Satellite observations for air quality

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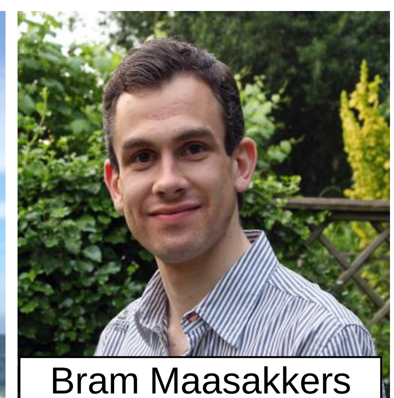
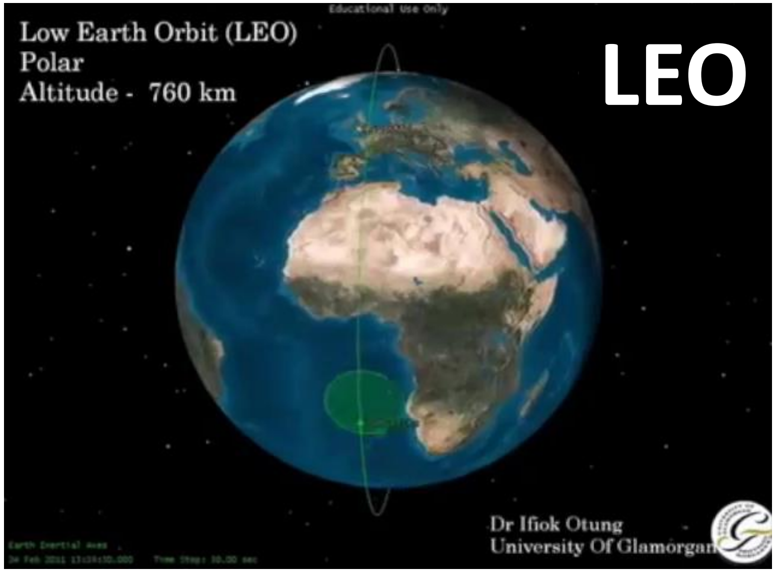
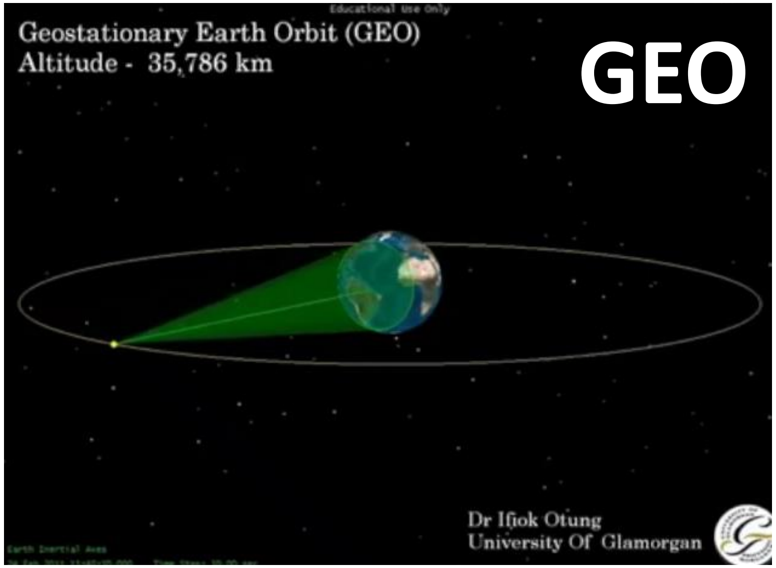


Observation orbits:
LEO (low Earth orbit) and GEO (geostationary)



500-1000 km altitude
Global observation (for polar orbit)
Revisit time: 1 day to weeks

