Supplemental information

Code: https://github.com/bujinb/UWcovid

Contents:

- 1. Monitor inclusion flow diagram
- 2. Example of temporal correction
- 3. Sensitivity analysis of temporal adjustment (5-year temporal adjustment)
- 4. Example results of partial autoregression test
- 5. Robust differences results where time axis is calendar weeks
- 6. Robust differences US map where time axis is calendar weeks
- 7. Additional analysis for ozone (includes more monitors than analysis in the main text)
- 8. Robust differences US map before, during, and after stay-at-home orders (states did not issue a stay-at-home order are included)
- 9. Linear regression results aggregated by weeks before, during, and after stay-at-home orders.
- 10. Ozone concentrations in two upwind locations (LAV and THD)
- 11. Robust differences by population density (low, medium, high).
- 12. Population weighted robust differences results
- 13. Weekend/Weekday analysis
- 14. Comparison of year-2020 observed values and historical median of meteorological variables.
- 15. Comparison of year-2020 observed and historical normalized values of meteorological variables.
- 16. Weekly median mobility trends before, during and after stay-at-home orders
- 17. Before, during, and after stay-at-home order periods by state
- 18. Start and end date of each week during 2020 (a leap year)
- 19. Year-2020 criteria pollutants concentrations and robust differences by state
- 20. Median (IQR) temporal correction and R² among all monitors
- 21. Results from multivariate linear autoregression method, before and after a state's stay-at-home order.
- 22. Results from multivariate spline autoregression method, before and after a state's stay-at-home order.



Fig. S1. Monitor inclusion rule flow diagram. Numbers indicate the number of monitors.



Fig. S2. Examples of temporal (10-year) corrections for PM_{2.5}. For each year 2010-2019, median and interquartile range (IQR) for that week +/- 2 weeks; for 2020, median and IQR for that week. The slope of the best-fit line across 2010-2019 is the temporal (10-year) correction. Palm Springs, CA, monitor for week 13 (left) and Oakland West, CA, monitor for week 16 (right). Slopes (units: $\mu g m^{-3} y^{-1}$) are -0.17 (left), 0.24 (right). Temporal (10-year) corrections are used to adjust 2010-2019 pollution levels to an "expected" year-2020 level. These two monitor-weeks were chosen as examples because their slopes have similar magnitude but opposite signs; and, both the slope and the R² for the left plot are approximately equal to the national medians. (Median temporal correction slopes and R² for all pollutants are shown in Table S4.)



Fig. S3. This figure (left) is analogous to Fig. 1 but using historical trends derived from 5 years of data (2015-2019) instead of 10 years (2010-2019). (In the main text, the historical median is the 10-year median, here it is the 5-year median.)



Fig. S4. Example of reducing autocorrelation using autoregressive analysis. Autoregression in PM_{2.5} monitor in Hawaii before (left) and after (right) using multivariate autoregressive analysis.



Fig. S5. Robust differences (equation 1) between year-2020 and the long-term average for that week, for PM_{2.5}, ozone, NO₂, CO and PM₁₀ concentrations (from top to bottom rows, respectively), for the whole US (left column) and for 6 large US states (right columns): upper row: California (CA), Florida (FL), and Illinois (IL); lower row: New York (NY), Texas (TX), and Washington (WA). The start date for stay-at-home orders differs by state, as shown via the vertical dashed line for that state. (The vertical dashed line in the left plot [whole US] indicates timing of the first stay-at-home order in the US: week 12 [CA].) Y-axis is the "robust differences" (see Eq. 1): a value of 0 means the year-2020 concentration is equal to the long-term median, a value of 1 means year-2020 is one interquartile range above the long-term average. X-axis is time: weeks of the year for 2020 (e.g., week 1 is January 1-7). Numbers after the state names are the number of monitoring stations included in the analysis.



