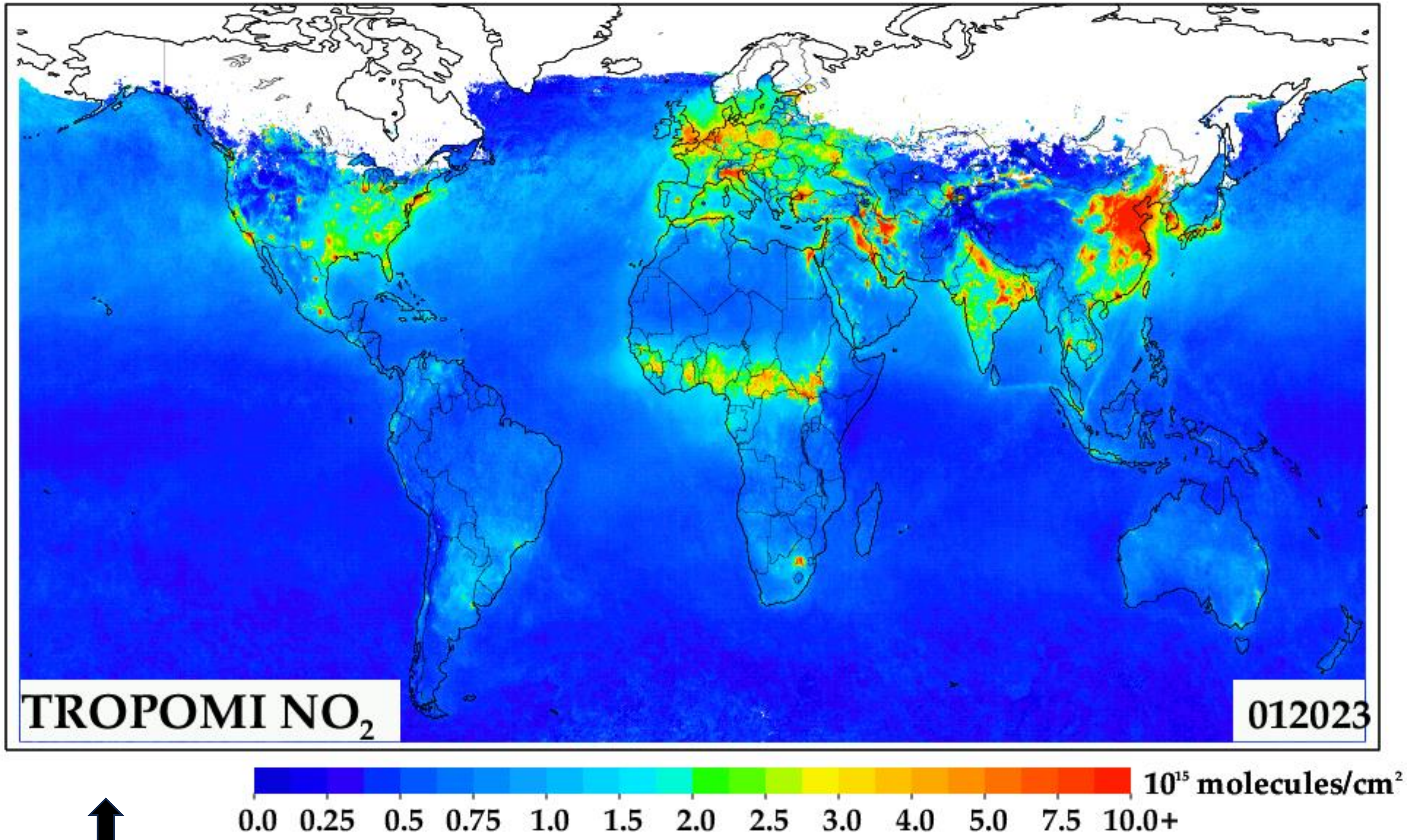
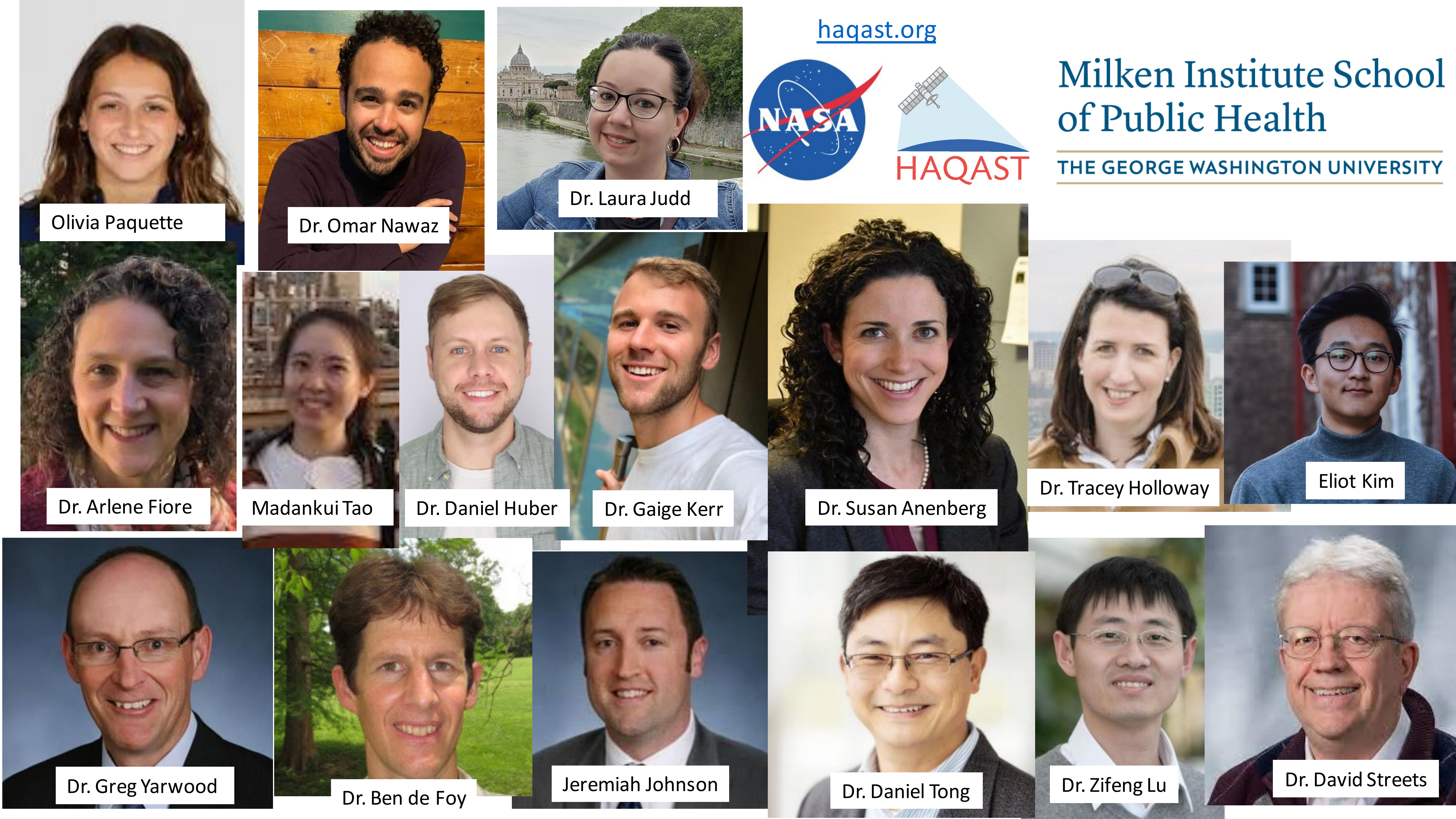
Applications of OMI and TROPOMI NO_2 satellite data for Public Health at Urban Scales



By: Dan Goldberg
Assistant Research Professor
George Washington University

NASA HAQAST
Massachusetts
June 4, 2024

Follow @DGoldbergAQ on X or visit tropomino2.us for more images like these


haqast.org
NASA
HAQAST
Milken Institute School of Public Health
THE GEORGE WASHINGTON UNIVERSITY
Olivia Paquette
Dr. Omar Nawaz
Dr. Laura Judd
Dr. Arlene Fiore
Madankui Tao
Dr. Daniel Huber
Dr. Gaige Kerr
Dr. Susan Anenberg
Dr. Tracey Holloway
Eliot Kim
Dr. Greg Yarwood
Dr. Ben de Foy
Jeremiah Johnson
Dr. Daniel Tong
Dr. Zifeng Lu
Dr. David Streets

This research presentation was supported (in part) by funding from the Texas Commission on Environmental Quality (TCEQ). The findings, opinions, or conclusions expressed do not necessarily represent those of the TCEQ.

Atmospheric Composition Modeling and Analysis Program (ACMAP)

OMI vs. TROPOMI

Ozone Monitoring Instrument (OMI)

Launched July 2004;
data since Fall 2004

Spatial resolution of
24 x 13 km^2 at nadir;
coarser at swath edge

Great for long-term trends;
data record of 20(!) years

Row anomaly ☹ half the
data is missing since 2007

Both

Measure column NO_2, HCHO,
and O_3 (among other gases)

Similar algorithms / techniques
to measure the columns

Polar-orbiting with 13:30
local time overpass;
once per day

Tropospheric Monitoring Instrument (TROPOMI)

Launched Oct 2017;
data since Spring 2018

Spatial resolution of
5.5 x 3.5 km^2 at nadir;
similar at swath edge

Instrument signal-to-noise
ratio is excellent; uncertainty
of measurements are lower

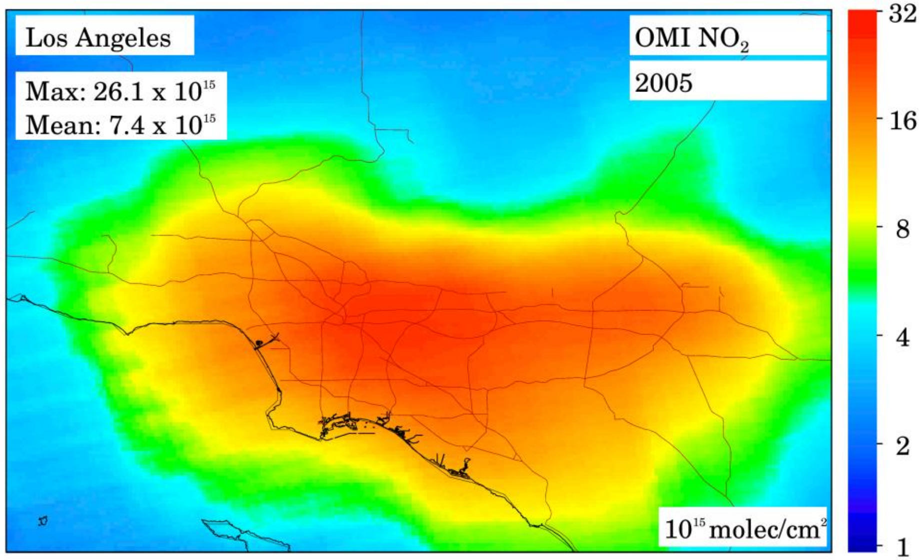
Better for urban-scale studies

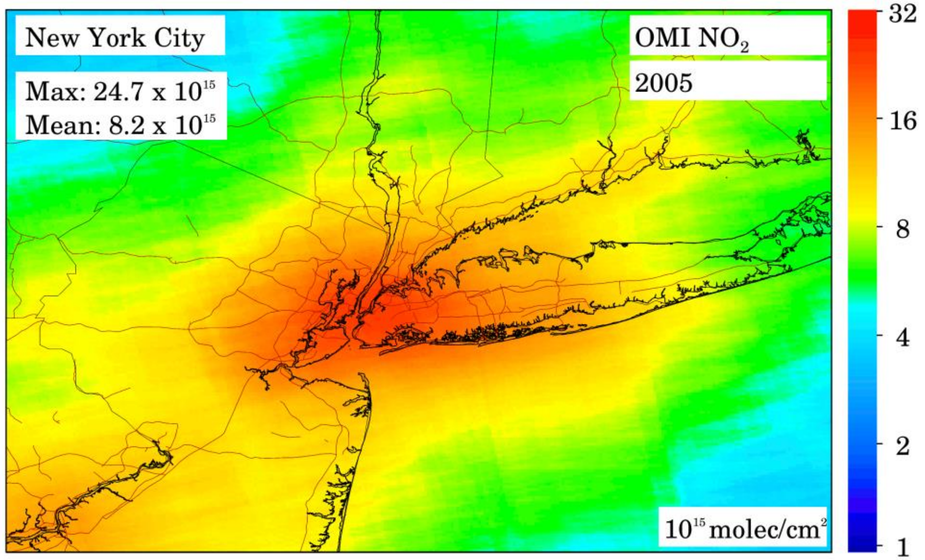
Better for short timescale studies

Better for recent trends

Urban NO_2 changes since 2005, as observed by OMI
(more images in the supplemental)

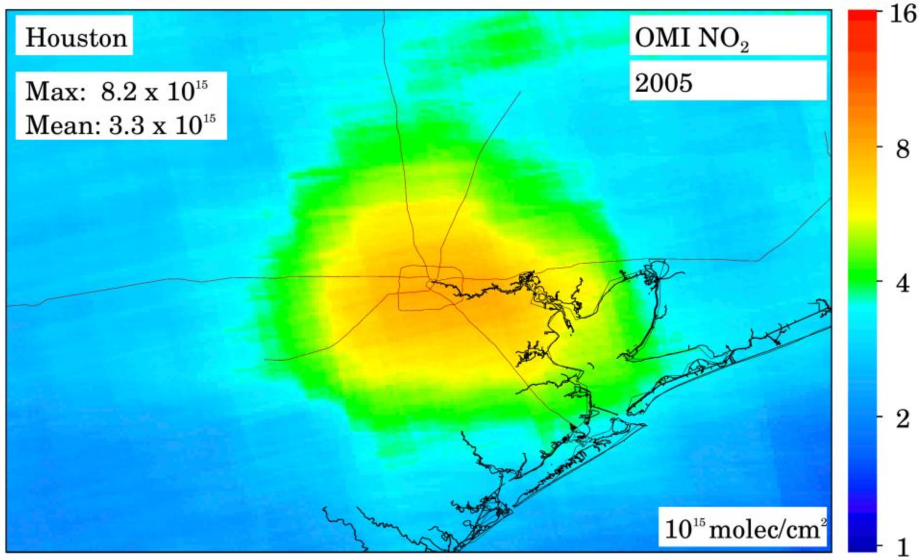
59% drop

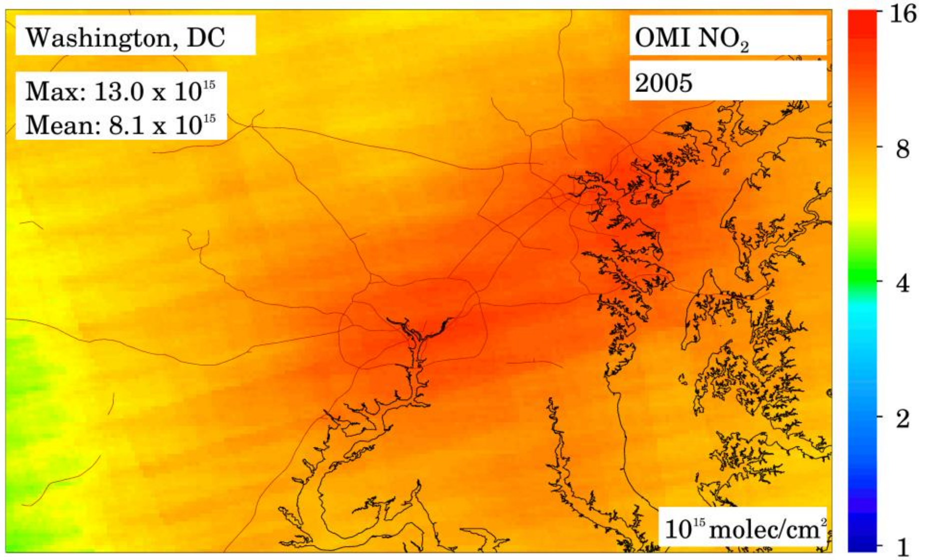




57% drop

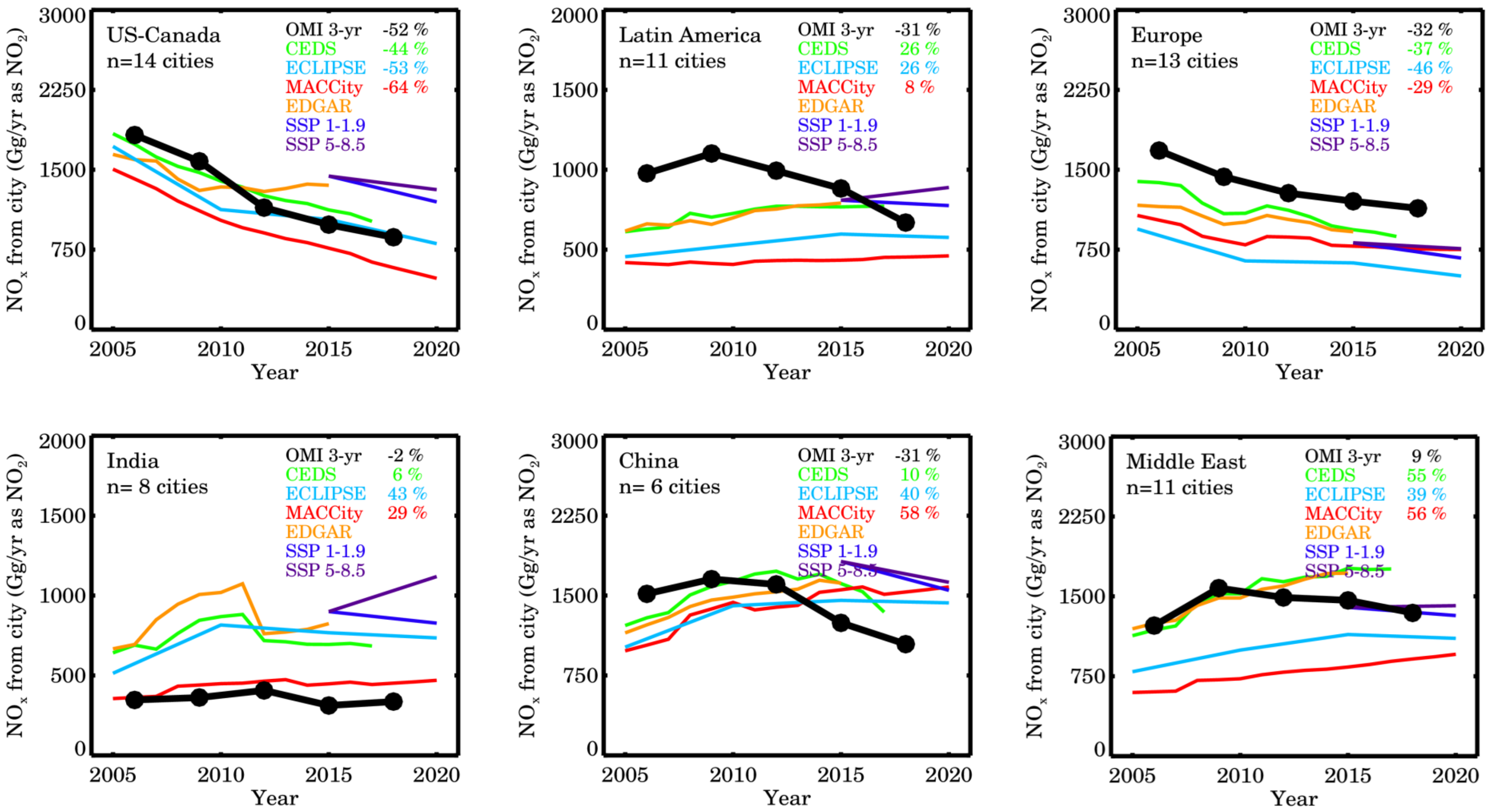
31% drop





62% drop

Urban NO_x changes since 2005, as observed by OMI
(Goldberg et al., 2021, ERL)



