modeling. Although the observational evidence for aerosol direct effects is unequivocal, and their model representation is satisfactory, it is more difficult to draw definitive conclusions about aerosol-cloud interactions from the observed shortwave all-sky flux. By leveraging the latest observational and modeling capabilities, the framework described in this study is ideal for studying the radiative impacts of the ongoing COVID-19 pandemic, and the resulting perturbations to the energy balance in other parts of the world, such as North America.



Variations in solar all-sky reflection

Time series of the anomaly in aerosol optical depth (AOD) over the East Asian Marginal Seas in March from 2003 to 2020. The black line is from MODIS satellite observations, and the blue line is from the control simulation. The vertical bar denotes the detection limit (one standard deviation of the differences between the observations and the control simulation from 2003-2019). The orange, green, and red dots denote the perturbation simulations of 20%, 40%, and 60% emissions reductions, respectively. "r" is the correlation coefficient between simulation and observation. (b) Same as (a), but for CERES satellite clear-sky shortwave radiative flux.

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Susceptible Supply Limits the Role of Climate in the Early SARS-CoV-2/COVID-19 Pandemic

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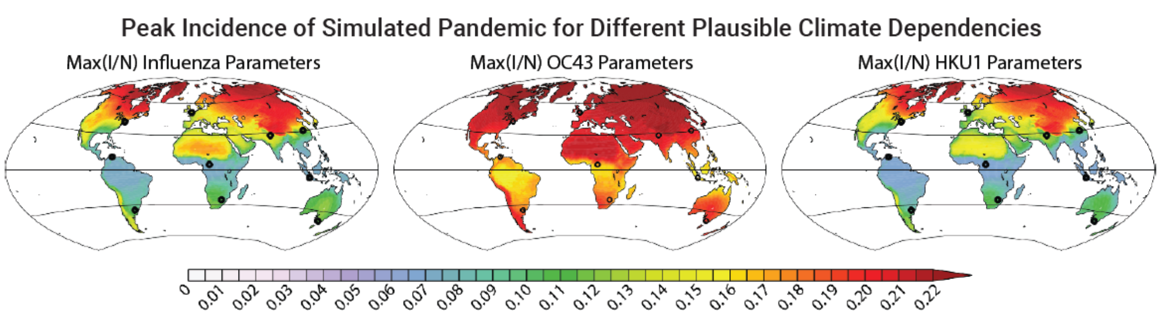
Recently published research shows that local climate is not likely to have much influence on the spread of COVID-19. Researchers found that warmer or more humid climates will not slow the virus at the early stages of the pandemic. <u>The vast number of people vulnerable to an emerging pathogen, and the speed at which it can spread are the core drivers. Climate conditions are likely to have only a minor influence on the size and timing of the pandemic</u>.
An interdisciplinary team of scientists from Princeton University and the National Institutes of Health used a climate-dependent epidemic model to simulate the pandemic, probing different scenarios based on what is known about the role seasonal variations have on the occurrence of similar viruses. In these simulations, climate became a mitigating factor only when large portions of the human population were immune or resistant to the virus. For all climate regimes in the planet we see the development of an epidemic independent of the climate-dependence of the pathogen. Experience with other viruses suggests that, without a vaccine or other control measures, COVID-19 will likely only become responsive to seasonal changes after the supply of unexposed hosts is reduced. A simulation that accounted for the impact of control measures such as social distancing suggested that the longer these measures are in place and slow the transmission of COVID-19, the more sensitive the virus becomes to warmer weather. The study has broader implications for refining the integration of meteorological information into understanding disease outbreaks.



Model results showing the proportion infected (I = infected/N = population) at the peak of the simulated epidemic for all global locations. The three maps show different scenarios of climate-dependence based on influenza and two Beta Coronaviruses: OC43 and HKU1. The fraction of the population that is infected at any particular point in time is one measure of intensity of infection, and will, in an approximate sense, represent a strain on society among other factors. Since the climate dependence of SARS-CoV2 is not known directly, and because the epidemic has a number of factors that make detecting such an effect problematic, this study used two other Beta Coronaviruses that are *endemic in the US (HKU1 and OC43) and influenza, for which we can estimate the range of plausible climate dependence. (The black circles represent cities that are explored in more detail in the paper).*

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Investigating the Predictability of West Nile Virus Disease from Using Climate Data

Karen Holcomb (Centers for Disease Control and NOAA Global Systems Laboratory), Stan Benjamin (NOAA Global Systems Laboratory), Hunter Jones (NOAA Climate Program Office), et al.

