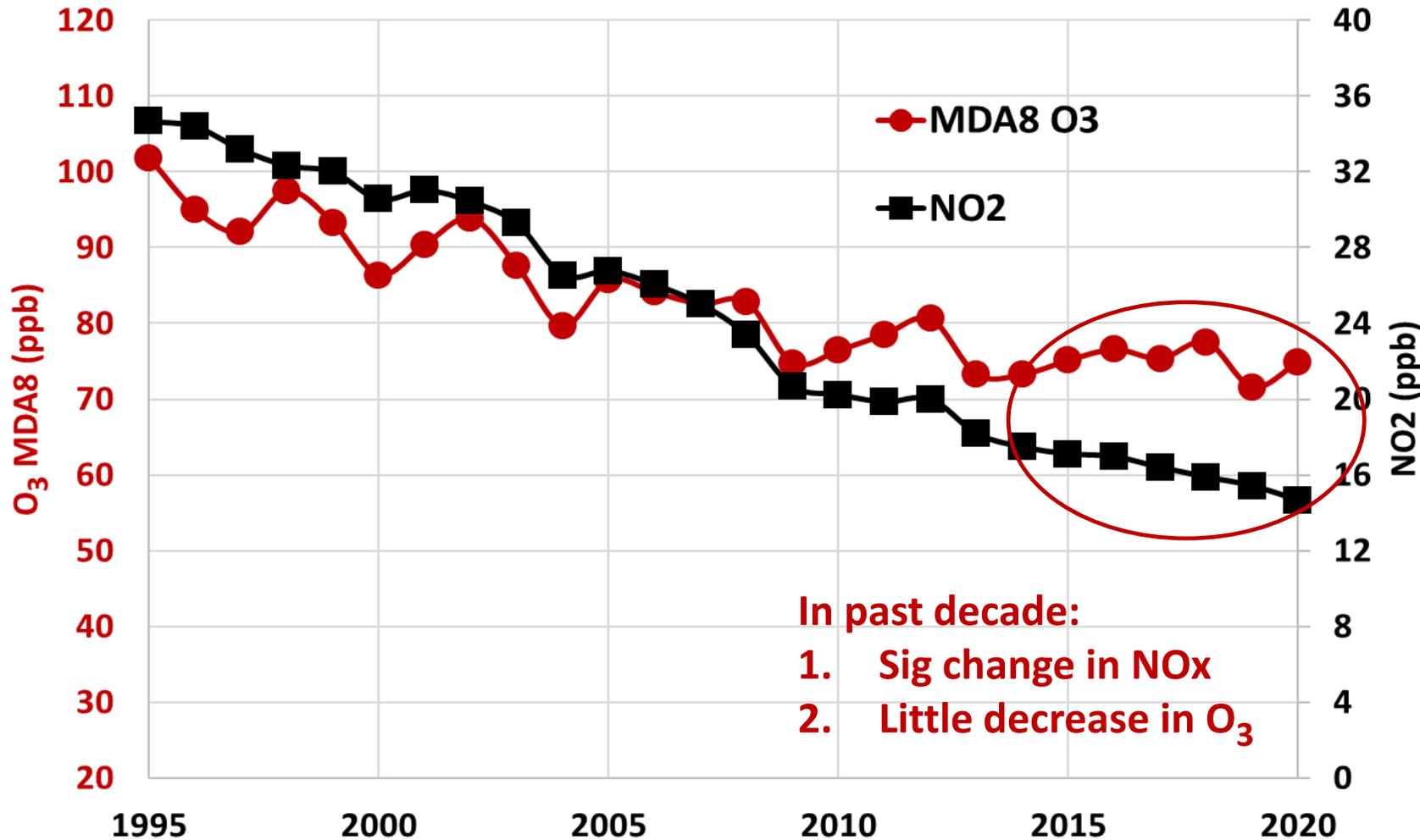# What can the pandemic tell us about NOx and Ozone in the U.S.?
Dan Jaffe, University of Washington

MOTIVATION:

1. Given strong reductions in all of the primary pollutants over past decades why hasn't O_3 declined as much?

2. How much do we need to reduce NOx to meet the O_3 standard?

3. Given 2020 COVID related reductions in VMT and NOx, do we see the expected O_3 reductions?

In past decade:
1. **Sig change in NOx**
2. **Little decrease in O_3**

Annual 4th highest MDA8 and May-Sept mean 1 hr daily max NO_2 for 32 U.S. Non-Attainment Areas (NAAs)
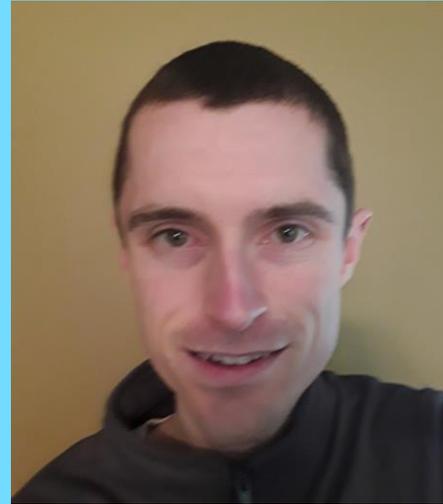
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Acknowledgements

Dr. Nate May, post doc, Mt. Bachelor orbs and IAQ

Dr. Matt Ninneman, post doc, photochemical modeling of smoke

Dee Ann Lommers-Johnson, admin support

Ruby Chan, former ug, Analysis of O$_3$ and NO$_x$ data.

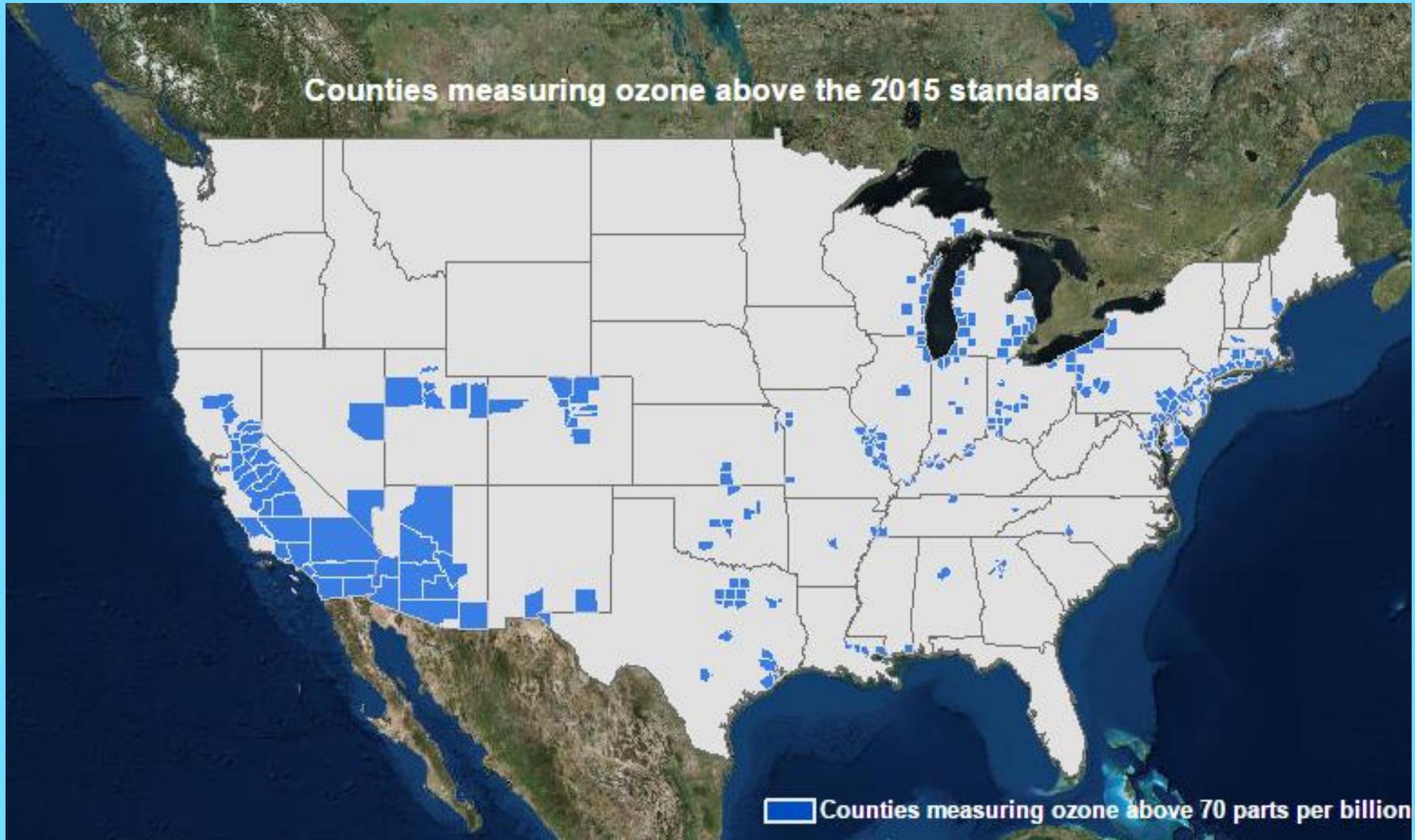**Colleen Miller, former ug, Mt. Bachelor obs and analysis of low cost sensor data**

Noah Bernays, Mt. Bachelor site tech

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~130 million people are exposed to unhealthy levels of O₃

Counties measuring ozone above the 2015 standards

Counties measuring ozone above 70 parts per billion

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>130 million people are exposed to unhealthy levels of O_3

Counties measuring ozone above the 2015 standards

Western U.S. (n=20)

Midwest (n=6)

East coast +Atlanta (n=6)