Aerosol interference in India might be causing low measurements

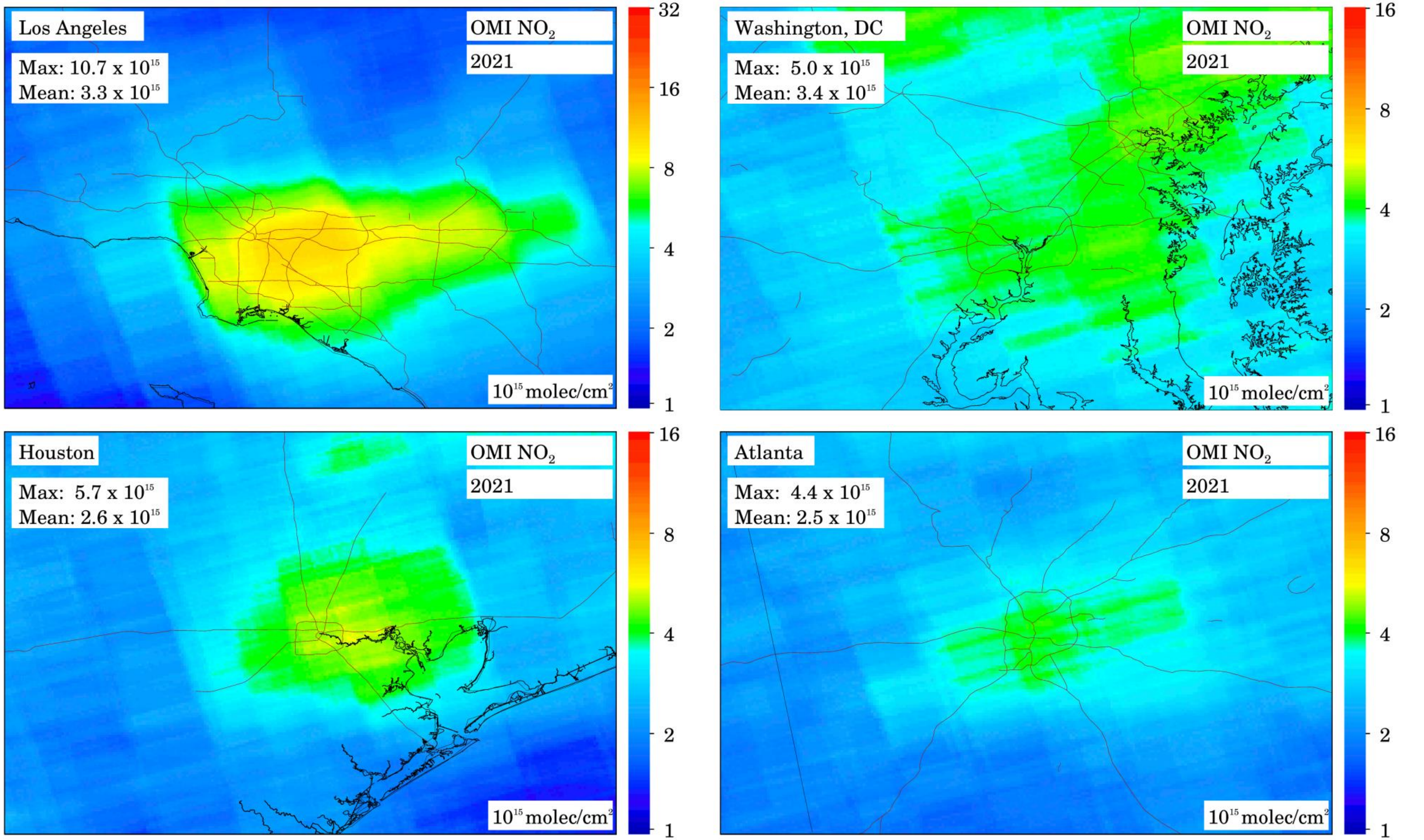
Satellite-based NOx trends match inventory in US & Europe through 2019 (in a relative sense)

Satellite-based NOx trends don't match inventory in the Middle East and Latin America

Ahn et al., submitted
shows similar regional satellite vs. inventory mismatches for CO_2 using OCO-3

OMI vs. TROPOMI: Spatial comparisons

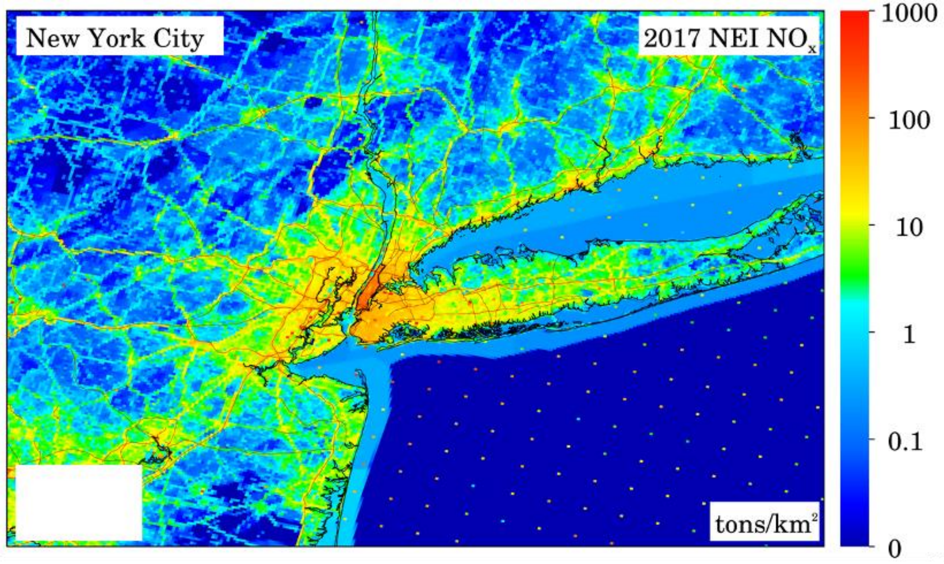
(Goldberg et al., 2021, Earth's Future) (more images in the supplemental)

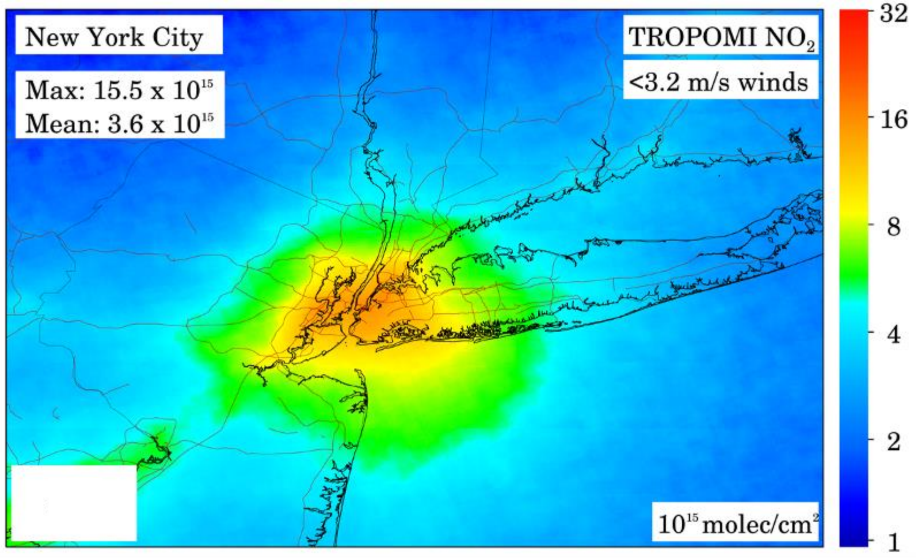


TROPOMI observes known urban NO_2 spatial heterogeneities better

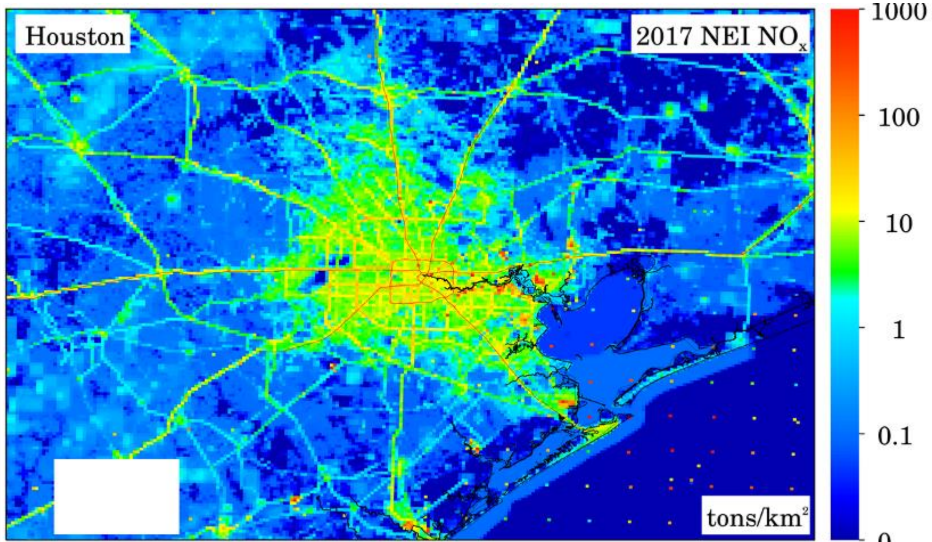
Great *spatial agreement* between TROPOMI NO_2 and inventory NOx (used in model) with some exceptions (warehouses & EJ)

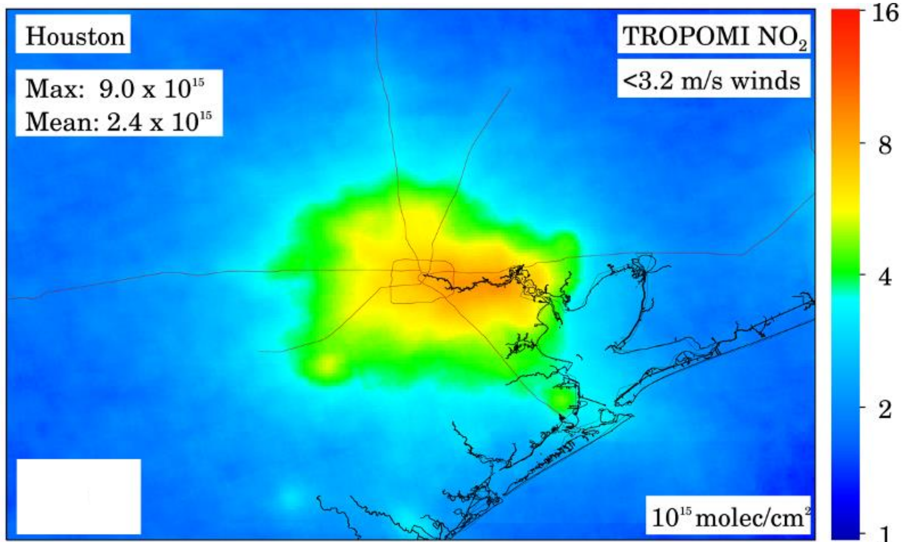
Goldberg et al., 2024, *Remote Sensing of the Environment*
Kerr et al., *Nature Communications*, accepted





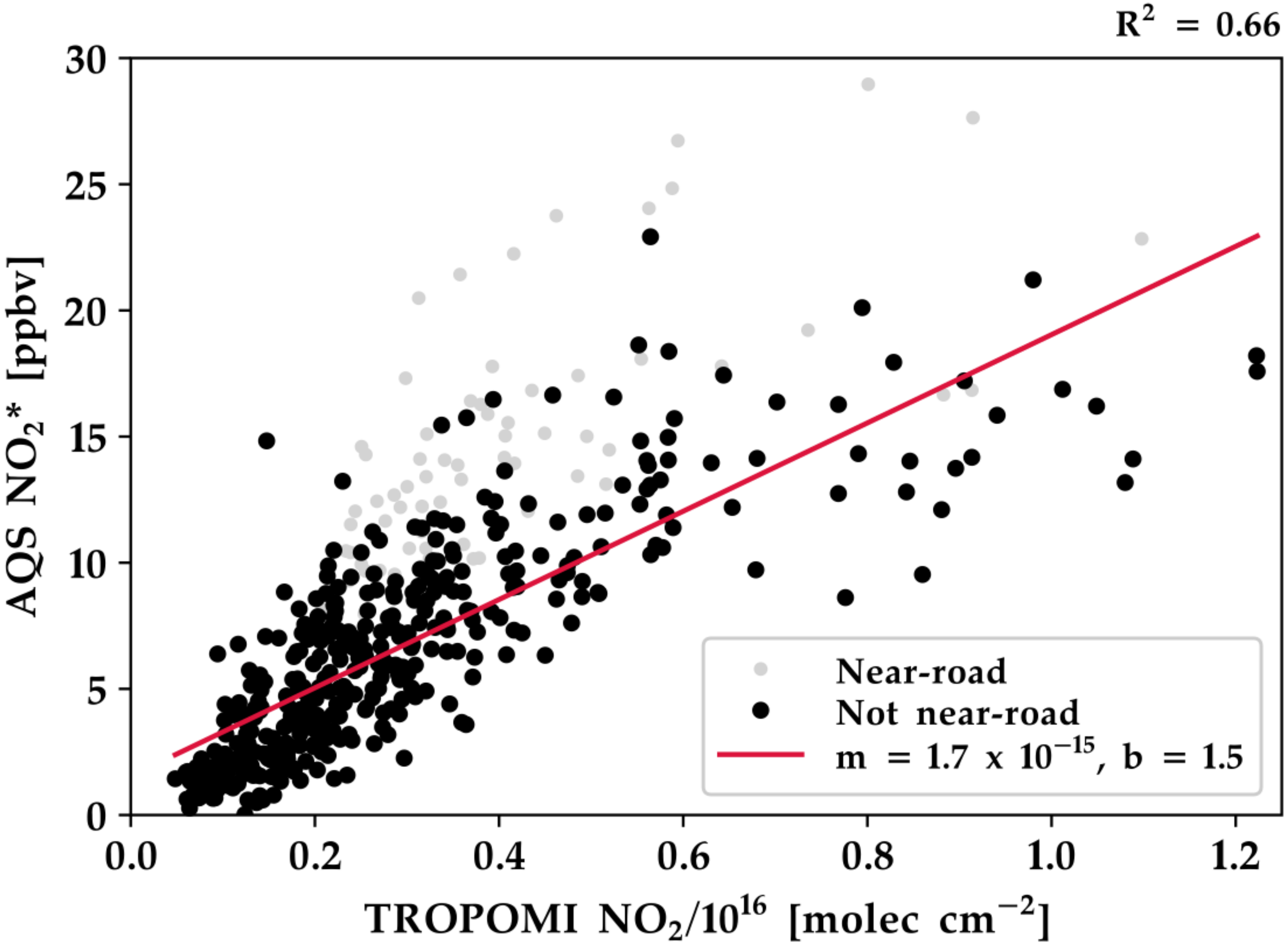
$r^2 = 0.81$





$r^2 = 0.78$

TROPOMI NO_2 column measurements have great correlation (r^2 = 0.6 – 0.7) with annual NO_2 surface measurements
(Goldberg et al. 2021, Earth's Future)



A very rough heuristic to convert column NO_2 measurements to surface concentrations is to multiply column measurements by 2 x 10^{-15}

But we have also developed more rigorous strategies to estimate surface concentrations…

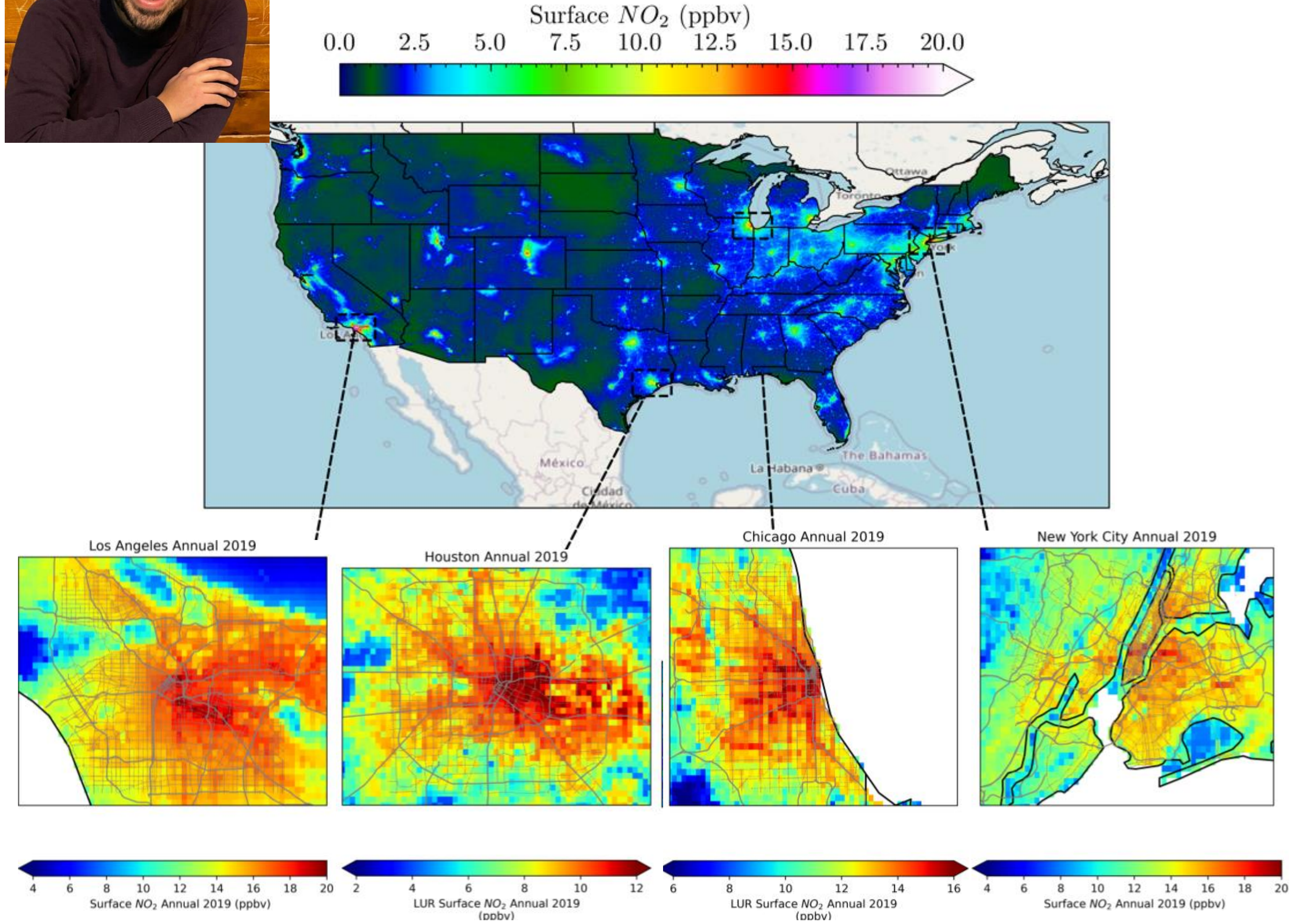
TROPOMI NO_2 surface estimates (two flavors)

Only a limited # of other variables included, we want TROPOMI to drive the estimates!

(Nawaz et al., in prep; Kim et al., under review) (more in supplemental)

Lasso Regression – Monthly timescales

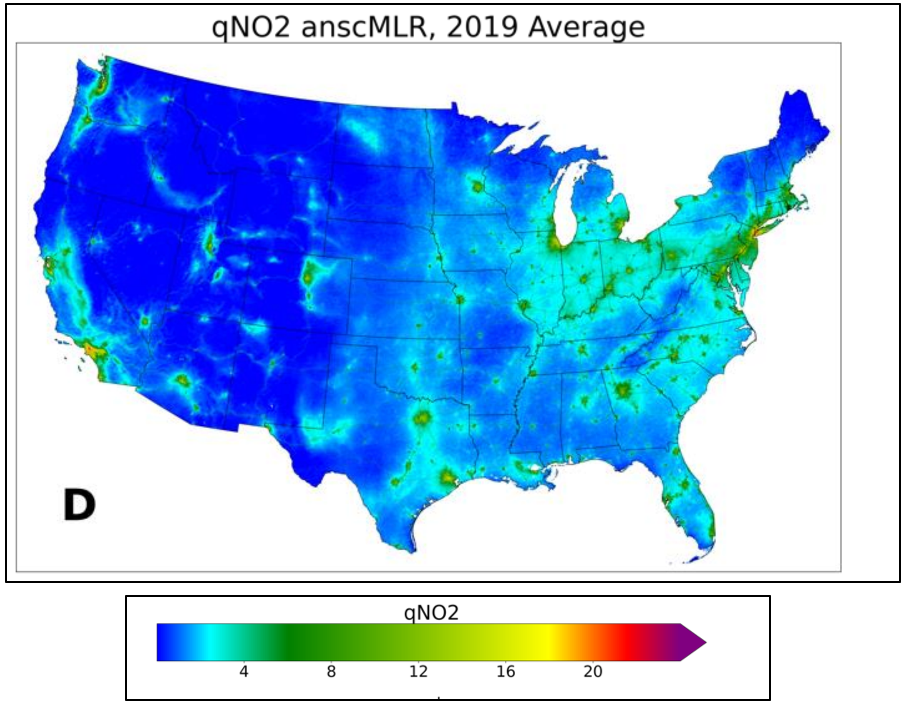
r^2 = 0.72; Nawaz et al., in prep.



Regression w/ Anscombe Transform – Annual

r^2 = 0.77; Kim et al., under review

THE HOLLOWAY GROUP @ SAGE



TROPOMI NO_2 satellite data is the driver of the NO_2 estimates; the same cannot be said of previous surface NO_2 estimates

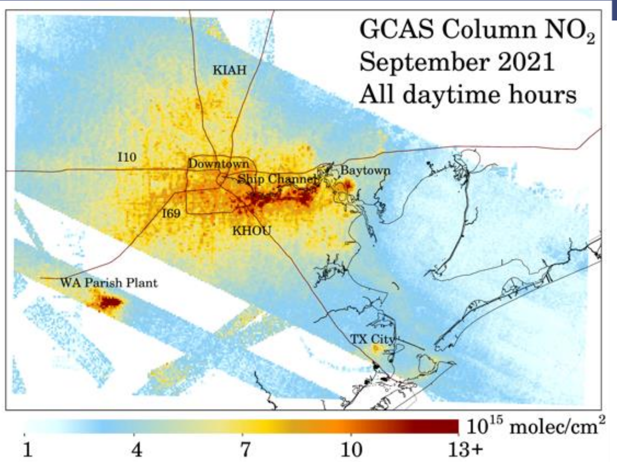
Model performance drops dramatically when TROPOMI data is excluded
Higher resolution satellite data leads to simpler LUR models with improved performance

	% Reduction in R^2	
	TROPOMI LUR (Nawaz et al., in prep)	OMI LUR (Larkin et al., 2023)
Satellite Remote Sensing	29.0	6.2
All Major Road	3.7	8.6
Built Environment	3.5	1.6
Surface Pressure	2.4	0.1
UV Backscatter	1.9	N/A
Temperature	0.6	0.5
Population Density	N/A	1.5
Tree Cover	N/A	1.1
All Residential Road	N/A	0.8
Water Body	N/A	0.7

Nawaz et al., in prep.