Fig. S6. This figure is analogous to Fig. 1 and 2 but includes ozone monitors that have $\geq 14\%$ data completeness on an annual basis. (In the main paper, we exclude monitors with <75% data completeness on an annual basis.)

https://public.tableau.com/profile/bujin3200#!/vizhome/USPM2_52020RobustDifferenceMap/PM2_5Ma pUS?publish=yes

Fig. S7. Robust Differences aggregated by state.

[Note: we will work with the journal to link to this interactive site, following the journal's preferences for how to do so.]



Fig. S8. This figure is analogous to Fig. 3 but including robust differences in states that did not issue a stay-at-home order. States shown in grey have no monitors that meet selection criteria. The number of percentages (right-side of each US map) indicate overall average robust differences in percentage of its IQR. Dates of shutdown and reopening of California were used for the states that did not issue a stay-at-home order.



Fig. S9. This figure is analogous to Fig. 3 but aggregated by counties. Counties shown in grey have no monitors that meet selection criteria. The number of percentages (right-side of each US map) indicate overall average robust differences in percentage of its IQR.



Fig. S10. Estimated coefficients (equation 2) of year-2020 concentrations after correcting for meteorology and temporal trend, for PM_{2.5}, ozone, NO₂, CO, and PM₁₀ concentrations (top to bottom rows, respectively), with time adjusted to match each state's stay-at-home order. These plots are analogous to Fig. 2, but using the results from linear regression method (Eq.2). Left column: time = 0 reflects the day that stay-at-home started. These plots compare before (time<0) and during (time>0) stay-at-home. Right column: time = 0 reflects the day that stay-at-home stopped. These plots compare during (time<0) and after (time>0) stay-at-home. The change in number of states included in the analysis is indicated via the yellow shading. The box-plots show 10th, 25th, 75th, and 90th percentiles, 50th percentile (horizontal line), and the mean (dot); these are summary statistics of monitors throughout the US.



Fig. S11. Ozone concentrations at two upwind locations ((Lassen Volcanic National Park, California [LAV] and Trinidad Head, California [THD]) for 2010-2020, analyzed in the same manner as data in Fig. 1.



Fig. S12. Criteria pollutant level in low-, medium-, and high-density areas (categories, in people per square mile: <50, 50-1000, >1000). Number in parentheses is number of monitors. The orange vertical dashed line indicates timing of the first stay-at-home order in the contiguous US: week 12 [CA]



Fig. S13. Robust differences using population-weighting. The plots are analogous to Fig. S5, but using population-weighting instead of the straightforward average of monitors. Population weighting is based on Census Tract population and centroids: for each Census Tract, we found the nearest monitor; we then calculated a population-weighted average of all Tracts, based on concentrations at the nearest monitor. In this manner, the unit of analysis here is a person (based on the nearest monitor), versus (in the main text) a monitor. The orange vertical dashed line indicates timing of the first stay-at-home order in the contiguous US: week 12 [CA]



Fig. S14. This figure is analogous to Fig. 1 but disaggregating weekdays and weekends. The orange vertical dashed line indicates timing of the first stay-at-home order in the contiguous US: week 12 [CA]



Fig. S15. Transit mobility changes in percentage from median base level (median traffic during 5 week period Jan 3 - Feb 6, 2020). Left column: time = 0 reflects the day that stay-at-home started. These plots compare before (time<0) and during (time>0) stay-at-home. Right column: time = 0 reflects the day that stay-at-home stopped. These plots compare during (time<0) and after (time>0) stay-at-home. Numbers inset near the top of each panel indicate the number of states and counties with both mobility and monitoring data available. (The data is from Google Covid-19 transit stations mobility report https://www.google.com/covid19/mobility/)

Table S1. Before, during, and after stay-at-home order periods by state*

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* Source: "See Which States Are Reopening and Which Are Still Shut Down"

https://www.nytimes.com/interactive/2020/us/states-reopen-map-coronavirus.html [Accessed August 25, 2020]. This representation is taken from widely read and cited news media. It may offer a simplified representation of complex social and political processes, e.g., phased closing and re-opening in some states.

