Supplemental information

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

Contents:

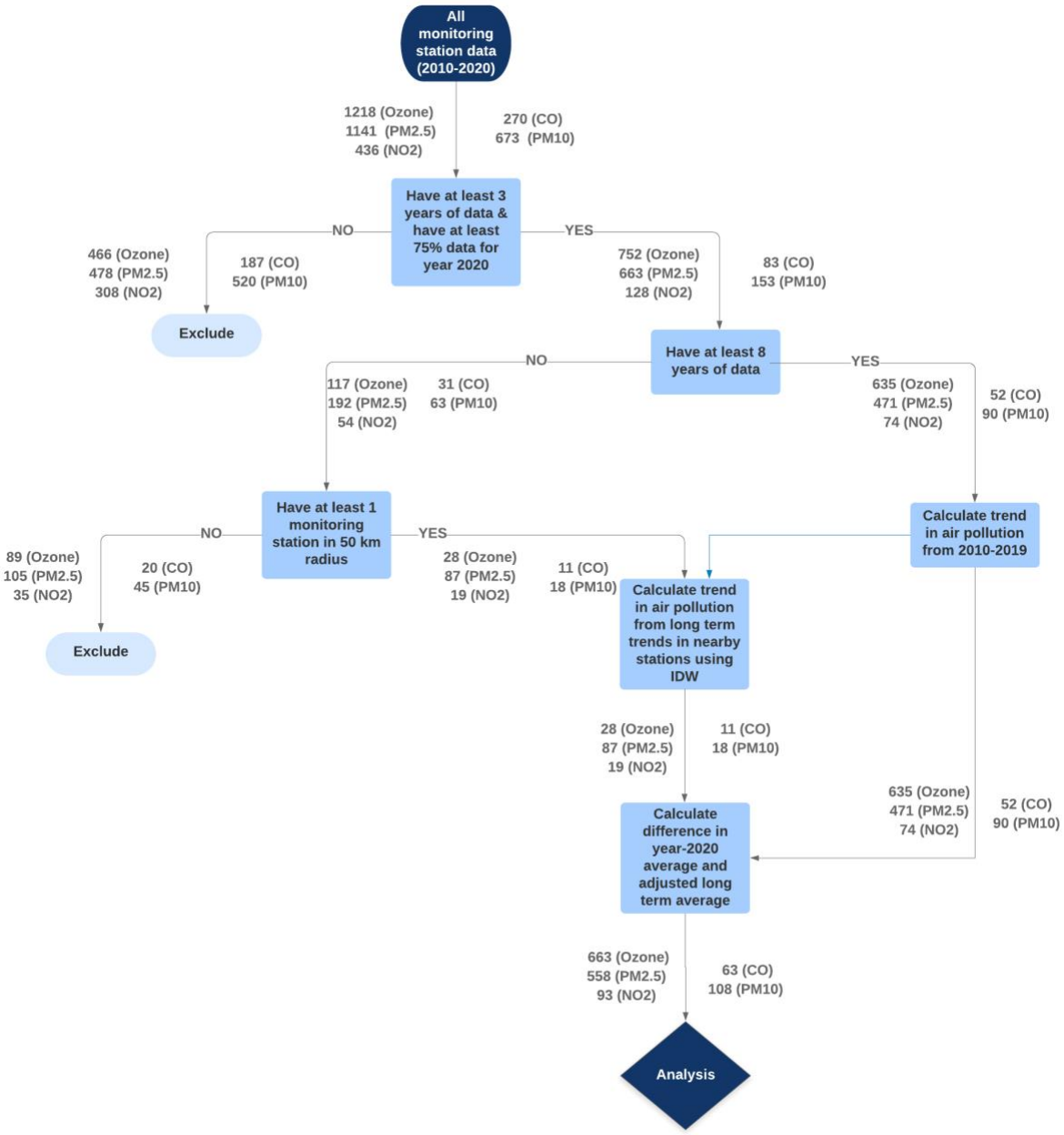

Fig. S1. Monitor inclusion rule flow diagram. Numbers indicate the number of monitors.

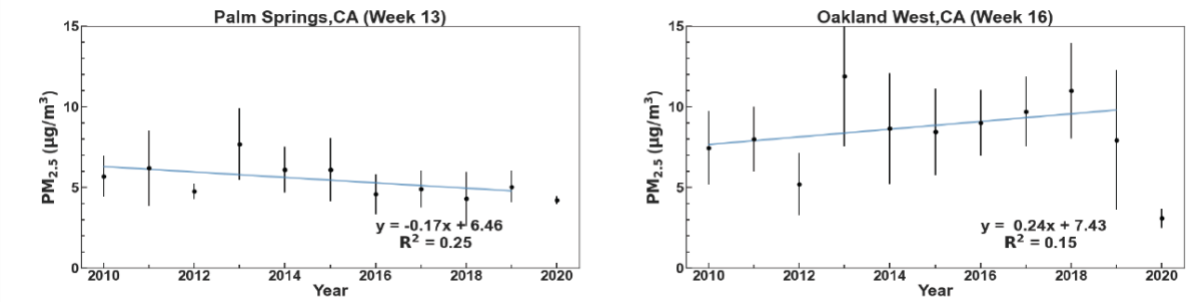

Fig. S2. Examples of temporal (10-year) corrections for $PM_{2.5}$. For each year 2010-2019, median and interquartile range (IQR) for that week +/- 2 weeks; for 2020, median and IQR for that week. The slope of the best-fit line across 2010-2019 is the temporal (10-year) correction. Palm Springs, CA, 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 R^2 for the left plot are approximately equal to the national medians. (Median temporal correction slopes and R^2 for all pollutants are shown in Table S4.)