Use of remote sensing to constrain sector NOx in Houston

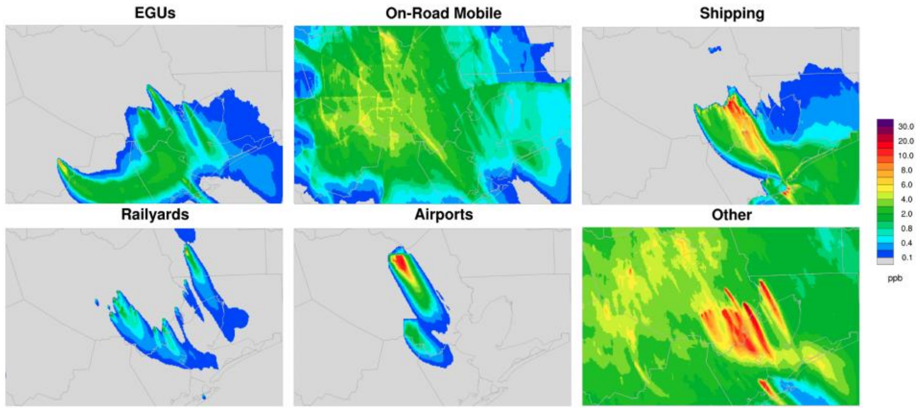
(Goldberg et al., submitted, ES&T Air, pre-print on chemrxiv)

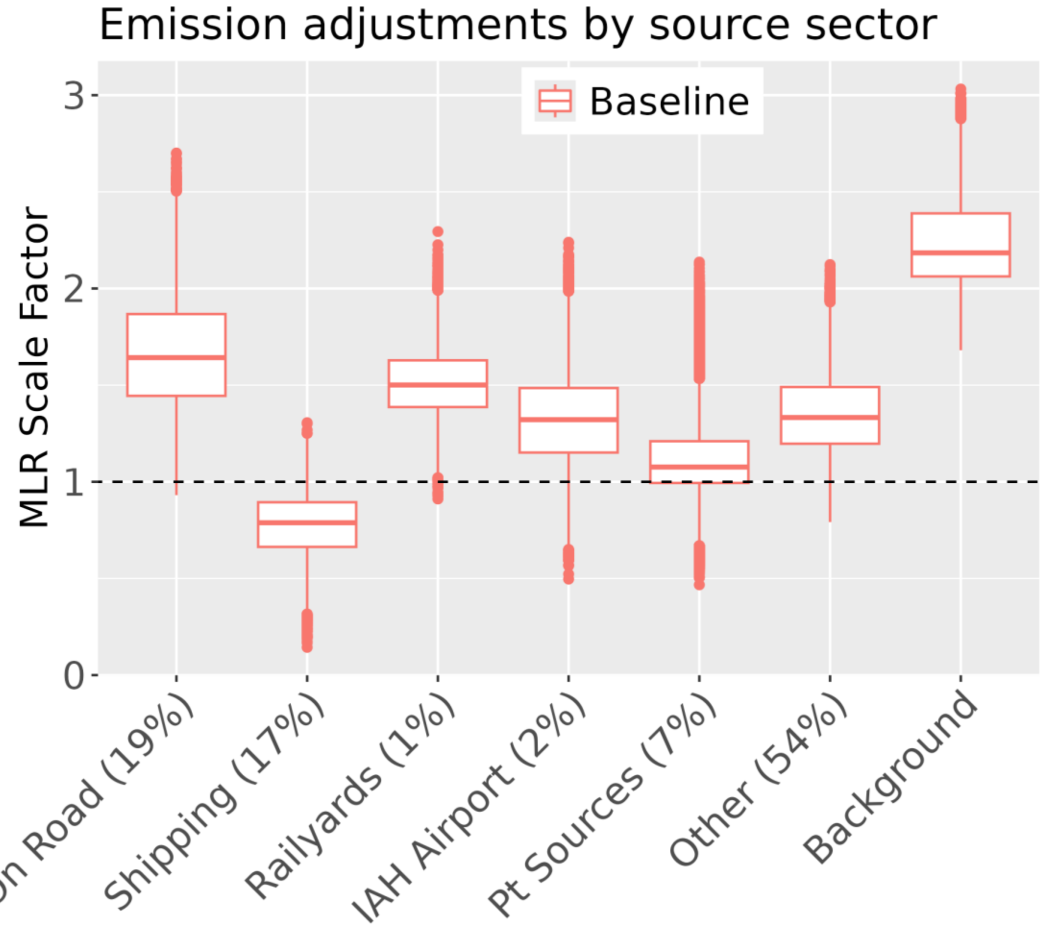


GCAS Aircraft NO_2 Data

Multiple linear regression

Model NO_2 Source Apportionment



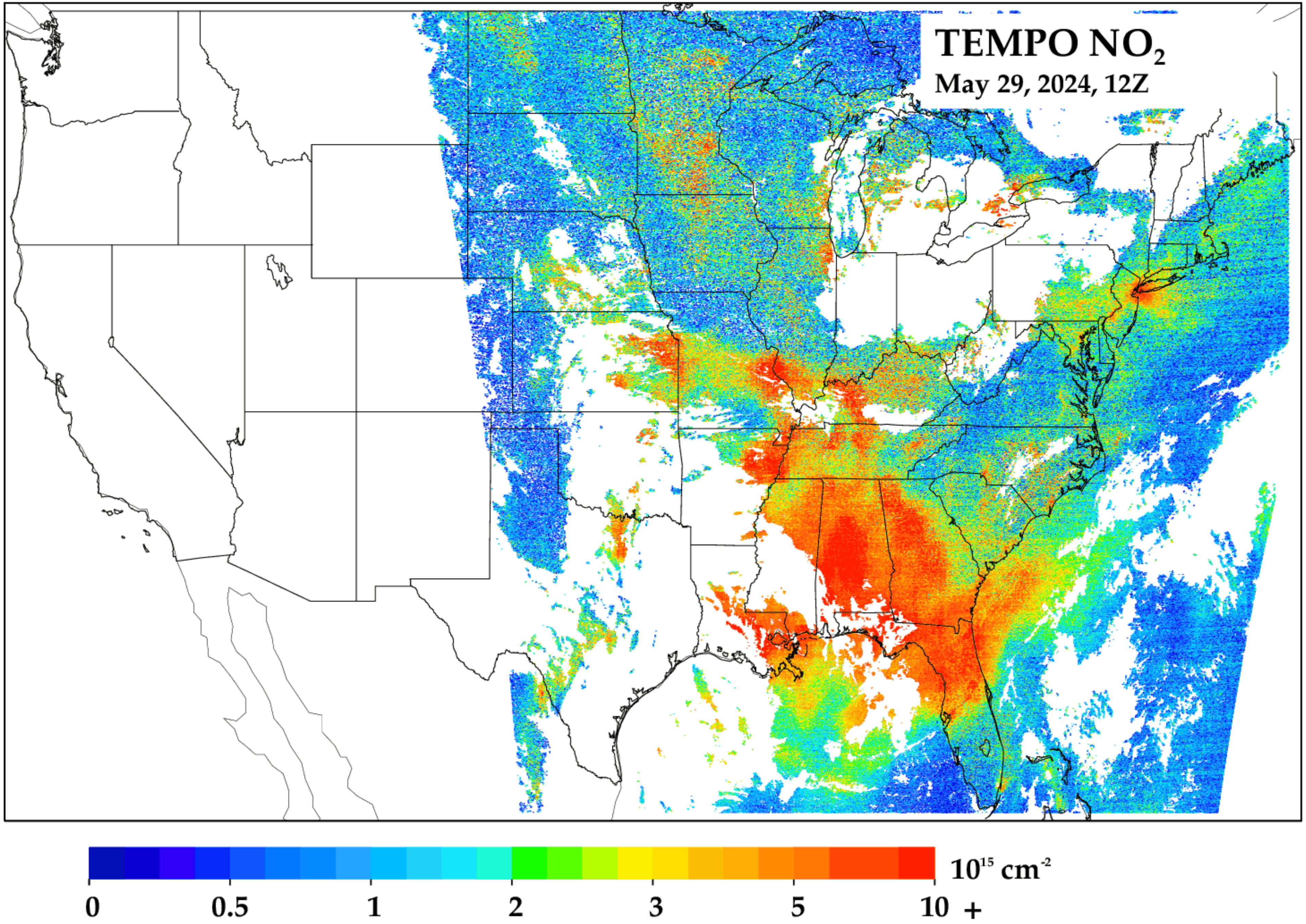


On Road NOx in model needs to be *increased*

Shipping NOx in model needs to be *decreased*

Background NO_2 in model needs to be *increased*

EXTRA



BETA V3 NO_2 product

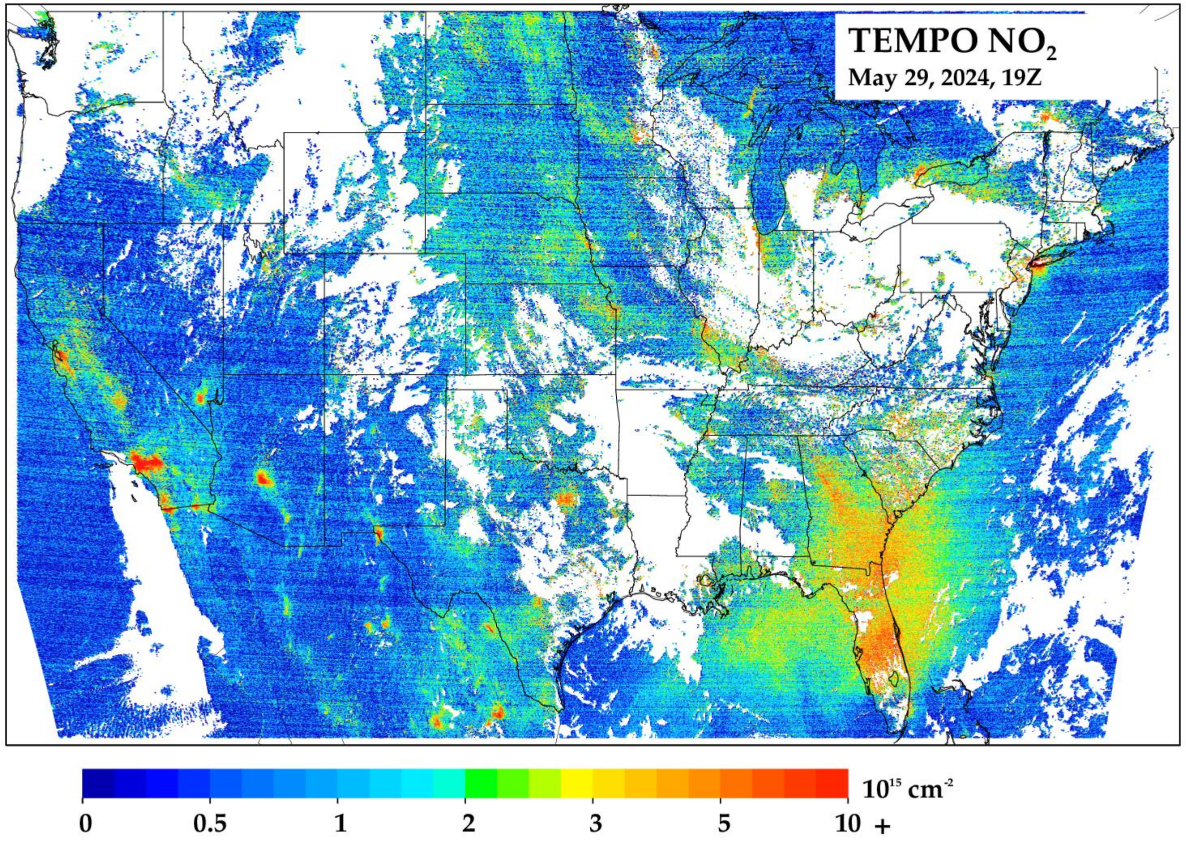
Cloud fractions >0.15 filtered out

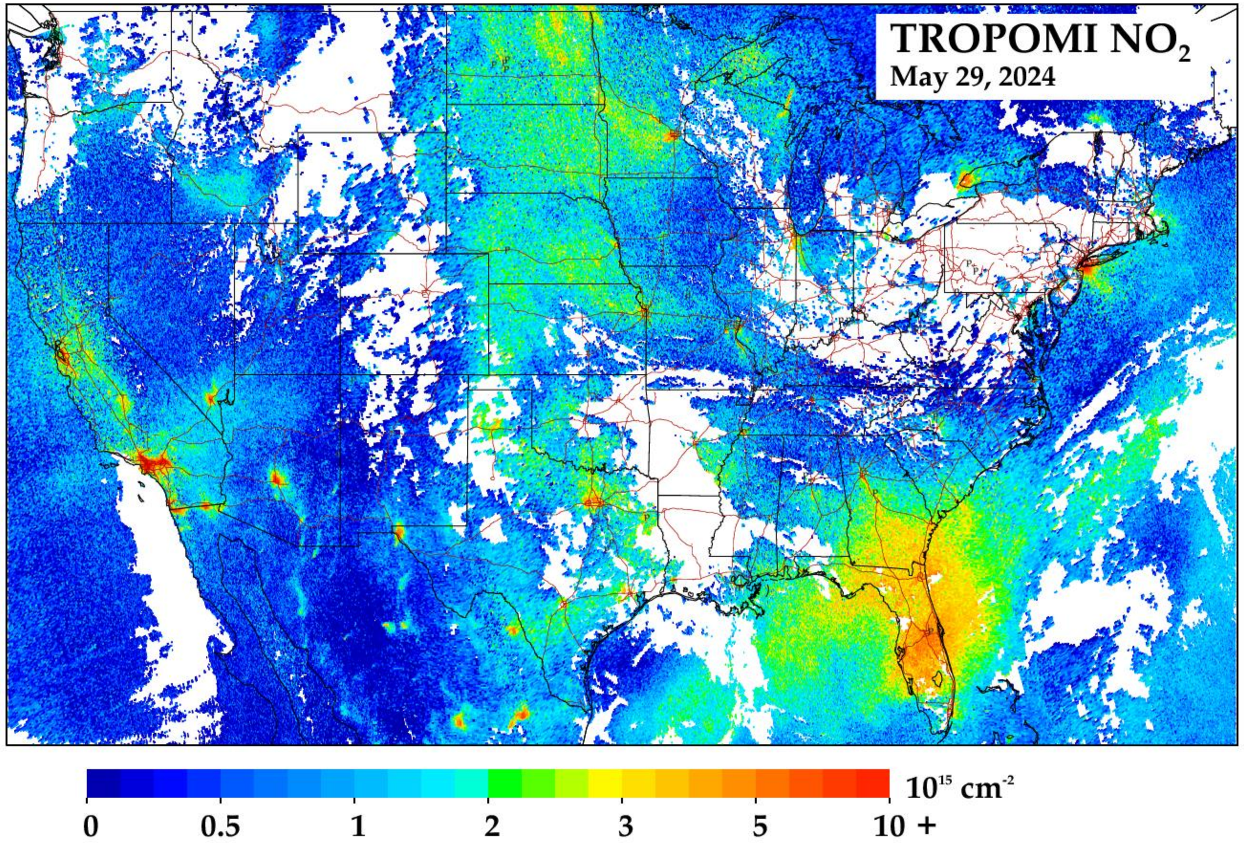
Negative values screened out for clarity

NO_2 in SE US likely from lightning NOx

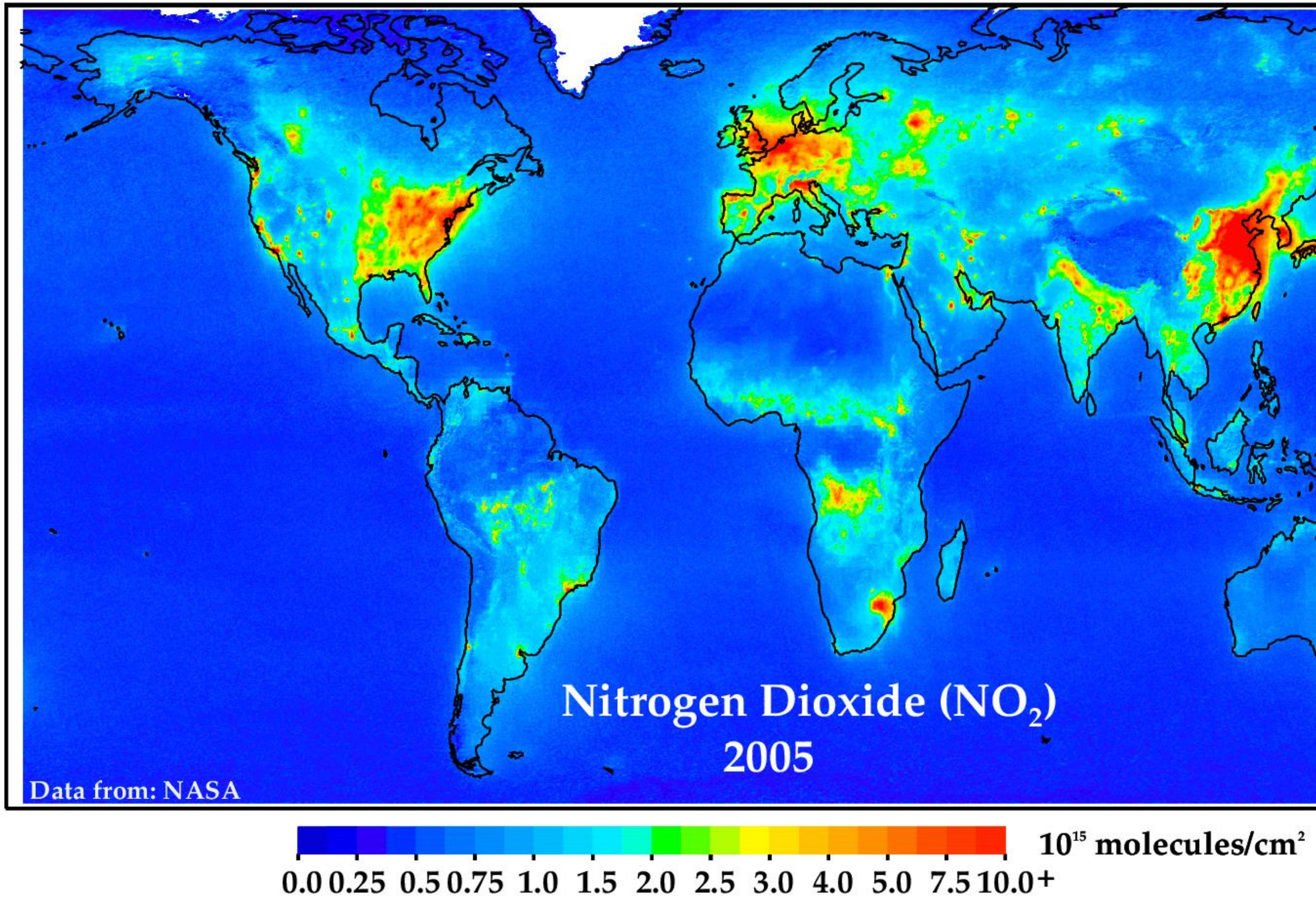
NO_2 in North Central US likely from soil NOx