West Nile Virus (WNV) is the "leading cause of mosquito-borne disease in the continental U.S." (CDC). When humans are infected with WNV from a mosquito bite, approximately 80% of human infections are asymptomatic, while approximately 20% result in a flu-like illness and <1% result in the neuroinvasive form of the disease with manifestations including encephalitis, meningitis, and acute flaccid paralysis. Roughly 10% of individuals that contract the neuroinvasive form of infection will die, and those that recover often have long-term physical and mental disabilities. There is large spatial and temporal variability in annual reported WNV cases (average of 1,174 total neuroinvasive cases reported annually, range: 19 - 2,946). This makes it difficult to target preventative measures to control the disease and its vector (mosquitos), which are best put in place with advanced early warning. Fortunately, outbreaks of WNV are strongly influenced by environmental and atmospheric drivers. Identifying sources of predictability from environmental factors may enhance the skill of WNV predictions.

We first investigated the current use and value of weather/climate data in WNV predictions through the lens of the CDC's 2020 WNV Forecasting Challenge (hereafter "Challenge"). Modeling teams that participated in the Challenge submitted forecasts predicting the total number of human neuroinvasive cases[2] by county in the continental US for 2020[3] and were evaluated[4] based on the accuracy of their predictions. We also assessed contextual factors and model characteristics associated with better predictive performance (Fig 1). While models based on historical incidence of WNV performed among the top models, we found that teams that included climate or demographics datasets in their modeling framework performed better on average than those that did not include either of these covariates. Inclusion of land use datasets or simulated mosquito distributions resulted in worse predictive performance, potentially due to overfitting or the low spatial coverage of mosquito data.

[2] Neuroinvasive cases were chosen as the outcome because the severe manifestations of the disease are most likely to be accurately captured in the hospitalization records.

[3] Forecasts were submitted April 30, May 31, June 30, and July 31, 2020.

[4] Evaluation began November 2021 when case counts from 2020 were finalized by CDC. COVID-related disruptions delayed the completion and validation of the data.

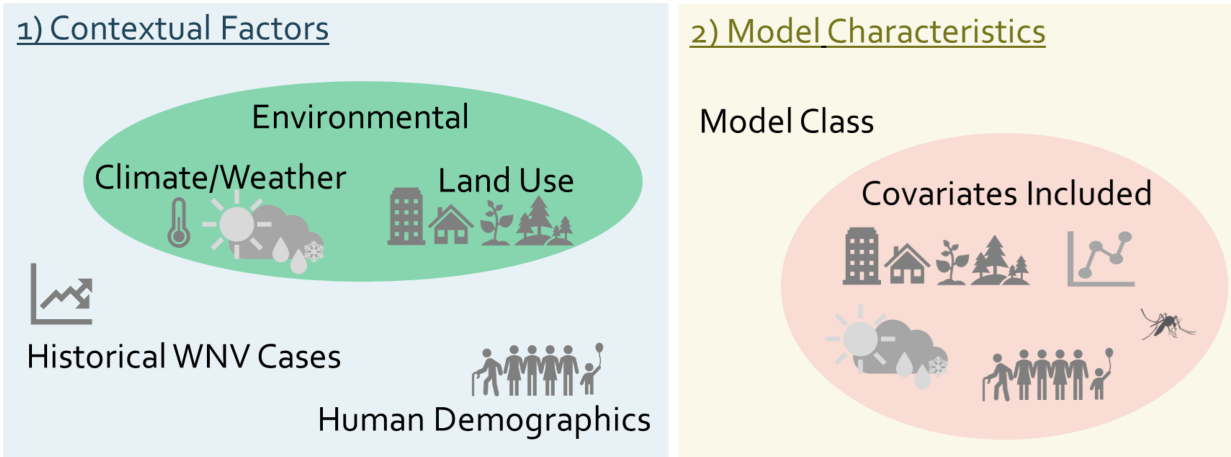

Fig 1. Contextual factors and model characteristics investigated in association with performance of West Nile virus (WNV) predictions in the CDC 2020 WNV Forecasting Challenge. Separate analyses were performed for contextual and model characteristics. Contextual factors were assessed on the county scale and included land use, climate/weather (minimum winter temperature), historical WNV cases, and human demographics to identify factors associated with improved or decreased predictive skill. Model characteristics assessed included model class and inclusion of covariates for land use, historical WNV cases, climate/weather, demographic data, and mosquito distributions to identify modeling techniques associated with improved prediction.

We then used statistical models to explore the relationship between near-surface temperature and precipitation conditions and WNV neuroinvasive cases. Based on findings that a simple autoregressive time series compared well to models submitted to the Challenge, we used an autoregressive framework to assess the impact of these climate variables on predicting the total 2020 WNV neuroinvasive case counts, using WNV data from 2000-2019 and climate data from 2019-2020. We considered monthly and seasonal aggregations of these climate/weather conditions at the county scale (i.e., average temperature, mean minimum temperature, total precipitation, and anomalies in temperature and precipitation). Preliminary analyses yielded promising results of spatial and temporal trends (Fig 2).