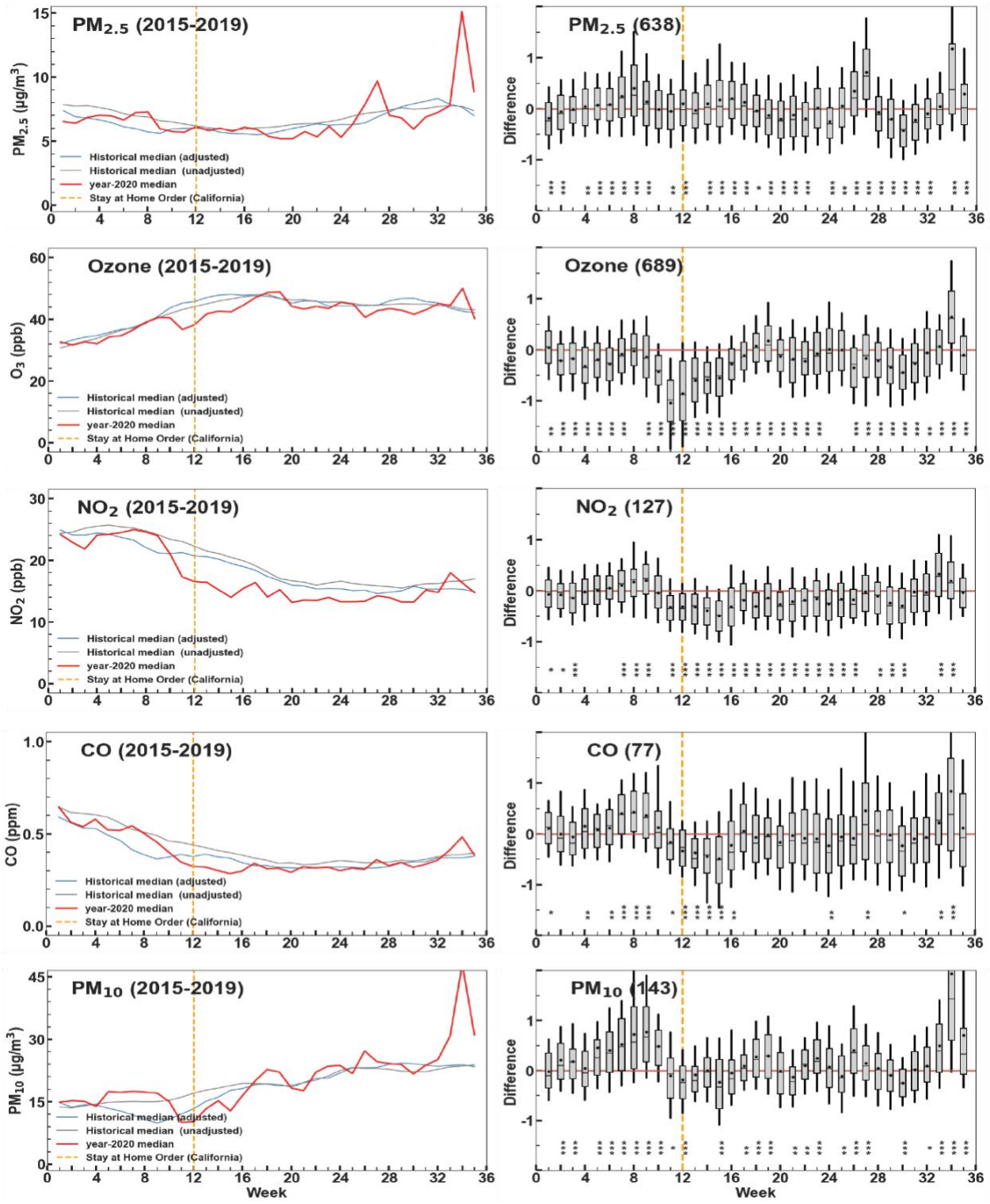

Fig. S3. This figure (left) is analogous to Fig. 1 but using historical trends derived from 5 years of data (2015-2019) instead of 10 years (2010-2019). (In the main text, the historical median is the 10-year median, here it is the 5-year median.)

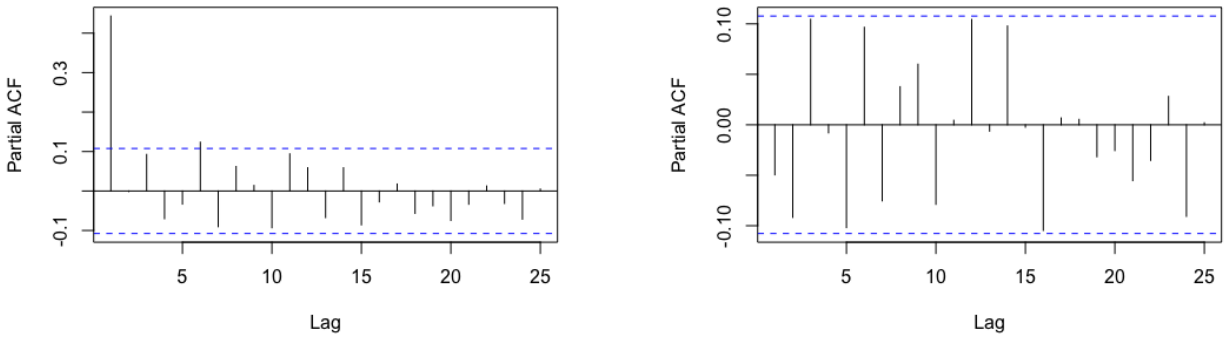

Fig. S4. Example of reducing autocorrelation using autoregressive analysis. Autoregression in $PM_{2.5}$ monitor in Hawaii before (left) and after (right) using multivariate autoregressive analysis.

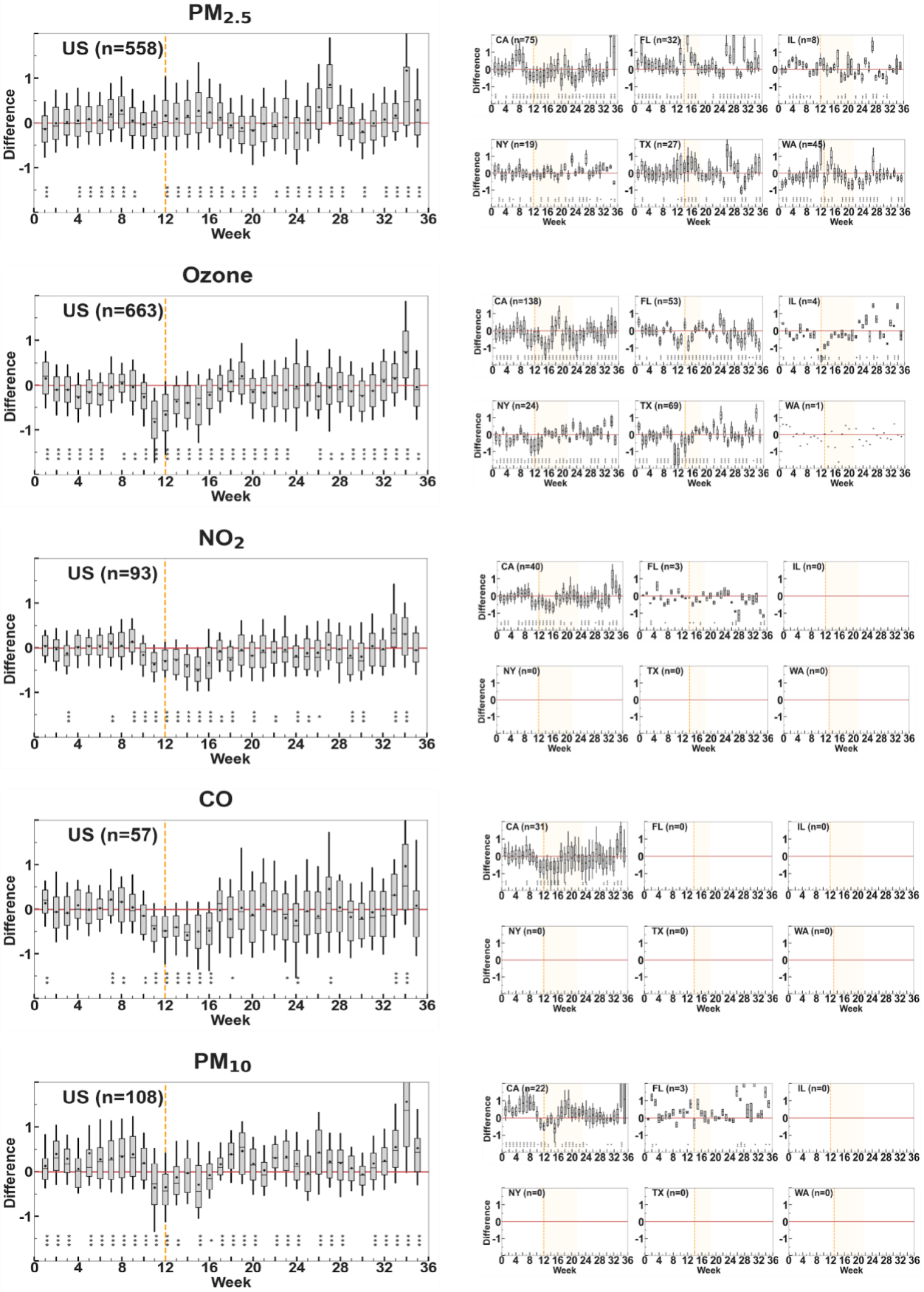
PM2.5
US (n=558)
CA (n=75)
FL (n=32)
IL (n=8)
NY (n=19)
TX (n=27)
WA (n=45)
Ozone
US (n=663)
CA (n=138)
FL (n=53)
IL (n=4)
NY (n=24)
TX (n=69)
WA (n=1)
NO2
US (n=93)
CA (n=40)
FL (n=3)
IL (n=0)
NY (n=0)
TX (n=0)
WA (n=0)
CO
US (n=57)
CA (n=31)
FL (n=0)
IL (n=0)
NY (n=0)
TX (n=0)
WA (n=0)
PM10
US (n=108)
CA (n=22)
FL (n=3)
IL (n=0)
NY (n=0)
TX (n=0)
WA (n=0)
Difference
Week