All air quality observations so far are from polar sun-synchronous LEO

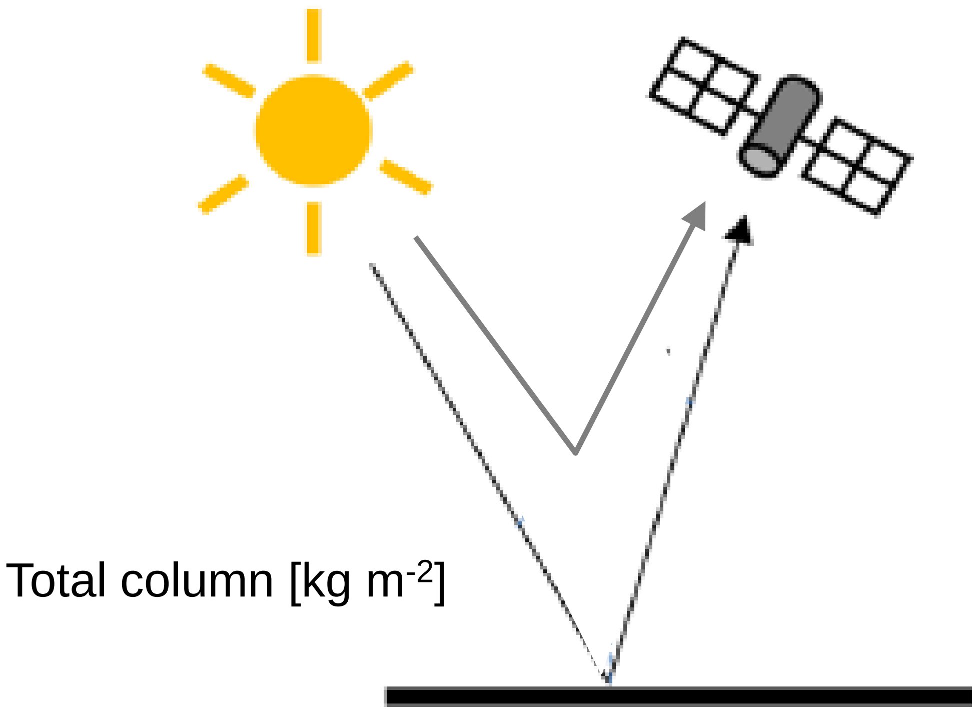


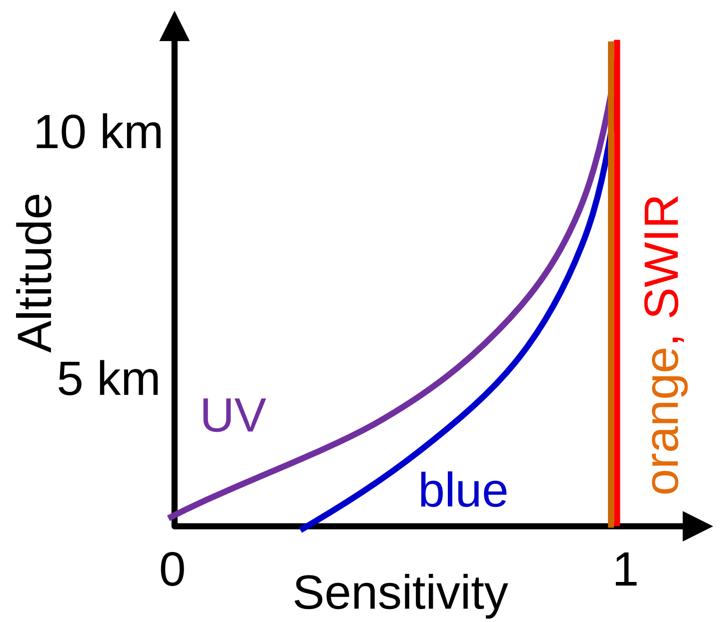
36,000 km altitude
Regional-continental observation
Revisit time: hours

Geostationary constellation to be launched in 2020-2022:
TEMPO over N. America,
GEMS over E. Asia,
Sentinel-4 over Europe

Observing air pollution from space: solar backscatter instruments

UV: SO_2, formaldehyde, ozone, BrO
Blue: NO_2, glyoxal
Visible: Aerosol
Orange: ozone
Shortwave IR (SWIR): CO, methane, CO_2