TROPOMI NO_2 vs. TEMPO NO_2

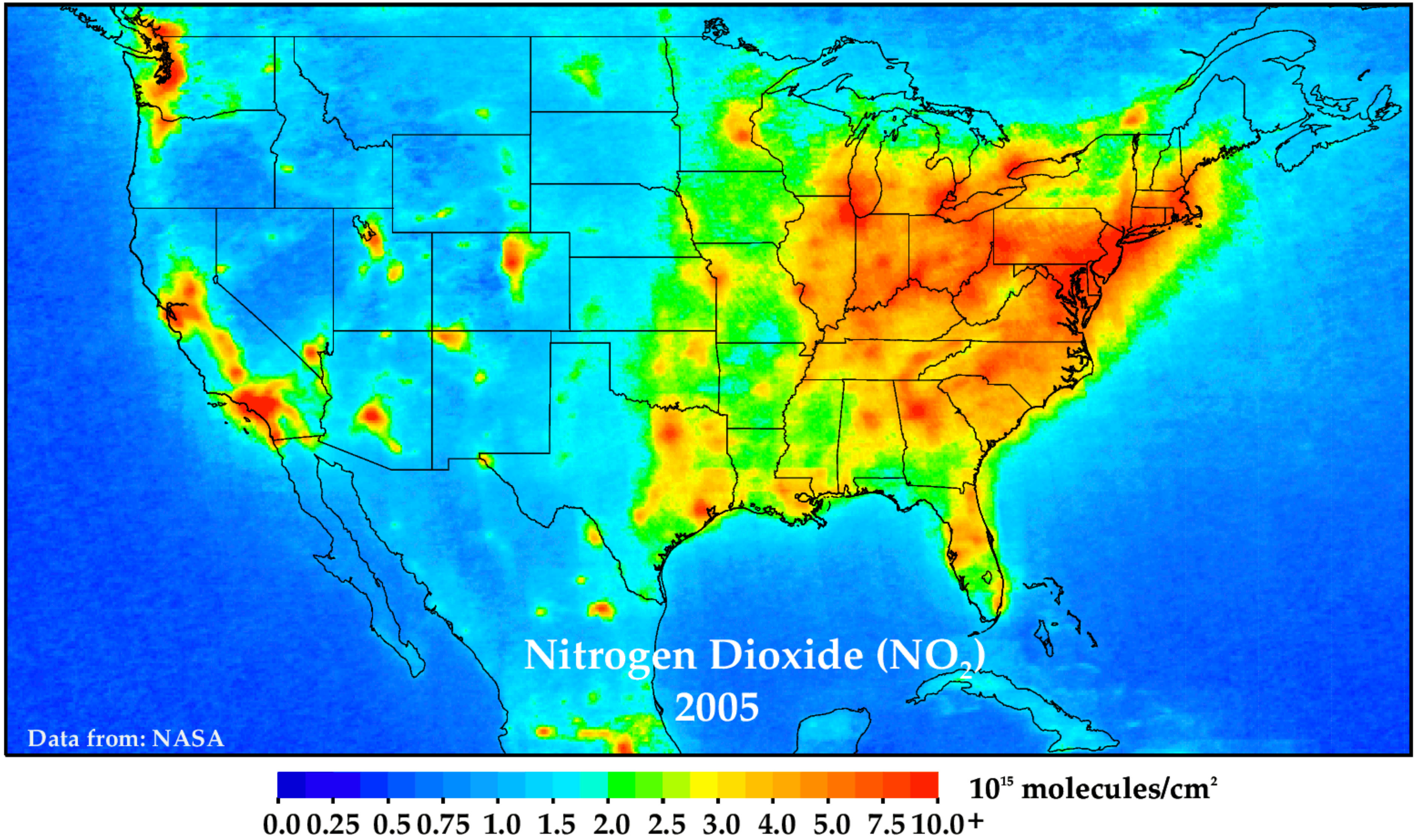




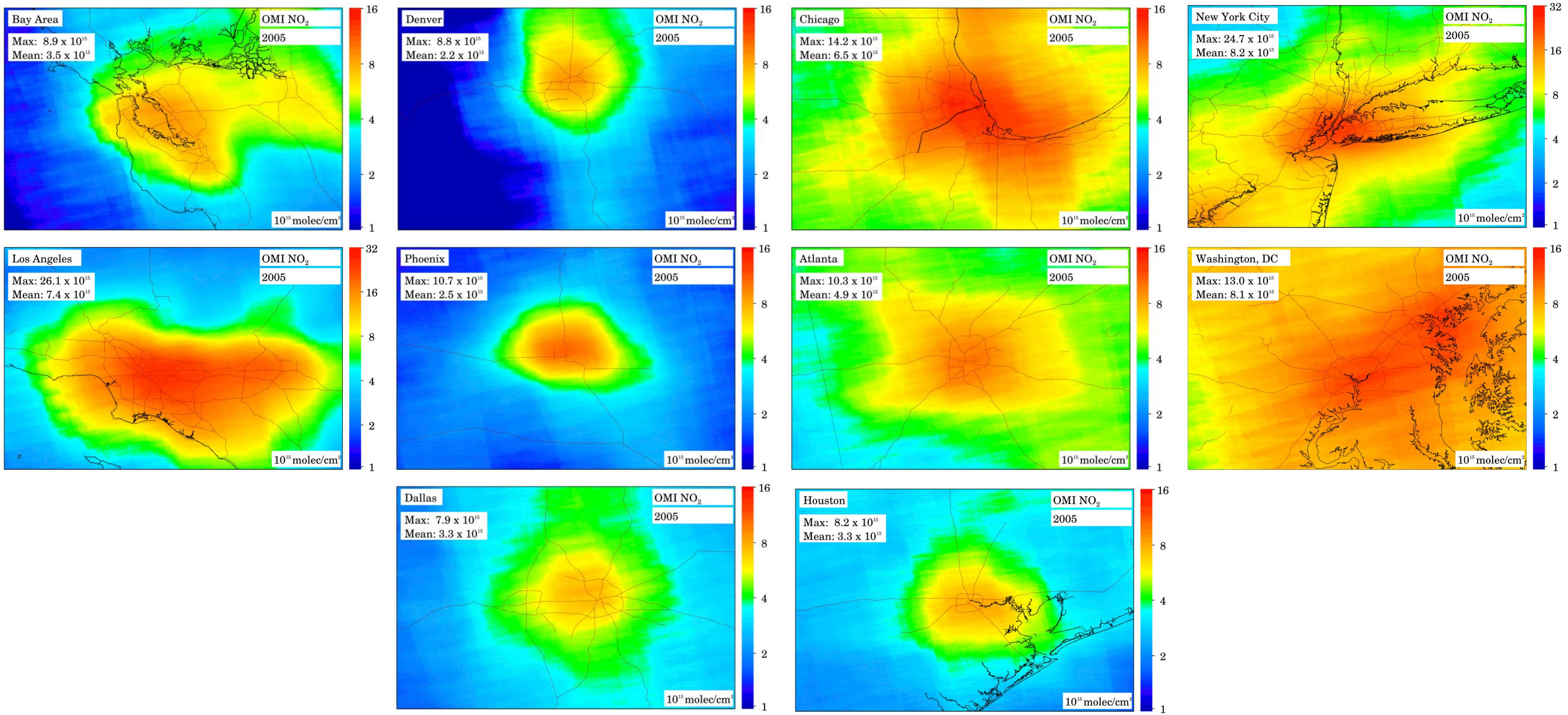
OMI NO_2 trends



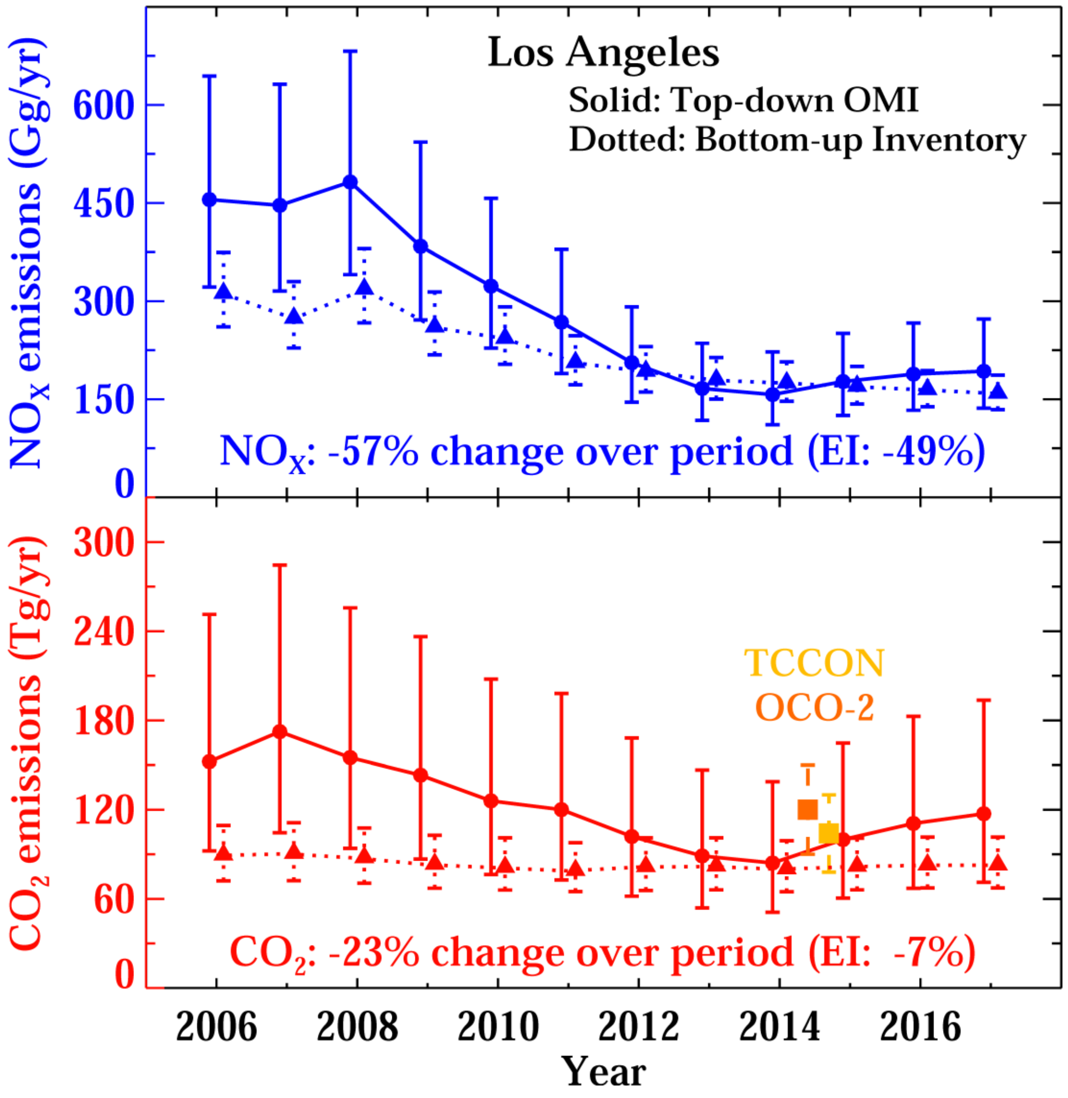
OMI NO_2 trends



OMI NO_2 trends



OMI "CO_2" estimates for Los Angeles; matches observations relatively well (Goldberg et al., 2019, STOTEN)

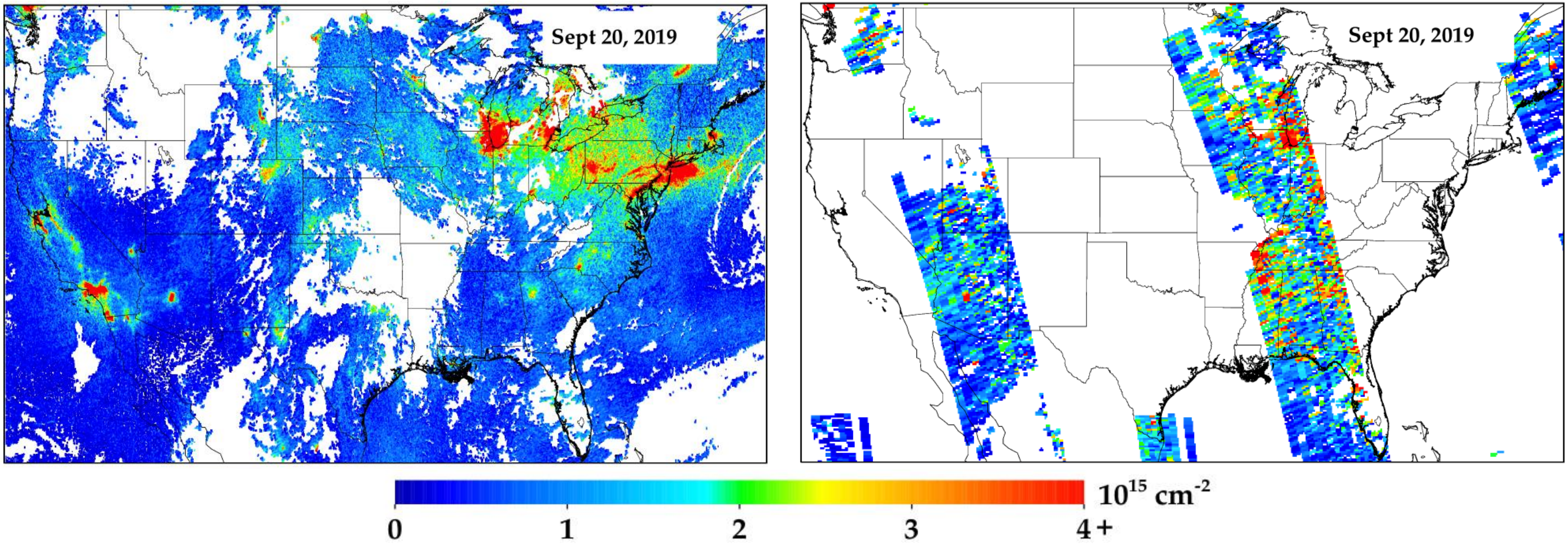


Top-down NO_X computed using oversampled OMI data over a 3-year warm season (e.g., 2006 = Apr thru Sept 2005 thru 2007)

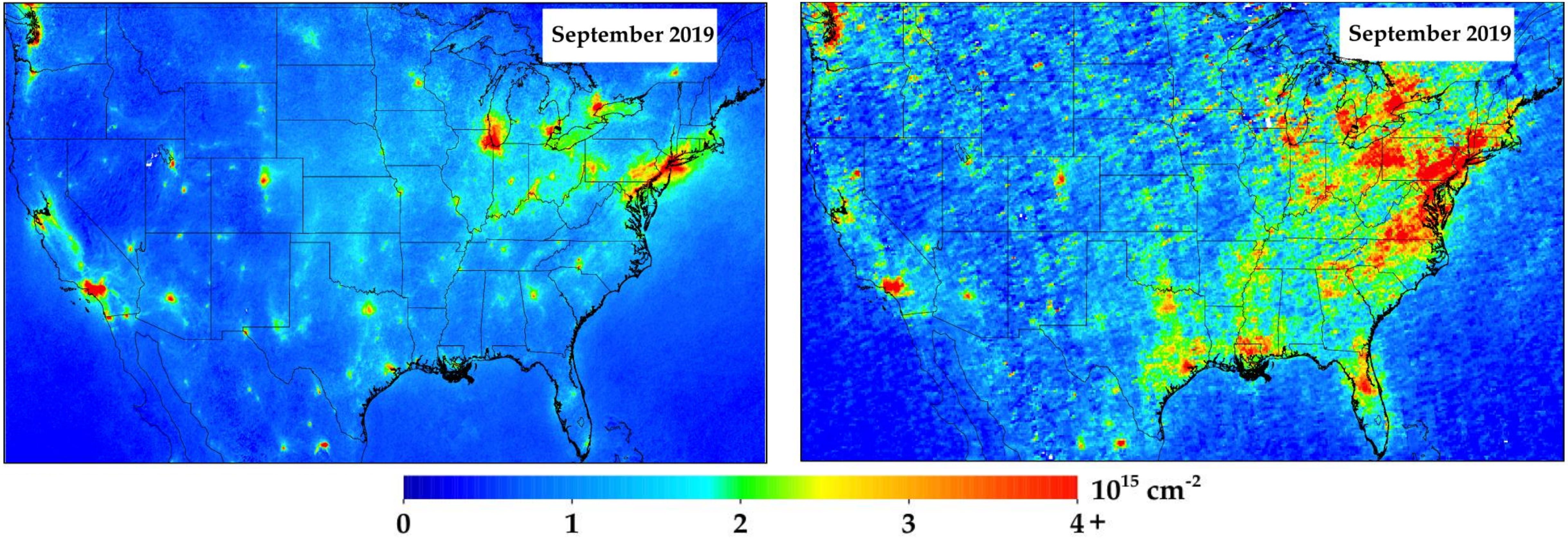
Top-down CO_2 computed by dividing the top-down NO_X emissions rate by the local (within 75 km radius) NO_X-to-CO_2 ratio.

Ahn et al., submitted
is a major advancement,
check it out when it arrives!