Fig. S5. Robust differences (equation 1) between year-2020 and the long-term average for that week, for $PM_{2.5}$, ozone, NO_2, CO and PM_{10} 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.

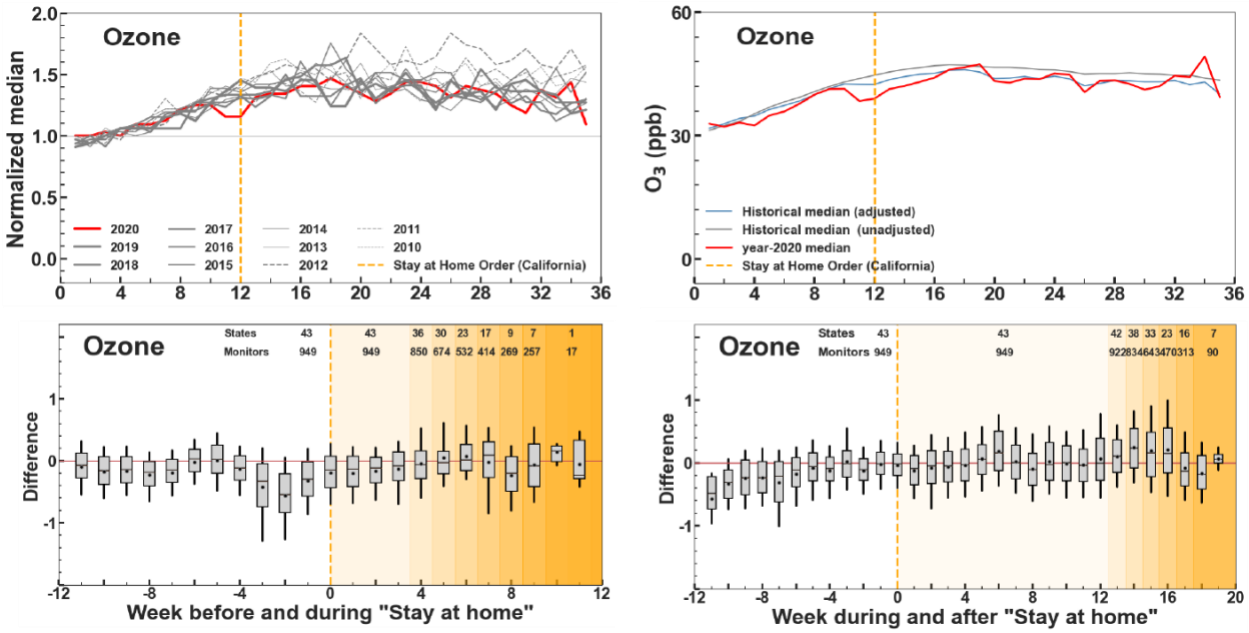

Fig. S6. This figure is analogous to Fig. 1 and 2 but includes ozone monitors that have ≥14% data completeness on an annual basis. (In the main paper, we exclude monitors with <75% data completeness on an annual basis.)

https://public.tableau.com/profile/bujin3200#!/vizhome/USPM2_52020RobustDifferenceMap/PM2_5MapUS?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.]