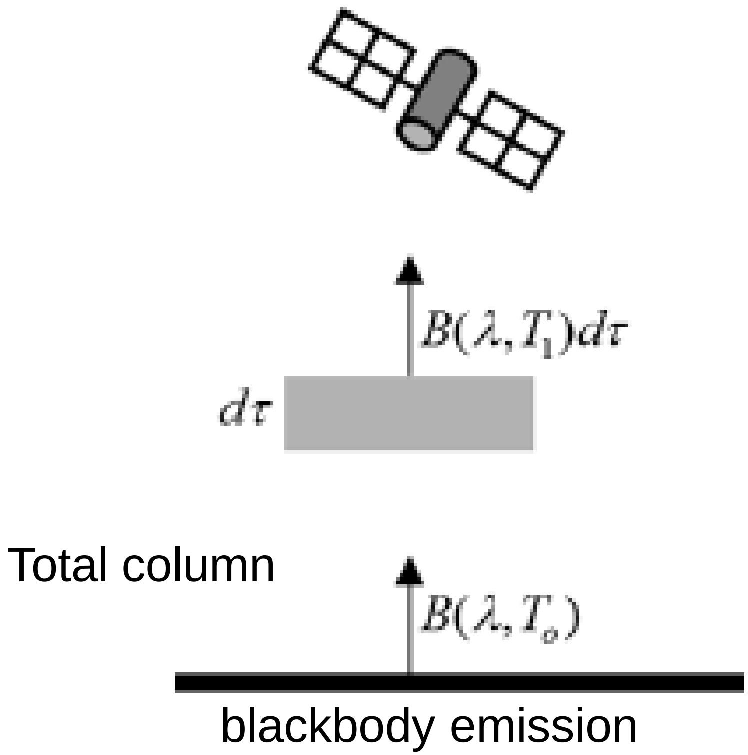


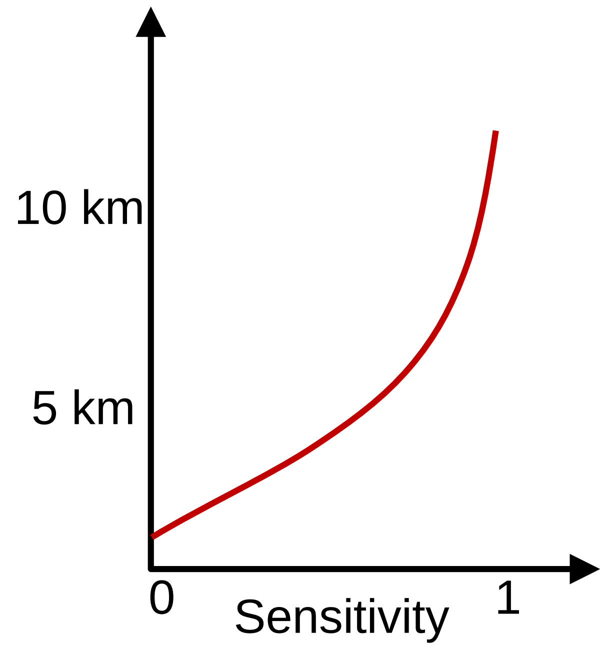


Gases: OMI, GOME-2, OMPS, MOPITT, GOSAT, OCO-2, TROPOMI, TEMPO
Aerosol: MODIS, MISR, VIIRS

Observing air pollution from space: thermal emission instruments

Thermal IR (TIR): CO, ozone, ammonia, methane

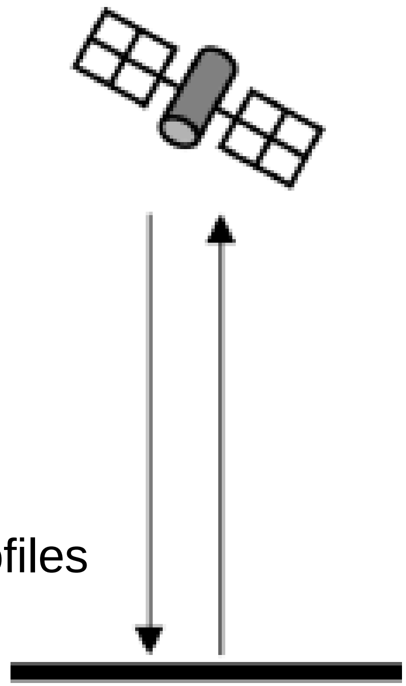




MOPITT, TES, AIRS, IASI, CrIS

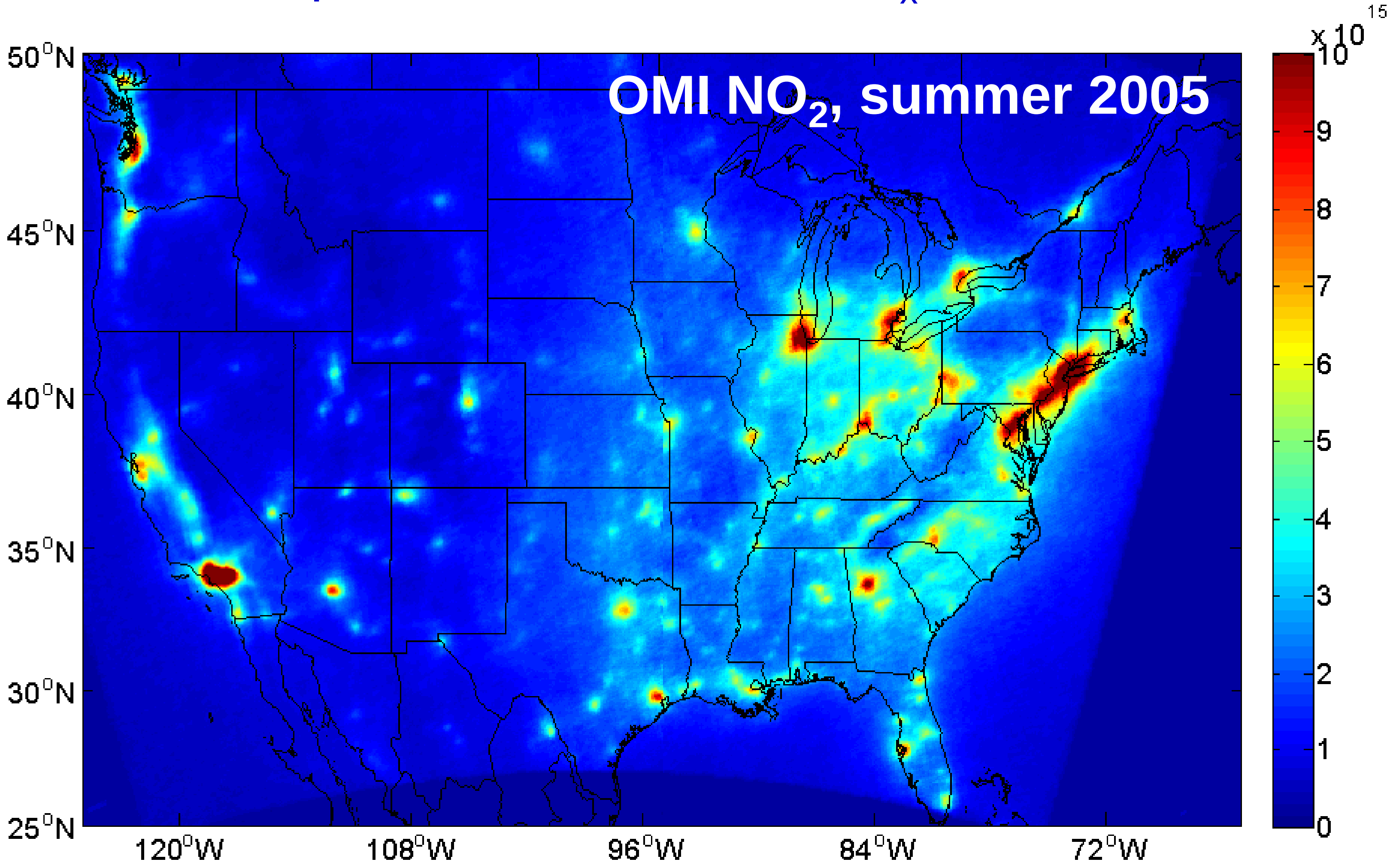
Observing air pollution from space: lidar instruments