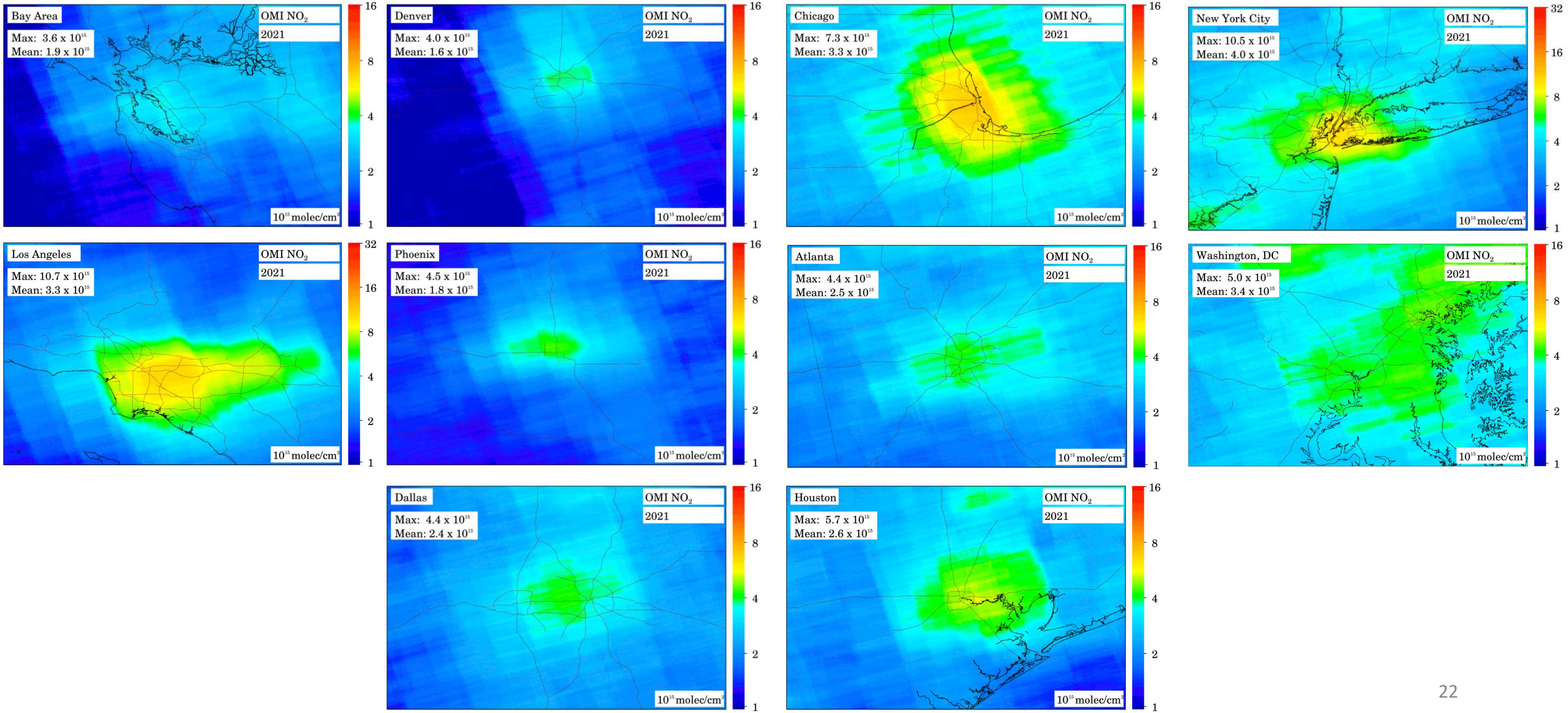
OMI vs. TROPOMI



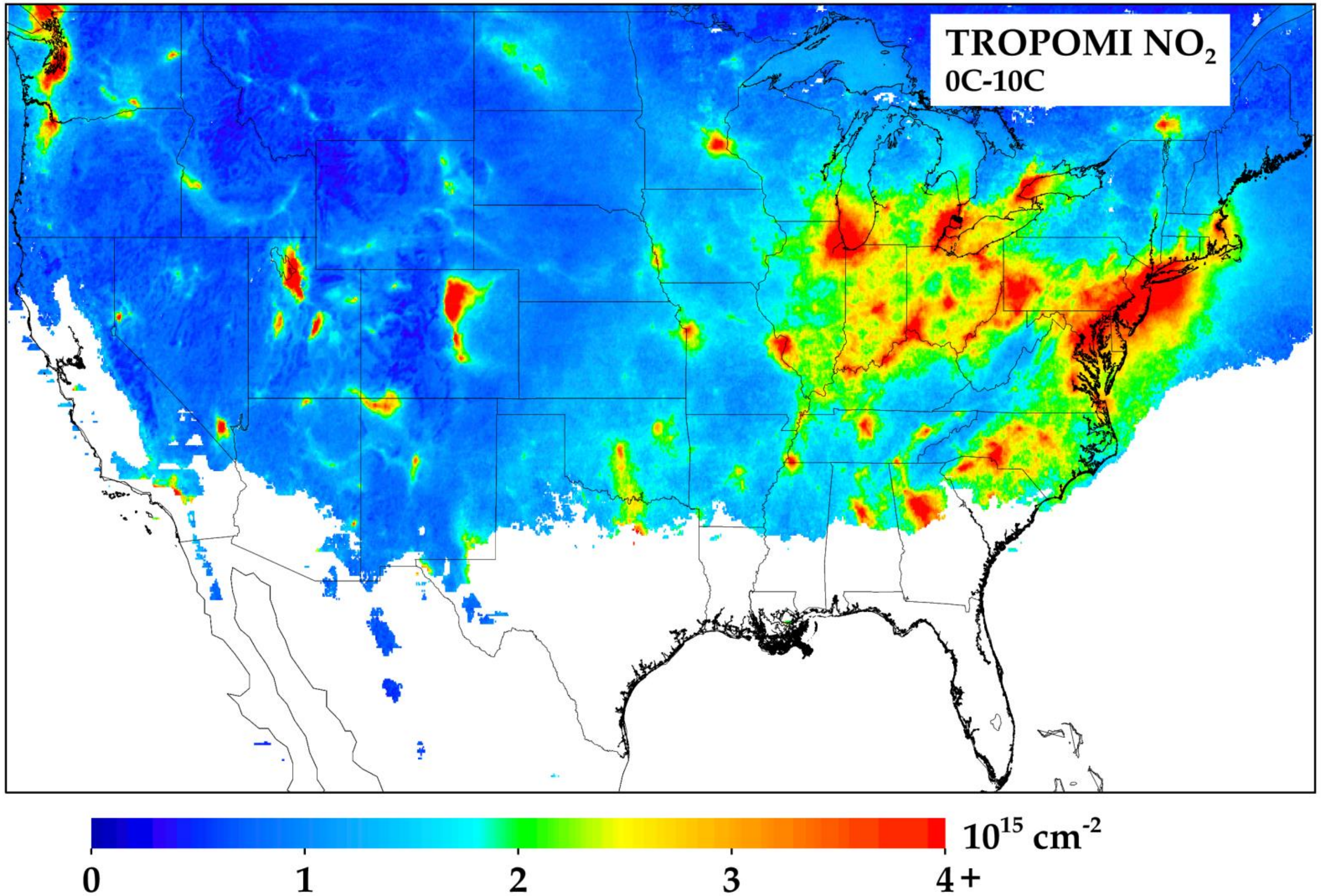
OMI vs. TROPOMI

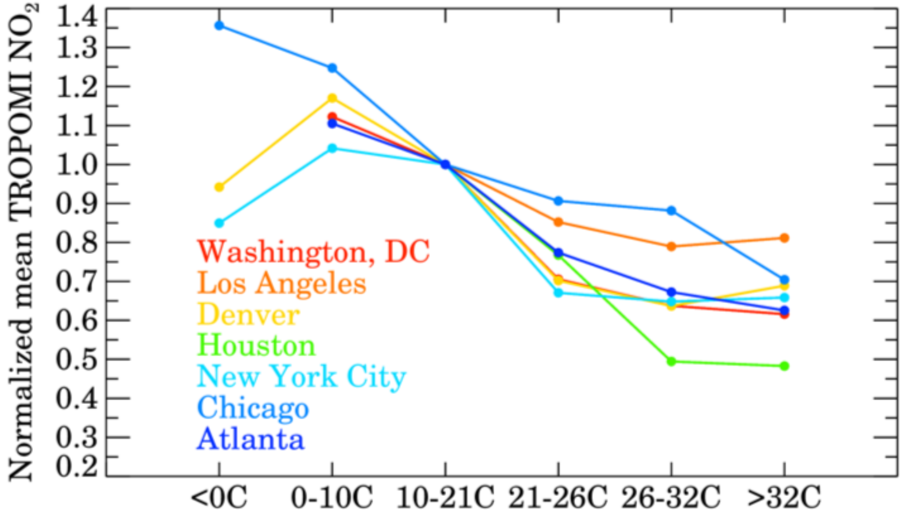


OMI vs. TROPOMI

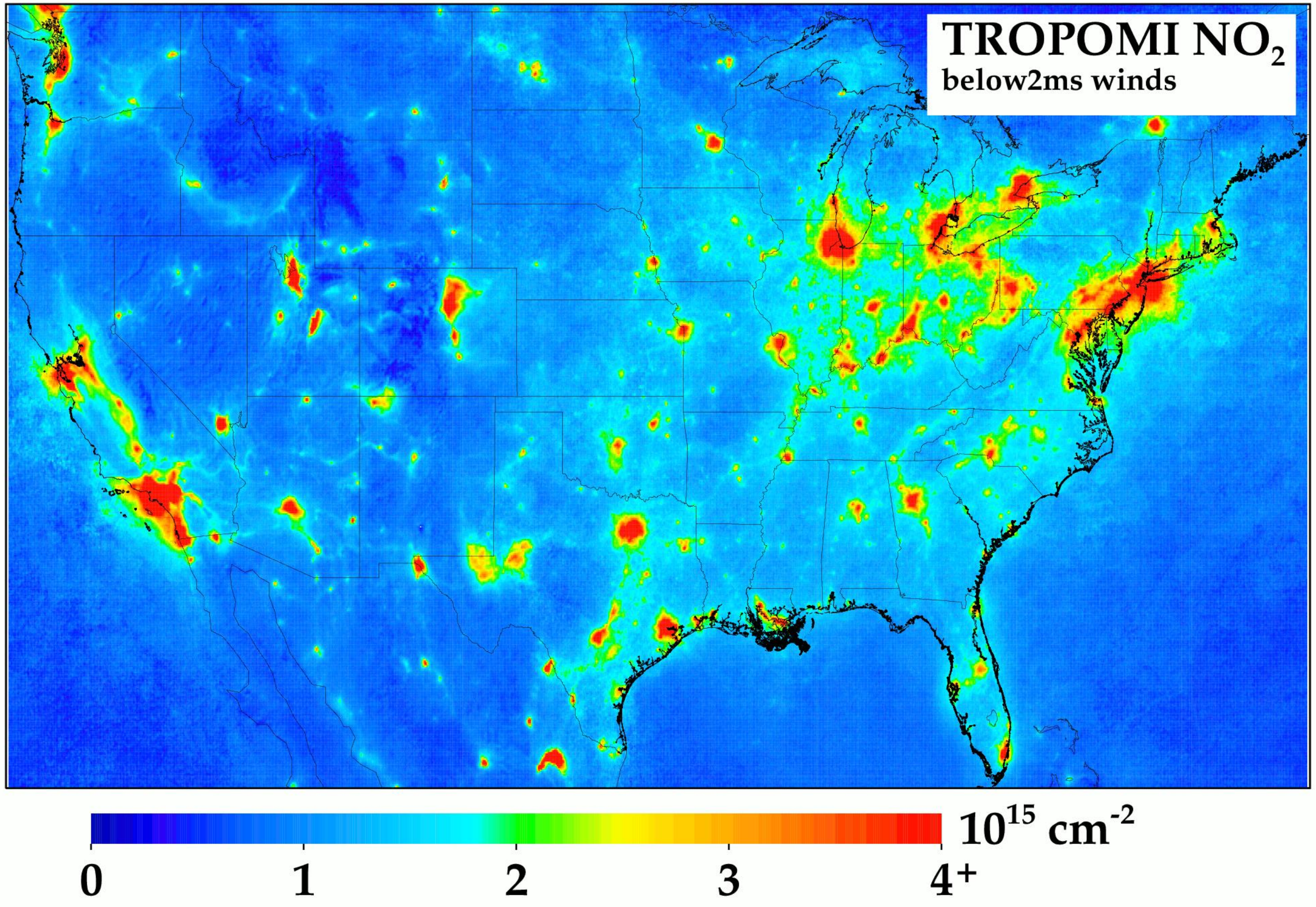


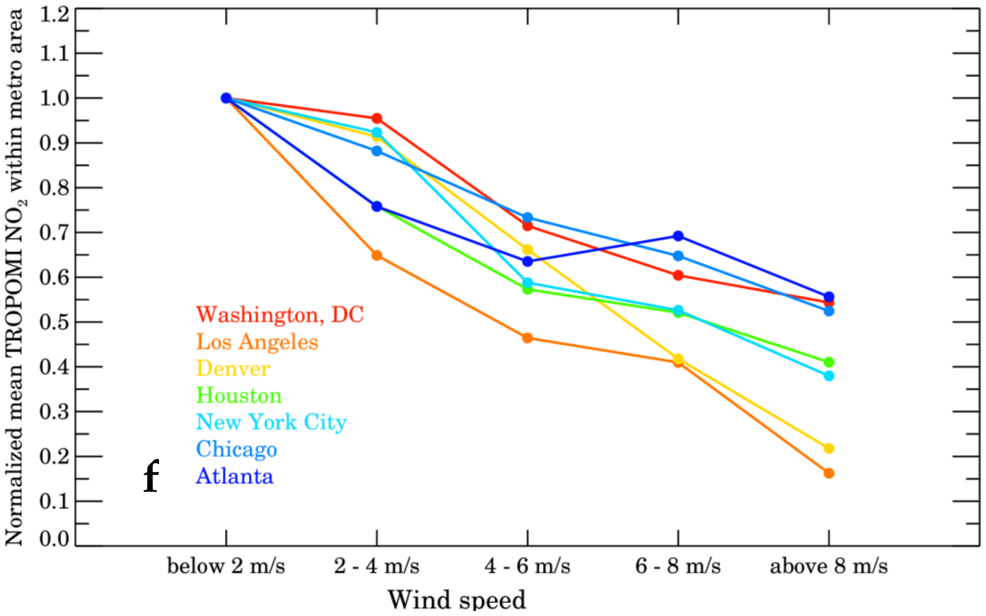
Applications of TROPOMI: NO_2 vs. temperature



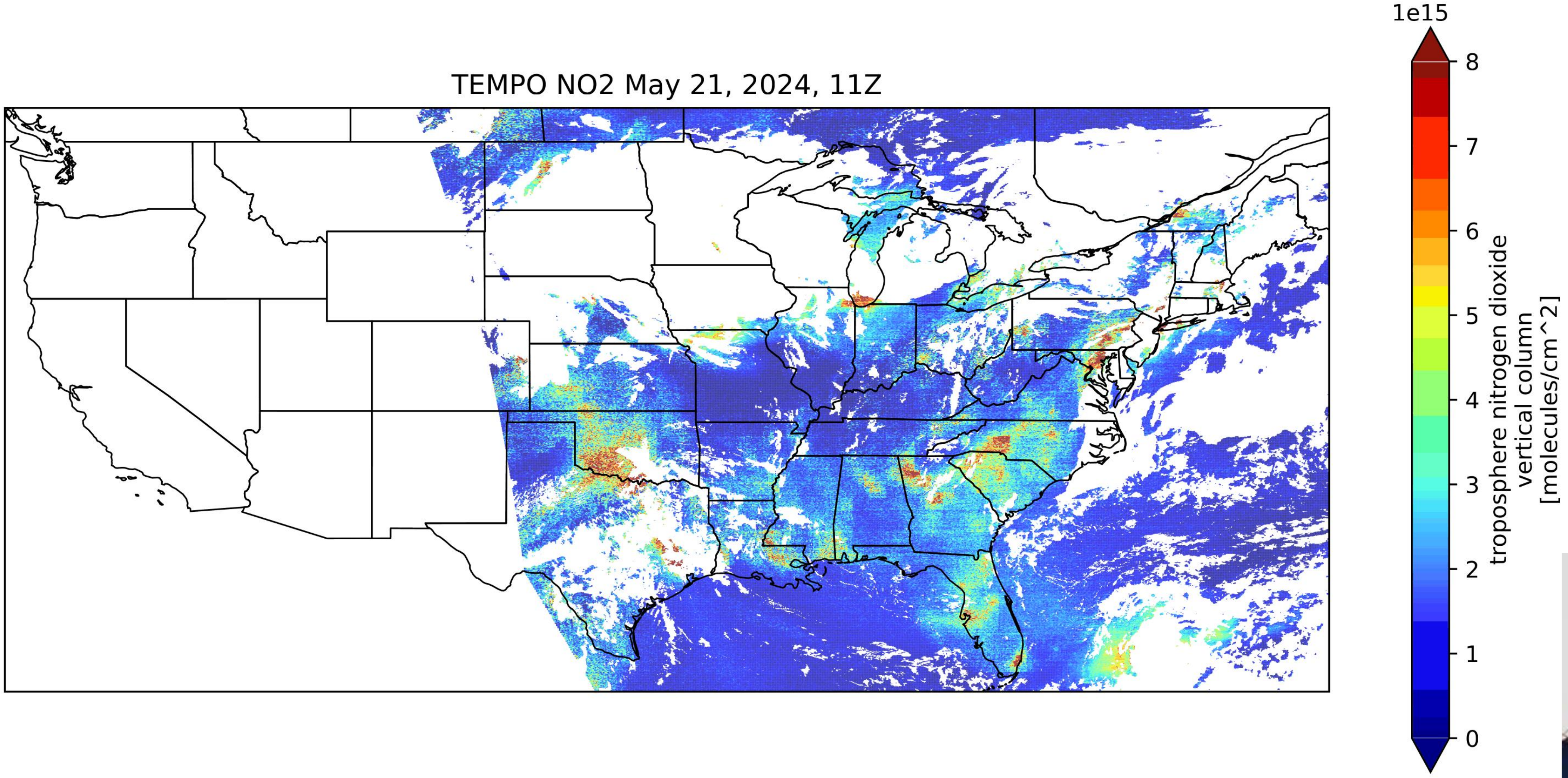


Applications of TROPOMI: : NO_2 vs. wind

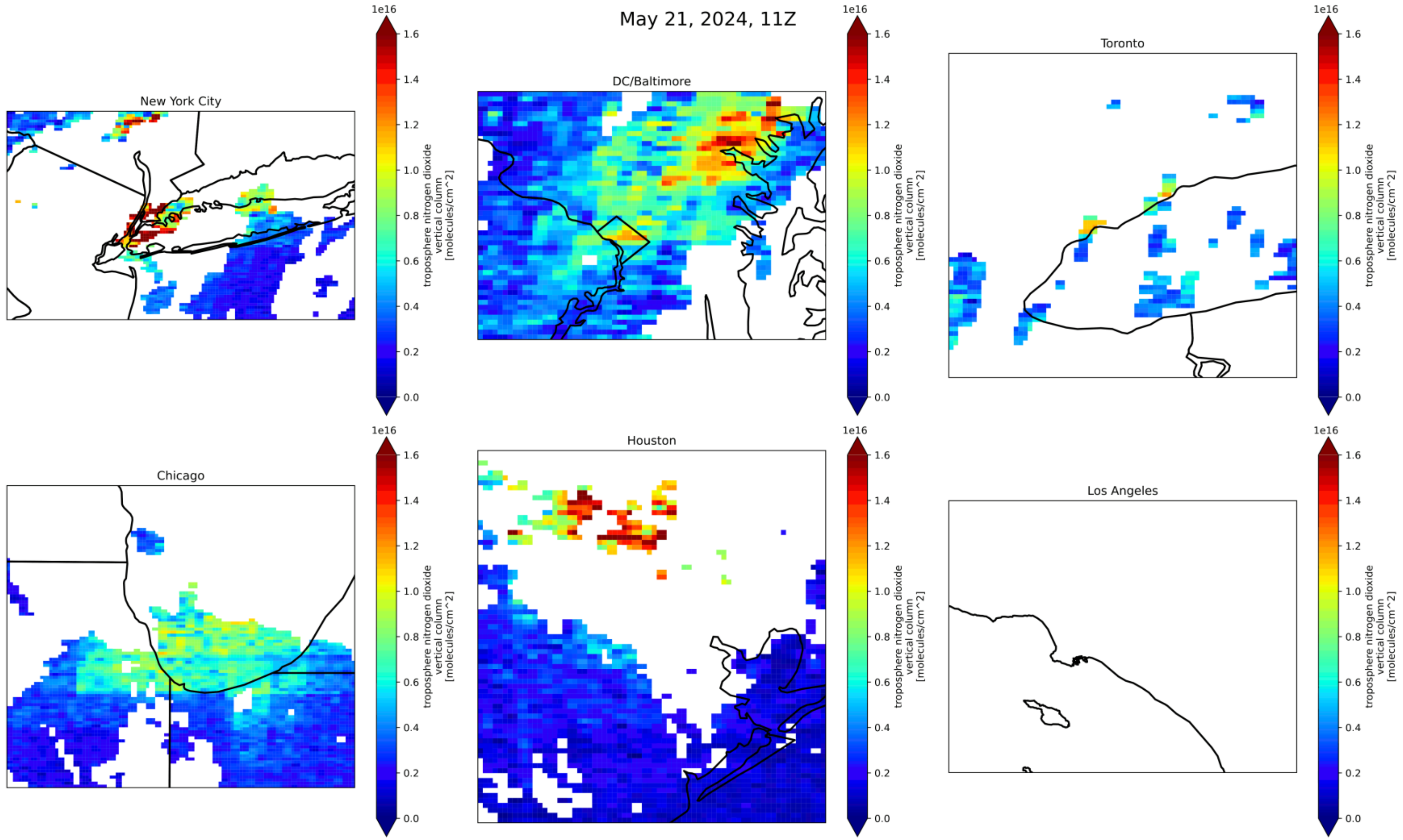




TEMPO NO_2: May 21, 2024



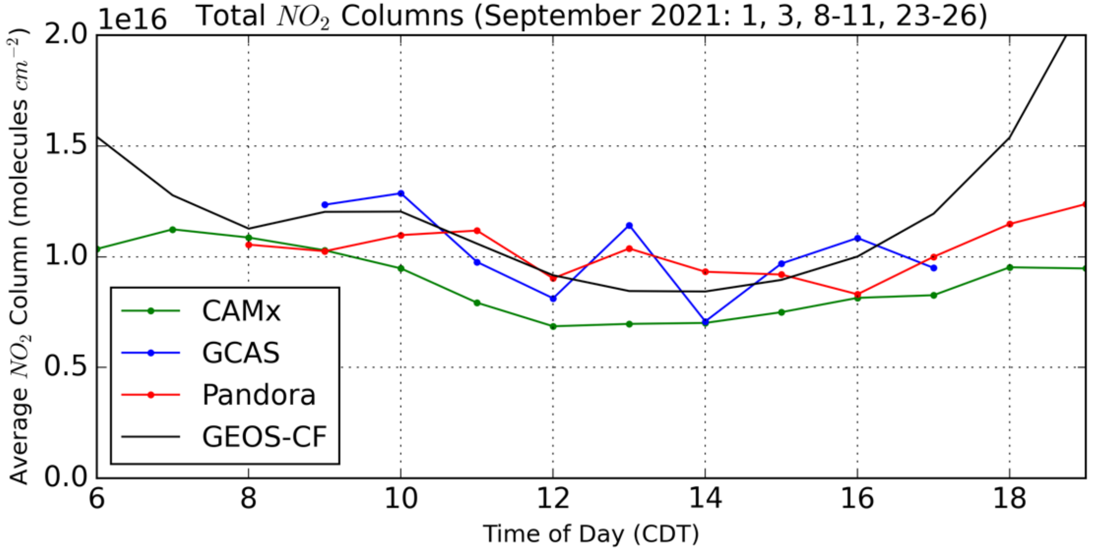
TEMPO NO_2: May 21, 2024

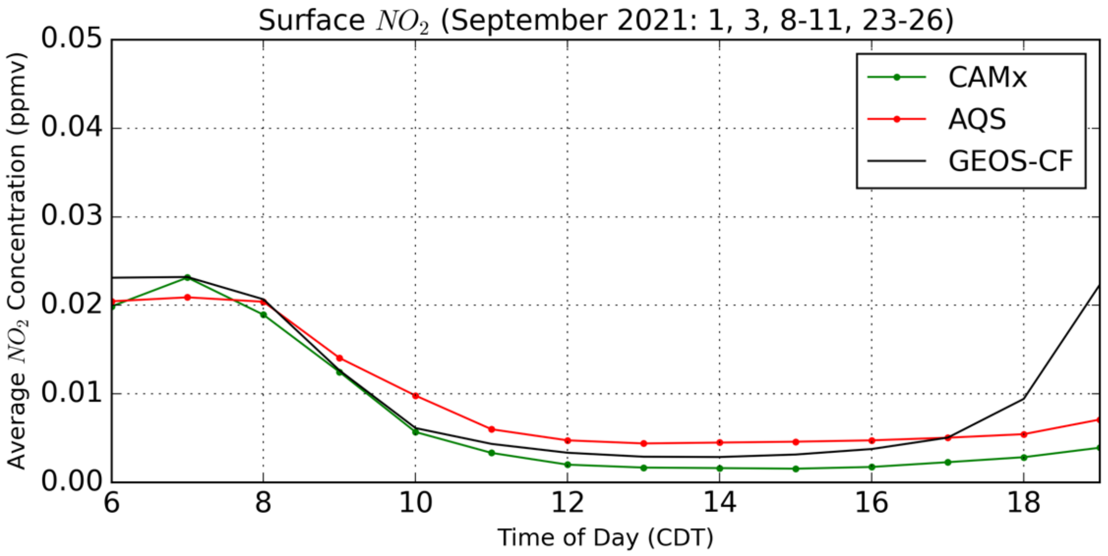


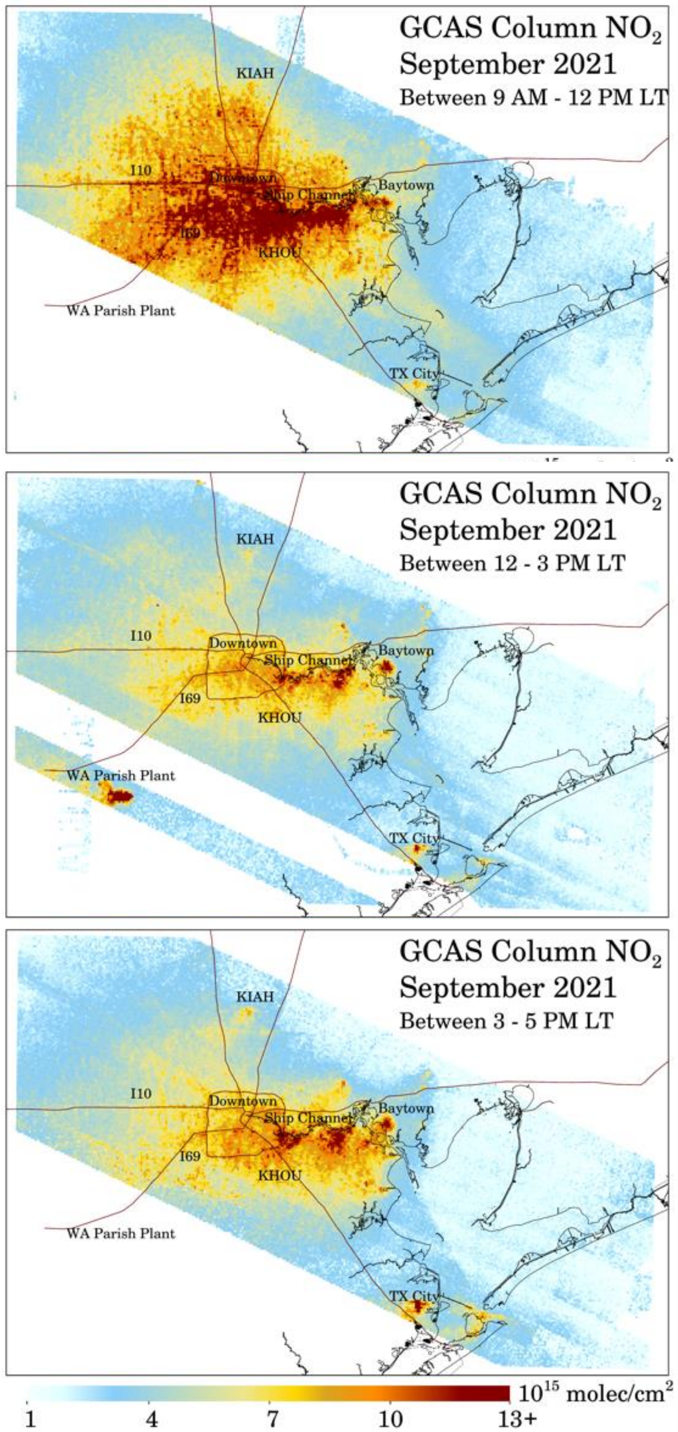
TRACER-AQ informing TEMPO NO_2...
(Nawaz et al., ACP, accepted)

Column NO_2 peaks ~10 AM with small declines in afternoon

Diurnal cycle different at the surface. Peaks ~7 AM and drops dramatically in afternoon







Late AM

Early PM

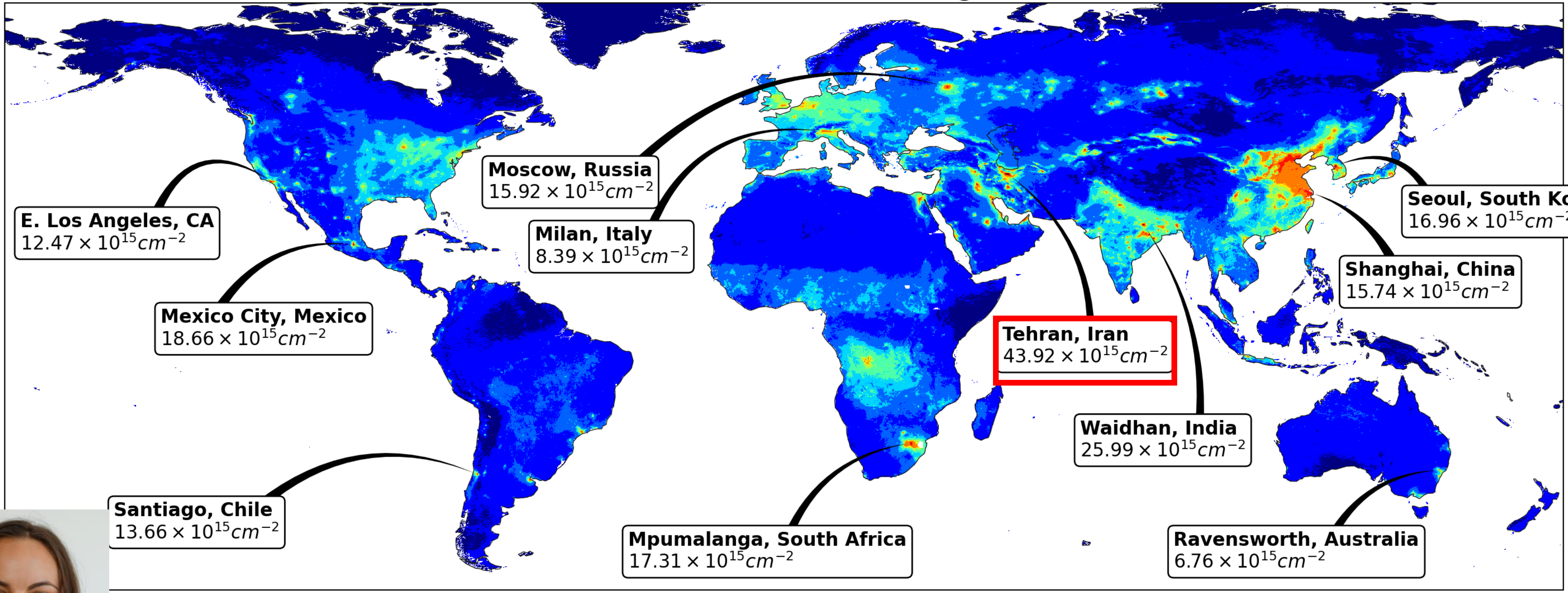
Late PM

Recent trends in NO_2 pollution (2023)

Where is the worst* NO_2 pollution the world?