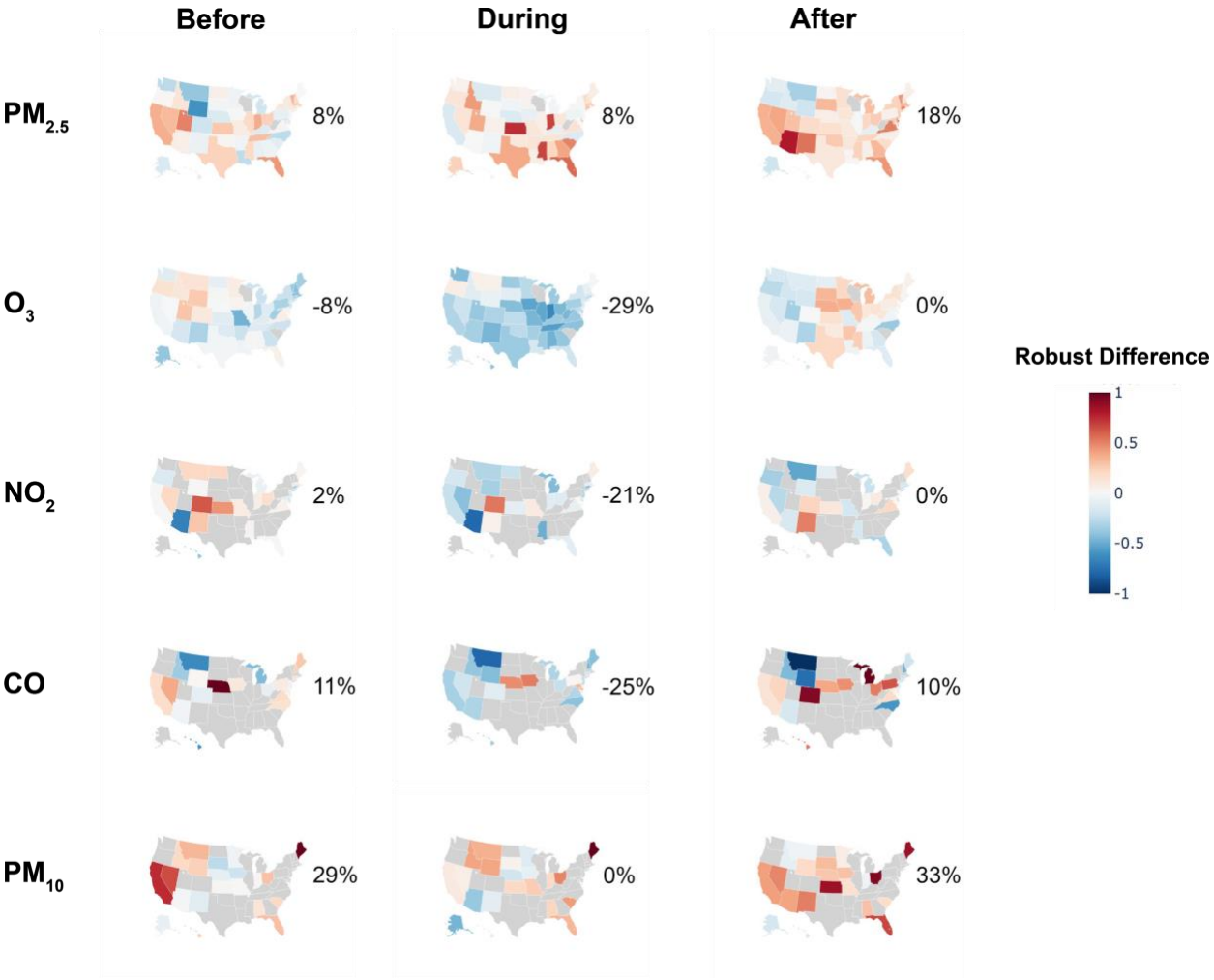

Fig. S8. This figure is analogous to Fig. 3 but including robust differences in states that did not issue a stay-at-home order. States shown in grey have no monitors that meet selection criteria. The number of percentages (right-side of each US map) indicate overall average robust differences in percentage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

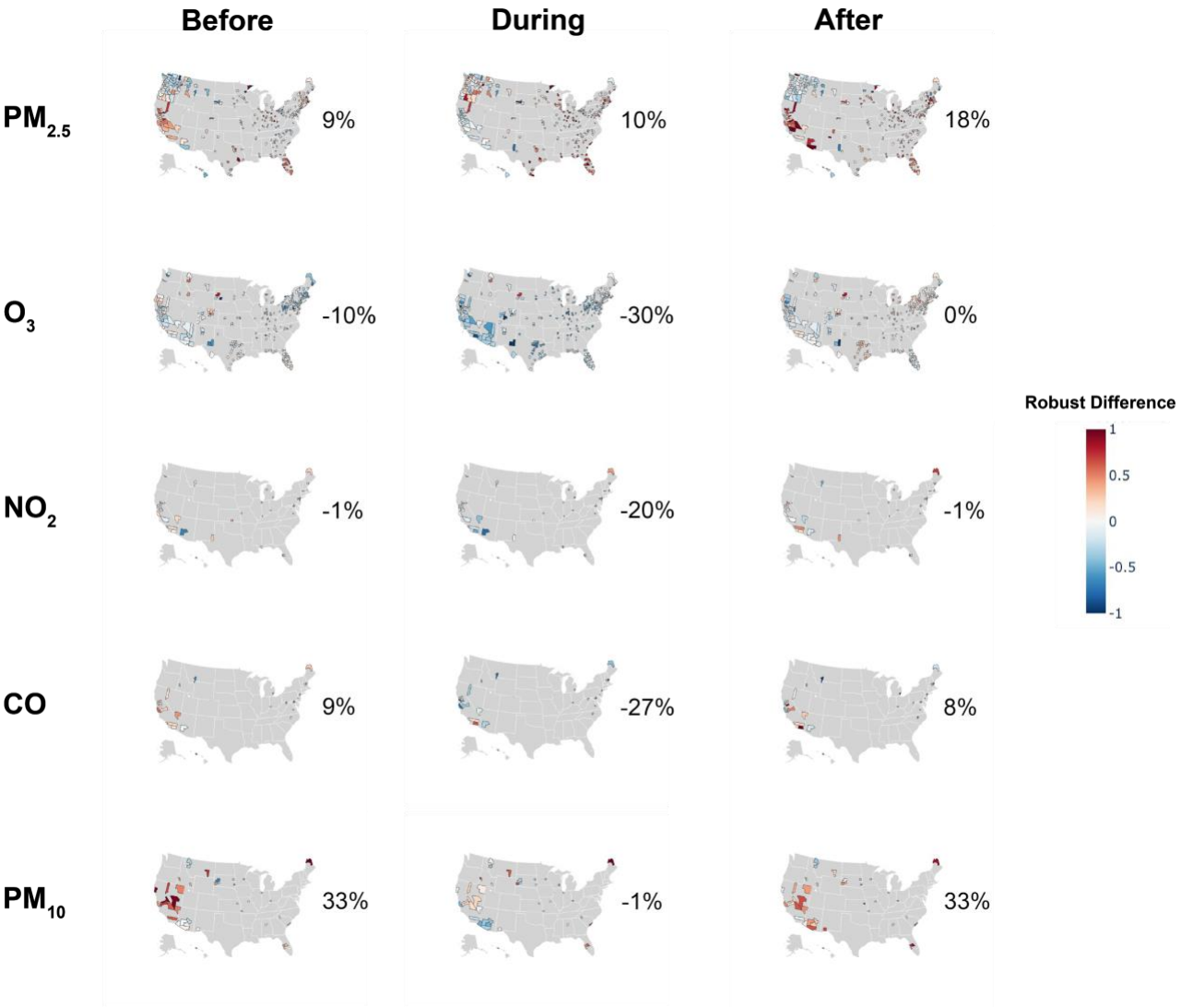

Fig. S9. This figure is analogous to Fig. 3 but aggregated by counties. Counties shown in grey have no monitors that meet selection criteria. The number of percentages (right-side of each US map) indicate overall average robust differences in percentage of its IQR.