Visible: Aerosol
SWIR: methane



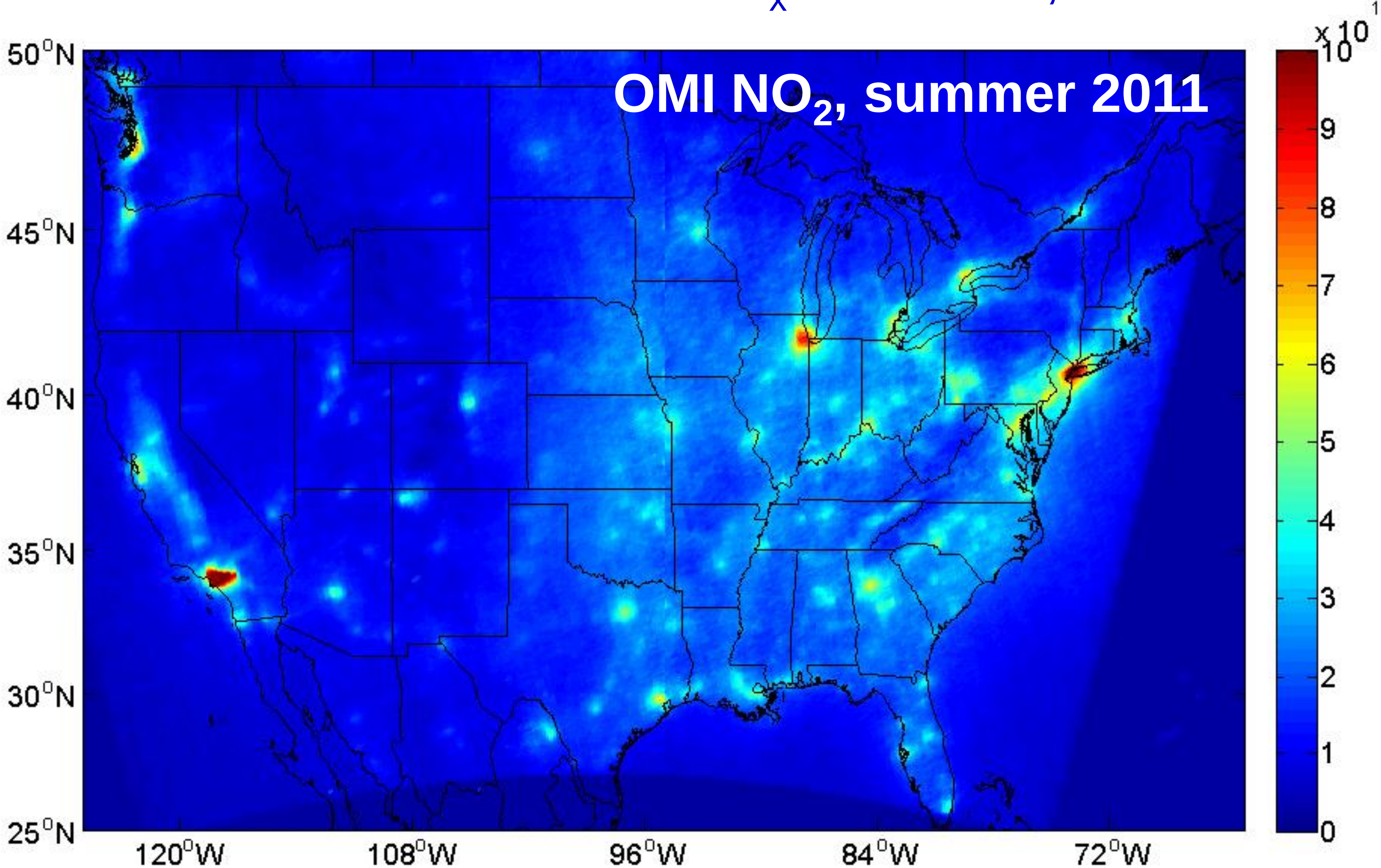
CALIOP (aerosol), MERLIN (methane)