■ Counties measuring ozone above 70 parts per billion

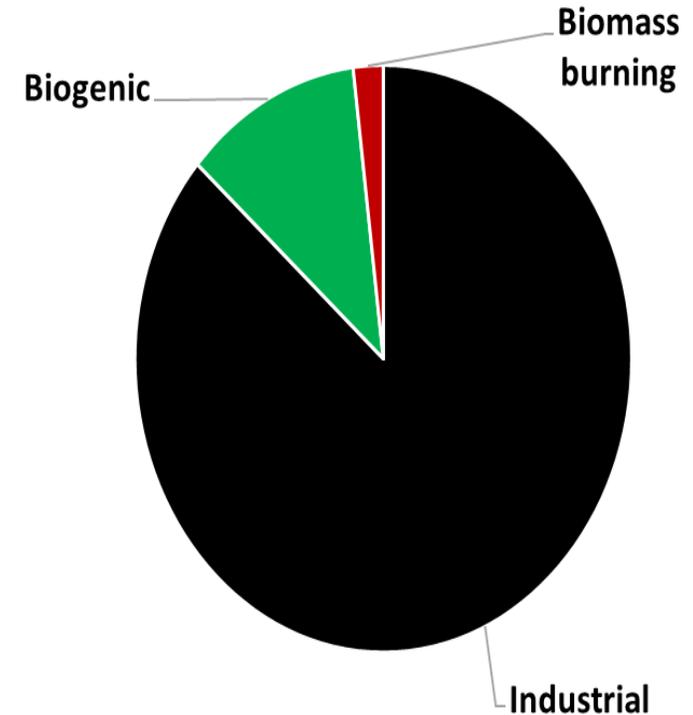UNIVERSITY of WASHINGTON
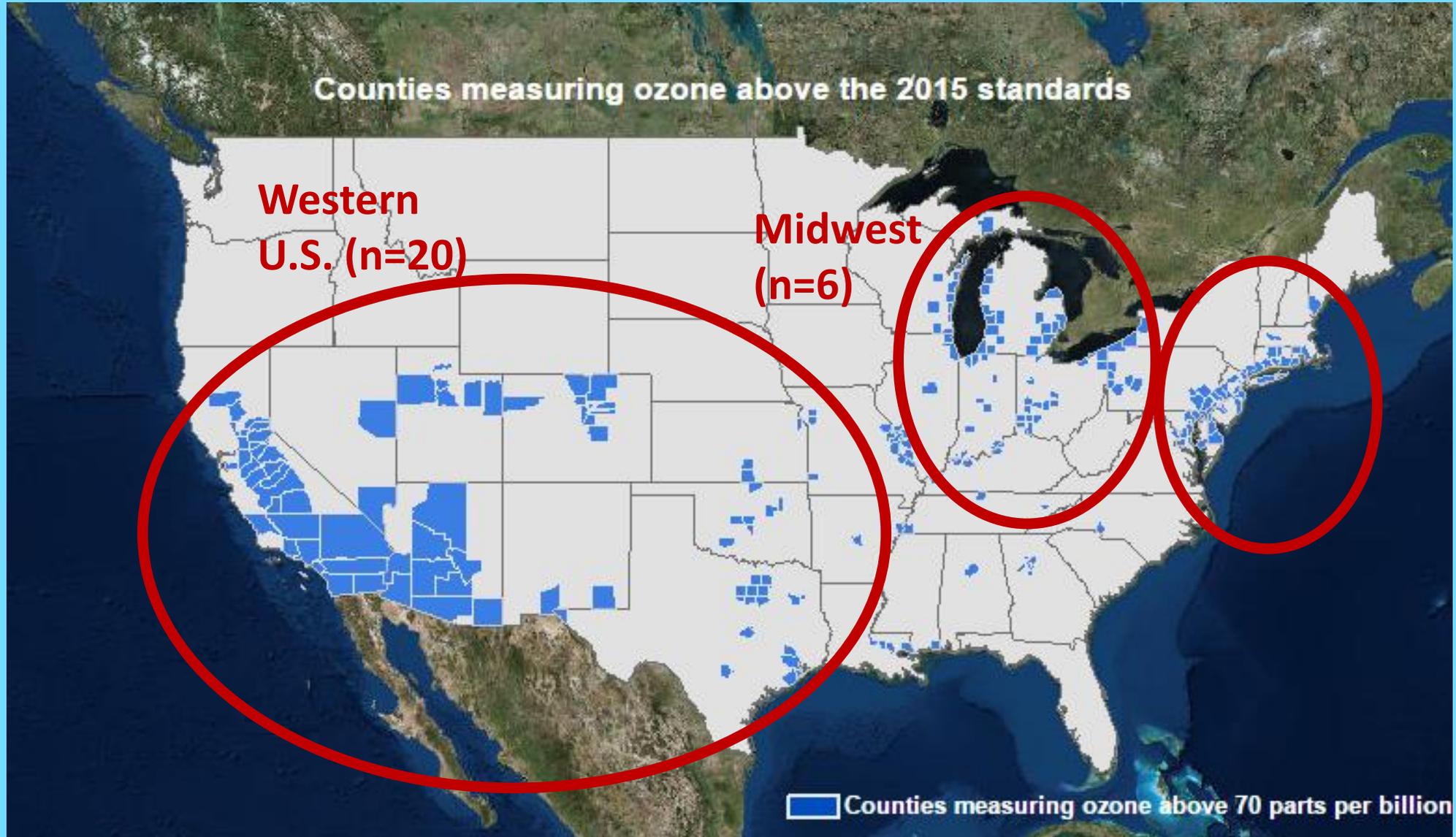
U.S. Emissions of NOx and VOCs

- NOx is 87% from industrial/sources sources (30% from on-road vehicles)
- VOCs are 29% from industrial/anthro sources

U.S. VOC emissions — Biomass burning, Industrial, Biogenic
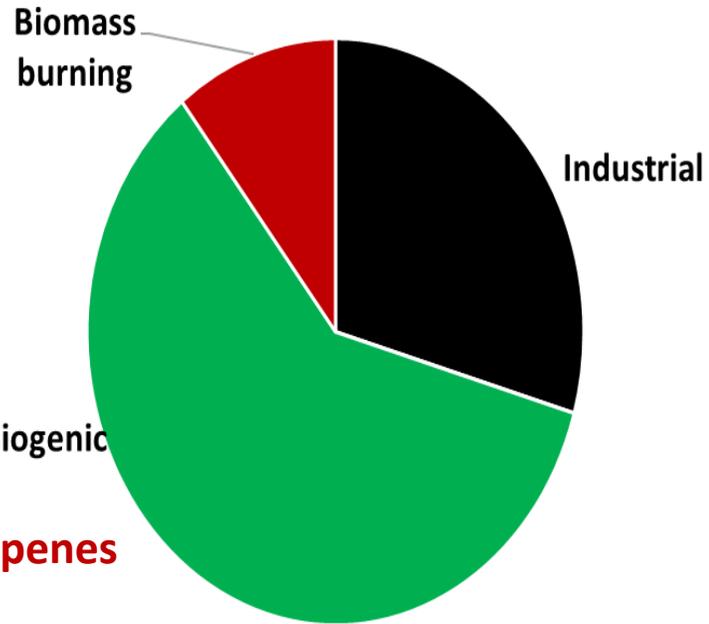
- Isoprene
- Mono-terpenes
- α-pinene
- etc

U.S. NOx emissions — Biogenic, Biomass burning, Industrial
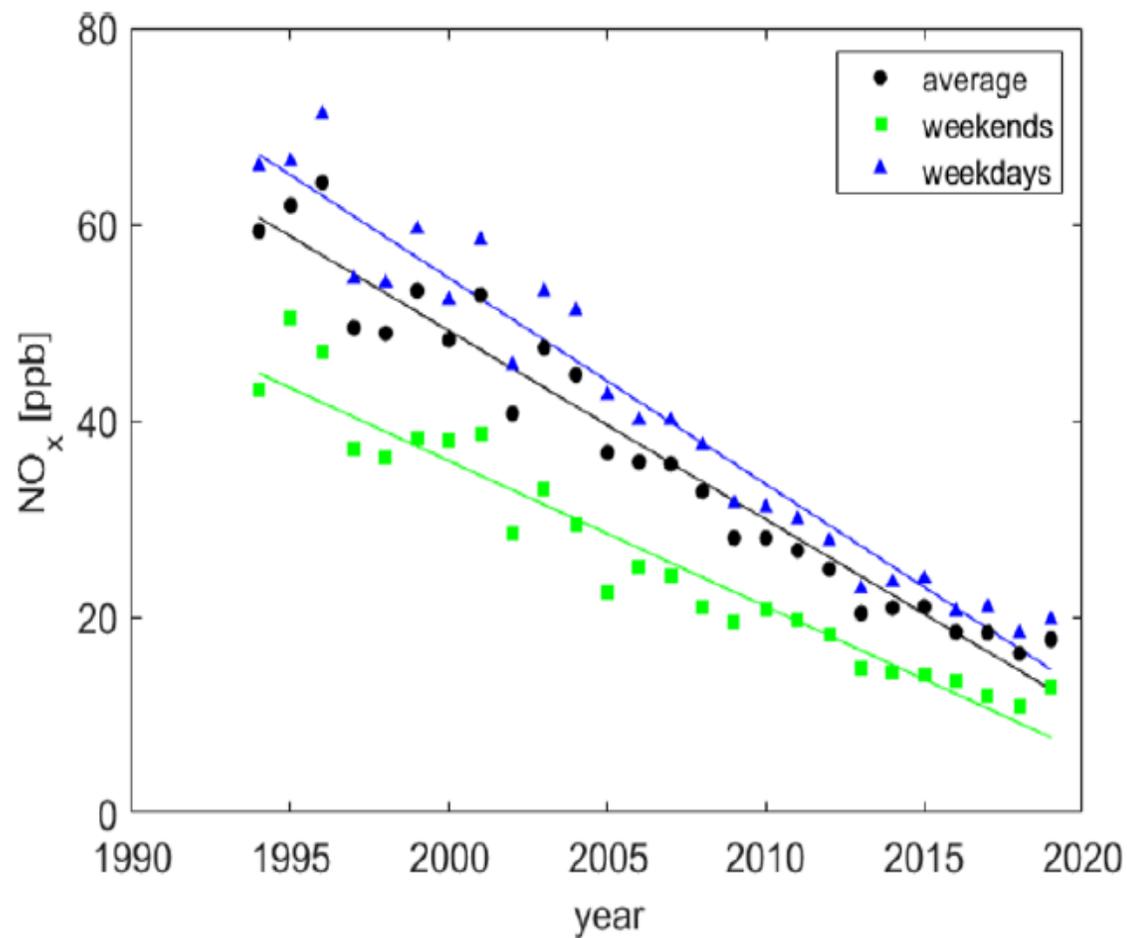
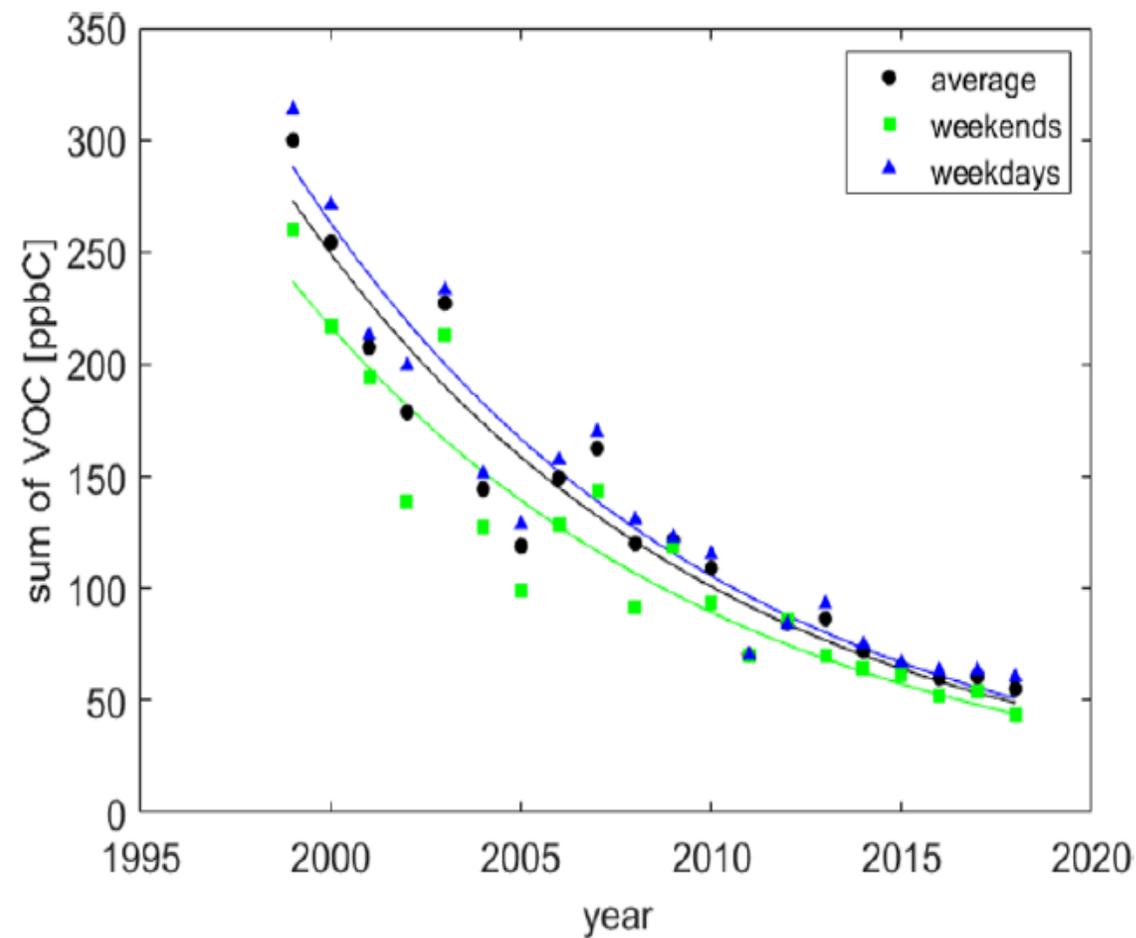Source: EPA 2017 National Emission Inventory