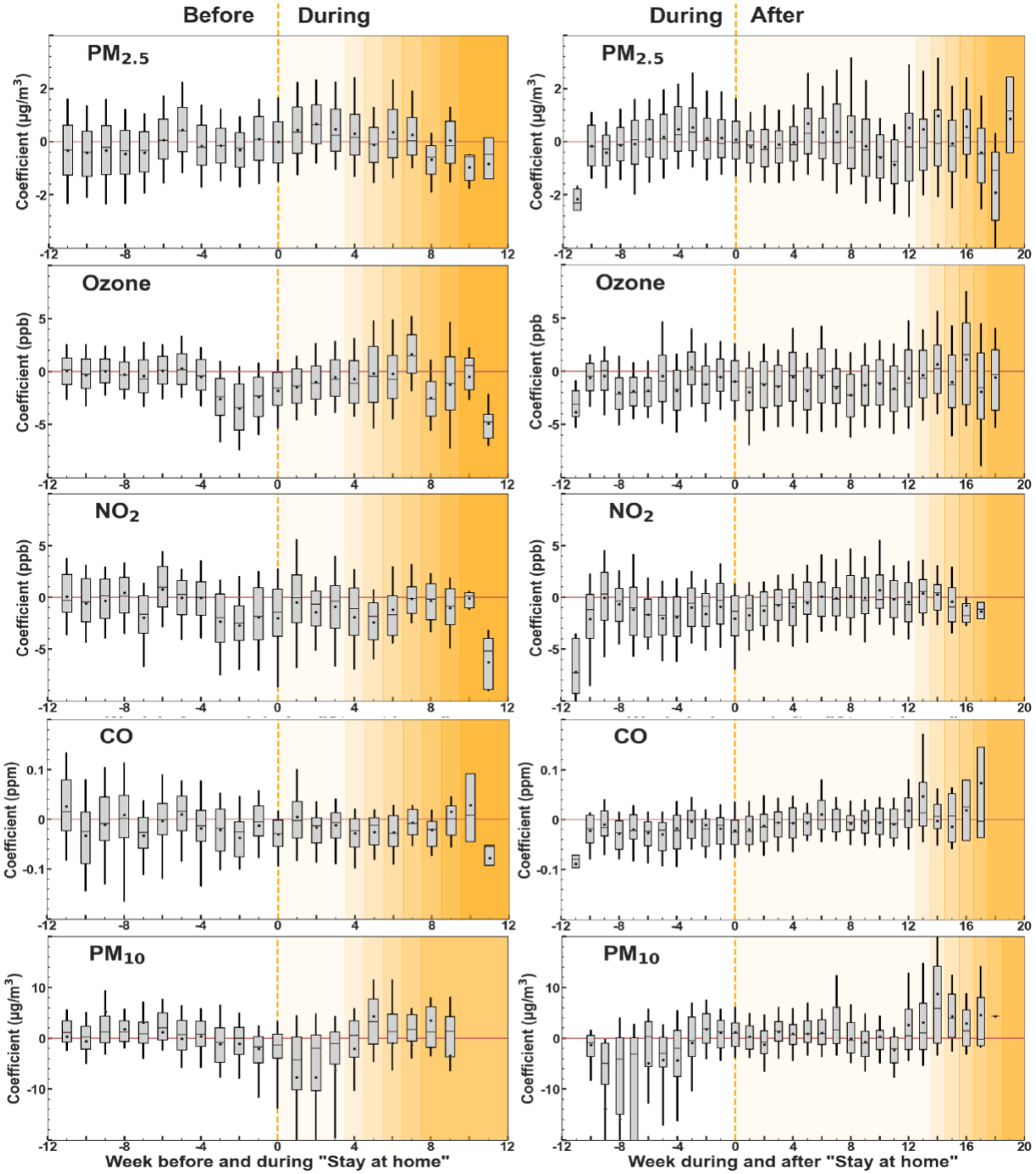

Fig. S10. Estimated coefficients (equation 2) of year-2020 concentrations after correcting for meteorology and temporal trend, for $PM_{2.5}$, ozone, NO_2, CO, and PM_{10} concentrations (top to bottom rows, respectively), with time adjusted to match each state's stay-at-home order. These plots are analogous 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.

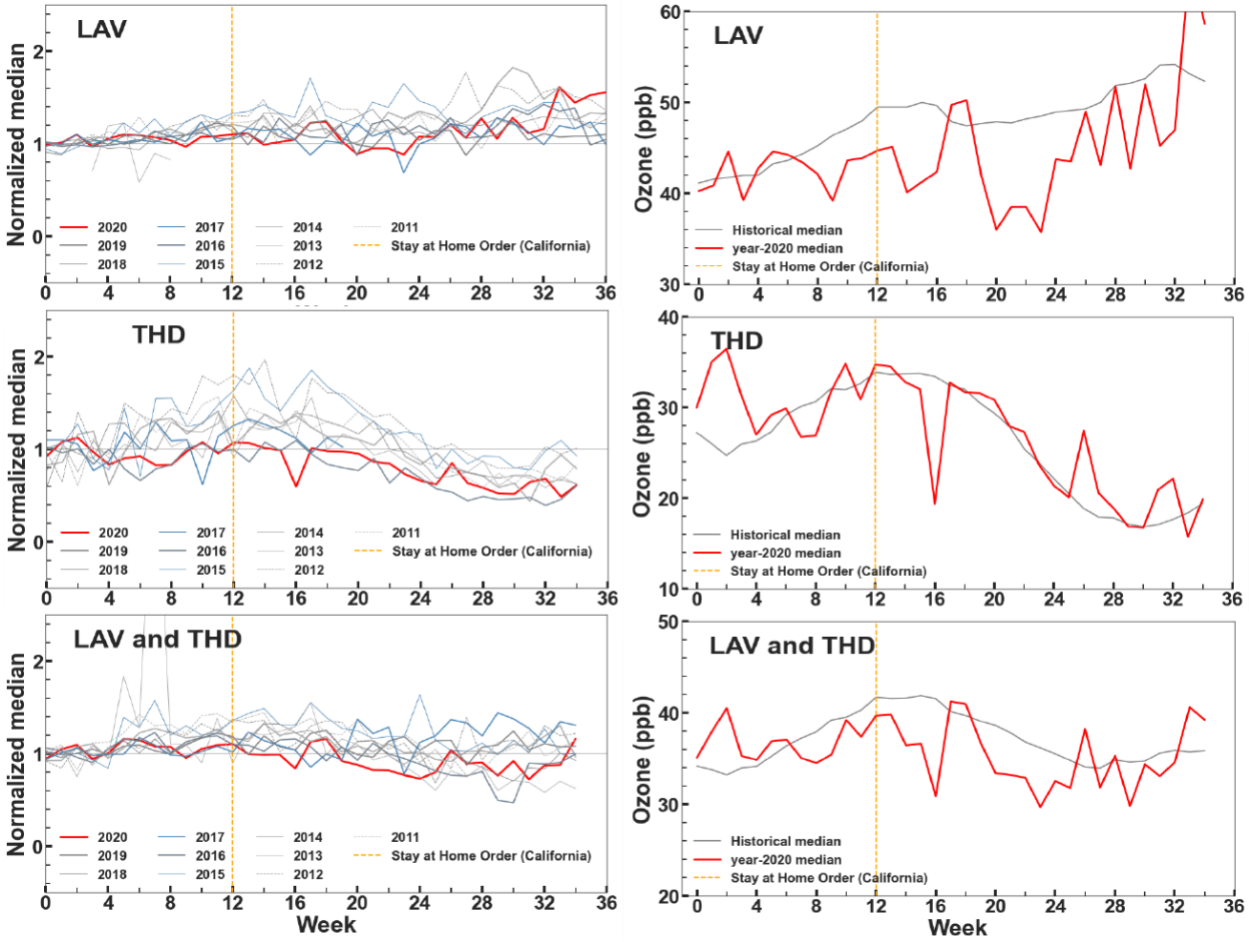

Fig. S11. Ozone concentrations at two upwind locations ((Lassen Volcanic National Park, California [LAV] and Trinidad Head, California [THD]) for 2010-2020, analyzed in the same manner as data in Fig. 1.