Satellite observations of tropospheric NO_2 columns as top-down estimates of NO_x emissions



Russell et al. , ACP 2012

OMI observations of tropospheric NO_2 columns show fast decrease of US NO_x emissions, 2005-2011



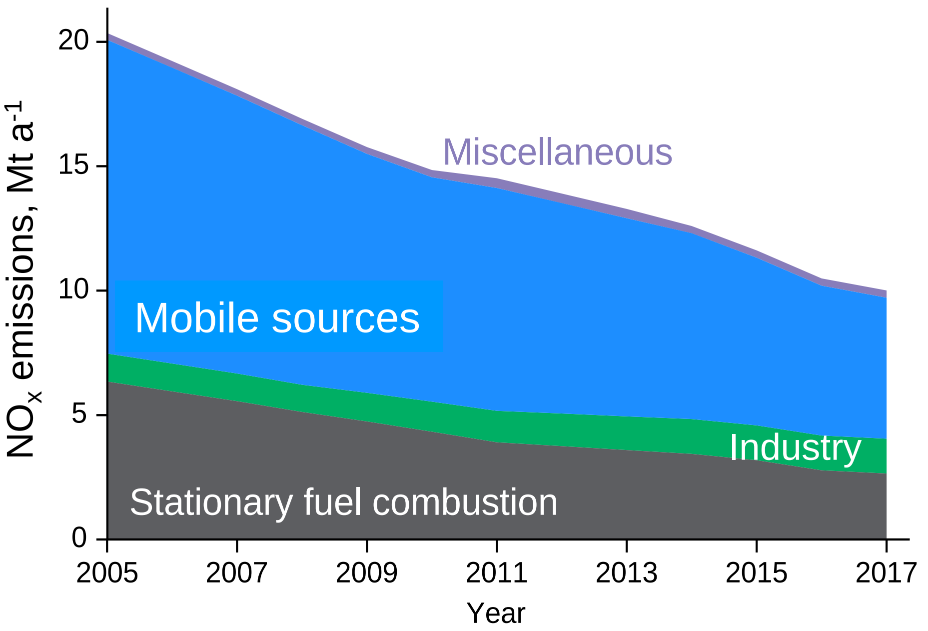
30% decrease in NO_x emissions from 2005 to 2011

Russell et al., ACP 2012

US NO_x emissions have continued to decrease since 2011 according to EPA…
but OMI tropospheric NO_2 column observations suggest otherwise!

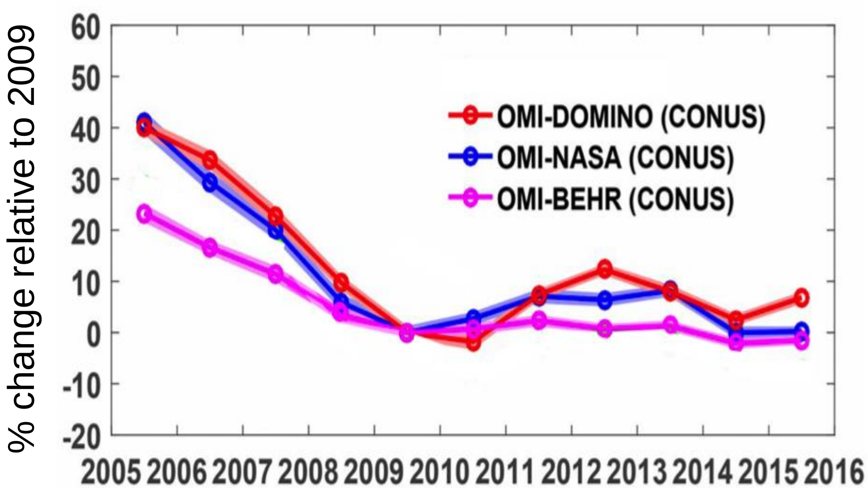
EPA National Emission Inventory (NEI):
53% sustained decrease of NO_x emissions over 2005-2017