*In 2023, as seen by satellite, averaged annually to a 10 km grid box

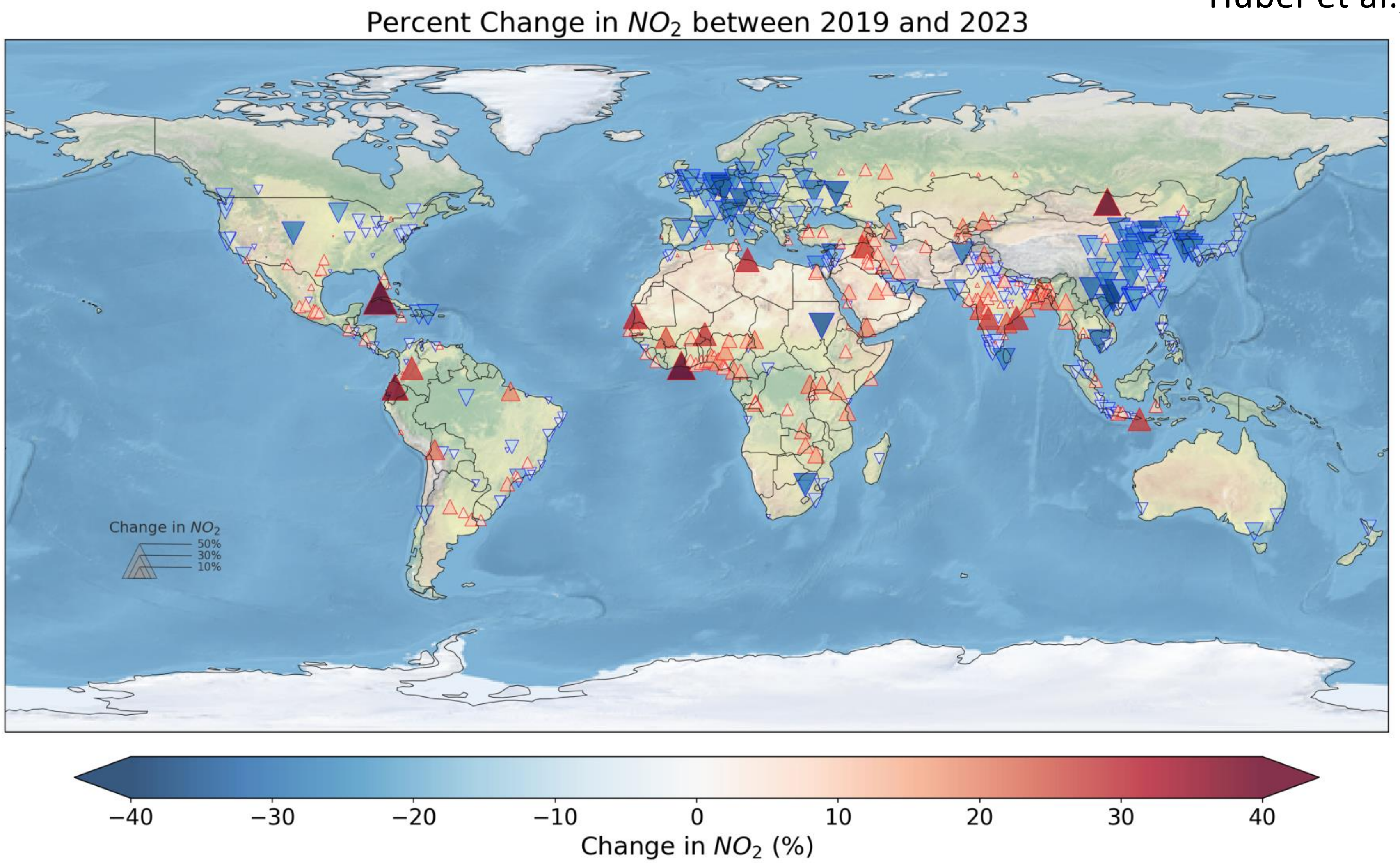
Huber et al., in prep.



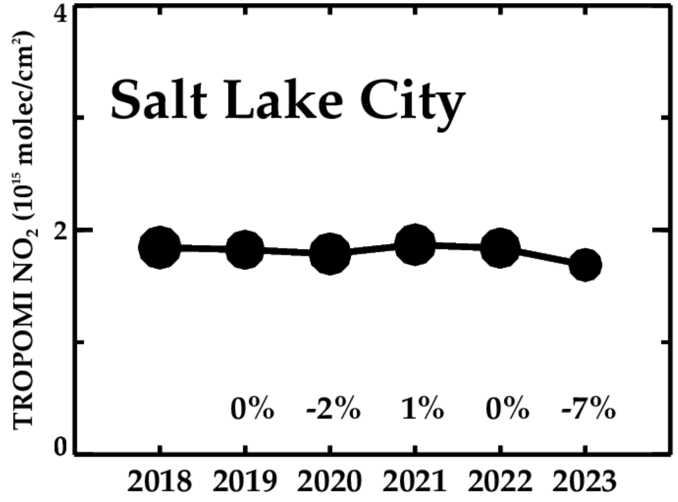
Recent trends in NO_2 pollution (2019 vs. 2023)

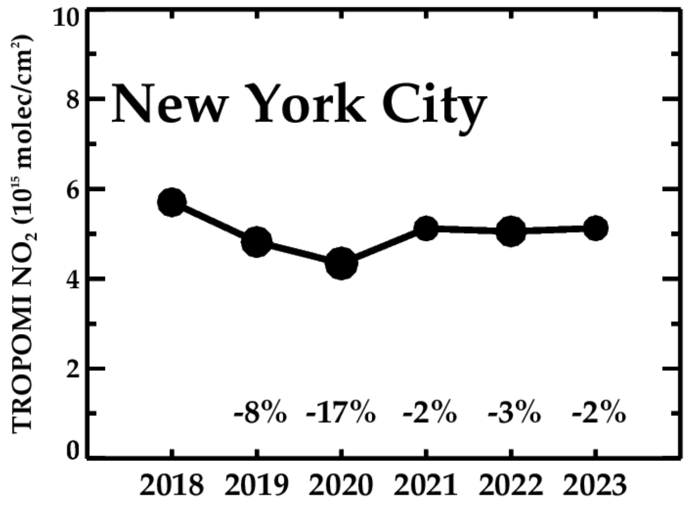
Large NO_2 reduction in China, NO_2 reductions in Europe, NO_2 increases in tropics, mixed but mostly down in the U.S.

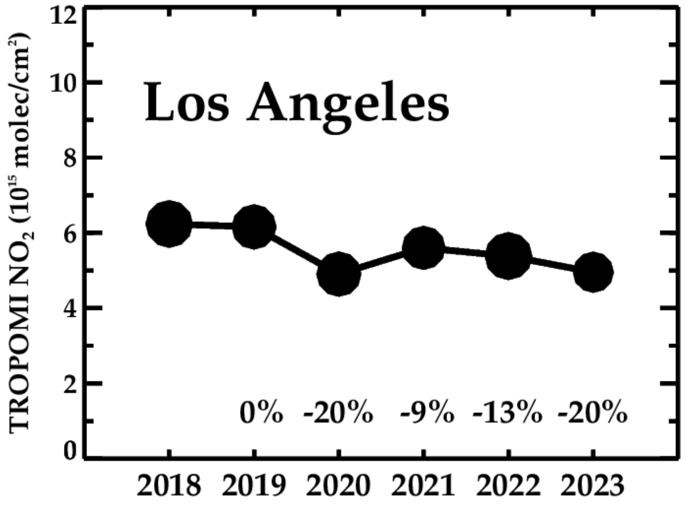
Huber et al., in prep.

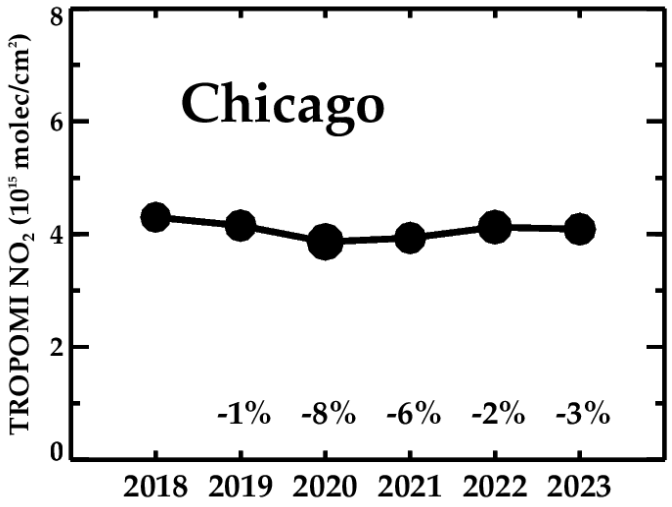


Recent summer trends in NO_2 pollution







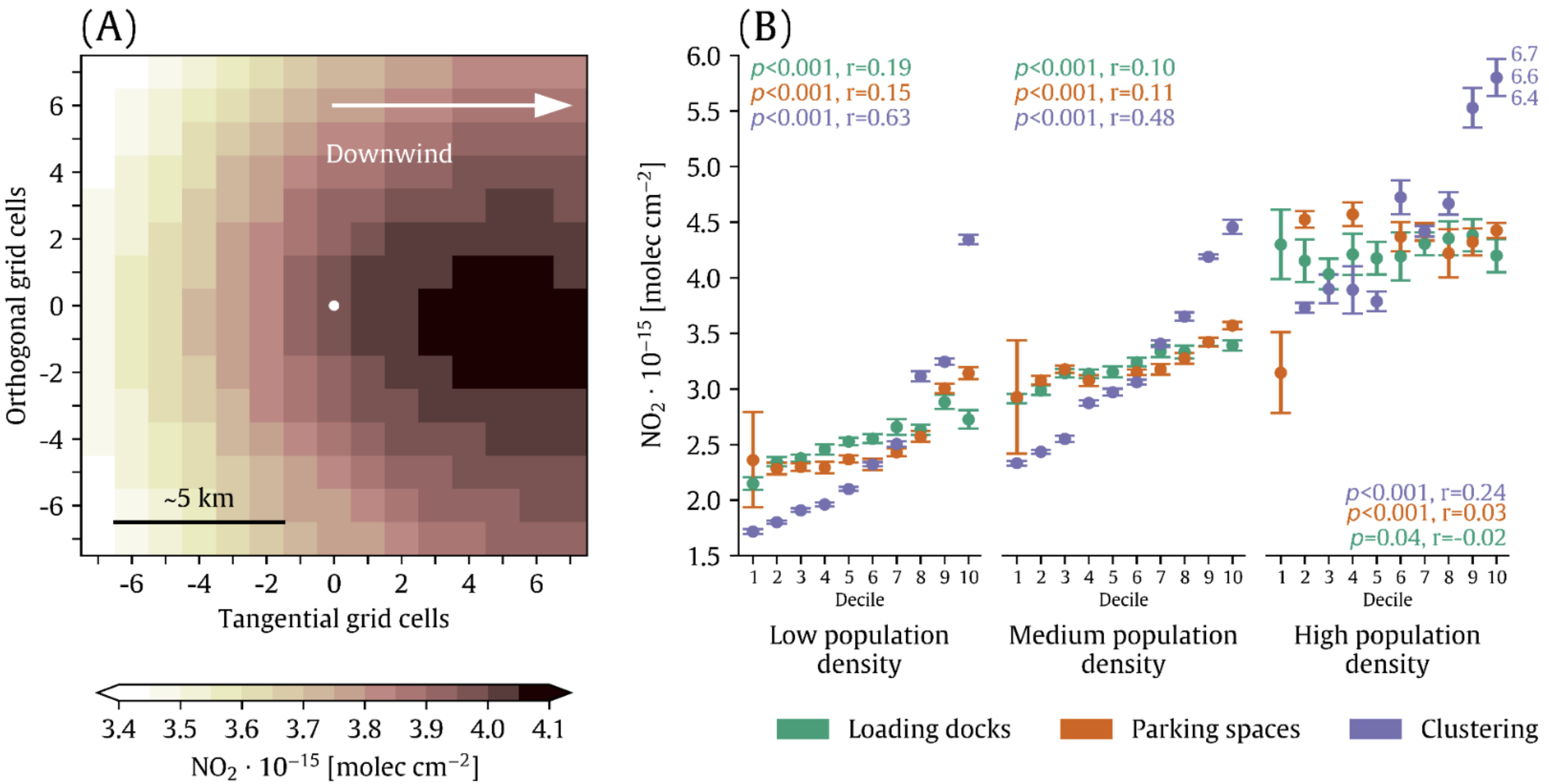


- Most U.S. cities saw a NO_2 recovery after 2020, but not a super-recovery
- Largest NO_2 decrease by percentage and by absolute magnitude has been in Los Angeles
- Too early to tell if urban NO_2 changes are in line with the U.S. EPA National Emissions Inventory (NEI)

2023 NEI Data and Documentation

The 2023 NEI inventory year is in progress and will not be published until March of 2026.

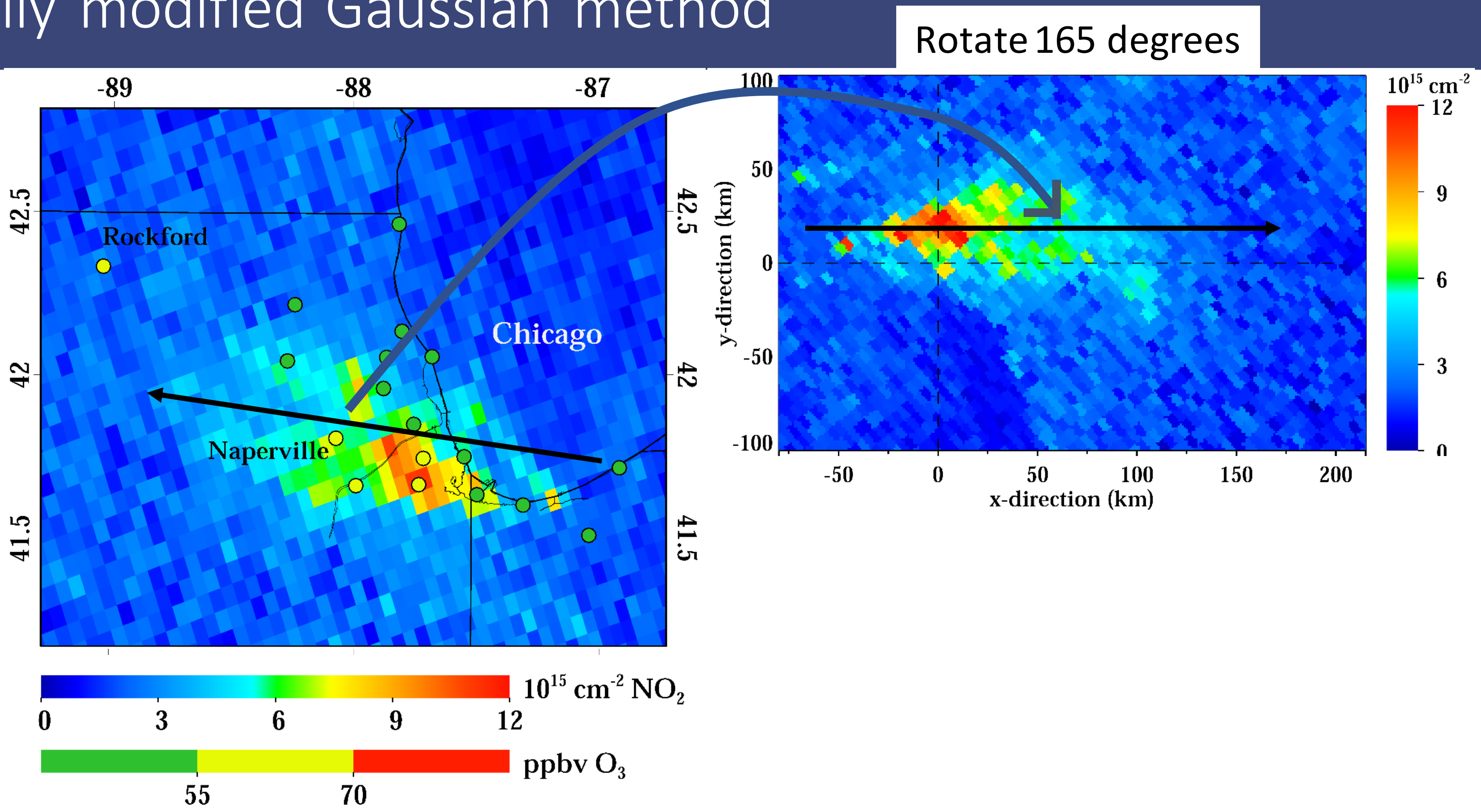
Warehouse NO_2 pollution can be seen from space!



- Column NO_2 enhanced by 20% downwind of warehouses
- On-the-ground NO_2 enhancements probably larger

How does inverse modeling work?

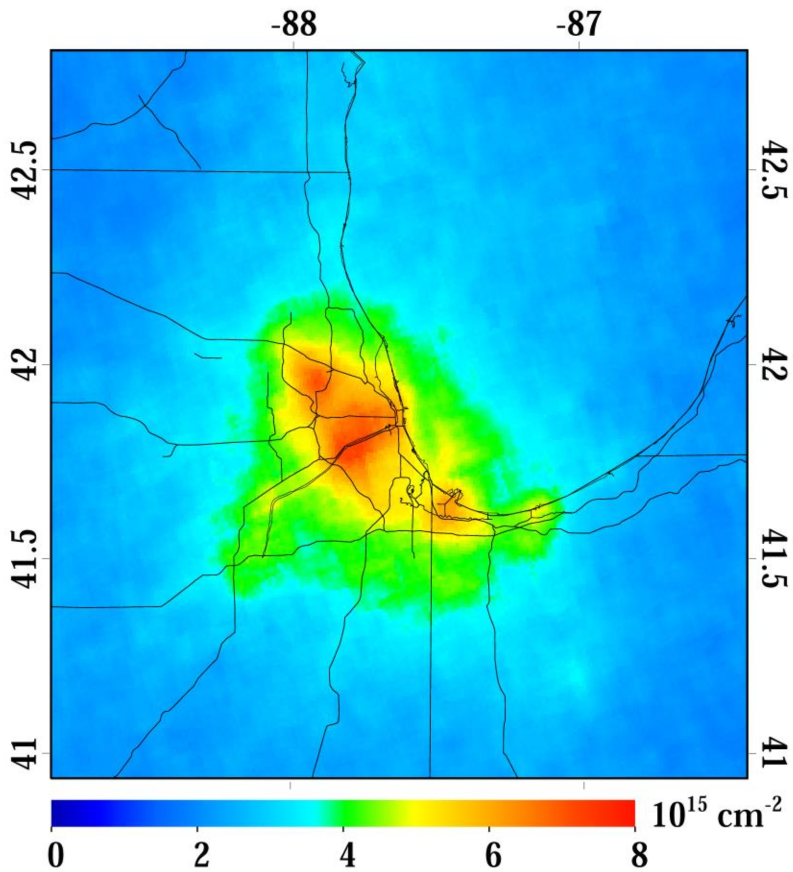
Exponentially modified Gaussian method

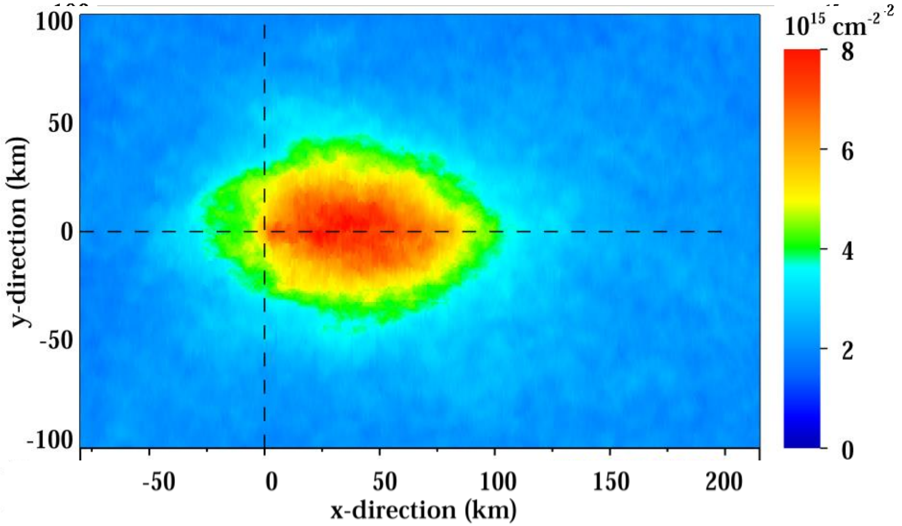


Goldberg et al., 2019a

How does inverse modeling work?