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NOx and VOC emission trends, So.Cal
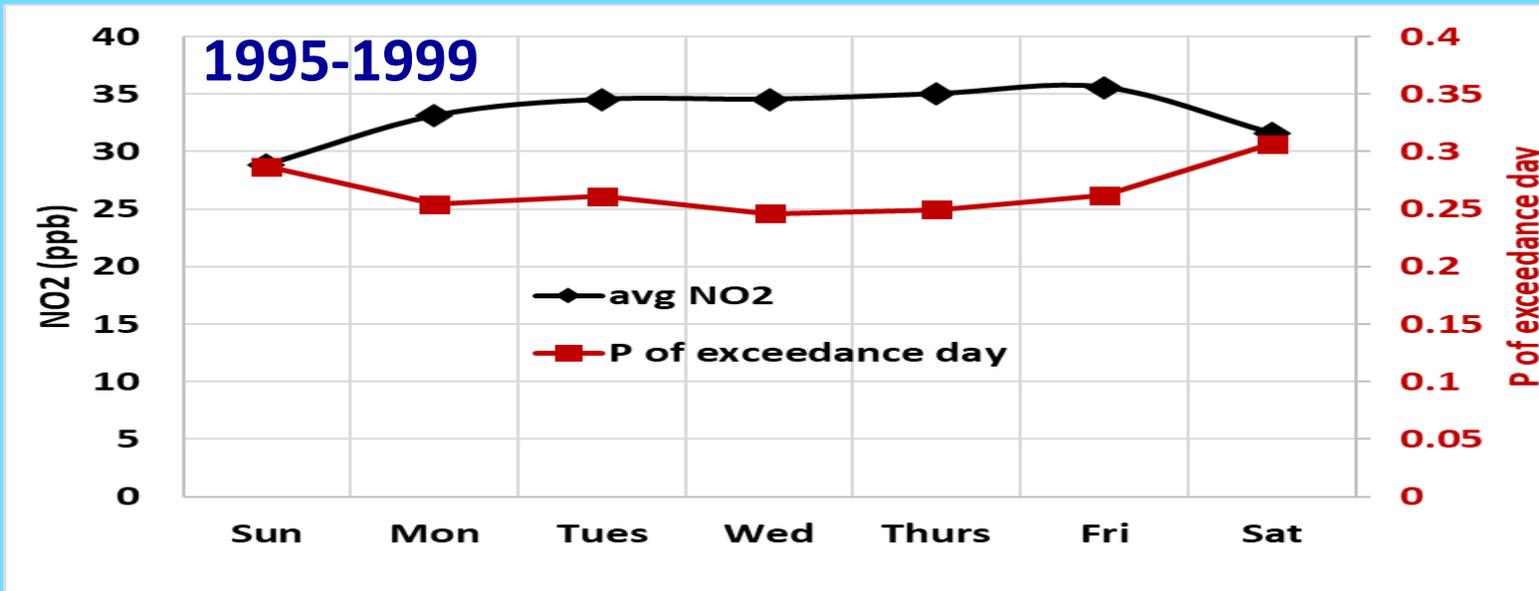

(a) NO_x

(b) VOC

NO$_2$ and probability of an O$_3$ exceedance by day of week, <u>all sites</u>

1995-1999, May-Sept:

NOx saturation means that high O$_3$ days are more likely on <u>weekends.</u>
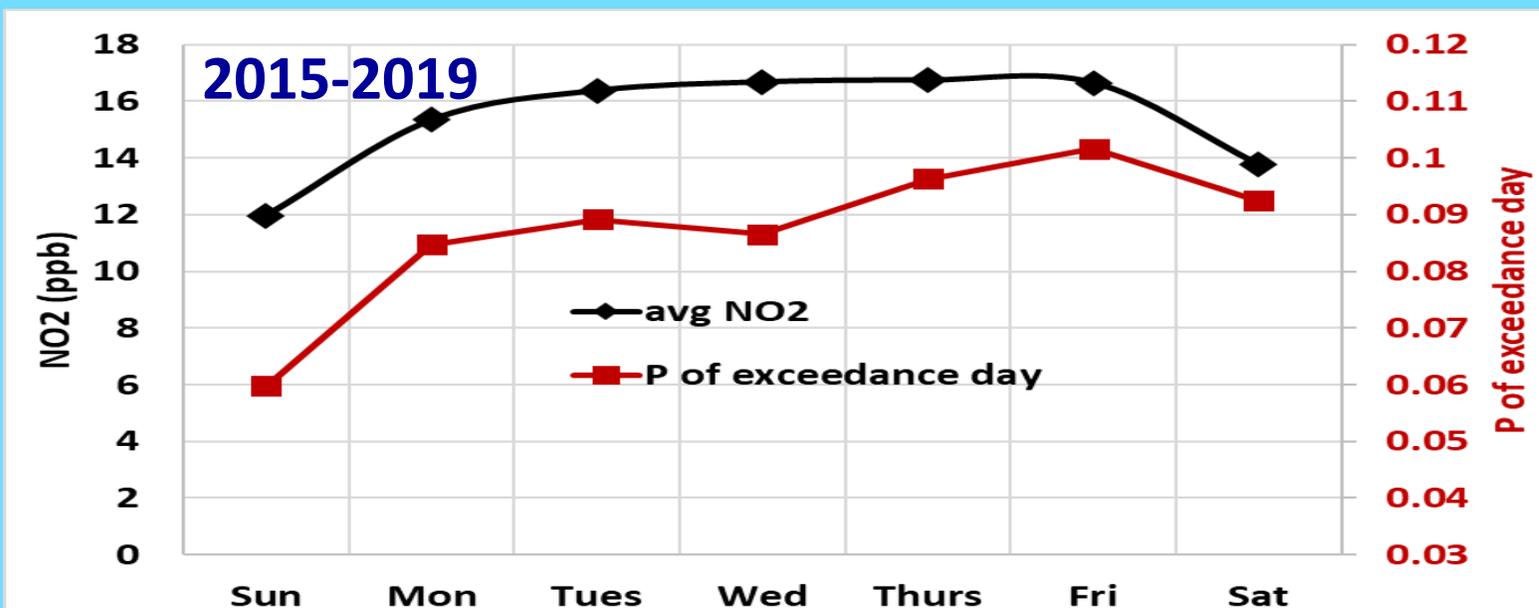
2015-2019, May-Sept:

NOx limitation means that high O$_3$ days are more likely on <u>weekdays.</u>

This patterns holds in 30 out of 32 areas. Only exception is LA/ Riverside area.

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How did the Pandemic impact air quality?

Column NO$_2$ from OMI (Aura) or TROPOMI (Sentinel-5P)

- OMI and TROPOMI instruments for column NO$_2$ on polar orbiting satellites.

- Both use backscattered UV-Vis to measure NO$_2$.

- Need to subtract stratospheric NO$_2$ to get trop column.

- Daytime observations synched with equatorial crossing time.