Week Number	Start Date	End Date		
1	01 January 2020	07 January 2020		
2	08 January 2020	14 January 2020		
3	15 January 2020	21 January 2020		
4	22 January 2020	28 January 2020		
5	29 January 2020	04 February 2020		
6	05 February 2020	11 February 2020		
7	12 February 2020	18 February 2020		
8	19 February 2020	25 February 2020		
9	26 February 2020	03 March 2020		
10	04 March 2020	10 March 2020		
11	11 March 2020	17 March 2020		
12	18 March 2020	24 March 2020		
13	25 March 2020	31 March 2020		
14	01 April 2020	07 April 2020		
15	08 April 2020	14 April 2020		
16	15 April 2020	21 April 2020		
17	22 April 2020	28 April 2020		
18	29 April 2020	05 May 2020		
19	06 May 2020	12 May 2020		
20	13 May 2020	19 May 2020		
21	20 May 2020	26 May 2020		
22	27 May 2020	02 June 2020		
23	03 June 2020	09 June 2020		
24	10 June 2020	16 June 2020		
25	17 June 2020	23 June 2020		
26	24 June 2020	30 June 2020		
27	01 July 2020	07 July 2020		
28	08 July 2020	14 July 2020		
29	15 July 2020	21 July 2020		
30	22 July 2020	28 July 2020		
31	29 July 2020	04 August 2020		
32	05 August 2020	11 August 2020		
33	12 August 2020	18 August 2020		
34	19 August 2020	25 August 2020		

Table S2. Start and end date of each week during 2020 (a leap year)

Table S3. Year-2020 criteria pollutants concentrations and robust differences by state

https://public.tableau.com/profile/bujin3200#!/vizhome/Ozoneconcentrationandrobustdifferencepreandpostcovid/PM2_5USRobustDifferenceTable?publish=yes

[Note: we will work with the journal to link to these data, following the journal's preference for how to do so.]

Table S4. Median (IQR) temporal correction and R^2 among all monitors and typical annual change represented by the temporal correction. Population weighting is based on Census Tract population and centroids: for each Census Tract, we found the nearest monitor; we then calculated a population-weighted average of all Tracts, based on historical median concentrations at the nearest monitor. The typical annual change is calculated by dividing the median slope by the population weighted average concentrations.

Pollutant	Temporal correction Median (IQR)	Doral correction R ² Median (IQR) Median (IQR)		Annual change Median (IQR)
PM _{2.5}	-0.22 (-0.41 to 0.06) $\mu g/m^3$	0.21 (0.06 to 0.42)	7.2 μg/m ³	-3.0% (-5.2% to -0.8%)
Ozone	-0.08 (-0.3 to 0.2) ppb	0.10 (0.03 to 0.24)	43 ppb	-0.2% (-0.7% to 0.4%)
NO ₂	-0.52 (-0.23 to -0.81) ppb	0.28 (0.10 to 0.48)	22.2 ppb	-2.1% (-1.3% to -3.9%)
СО	-0.007 (-0.02 to 0.0) ppm	0.13 (0.04 to 0.32)	0.5 ppm	-1.7% (-3.8% to 0.0%)
PM10	-0.37 (-0.85 to 0.07) $\mu g/m^3$	0.15 (0.03 to 0.37)	21.2 µg/m ³	-2.2% (-3.8% to 0.3%)

Table S5. Results from multivariate linear autoregression method, before, during, and after a state's stay-at-home order.