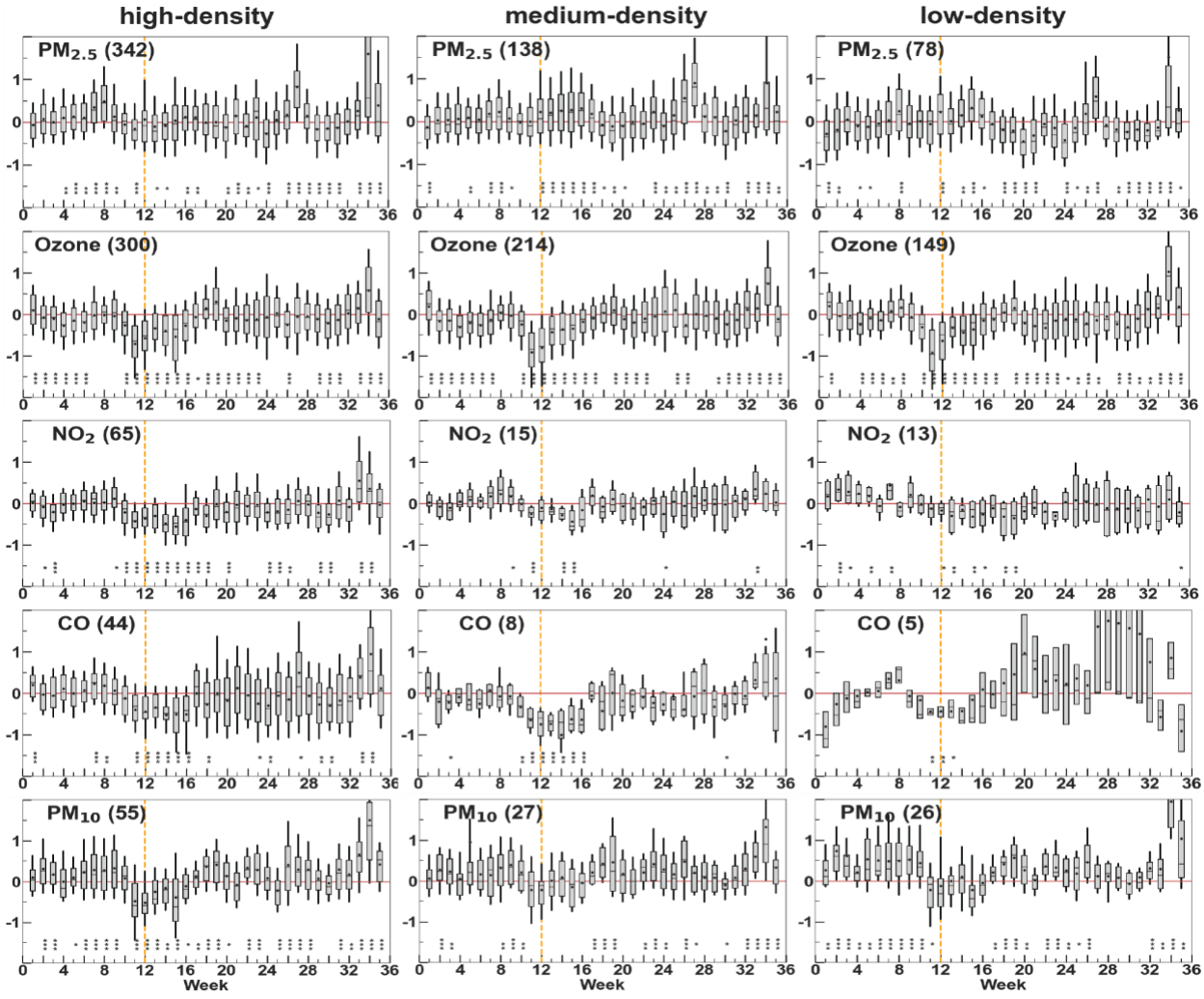

Fig. S12. Criteria pollutant level in low-, medium-, and high-density areas (categories, in people per square mile: <50, 50-1000, >1000). Number in parentheses is number of monitors. The orange vertical dashed line indicates timing of the first stay-at-home order in the contiguous US: week 12 [CA]