- OMI = Launched in 2004 with res of 13 × 24 km2 at nadir

- TROPOMI = Launched in 2017 with res of 7.2 × 3.5 km2 at nadir

The Afternoon Constellation
The NASA A-Train

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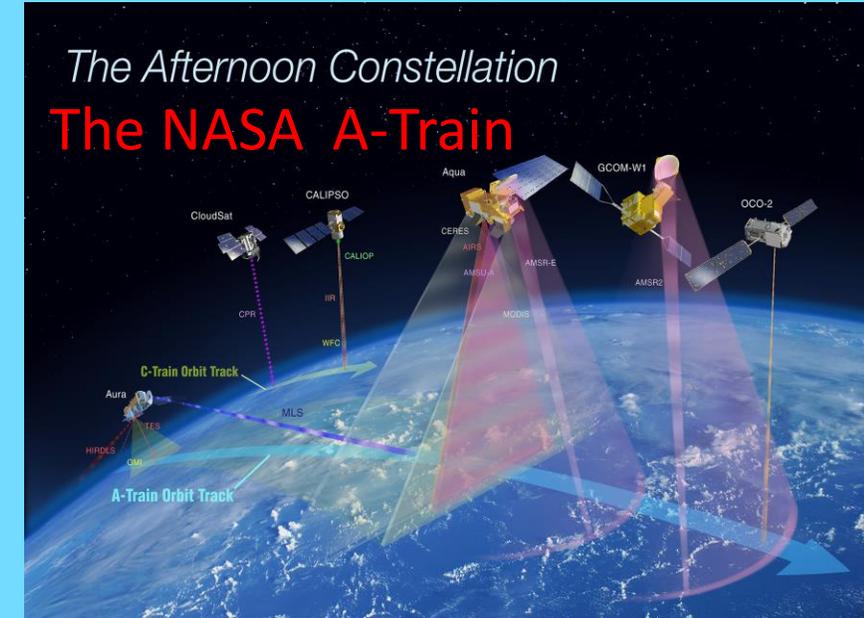
Analysis of satellite NO₂ data
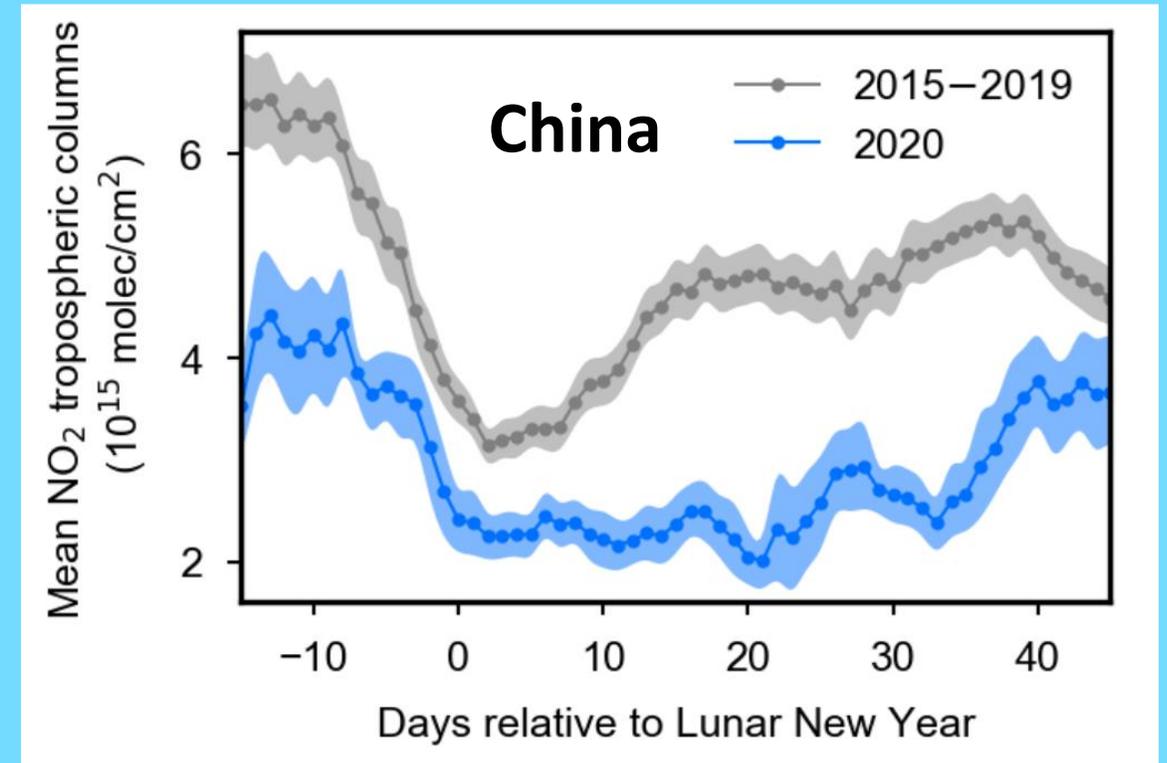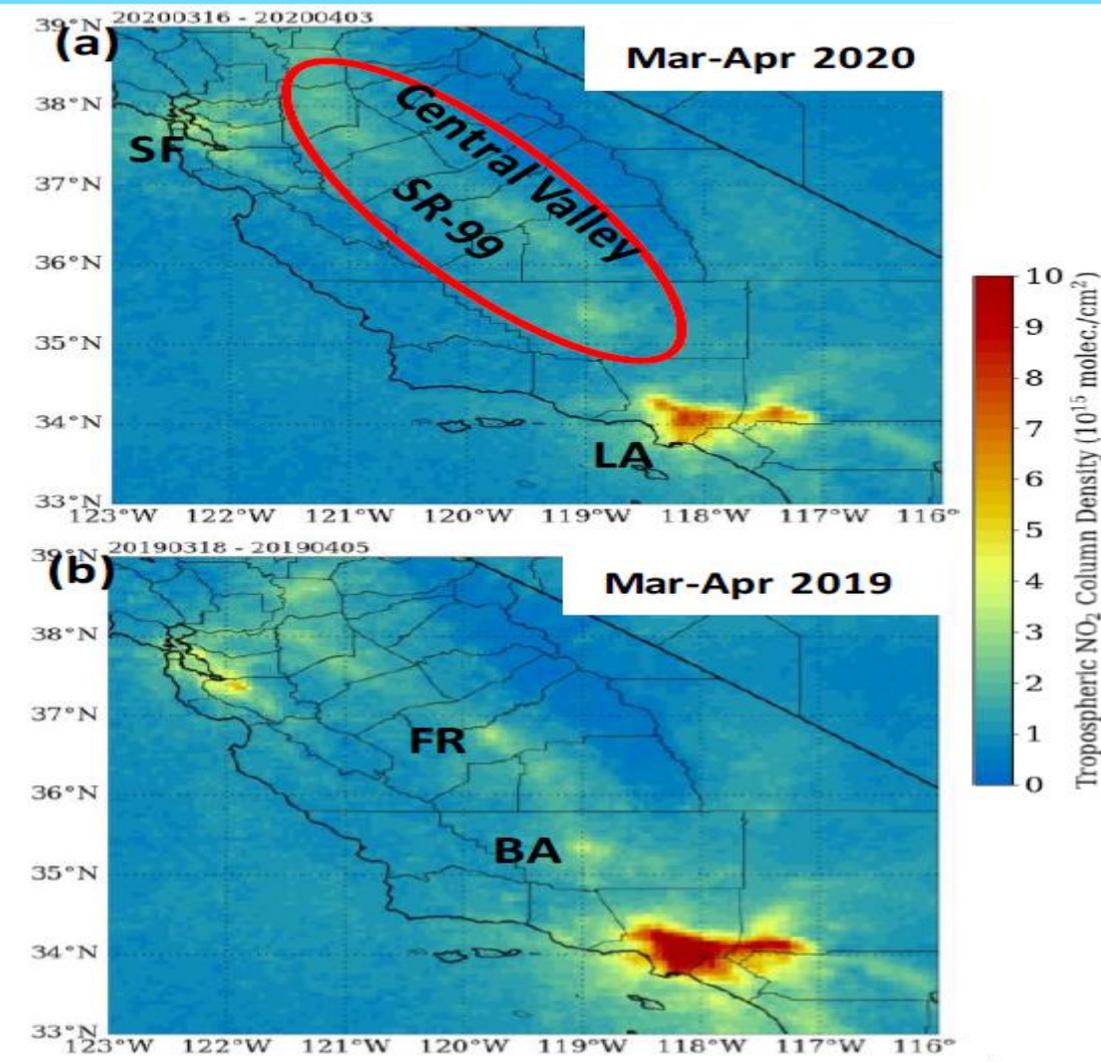
Naeger and Murphy 2020
TROPOMI data

Liu et al 2020

OMI data

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Given the reductions in NO_2 can we use this to understand changes in O_3?

- Many papers show NO_2 reductions due to Covid lockdowns. But comments in some papers made little sense, like looking for O_3 reductions in March….

- Need to understand, which is limiting reagent NOx or VOCs.

- Need to look for policy relevant changes in summer, when O_3 is elevated.

My strategy:

- Focus on 32 U.S. metropolitan regions that do not meet the O_3 standard (NAA: non-attainment areas)

- Look at annual fourth highest MDA8 at highest site by MSA (policy relevant metric).

- Use May-Sept mean of <u>daily 1-hour maximum</u> observed surface NO_2 to reflect <u>emissions</u>.

- Note that 1-hour NO_2 max is usually in early morning so these concentrations don't tell us much about the daytime concentrations. And because different regions have different # monitors, hard to compare actual concentrations between regions.

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Sites (n=32)

Eastern U.S. (n=6)	Midwest (n=6)	West (n=20)	
Atlanta, GA	Chicago, IL-IN-WI	Butte Cty/Chico, CA	Phoenix-Mesa, AZ
Baltimore, MD	Cincinnati, OH-KY	Dallas-Fort Worth, TX	Riverside County, CA
Hartford CT CBSA.	Cleveland, OH	Denver, CO	Sacramento Metro, CA
New York, NY-NJ-CT	Detroit, MI	Dona Ana County, NM	San Antonio, TX
Phil., PA-NJ-DE-MD	Milwaukee, WI	Houston, TX	San Diego County, CA
Wash., DC-MD-VA	St. Louis, MO-IL	Imperial County, CA	San Francisco, CA
		Bakersfield, CA	San Joaquin Valley, CA
		Las Vegas, NV	San Luis Obispo, CA
		Los Angeles- CBSA	Sutter Butte/Yuba City, CA
		SLC, UT	Ventura County, CA

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Fourth highest O₃ MDA8 and May-Sept mean NO₂
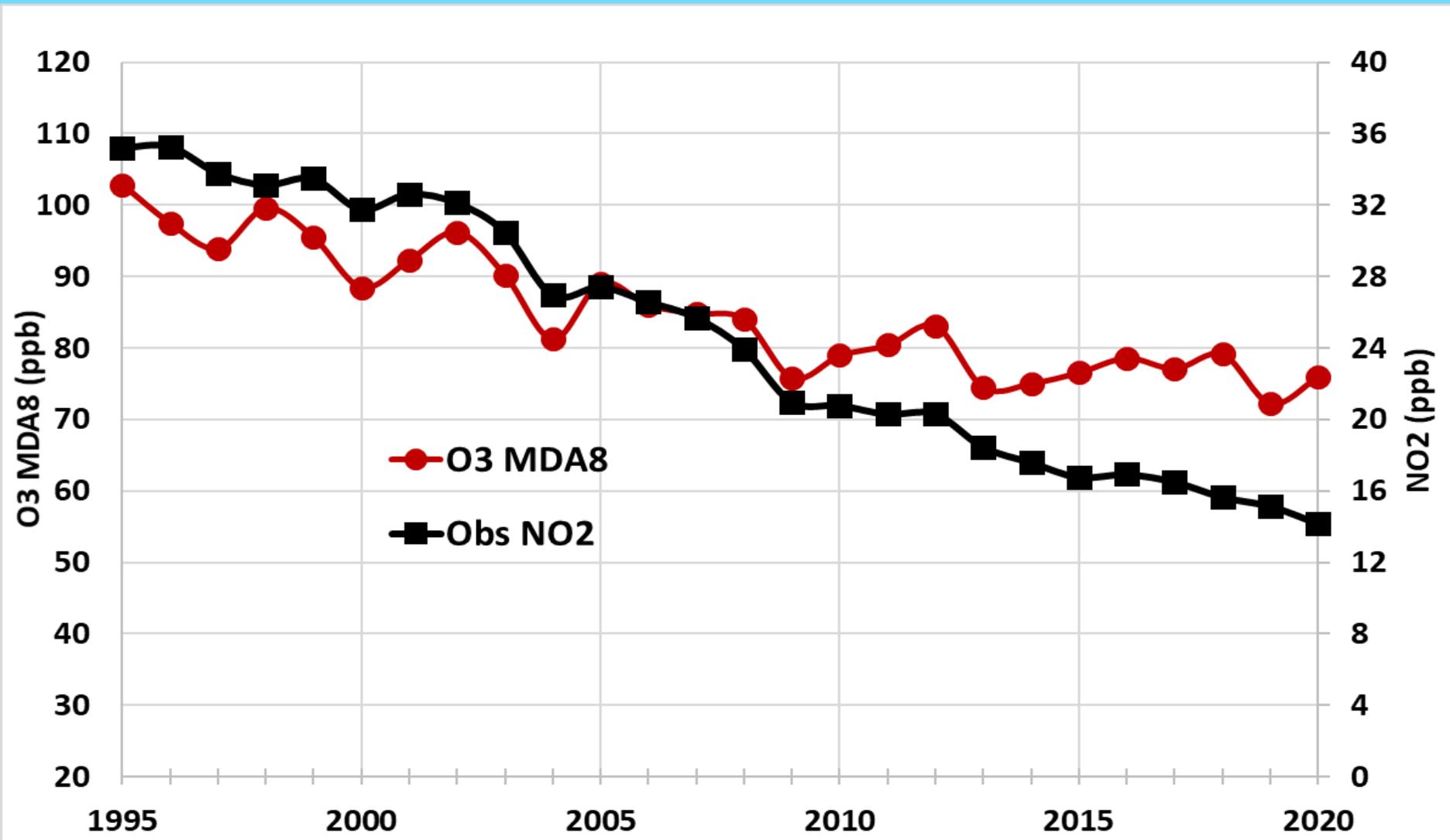
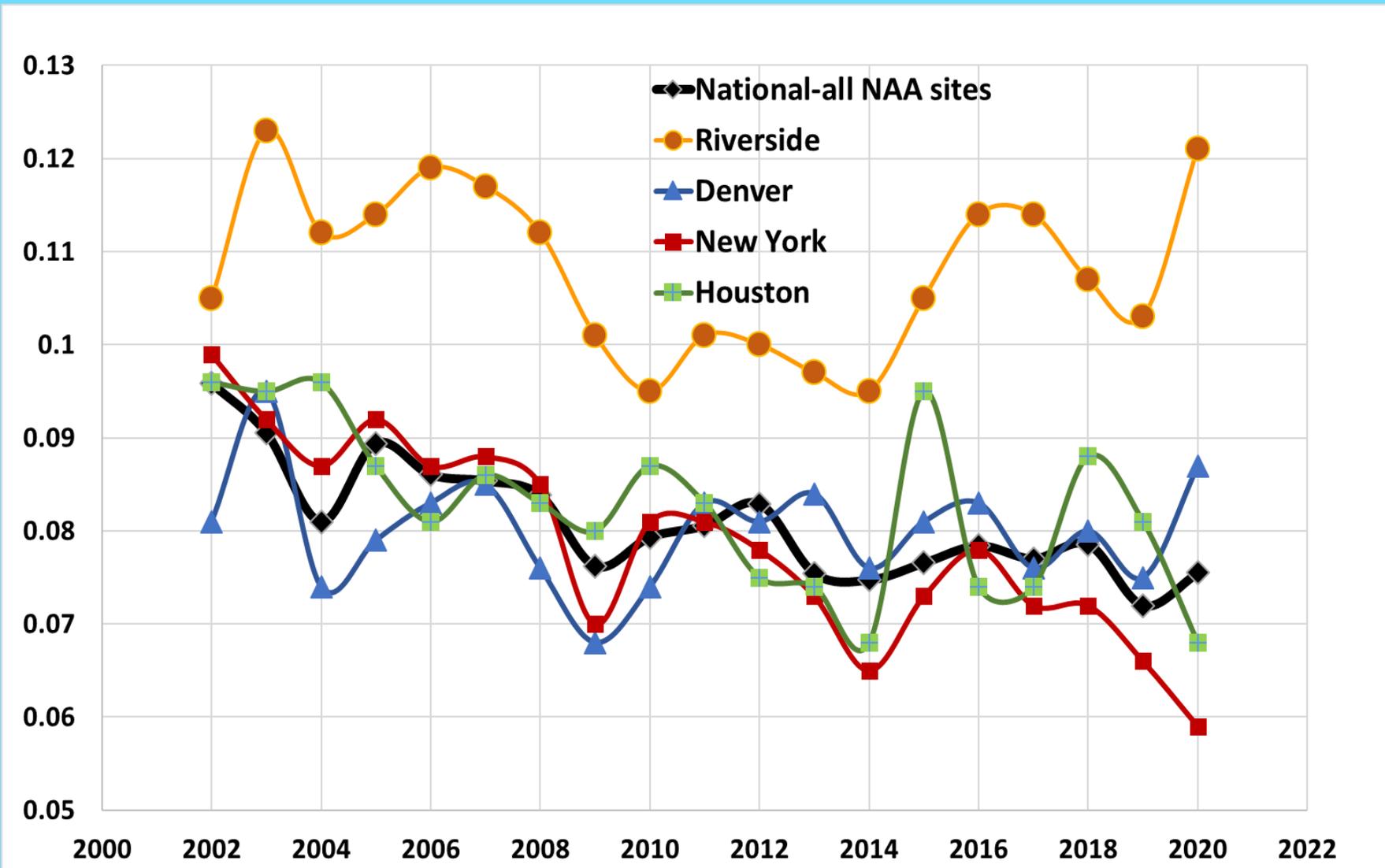**Averaged across the 32 U.S. NAAs, the policy relevant O₃ metric went up, not down!**