Exponentially modified Gaussian method





<u>Calculate NO_2 Burden and Lifetime based on an exponentially modified Gaussian fit:</u>

$$E = 1.32 \cdot \alpha / \tau_{\text{effective}} = 1.32 \cdot \alpha \cdot w / x_0$$

NO_x emissions

NO_x/NO_2 ratio

Burden (Mg)

Wind speed (km/hr)

Decay distance (km)

Goldberg et al., 2019a

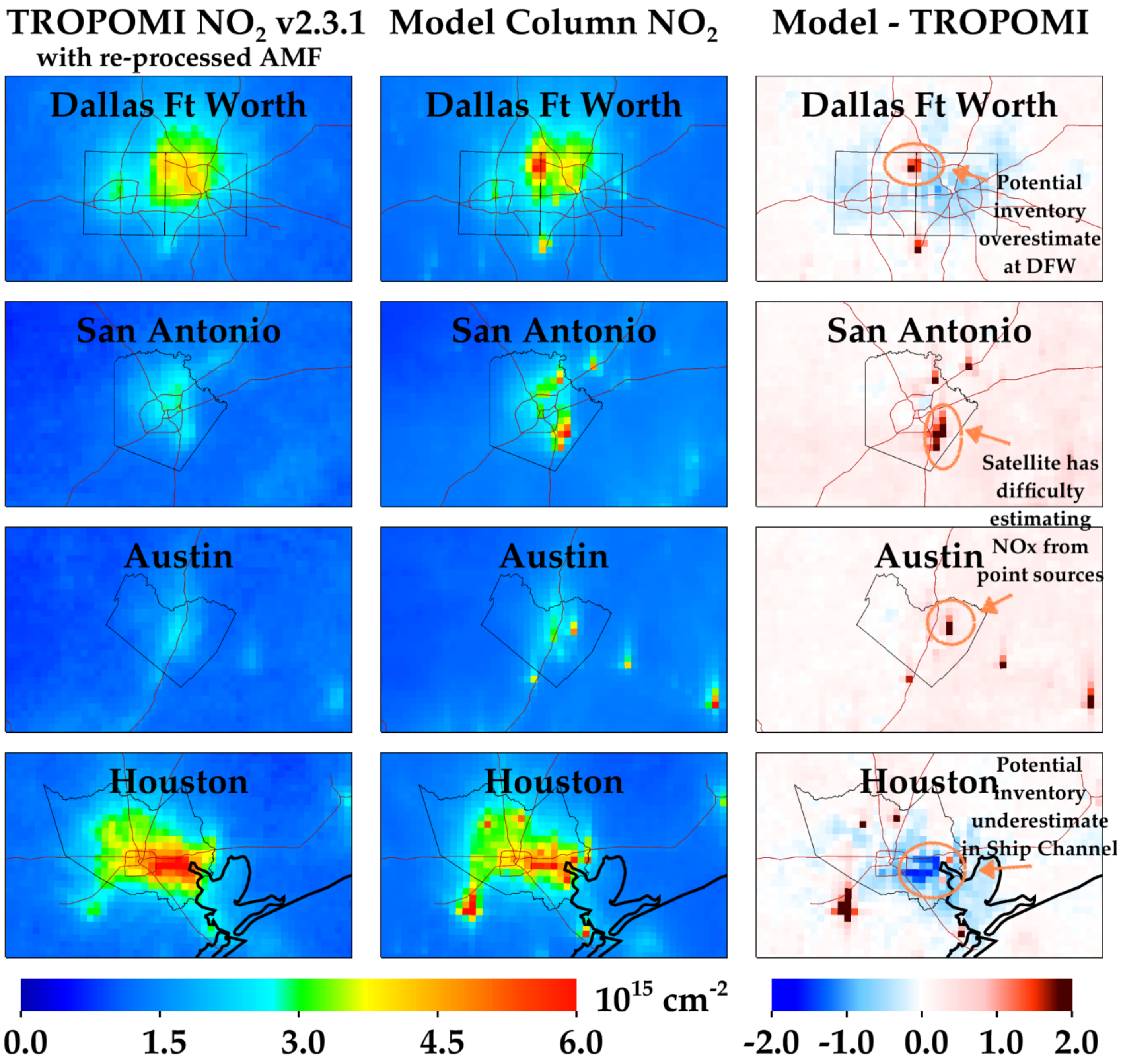
New paper published in *Atmospheric Chemistry and Physics*

Goldberg et al., 2022

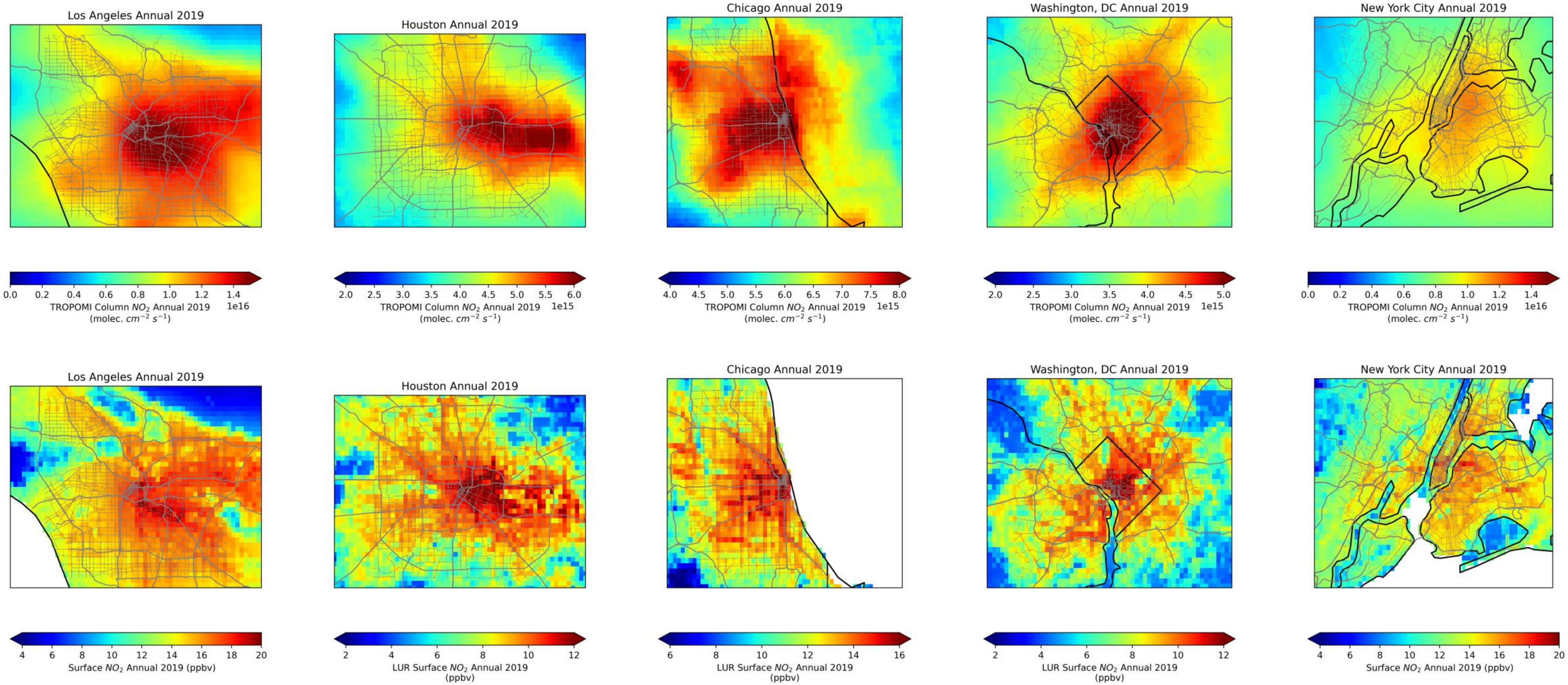
Also see Twitter thread for summary

- Satellite and inventory NOx emissions generally agree within 20% in Texas

- Worse agreement near point sources



TROPOMI NO_2 vs. TROPOMI-based NO_2 surface estimates

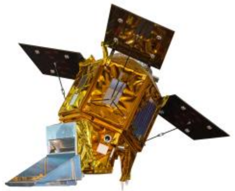


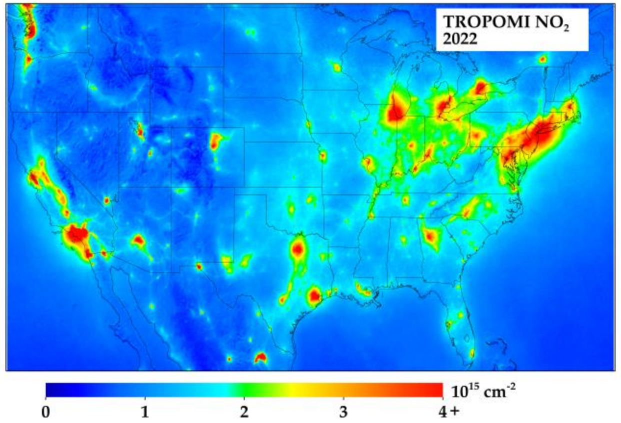
Tools to Investigate NO_2 continue to improve

Satellite data

e.g., TROPOMI, OMI, TEMPO

- Measuring column NO_2
- 5.5 x 3.5 km^2 can be oversampled to 1 x 1 km^2





Ground monitors

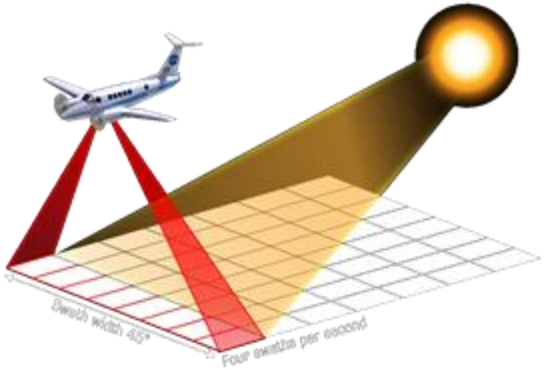
e.g., Pandora & AQS

- Stationary, but high temporal resolution
- Pandora measures column NO_2 and vertical distribution (sometimes)
- More instruments coming on-line

Aircraft data

e.g., GCAS

- Very high spatial and temporal resolution
- Limited timeframes and domains

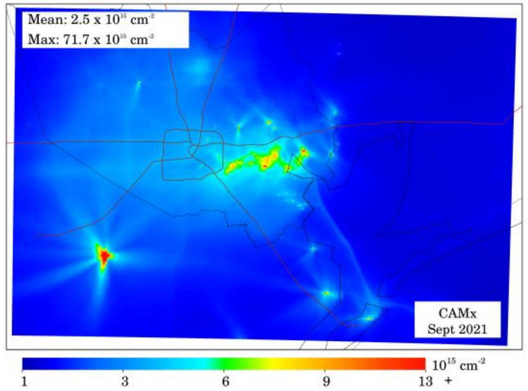


Chemical transport models

e.g., CAMx

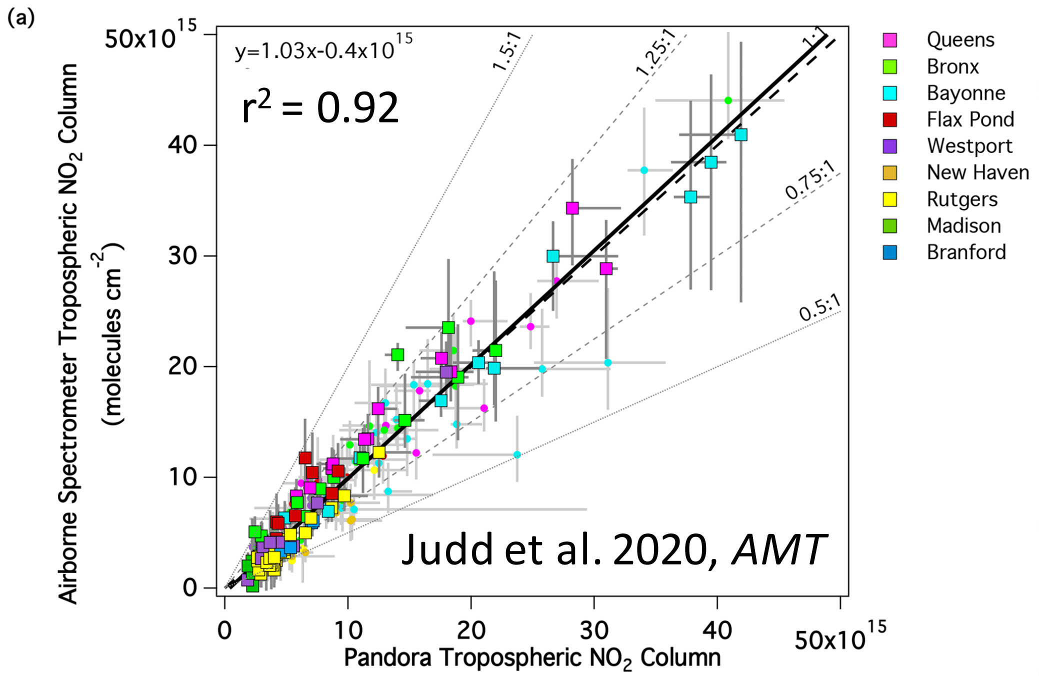
- Ability to run at sub-kilometer resolutions
- Continual model updates for chemistry, emissions, and dispersion
- Limited timeframes and domains

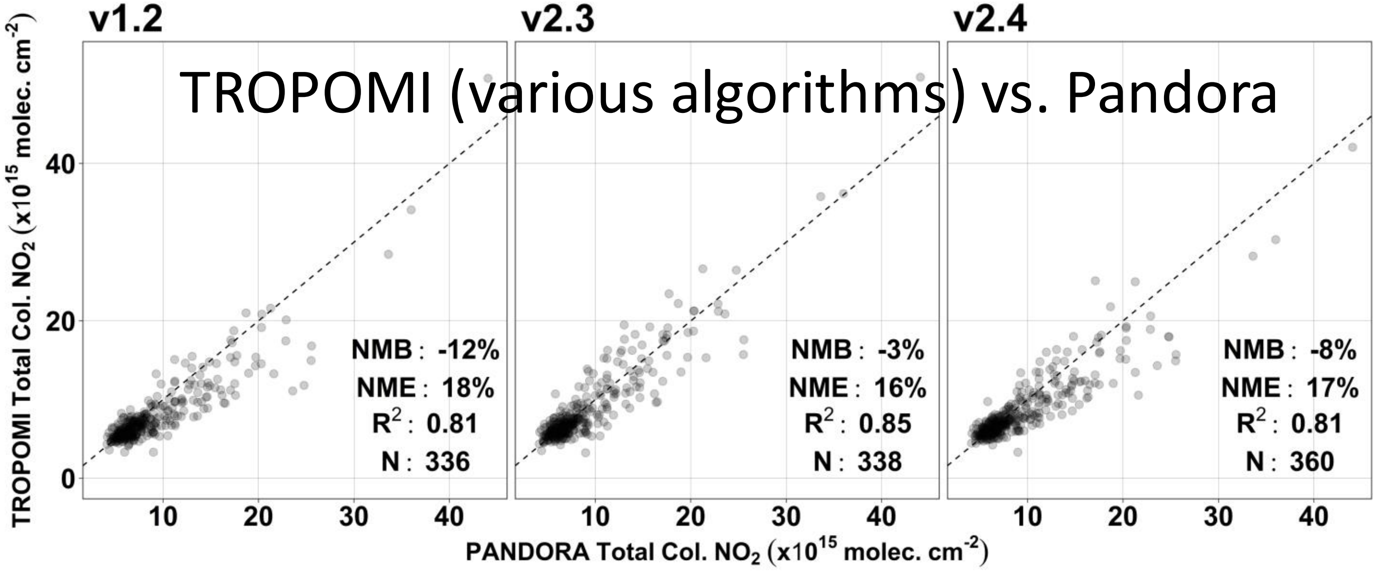
CAMx Ozone Particulates Toxics

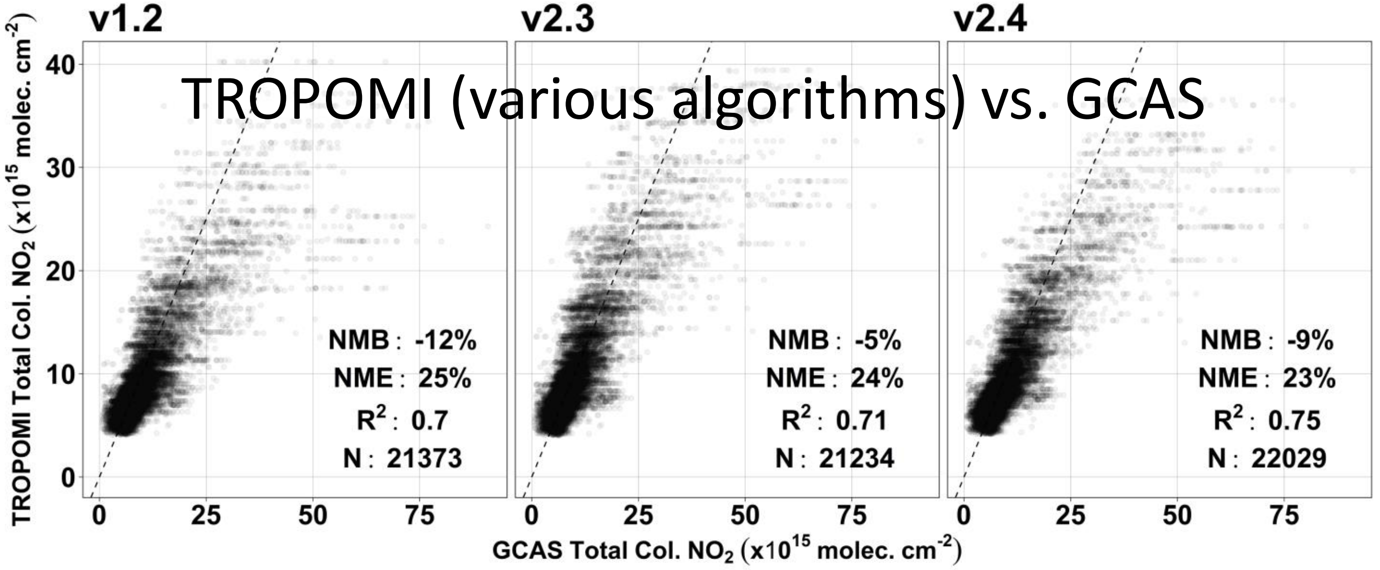


New York City LISTOS Summer 2018: Observations vs. Observations how do they compare?

GCAS vs. Pandora



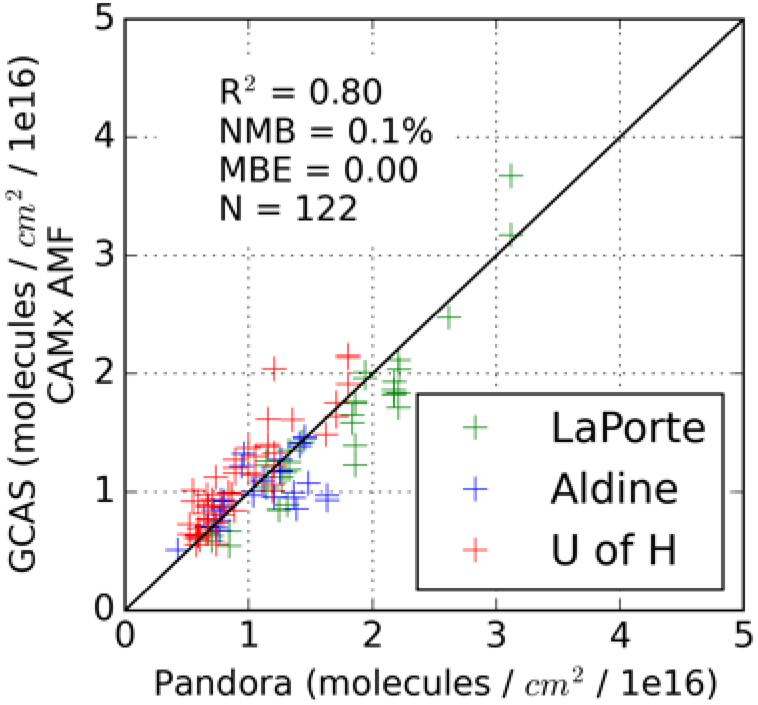




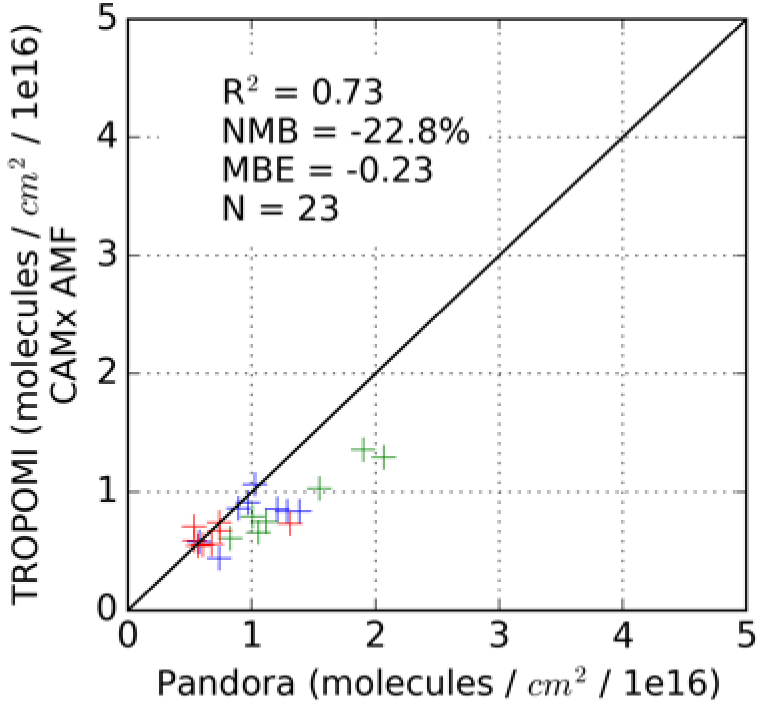
- Excellent agreement for NO_2 between GCAS and Pandora.
- TROPOMI NO_2 has low bias. Version 2.3 algorithm has less of a low bias than other algorithms, V2 has better correlation than V1.