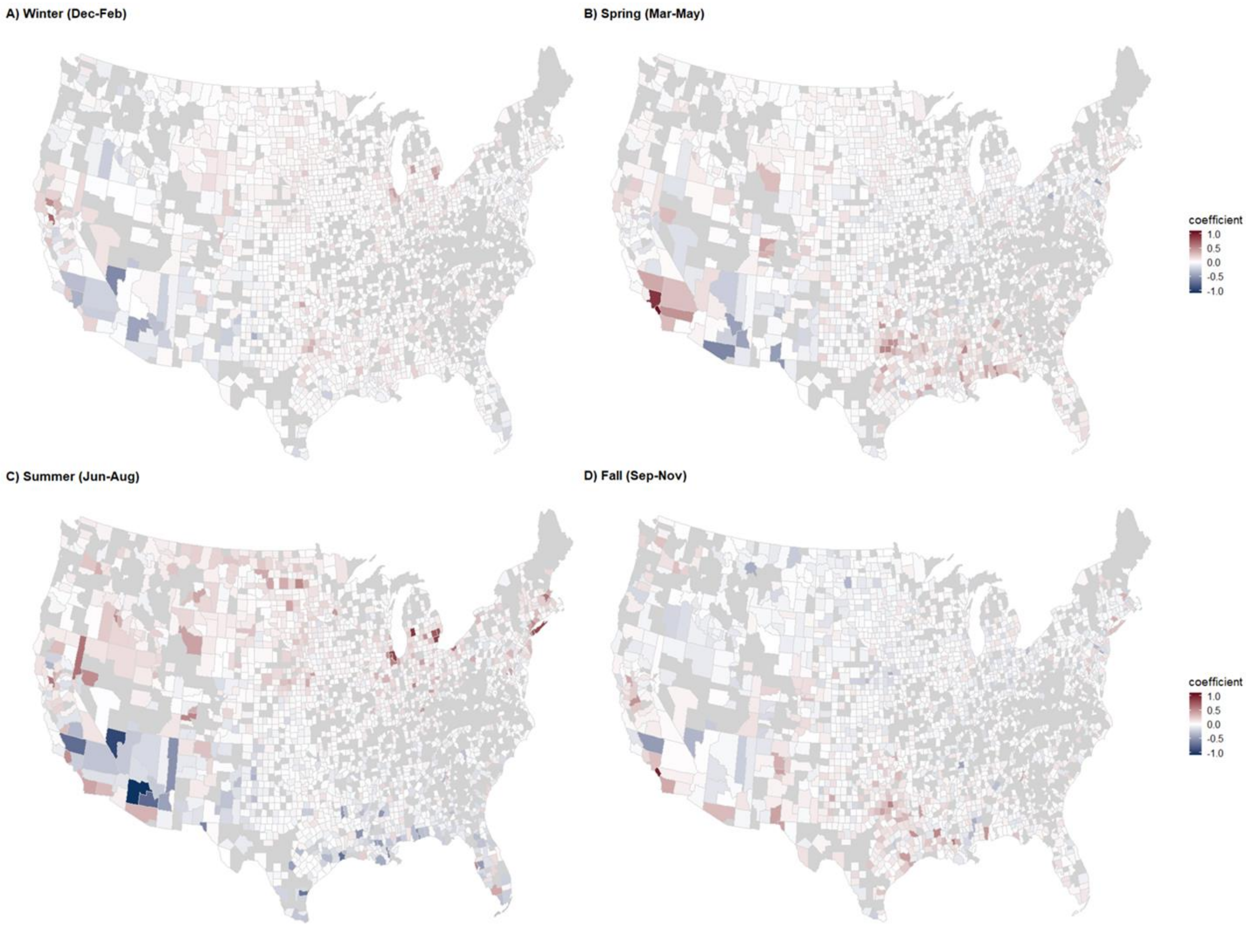

Fig 2. Impact of mean seasonal temperature on predicted number of WNV neuroinvasive cases. Plotted coefficient indicates direction and magnitude of relationship between mean temperature in A) winter, B) spring, C) summer, and D) fall and predicted number of total WNV neuroinvasive cases.

This project represents an important first step towards NOAA-CDC objectives of linking environmental/atmospheric and epidemiological science to improve prediction of vector-borne disease. Future directions of this specific project include quantifying the impact of environmental conditions on disease transmission potential and integration of NOAA weather forecasts into regional-scale early-warning predictions and short-term predictions on the sub-county scale. Long-term goals of this relationship aim to strengthen cross-agency collaboration to quantify the environmental drivers of diseases of public health relevance.