What went wrong?

Annual 4th highest O₃ MDA8

Averaged over all all U.S. NAA, O₃ went up in 2020! Why are some sites up and some down?

- Hyp1: In NOx limited case, reductions in NOx will decrease O₃.

- Hyp2: Climate/temp variations.

- Hyp3: Large 2020 fires may have exacerbated O₃ at some sites.

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Fourth highest O₃ MDA8 by region for U.S. non-attainment regions
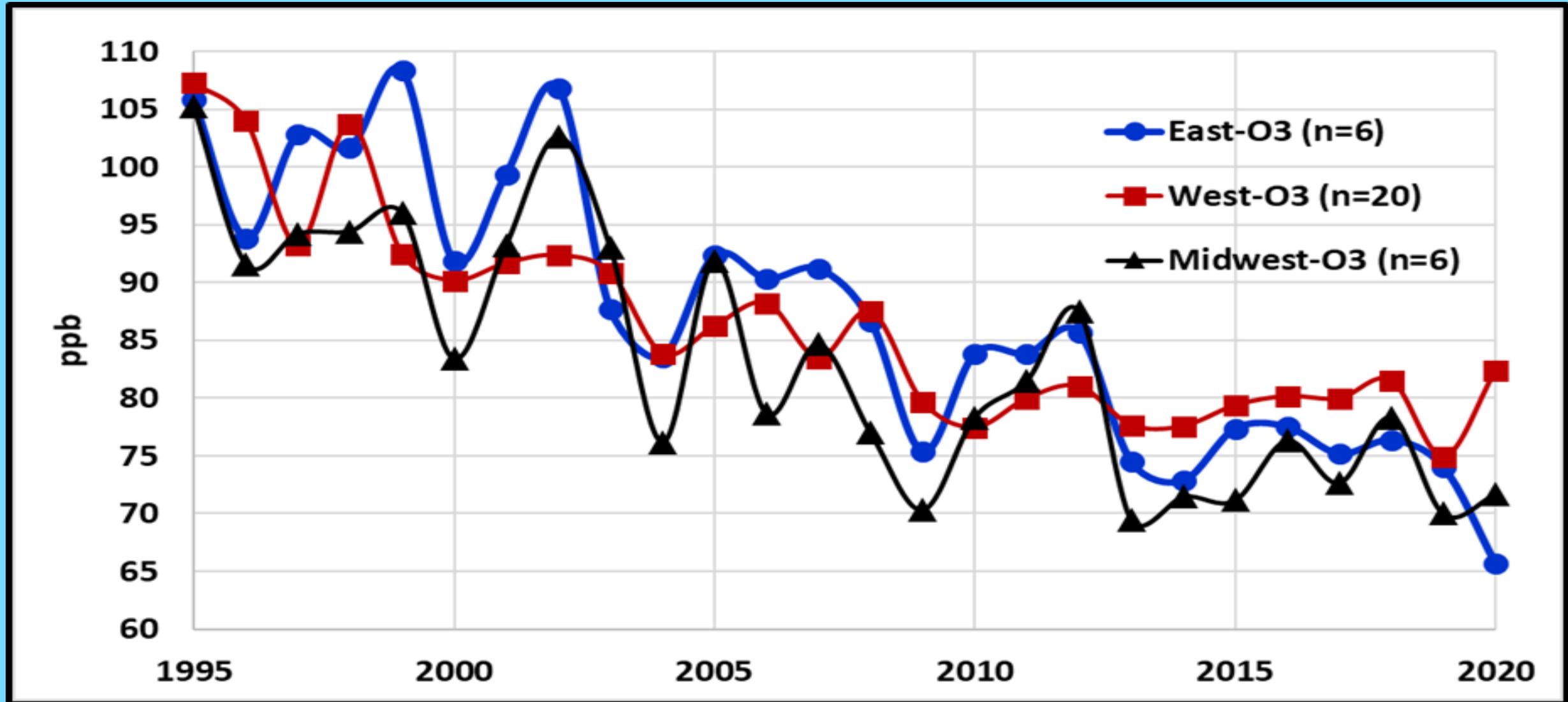
Twenty of the O₃ NAAs are in west, 12 in California. So this drives the national trend I showed a few slides back.

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2020 and 2019 NO$_2$ in Wash D.C. metro region

➢ **Data from 5 surface NO$_2$ monitors in WDC region.**

➢ **NO$_2$ in 2020 was 28% lower in March compared to 2019; 16% lower for May-Sept.**

➢ **We found little connection between surface NO$_2$ changes and satellite NO$_2$ column change (see**