EPA, 2018

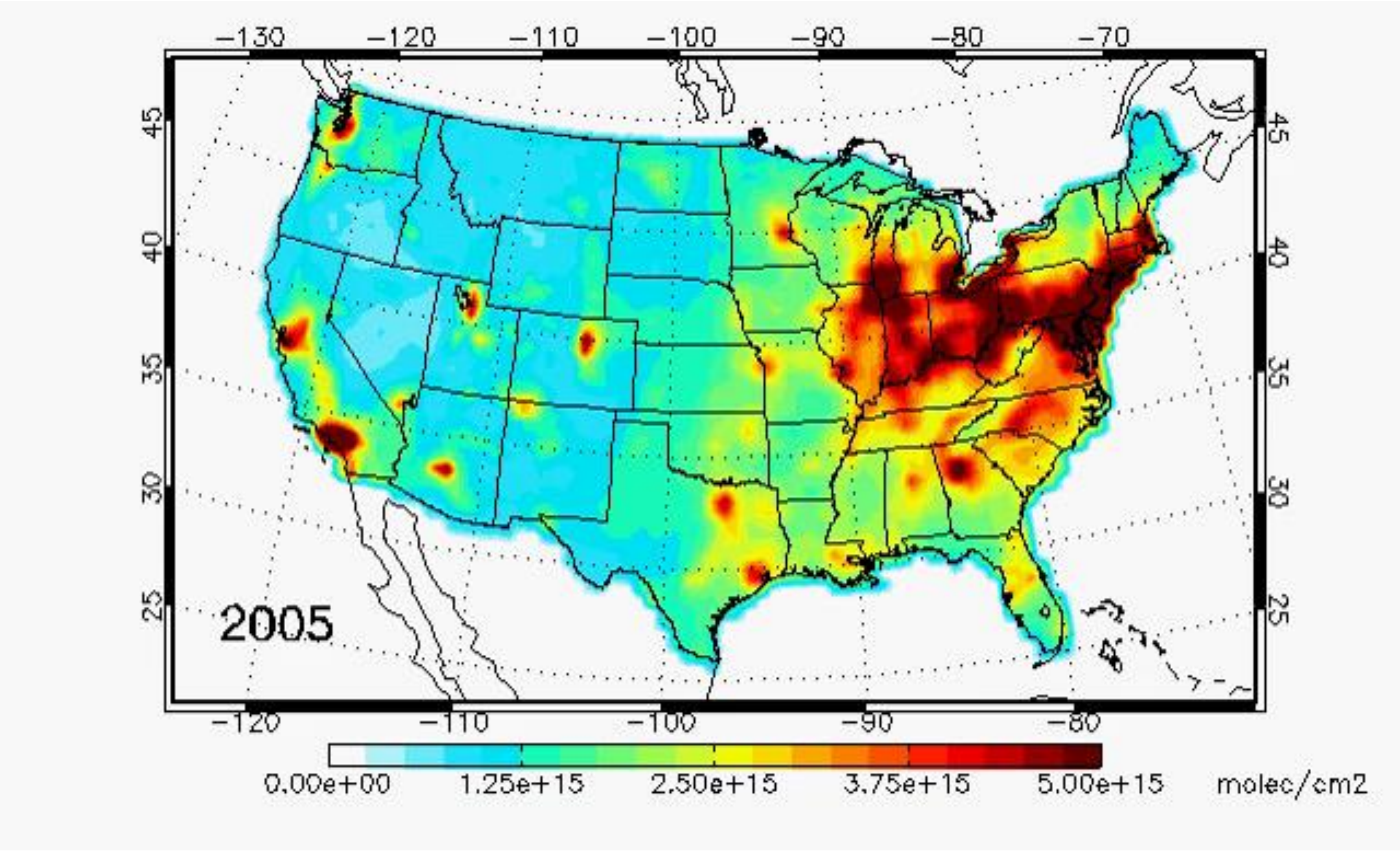


OMI NO_2 columns over CONUS, 2005-2016:
flat after 2011

Jiang et al., PNAS 2018



OMI annual NO_2 trends over CONUS, 2005-2017

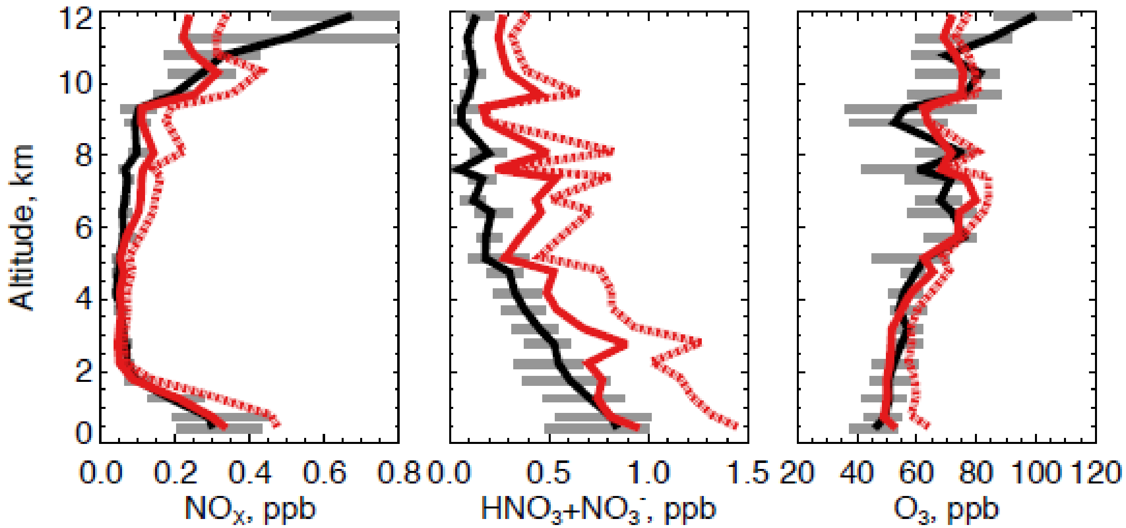


Silvern et al., ACPD 2019

Hypothesis #1:
EPA NO_x emission trends are wrong

Mobile sources in EPA inventory are too high, so maybe trends are wrong as well?