		Before stay- (weeks	Before stay-at-home orders (weeks -14 to -4)		During stay-at-home orders (weeks -3 to 12 of stay-at- home orders)		at-home orders to +20 <i>after the</i> stay-at-home rder)	
Pollutant	Population weighted average concentration (2010-2019)	Estimated coefficient	Effect before stay-at-home order	Estimated coefficient	Effect during stay-at-home order	Estimated coefficient	Effect after stay-at-home order	R ² Median (IQR)
PM _{2.5}	$7.2 \ \mu g/m^3$	$-0.11 \mu g/m^3$	-1.6%	$0.14 \ \mu g/m^3$	2.1%	$0.09 \ \mu g/m^3$	1.2%	0.41 (0.34 to 0.49)
Ozone	43.0 ppb	-0.09 ppb	-0.2%	-1.4 ppb	-3.3%	-1.1 ppb	-2.5%	0.42 (0.35 to 0.49)
NO ₂	22.2 ppb	-0.50 ppb	-2.3%	-0.81 ppb	-3.6%	-0.47 ppb	-2.1%	0.35 (0.24 to 0.45)
СО	0.5 ppm	0.00 ppm	0.1%	-0.02 ppm	-3.5%	0.01 ppm	2.1%	0.45 (0.34 to 0.57)
PM ₁₀	21.2 µg/m ³	$1.20 \ \mu g/m^3$	5.7%	-2.94 μ g/m ³	-14.0%	$1.55 \ \mu g/m^3$	7.4%	0.32 (0.19 to 0.44)

		Before stay-at-home orders (weeks -14 to -4)		During stay-at-home orders (weeks -3 to 12 of stay-at- home orders)		After stay-at-home orders (weeks +1 to +20 after the removal of stay-at-home order)		
Pollutant	Population weighted average concentration (2010-2019)	Estimated coefficient	Effect before stay- at-home order	Estimated coefficient	Effect during stay- at-home order	Estimated coefficient	Effect after stay-at-home order	R ² Median (IQR)
PM _{2.5}	7.2 μg/m ³	$-0.41 \mu g/m^3$	-5.8%	$0.07 \ \mu g/m^3$	1.1%	1.79 µg/m ³	24.9%	0.49 (0.41 to 0.51)
Ozone	43.0 ppb	-1.18 ppb	-2.8%	-1.71 ppb	-4.0%	-1.59 ppb	-3.7%	0.50 (0.45 to 0.53)
NO ₂	22.2 ppb	-0.27 ppb	-1.2%	-2.07 ppb	-9.4%	0.58 ppb	2.7%	0.45 (0.38 to 0.50)
СО	0.5 ppm	0.01 ppm	2.0%	-0.01 ppm	-2.5%	0.04 ppm	8.0%	0.54 (0.4 to 0.6)
PM ₁₀	21.2 μg/m ³	1.29 μ g/m ³	6.1%	-1.15 $\mu g/m^3$	-5.5%	1.67 $\mu g/m^{3}$	8.0%	0.41 (0.23 to 0.47)

Table S6a. Results from multivariate spline autoregression (degrees of freedom = 2) method, before and after a state's stay-athome order.

Table S6b. Results from multivariate spline autoregression (degrees of freedom = 3) method, before and after a state's stay-athome order.

		Before stay-at-home orders (weeks -14 to -4)		During stay-at-home orders (weeks -3 to 12 of stay-at- home orders)		After stay-at-home orders (weeks +1 to +20 after the removal of stay-at-home order)		
Pollutant	Population weighted average concentration (2010-2019)	Estimated coefficient	Effect before stay-at-home order	Estimated coefficient	Effect during stay-at-home order	Estimated coefficient	Effect after stay-at-home order	R ² Median (IQR)
PM _{2.5}	$7.2 \ \mu g/m^3$	-0.28 μ g/m ³	-3.8%	$0.08 \ \mu g/m^3$	1.1%	$0.01 \ \mu g/m^3$	0.1%	0.49 (0.41 to 0.57)
Ozone	43.0 ppb	-0.20 ppb	-0.5%	-0.17 ppb	-4.0%	-0.16 ppb	-3.7%	0.50 (0.43 to 0.57)
NO ₂	22.2 ppb	-0.52 ppb	-2.3%	-2.17ppb	-9.8%	-1.25 ppb	-5.6%	0.44 (0.33 to 0.55)
CO	0.5 ppm	-0.01 ppm	-2.9%	-0.02 ppm	-4.0%	0.05 ppm	9.8%	0.56 (0.44 to 0.66)
PM ₁₀	21.2 µg/m ³	$1.22 \ \mu g/m^3$	5.8%	-0.60 μ g/m ³	-2.8%	$0.85 \ \mu g/m^3$	4.0%	0.41 (0.29 to 0.53)