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Wash DC Fourth highest MDA8 O₃ and NO₂, 1995-2020
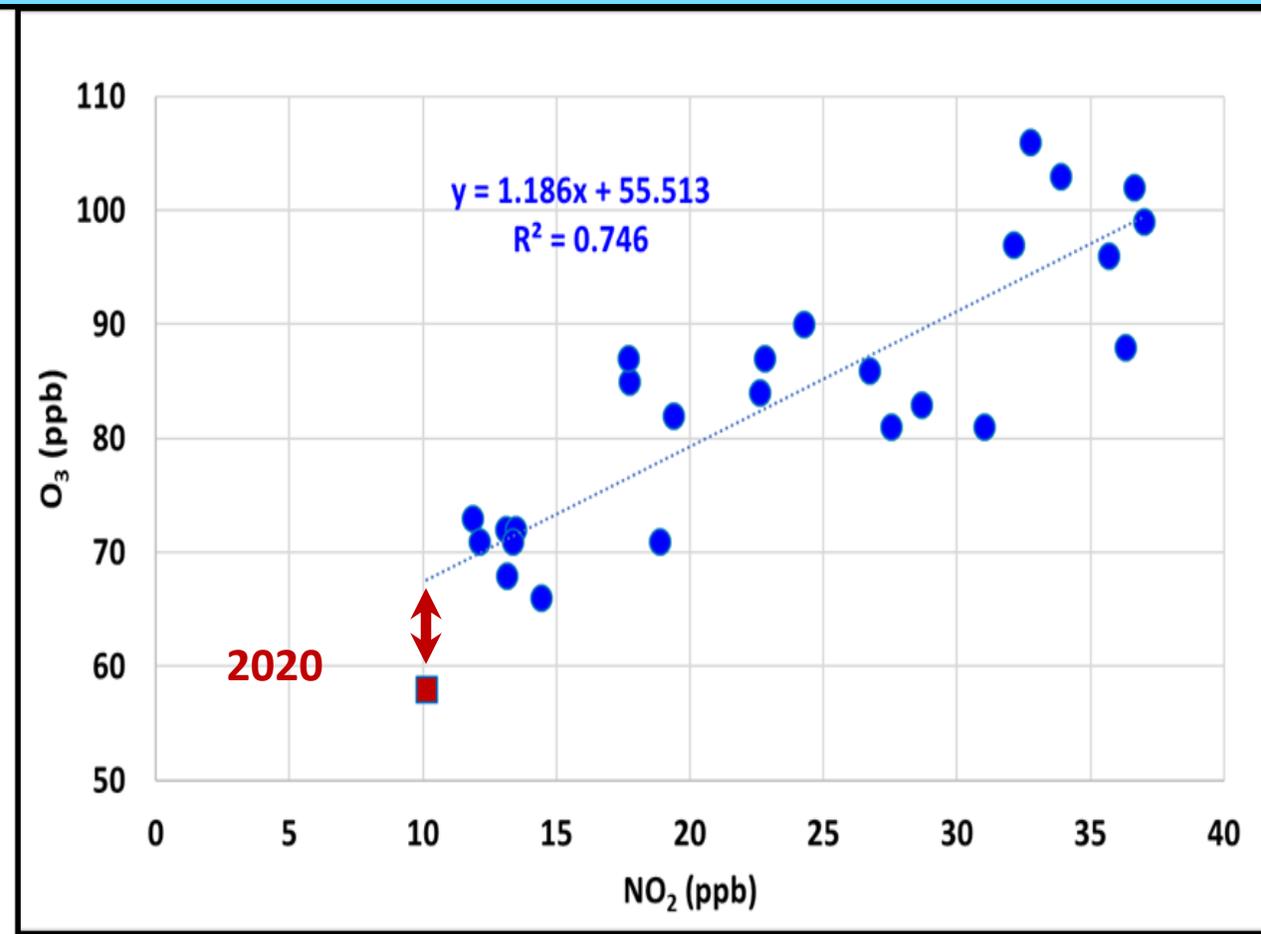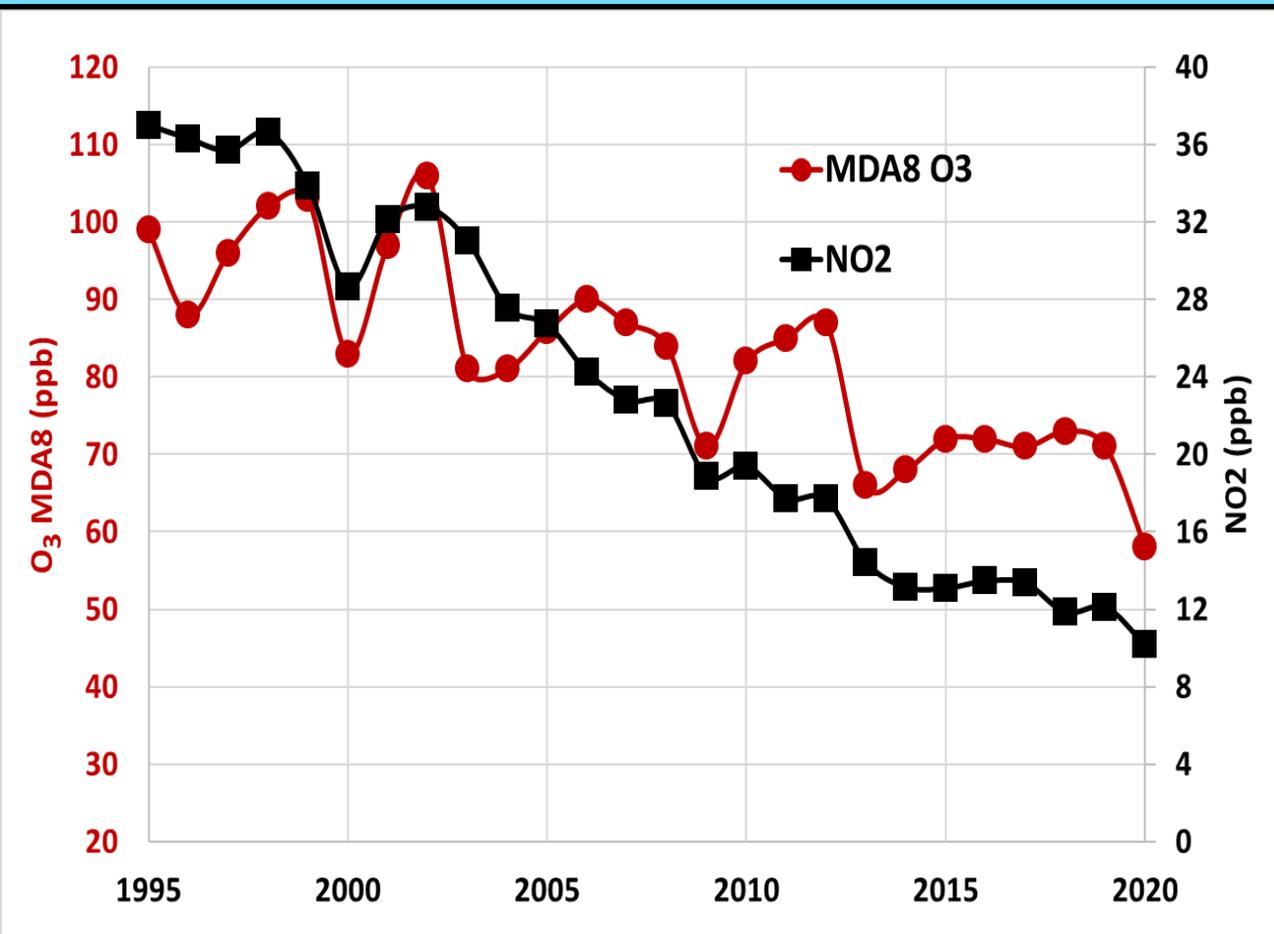
> **16% NOx reduction in 2020 (compared to 2019) in May-Sept was consistent with a sig reduction in O₃.**
> **2020 reductions were "super-linear". What did other eastern cities show?**

O₃ reductions in 2020 are "super-linear" at 5 Eastern cities

O₃ vs NO₂ (Eastern U.S.)

Long-term linear regression lines

2020 data points
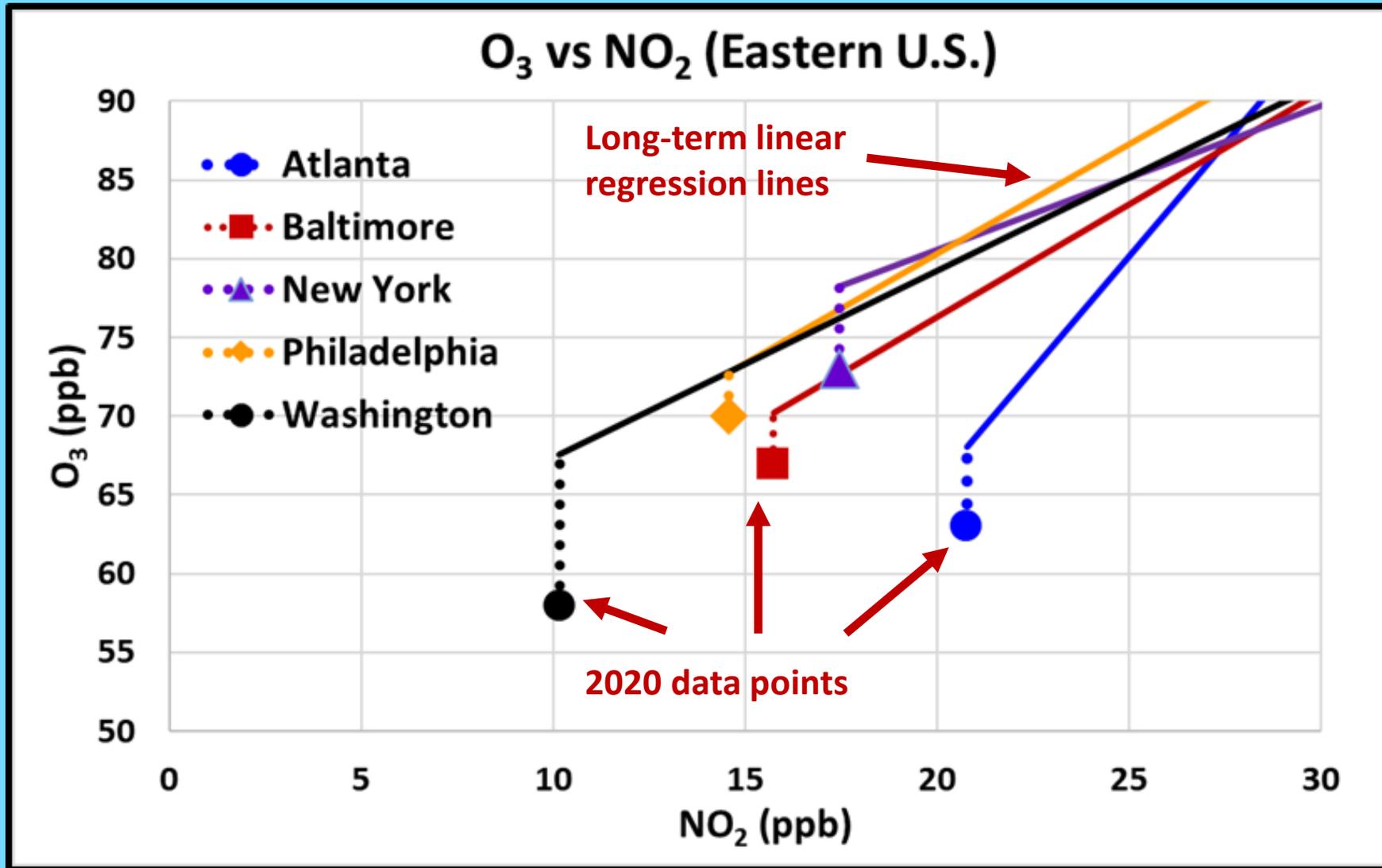
- **No evidence for unusual met in summer 2020. Only explanation for the non-linear reduction is chemical.**

- **Note that except for NYC, all cities were at or below 70 ppb, most for the first time.**

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Ozone Production Efficiency (OPE)

- **OPE is the number of O_3 molecules produced for each NO_x molecule converted to NO_y.**

- **Several researchers have reported that OPE is higher at lower NOx concentrations (Kleinman 2002; Henneman et al 2017).**


Henneman et al 2017

Henneman*, et al.*, Responses in ozone and its production efficiency attributable to recent and future emissions changes in the Eastern United States. *Environ. Sci. Technol.* 51, 13797–13805 (2017).

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May-Sept. 2020 changes in NOx and O_3 compared to 2019: Western U.S. (partial list)

Region	Surface NO_2 (%)	Satellite NO_2 (%)	O_3 (ppb)
Denver CO	-4	-11	12
Dallas-Fort Worth, TX	-3	-2	6
Las Vegas, NV	-11	-5	10
Los Angeles CA	1	-17	15
Phoenix-Mesa, AZ	0	-6	9
Riverside CA	8	-10	18
Sacramento Metro, CA	-8	+13	15

For the fourth highest MDA8 in the 20 areas in the W. US:
3 improved from 2019 to 2020 by an average of -8 ppb;
3 show no change from 2019 to 2020;
14 increased from 2019 to 2020 by an average of +11 ppb.