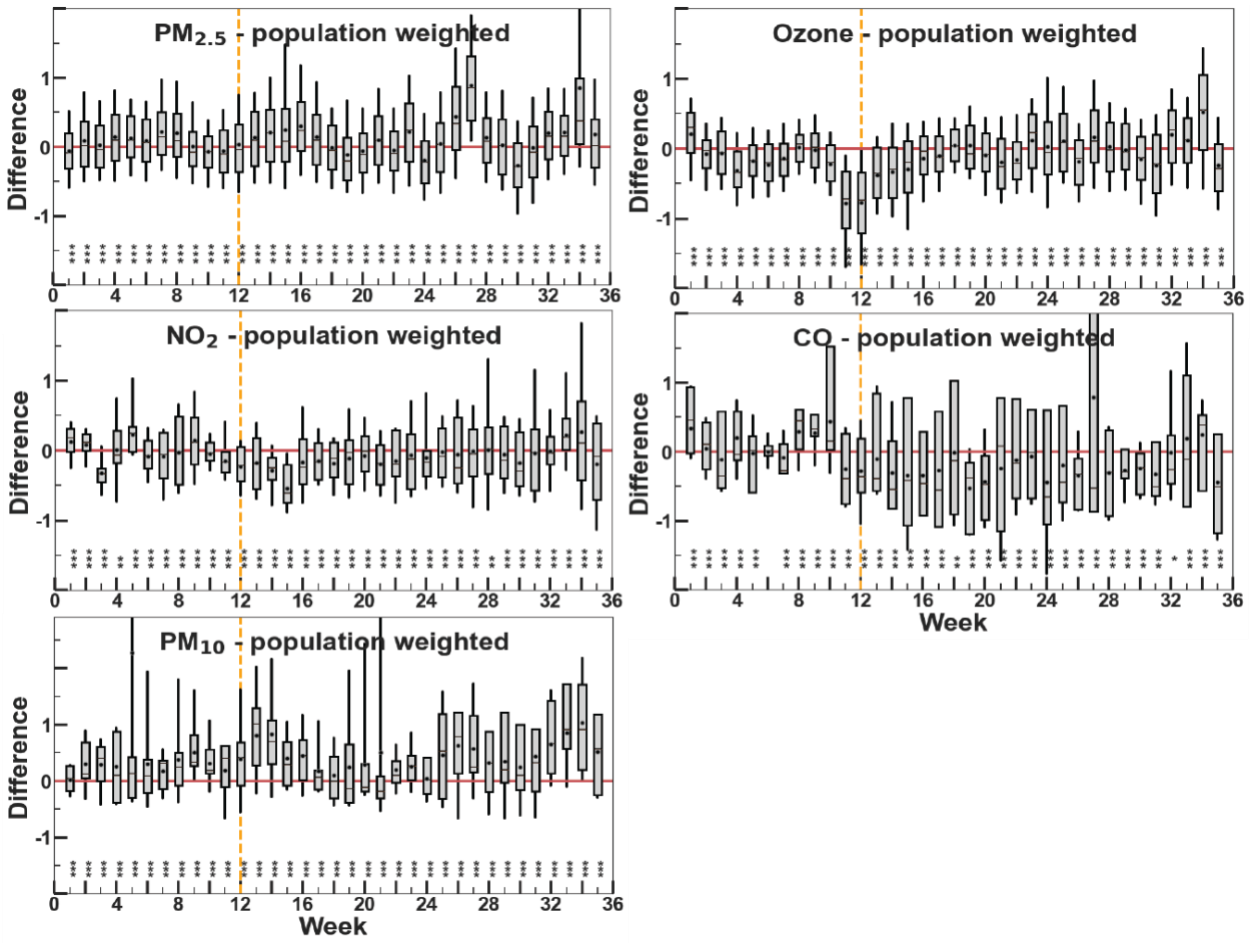

Fig. S13. Robust differences using population-weighting. The plots are analogous to Fig. S5, but using population-weighting instead of the straightforward average of monitors. Population weighting is based on Census Tract population and centroids: for each Census Tract, we found the nearest monitor; 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]

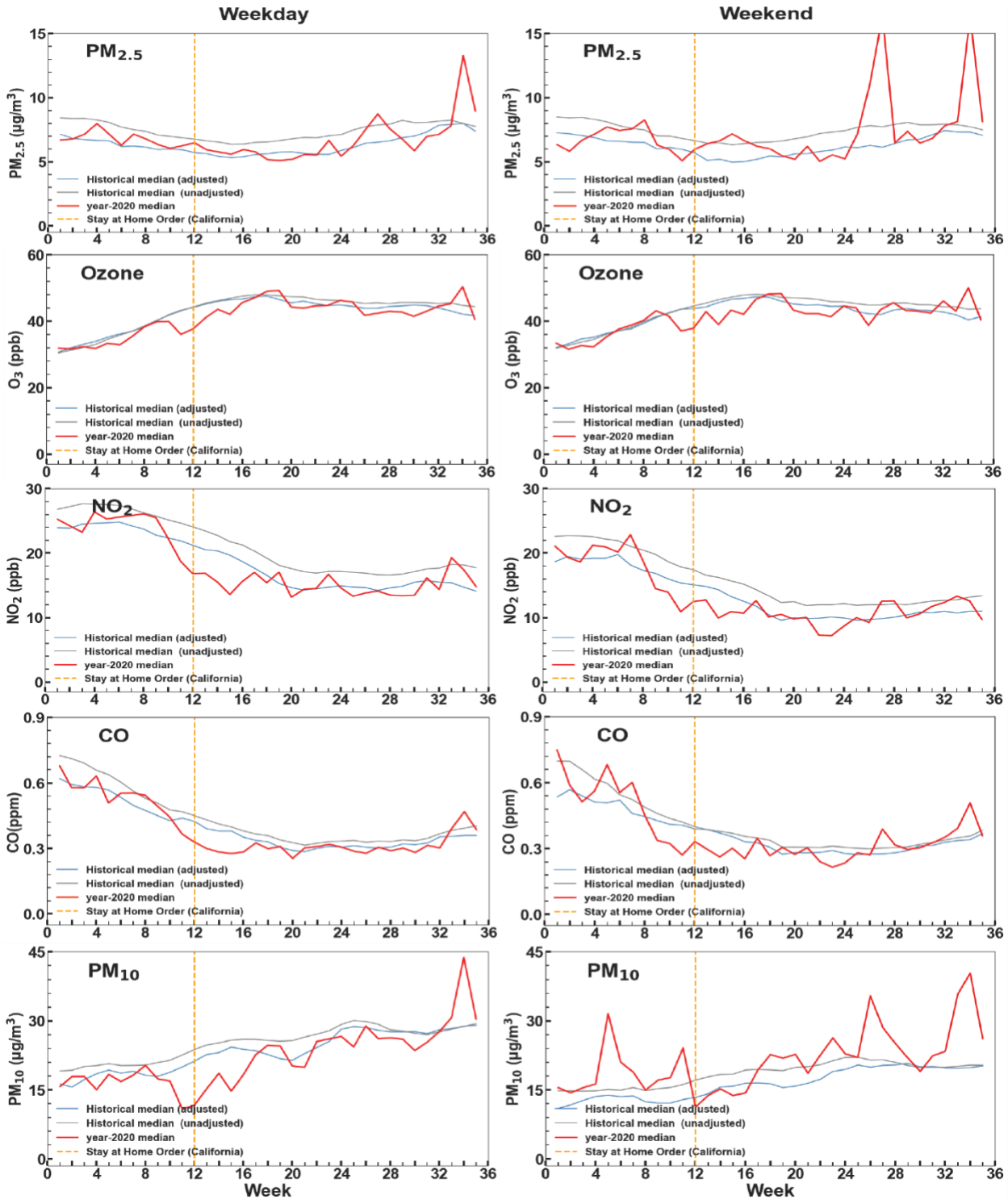

Fig. S14. This figure is analogous to Fig. 1 but disaggregating weekdays and weekends. The orange vertical dashed line indicates timing of the first stay-at-home order in the contiguous US: week 12 [CA]

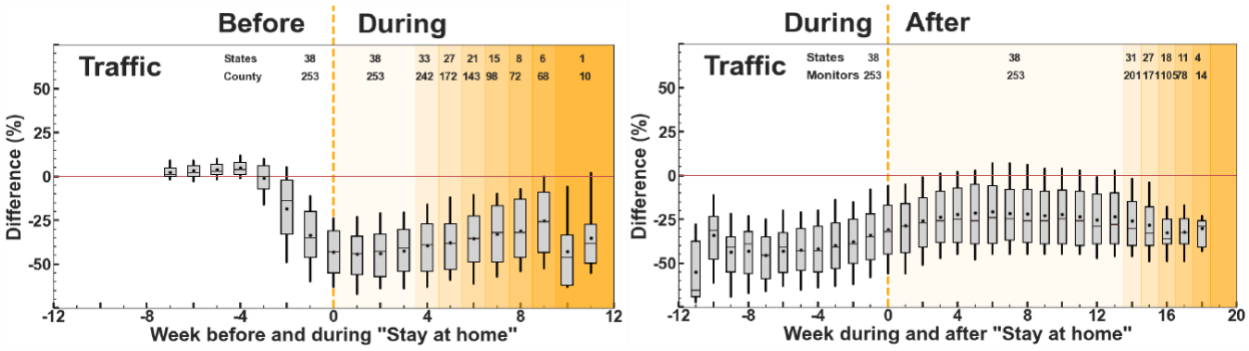

Fig. S15. Transit mobility changes in percentage from median base level (median traffic during 5 week period Jan 3 - Feb 6, 2020). Left column: time = 0 reflects the day that stay-at-home started. These plots compare before (time<0) and during (time>0) stay-at-home. Right column: time = 0 reflects the 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*