		Before stay-at-home orders (weeks -14 to -4)		During stay-at-home orders (weeks -3 to 12 of stay-at- home orders)		After stay-at-home orders (weeks +1 to +20 after the removal of stay-at-home order)		
Pollutant	Population weighted average concentration (2010-2019)	Estimated coefficient	Effect before stay-at-home order	Estimated coefficient	Effect during stay-at-home order	Estimated coefficient	Effect after stay-at-home order	R ² Median (IQR)
PM _{2.5}	$7.2 \ \mu g/m^3$	-0.23.µg/m ³	-3.2%	$0.30 \ \mu g/m^3$	4.2%	$0.54 \ \mu g/m^3$	7.5%	0.51 (0.43 to 0.59)
Ozone	43.0 ppb	-0.20 ppb	-0.5%	-1.1 ppb	-2.7%	0.98 ppb	2.3%	0.51 (0.45 to 0.58)
NO ₂	22.2 ppb	-0.66 ppb	-3.0%	-2.16ppb	-9.8%	1.44 ppb	6.5%	0.46 (0.39 to 0.58)
СО	0.5 ppm	-0.02 ppm	-4.3%	-0.01 ppm	-1.8%	-0.00 ppm	-0.8%	0.56 (0.44 to 0.67)
PM ₁₀	21.2 µg/m ³	$1.32 \ \mu g/m^3$	6.3%	2.34 μ g/m ³	11.1%	$6.95 \ \mu g/m^3$	32.8%	0.43 (0.32 to 0.55)

Table S6c. Results from multivariate spline autoregression (degrees of freedom = 4) method, before and after a state's stay-athome order.

Table S6d. Results from multivariate spline autoregression (degrees of freedom = 5) method, before and after a state's stay-athome order.

		Before stay-at-home orders (weeks -14 to -4)		During stay-at-home orders (weeks -3 to 12 of stay-at- home orders)		After stay-at-home orders (weeks +1 to +20 after the removal of stay-at-home order)		
Pollutant	Population weighted average concentration (2010-2019)	Estimated coefficient	Effect before stay-at-home order	Estimated coefficient	Effect during stay-at-home order	Estimated coefficient	Effect after stay-at-home order	R ² Median (IQR)
PM _{2.5}	$7.2 \ \mu g/m^3$	$-0.41 \mu g/m^3$	-5.8%	$0.93 \ \mu g/m^3$	12.9%	$1.79 \ \mu g/m^3$	24.9%	0.53 (0.46 to 0.61)
Ozone	43.0 ppb	-1.18 ppb	-2.8%	-0.42 ppb	-1.0%	-0.74 ppb	-1.7%	0.54 (0.47 to 0.60)
NO ₂	22.2 ppb	-0.27 ppb	-1.2%	-5.34 ppb	-24.0%	0.91 ppb	4.1%	0.49 (0.38 to 0.60)
СО	0.5 ppm	-0.02 ppm	-3.7%	-0.07 ppm	-13.9%	-0.16 ppm	-32.4%	0.59 (0.47 to 0.70)
PM ₁₀	21.2 µg/m ³	$1.09 \ \mu g/m^3$	5.1%	$3.1 \ \mu g/m^3$	14.7%	7.05 μ g/m ³	33.3%	0.45 (0.33 to 0.57)