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Photochemistry, O₃ and smoke.
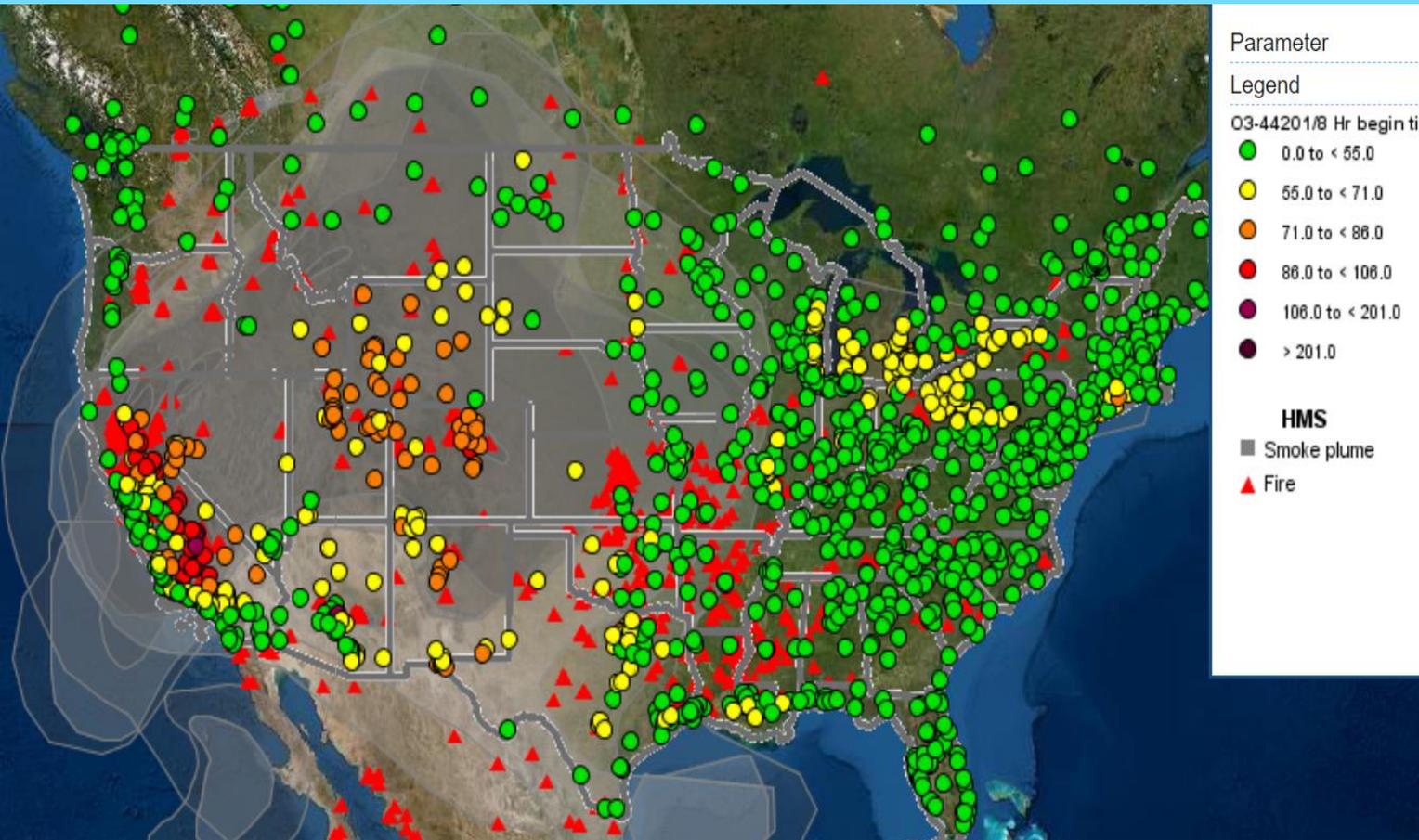
MDA8 O₃ values for Aug 22, 2020

- ➢ **We know that that smoke contributes to O₃ exceedances in urban areas, but processes poorly understood. (Jaffe et al 2004, 2008; 2018; 2020; Buysse et al 2019).**
- ➢ **Current work:**
- ➢ **Use machine learning/statistical models to tease out impacts of smoke (Gong et al 2017; McClure and Jaffe 2018; Jaffe and Gao 2021).**
- ➢ **Use photochemical box modeling (FOAM) to examine chemical processes in urban air+smoke (Ninneman et al 2021).**

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Fourth highest O₃ MDA8, PM₂.₅ and western area burned
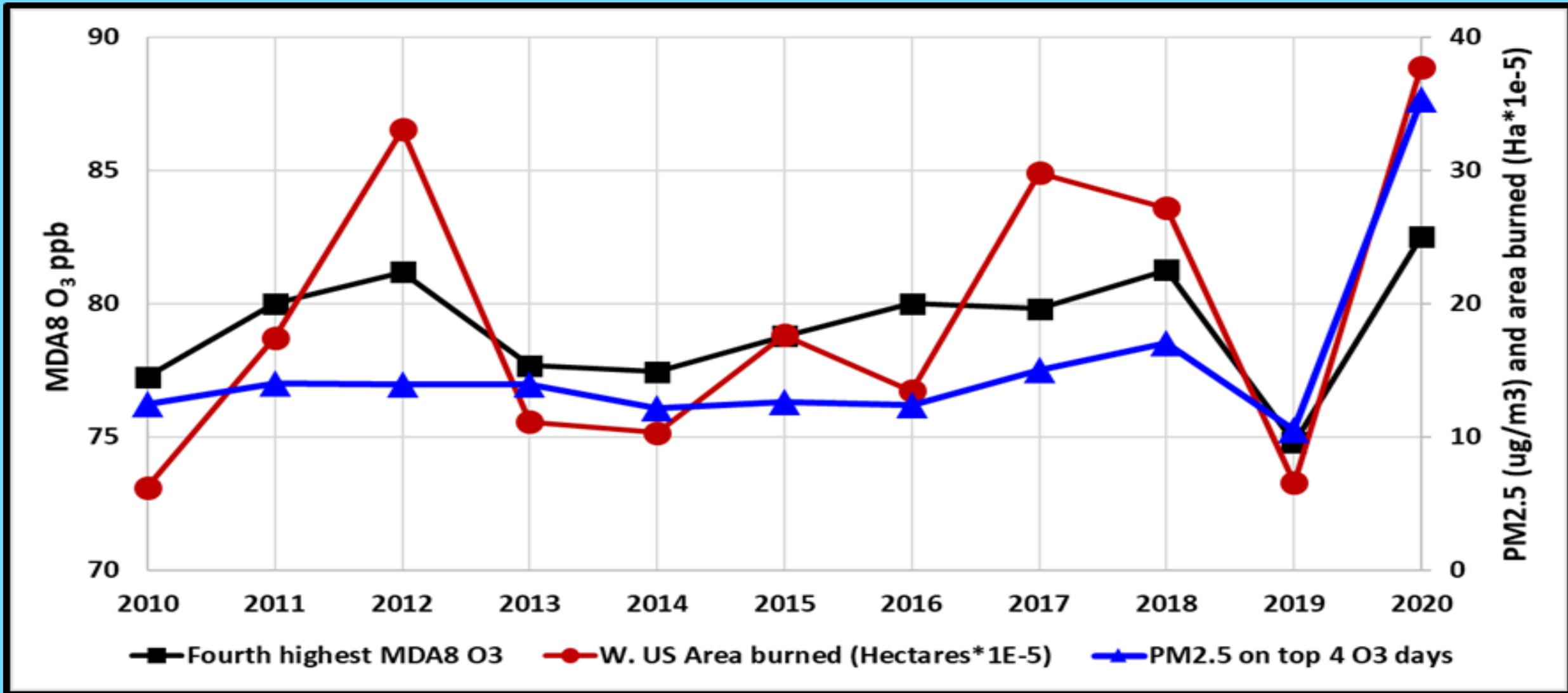
Summary: How did 2020 Pandemic, fires and temps influence policy relevant O_3 in the U.S.?

- **H1:** In NOx limited case, reductions in NOx will decrease O_3: **True for Eastern U.S. sites.**

- **H2:** Climate/temp variations can offset NO_2 reductions: **Maybe true for Midwestern sites.**

- **H3:** Large 2020 fires may have exacerbated O_3 at some sites: O_3: **True for Western U.S. sites.**

- **Eastern U.S. sites showed significant reductions in both NO_2 and O_3.** The reductions were super-linear, due to an increasing OPE at lower NOx concentrations. The 2020 NOx reductions allowed most eastern U.S. NAAs to achieve a level that is consistent with meeting the O_3 NAAQS for the first time.

- **Midwest sites were more variable.** NO_2 dropped slightly in the O_3 season, but a hot summer may have caused O_3 to increase at most sites.

- **Western sites had a big increase due to fires.** 2020 had the largest area burned for the last 50 years. This caused massive air quality issues around the western U.S. and increased the fourth highest MDA8 O_3 values by 5-15 ppb. The increase in O_3 on smoke days is roughly 50/50 due to the increased temp and smoke photochemistry.

- **Key uncertainty:** At this point we don't know how much VOCs might have changed in 2020 or whether they still partially control urban photochemistry. Evidence suggests we've mostly moved into NOx control, maybe… Stay tuned for more on this.

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Spares

References

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- McClure C.D. and Jaffe D.A. US particulate matter air quality improves except in wildfire-prone areas. Proc.Natl.Acad.Sci., DOI: 10.1073/pnas.1804353115, 2018.

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- Kaulfus, A.S., Nair, U., Jaffe, D.A., Christopher, S.A., and Goodrick, S.. Biomass burning smoke climatology of the United States: Implications for particulate matter air quality, Environmental Science & Technology 50, 11731-11741, doi: 10.1021/acs.est.7b03292, 2017.

- Gong X., Kaulfus A., Nair U. and Jaffe D.A. Quantifying O_3 impacts in urban areas due to wildfires using a Generalized Additive Model. Envir. Sci. Tech. DOI: 10.1021/acs.est.7b03130, 2017.

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Very high PM$_{2.5}$ does not lead to high O$_3$ in smoke
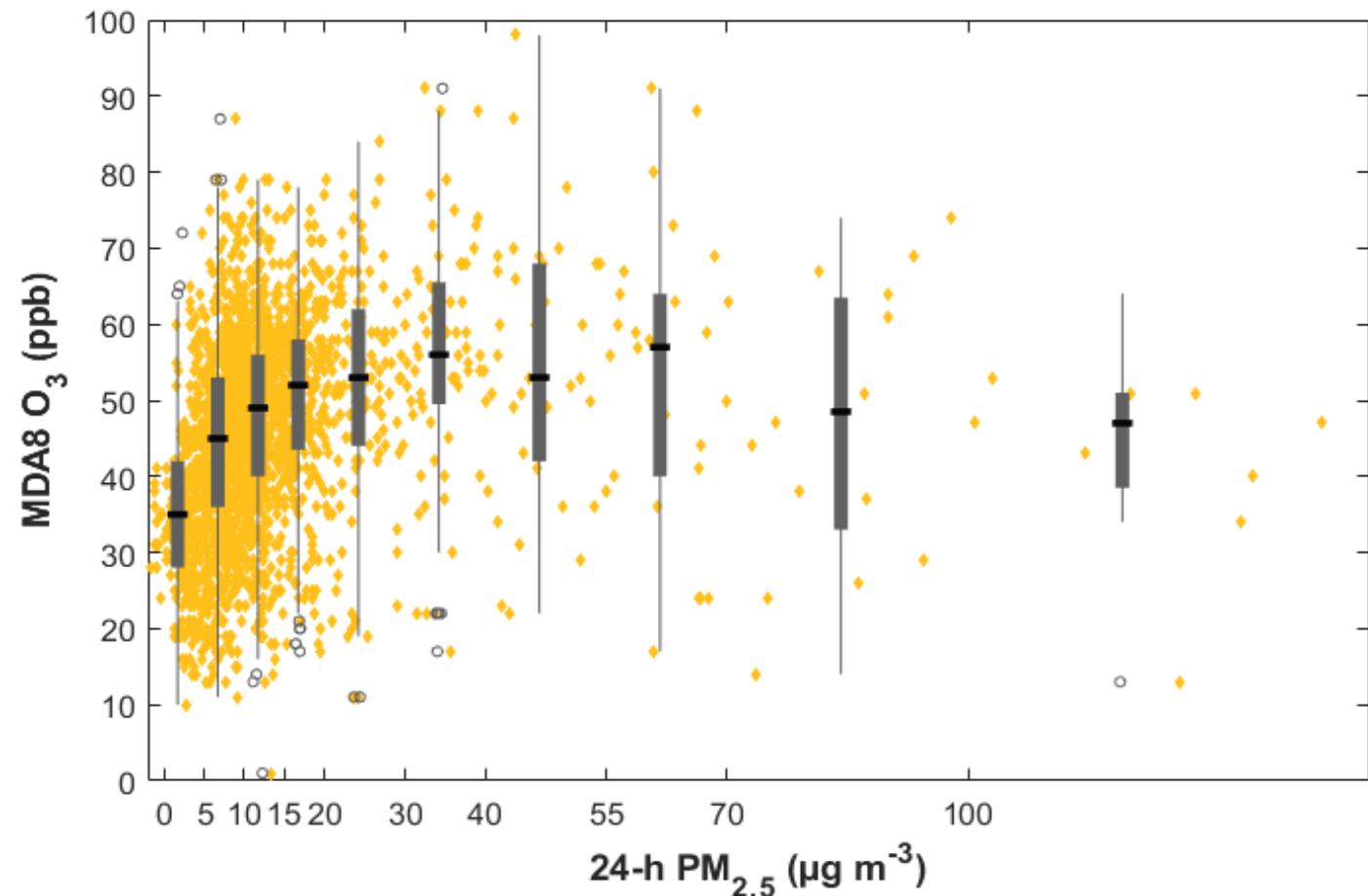
Buysse et al 2019.