Houston TRACER-AQ September 2021: Observations vs. Observations how do they compare?

GCAS vs. Pandora



TROPOMI v2.4 vs. Pandora

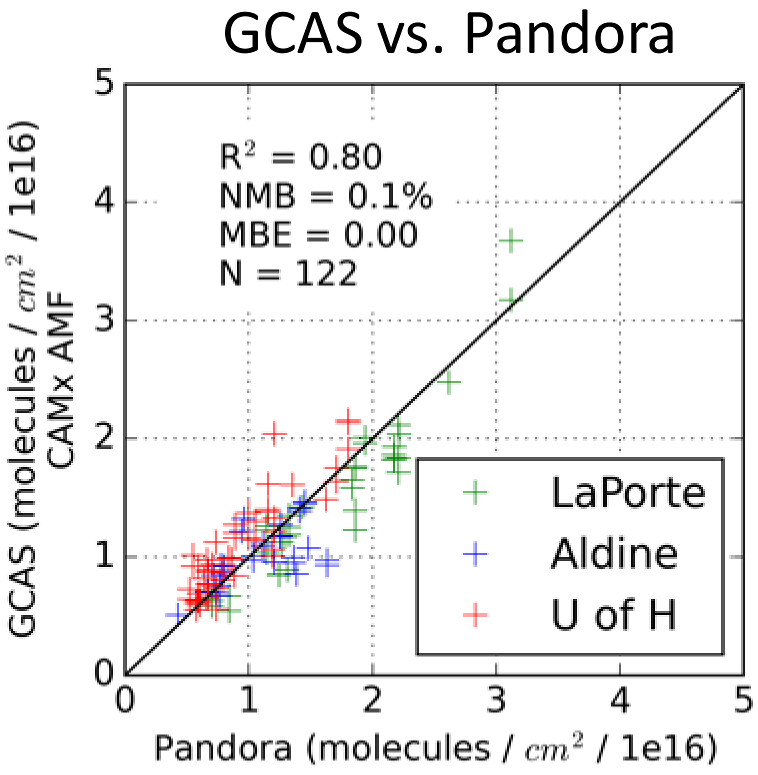


r^2 = 0.80 and no consistent bias

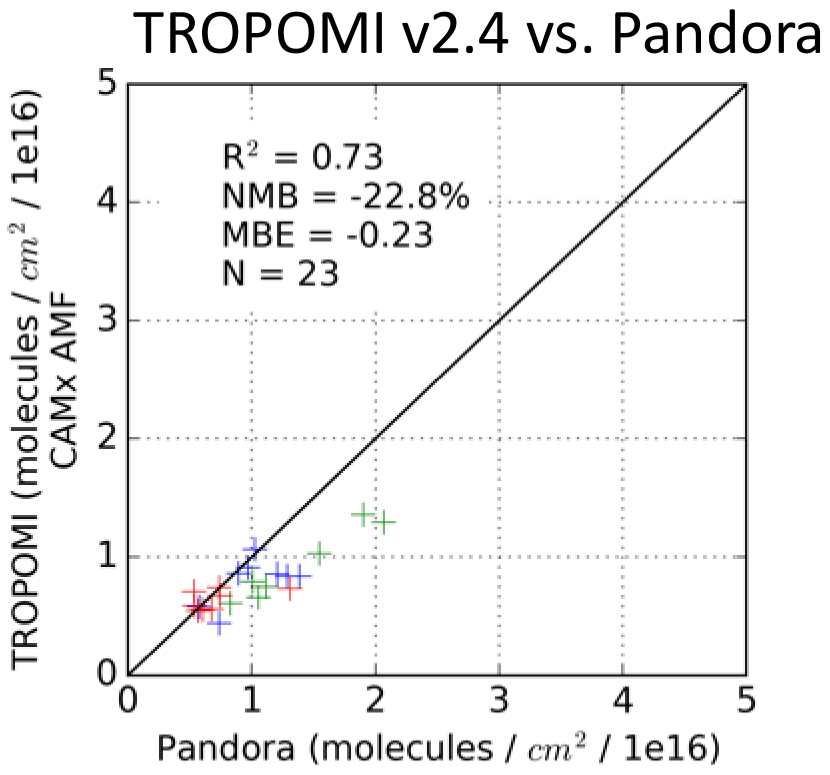
r^2 = 0.73 and a low bias

Nawaz et al., *ACP,* accepted

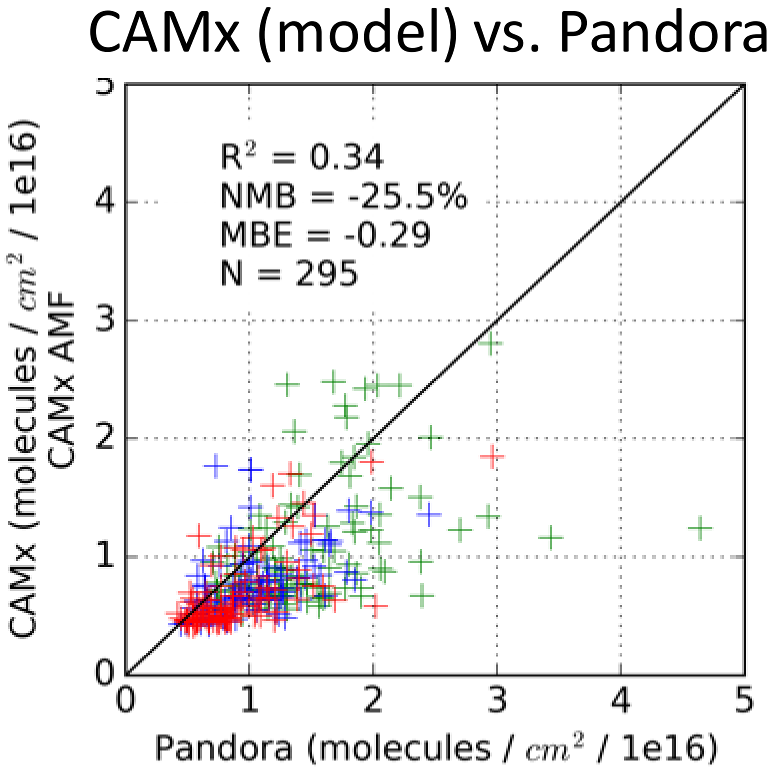
Houston TRACER-AQ September 2021: Observations vs. Model how do they compare?



r^2 = 0.80 and no consistent bias



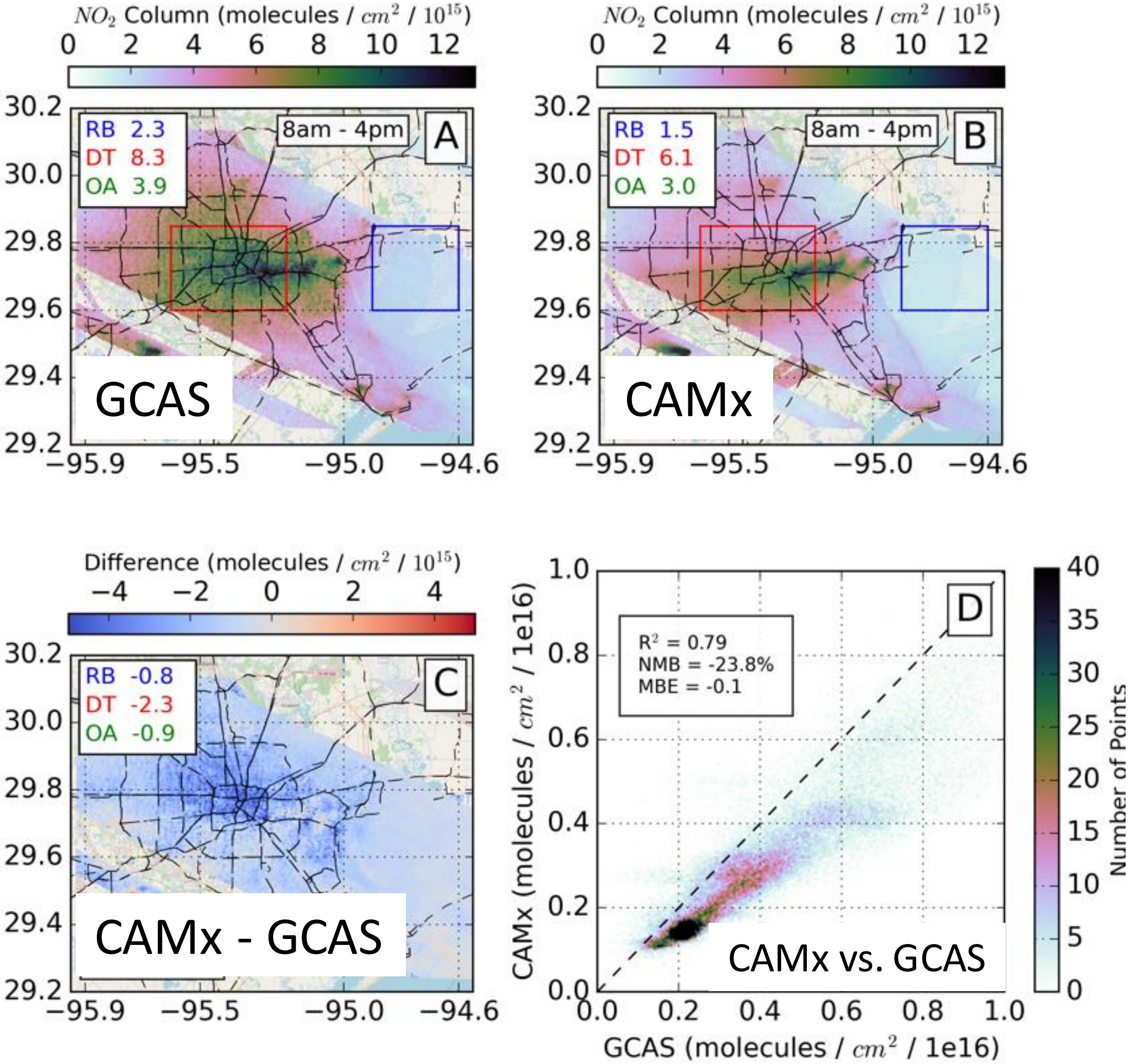
r^2 = 0.73 and a low bias



r^2 = 0.34 and a low bias

Nawaz et al., *ACP,* accepted

Houston TRACER-AQ September 2021: CAMx has low column NO_2 bias over most of Houston



GCAS NO_2 vs. CAMx NO_2:

Correlation between CAMx and GCAS was very strong ($r^2 = 0.79$) in contrast to CAMx correlation with Pandora ($r^2 = 0.34$)

Low model bias over most areas of the domain

Largest difference (by magnitude) between CAMx and GCAS is in the downtown section of Houston

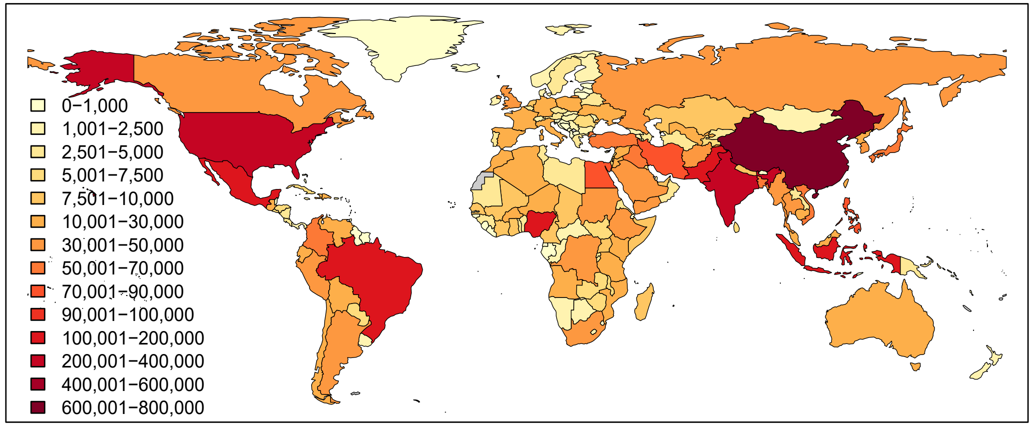
Nawaz et al., *ACP,* accepted

Why is NO_2 *by itself* an important air pollutant?

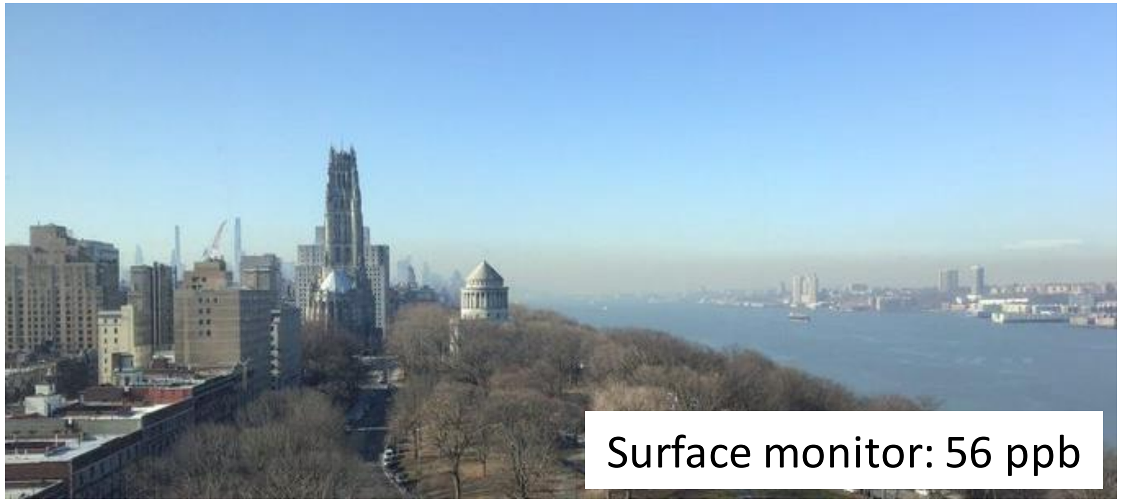
- Impairs cardiovascular function leading to potential cardiovascular diseases and premature mortality
- Causes and exacerbates asthma
- Co-emitted with other harmful pollutants (diesel PM, VOC air toxics, heavy metals, etc.)
- Inequitably distributed across the urban landscape; racialized, marginalized, and minoritized communities experience higher levels of this pollutant
- Impairs natural visibility

In 2019, 1.8 million (95% CI 0.9 - 2.8) children developed asthma due to NO_2 pollution, responsible for 16% of all asthma

(a) Number of new asthma cases due to NO_2 exposure



Achakulwisut et al., 2019; Anenberg, Goldberg et al., 2022



Picture courtesy: Roisin Commane, Ph.D.
Acquired March 22, 2021 in New York City, NY

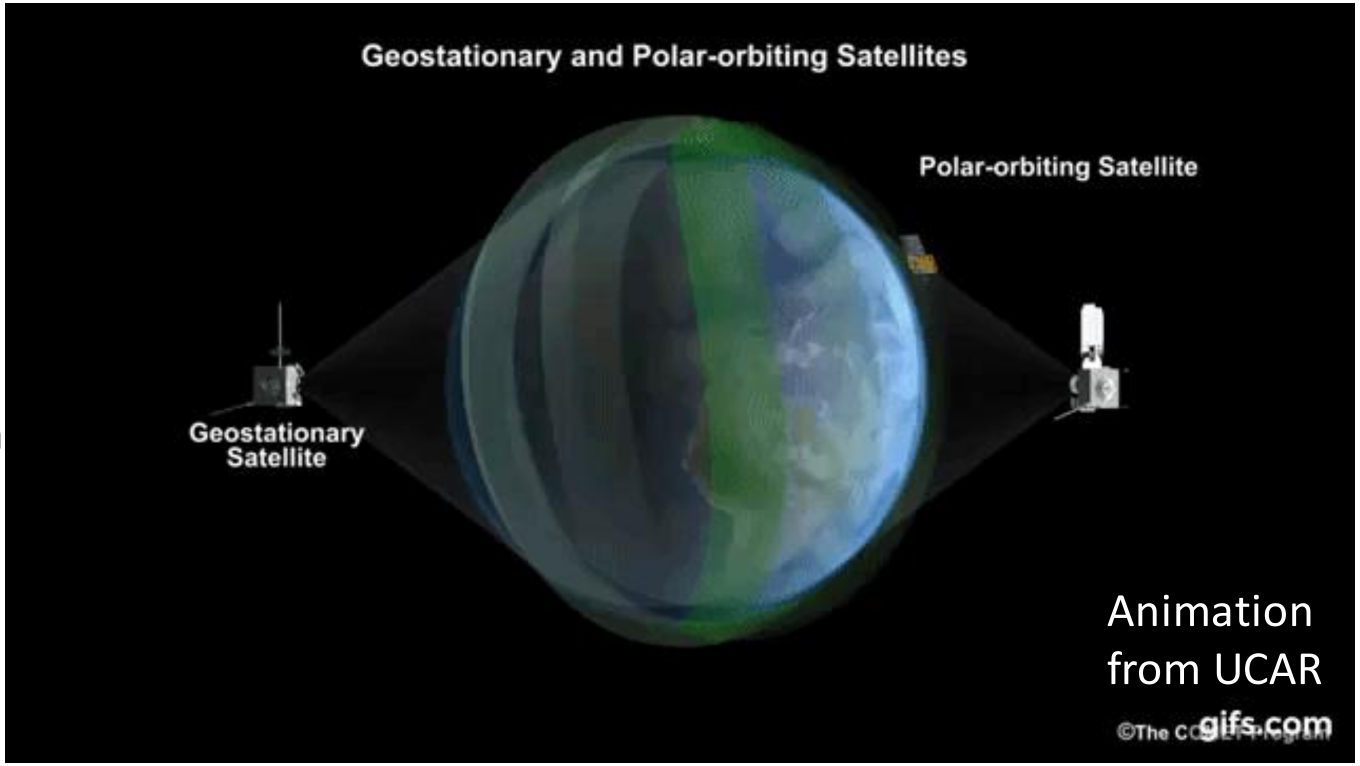
Four(!) satellite instruments measuring column NO_2

OMI - Ozone Monitoring Instrument
- Data record: Oct 2004 – present
- Spatial resolution: 24 x 13 km^2

TROPOMI - Tropospheric Monitoring Instrument
- Data record: May 2018 – present
- Spatial resolution: 5.5 x 3.5 km^2

TEMPO - Tropospheric Emissions: Monitoring of Pollution
- Data record: May 2018 – present
- Spatial resolution: 5.5 x 3.5 km^2

GEMS - Geostationary Environmental Monitoring Spectrometer
- Data record: Feb 2020 – present
- Spatial resolution: 4.5 x 2 km^2



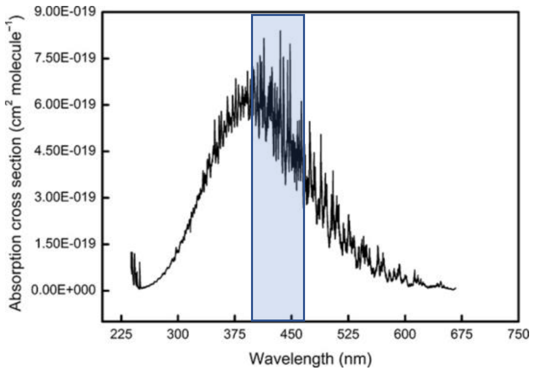
Animation from UCAR

TROPOMI and OMI are these → Polar-orbiting, or low-earth-orbiting, satellites have global coverage *but* only one snapshot (sometimes fewer) per day.

TEMPO and GEMS are these → Geostationary satellites have partial global coverage, but many snapshots (100x, 1000x) per day.

How is satellite-based NO_2 "measured"?

NO_2 Cross-Section from Vandaele et al., 1998



passive spectrometer

For more info: [Levelt et al., 2006]

1. Radiances measured in the 400-450 nm visible wavelength region (indigo) are used to create a *total slant column* between detector (700 km) and ground

2. Separate stratospheric component from tropospheric component using model or "clean" tropical measurement

3. Use information from a radiative transfer model AND chemical transport model to calculate an "air mass factor" to convert slant tropospheric column to vertical column

Steps 2 & 3 can be large sources of uncertainty (especially step 3)

Brandon Shores Power Plant, Maryland
Courtesy: Interstellar Drone