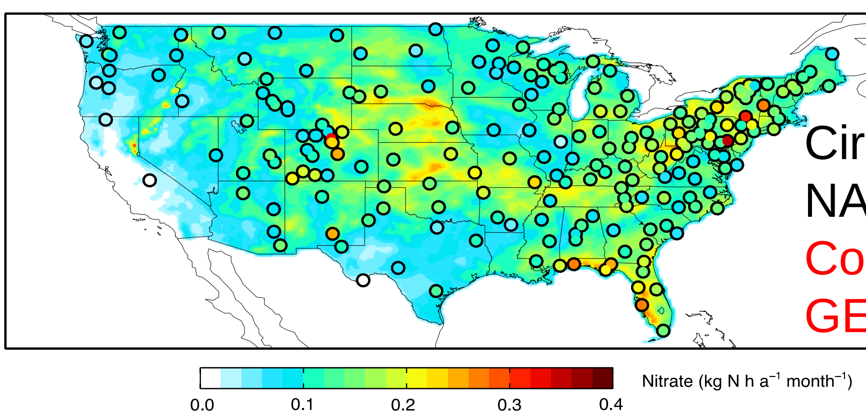
NASA SEAC^{4}RS aircraft campaign, Aug Sep 2013



Observed
GEOS-Chem model
with EPA NO_x emissions
with EPA NO_x emissions/2

Travis et al., ACP 2016

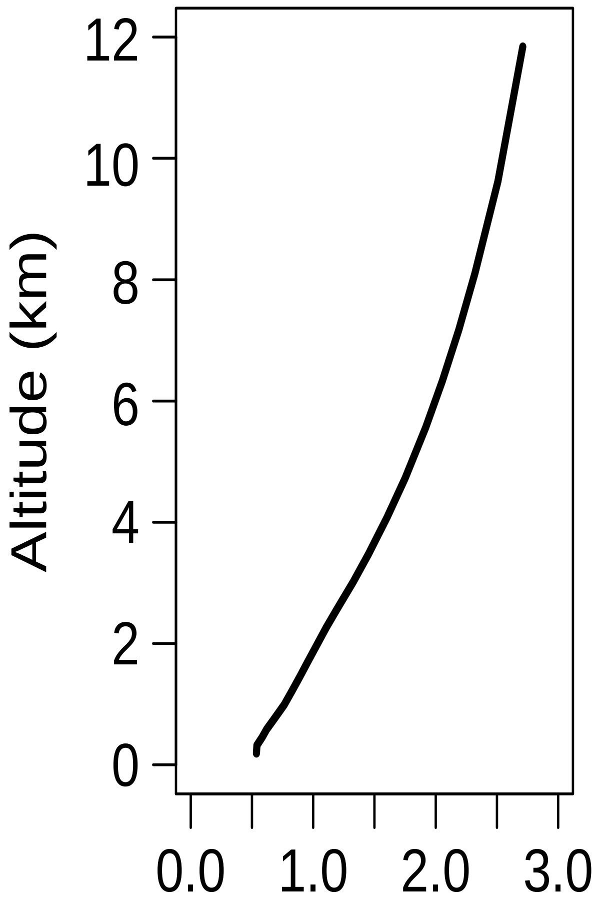
nitrate wet deposition fluxes, Aug-Sep 2013



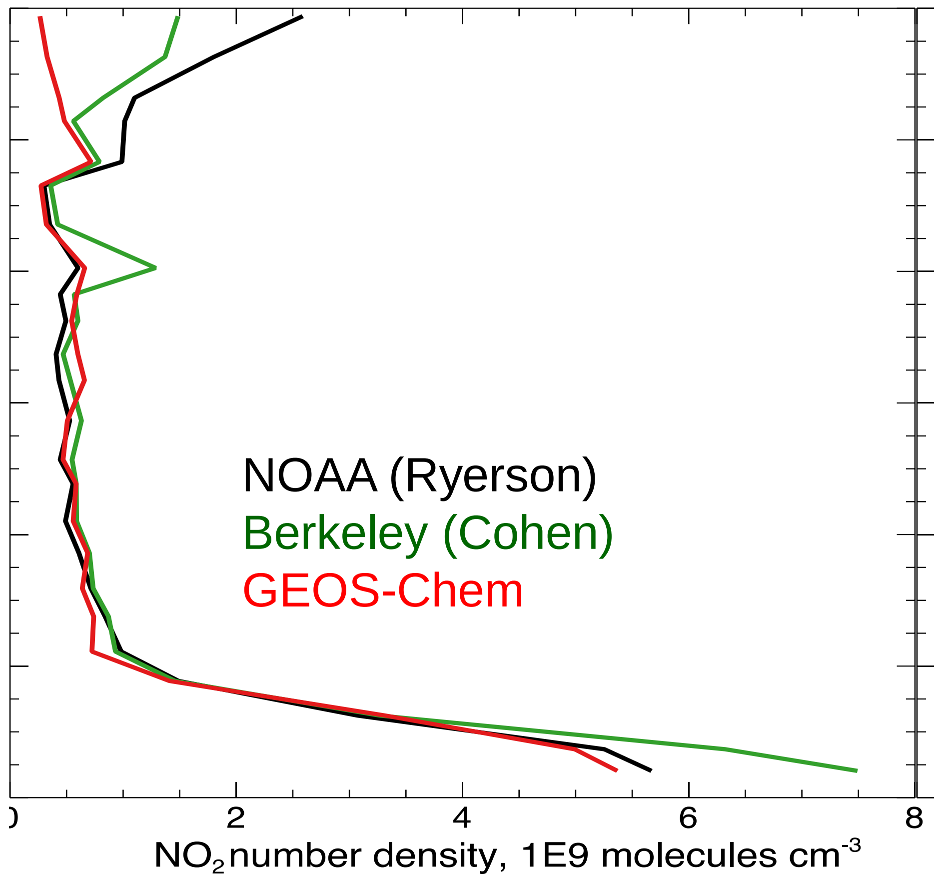
Circles:
NADP observations
Contours:
GEOS-Chem with EPA emissions/2