- Role of transport time and PM levels (McClure et al 2018; Buysse et al 2019); Role of UV Photolysis (Baylon et al 2018; Alvarado et al 2015).

- Role of Temperature (Gao et al 2020).

- Use of machine learning to predict O$_3$ MDA8 in smoke (Gong et al 2017; Gao et al 2020)

- Why not high O$_3$ at high PM$_{2.5}$?

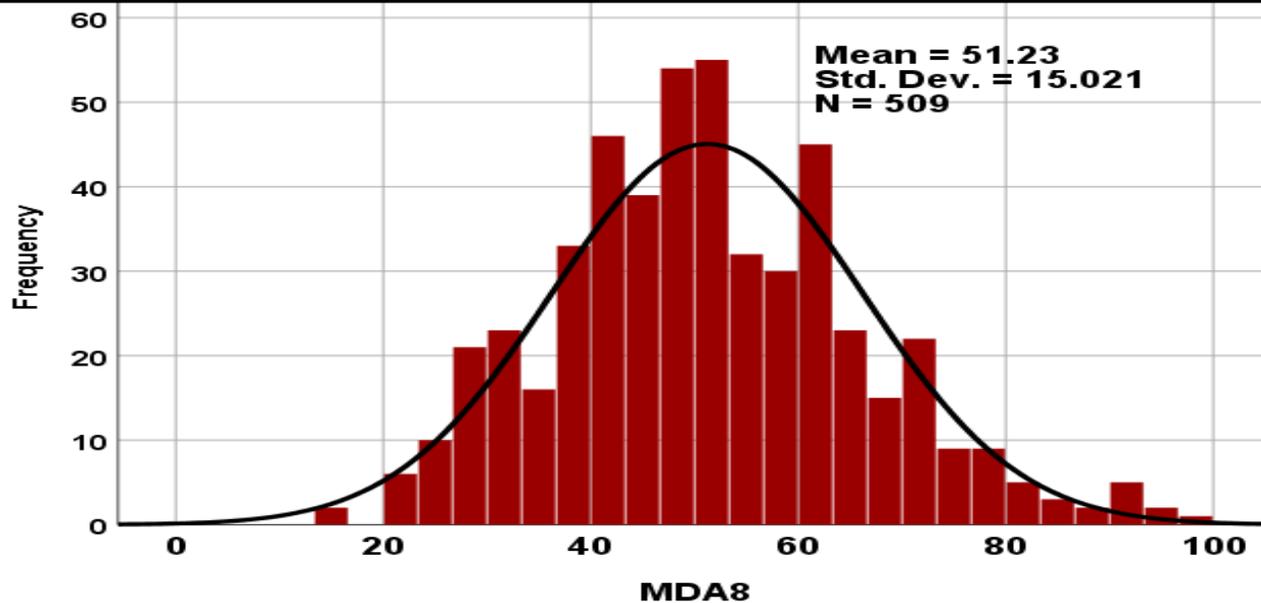Heterogenous chemistry?

Reduction in photolysis?

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Max daily 8-hour O₃ in and out of smoke for 5 cities in the PNW: May-Sept. 2007-2017.
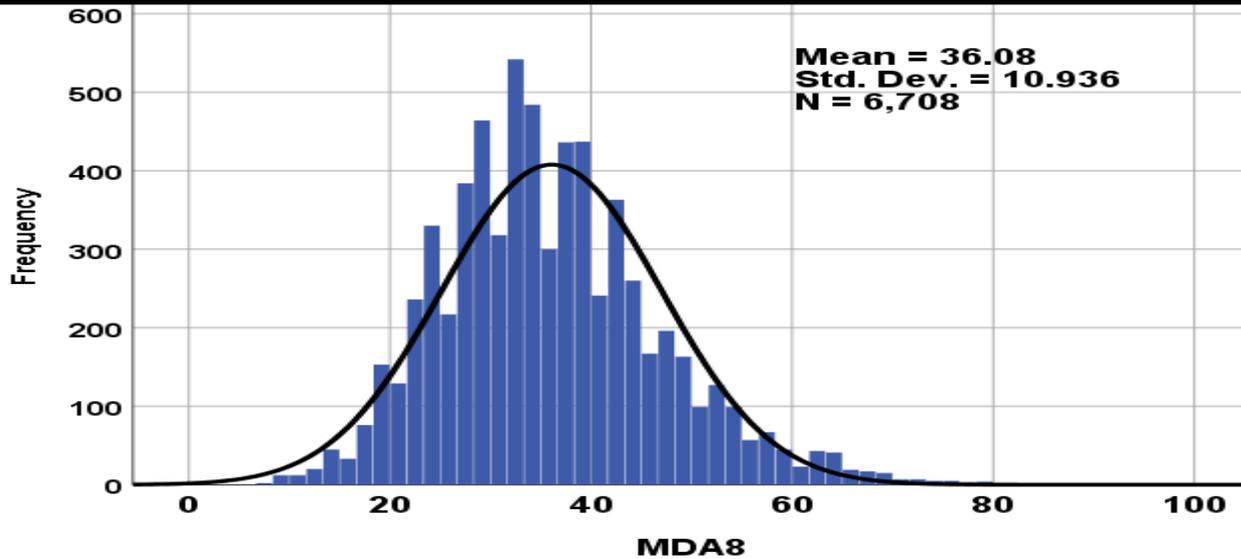

No smoke days:

- **Average MDA8 = 36 ppb**

- **Fraction of days that have MDA8 g.t. 70 ppb = 0.4%**

Smoke days:

- Average MDA8 = 51 ppb.

- Fraction of days that have MDA8 g.t. 70 ppb = 10.1%.

- Smoke days are 40% of all days with MDA8>70

- Using a machine learning algorithm, we find that smoke contributes about 8 ppb, on average, to the MDA8, but with lots of variability (Jaffe et al 2021).

MDA8 residuals vs daily max temp (mean +/- CI, ppb)
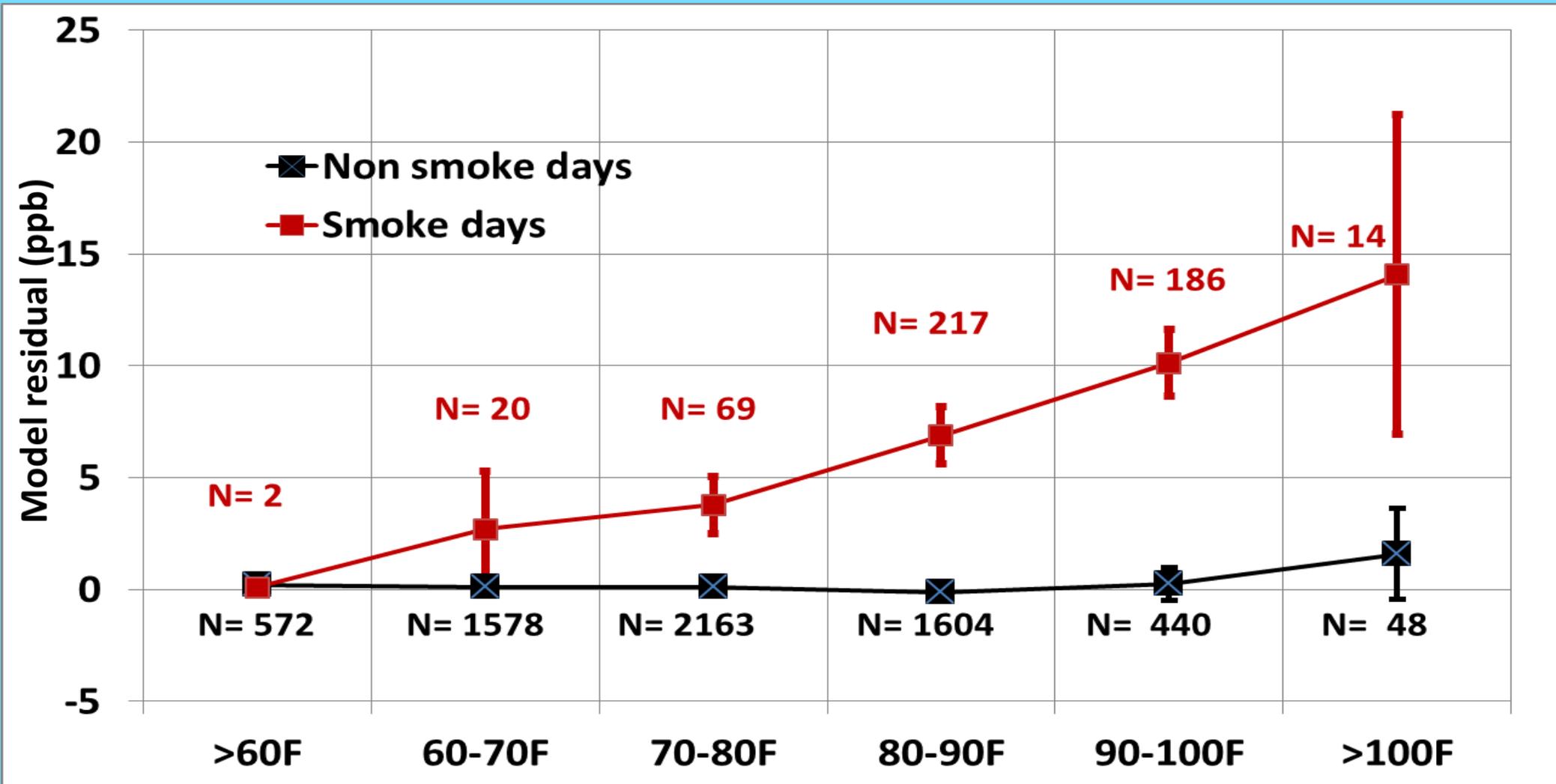
This demonstrates that the GAMs correctly predict O_3 as a function of temperature in the absence of smoke.

Jaffe et al 2021

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MDA8 O$_3$ temp relationship, SLC-BV site, May-Sept 2006-2018