	Before stay-at-home		During stay-at-home		After stay-at-home	
State	Start	End	Start	End	Start	End
Alabama	1-Jan	3-Apr	4-Apr	30-Apr	1-May	1-Sep
Alaska	1-Jan	27-Mar	28-Mar	24-Apr	25-Apr	1-Sep
Arizona	1-Jan	30-Mar	31-Mar	8-May	9-May	1-Sep
Arkansas						
California	1-Jan	18-Mar	19-Mar	25-May	26-May	1-Sep
Colorado	1-Jan	25-Mar	26-Mar	27-Apr	28-Apr	1-Sep
Connecticut	1-Jan	22-Mar	23-Mar	20-May	21-May	1-Sep
Delaware	1-Jan	23-Mar	24-Mar	1-Jun	2-Jun	1-Sep
Florida	1-Jan	2-Apr	3-Apr	4-May	5-May	1-Sep
Georgia	1-Jan	2-Apr	3-Apr	24-Apr	25-Apr	1-Sep
Hawaii	1-Jan	24-Mar	25-Mar	7-May	8-May	1-Sep
Idaho	1-Jan	24-Mar	25-Mar	1-May	2-May	1-Sep
Illinois	1-Jan	20-Mar	21-Mar	29-May	30-May	1-Sep
Indiana	1-Jan	23-Mar	24-Mar	4-May	5-May	1-Sep
Iowa						
Kansas	1-Jan	29-Mar	30-Mar	4-May	5-May	1-Sep
Kentucky	1-Jan	25-Mar	26-Mar	20-May	21-May	1-Sep
Louisiana	1-Jan	22-Mar	23-Mar	15-May	16-May	1-Sep
Maine	1-Jan	1-Apr	2-Apr	1-May	2-May	1-Sep
Maryland	1-Jan	29-Mar	30-Mar	15-May	16-May	1-Sep
Massachusetts	1-Jan	23-Mar	24-Mar	18-May	19-May	1-Sep
Michigan	1-Jan	23-Mar	24-Mar	1-Jun	2-Jun	1-Sep
Minnesota	1-Jan	26-Mar	27-Mar	18-May	19-May	1-Sep
Mississippi	1-Jan	2-Apr	3-Apr	27-Apr	28-Apr	1-Sep
Missouri	1-Jan	5-Apr	6-Apr	4-May	5-May	1-Sep
Montana	1-Jan	27-Mar	28-Mar	26-Apr	27-Apr	1-Sep
Nebraska						
Nevada	1-Jan	31-Mar	1-Apr	9-May	10-May	1-Sep
New Hampshire	1-Jan	26-Mar	27-Mar	11-May	12-May	1-Sep
New Jersey	1-Jan	20-Mar	21-Mar	9-Jun	10-Jun	1-Sep
New Mexico	1-Jan	23-Mar	24-Mar	16-May	17-May	1-Sep
New York	1-Jan	21-Mar	22-Mar	29-May	30-May	1-Sep
North Carolina	1-Jan	29-Mar	30-Mar	8-May	9-May	1-Sep
North Dakota						
Ohio	1-Jan	22-Mar	23-Mar	12-May	13-May	1-Sep
Oklahoma						
Oregon	1-Jan	22-Mar	23-Mar	15-May	16-May	1-Sep
Pennsylvania	1-Jan	31-Mar	1-Apr	15-May	16-May	1-Sep
Rhode Island	1-Jan	27-Mar	28-Mar	9-May	10-May	1-Sep
South Carolina	1-Jan	6-Apr	7-Apr	20-Apr	21-Apr	1-Sep
South Dakota						
Tennessee	1-Jan	30-Mar	31-Mar	27-Apr	28-Apr	1-Sep
Texas	1-Jan	1-Apr	2-Apr	1-May	2-May	1-Sep
Utah						
Vermont	1-Jan	24-Mar	25-Mar	15-May	16-May	1-Sep
Virginia	1-Jan	29-Mar	30-Mar	15-May	16-May	1-Sep
Washington	1-Jan	24-Mar	25-Mar	26-May	27-May	1-Sep
West Virginia	1-Jan	23-Mar	24-Mar	4-May	5-May	1-Sep
Wisconsin	1-Jan	24-Mar	25-Mar	13-May	14-May	1-Sep
Wyoming						

* 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.

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

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 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)	R^2 Median (IQR)	Population weighted average concentration during 2010-2019	Annual change Median (IQR)
$PM_{2.5}$	-0.22 (-0.41 to 0.06) μg/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%)
CO	-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%)
PM_{10}	-0.37 (-0.85 to 0.07) μg/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-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	-0.11μg/m^3	-1.6%	0.14 μg/m^3	2.1%	0.09 μg/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)
CO	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 μg/m^3	5.7%	-2.94 μg/m^3	-14.0%	1.55 μg/m^3	7.4%	0.32 (0.19 to 0.44)

Table S6a. Results from multivariate spline autoregression (degrees of freedom = 2) method, before and after a state's stay-at-home 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 μg/m^3	-0.41μg/m^3	-5.8%	0.07 μg/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)
CO	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 μg/m^3	6.1%	-1.15 μg/m^3	-5.5%	1.67 μg/m^3	8.0%	0.41 (0.23 to 0.47)

Table S6b. Results from multivariate spline autoregression (degrees of freedom = 3) method, before and after a state's stay-at-home 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 μg/m^3	-0.28 μg/m^3	-3.8%	0.08 μg/m^3	1.1%	0.01 μg/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 μg/m^3	5.8%	-0.60 μg/m^3	-2.8%	0.85 μg/m^3	4.0%	0.41 (0.29 to 0.53)

Table S6c. Results from multivariate spline autoregression (degrees of freedom = 4) method, before and after a state's stay-at-home 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 μg/m^3	-0.23.μg/m^3	-3.2%	0.30 μg/m^3	4.2%	0.54 μg/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)
CO	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 μg/m^3	6.3%	2.34 μg/m^3	11.1%	6.95 μg/m^3	32.8%	0.43 (0.32 to 0.55)

Table S6d. Results from multivariate spline autoregression (degrees of freedom = 5) method, before and after a state's stay-at-home 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 μg/m^3	-0.41μg/m^3	-5.8%	0.93 μg/m^3	12.9%	1.79 μg/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)
CO	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 μg/m^3	5.1%	3.1 μg/m^3	14.7%	7.05 μg/m^3	33.3%	0.45 (0.33 to 0.57)