Hypothesis #2:
US NO_x emissions are now so low that OMI mostly sees background

OMI NO_2 sensitivity vs. altitude



Mean SEAC^{4}RS NO_2 profile over Southeast US

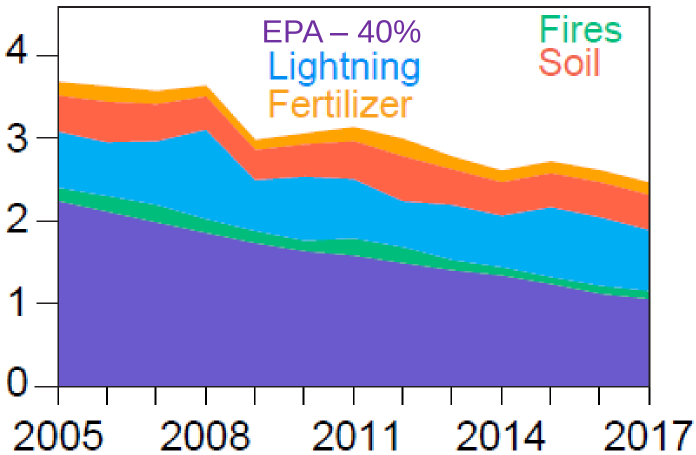


Boundary layer below 2 km accounts for only 20-35% of tropospheric NO_2 column as seen by OMI

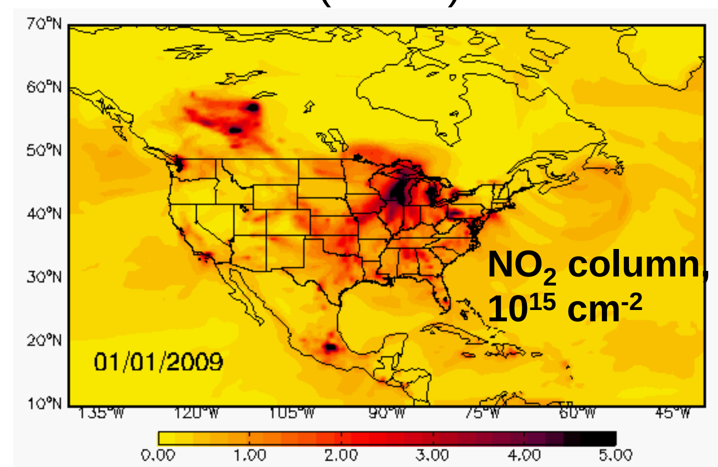
Travis et al. , ACP 2016; Silvern et al., GRL 2018

Use GEOS-Chem model to interpret trends from different data sets

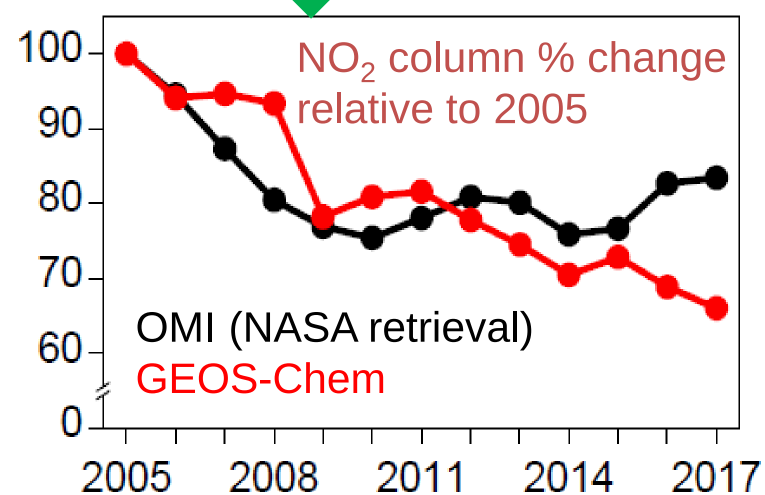
GEOS-Chem NO_x emissions
(Tg N a^{-1})



2005-2017 GEOS-Chem simulation
0.5°x0.625° (50 km) resolution



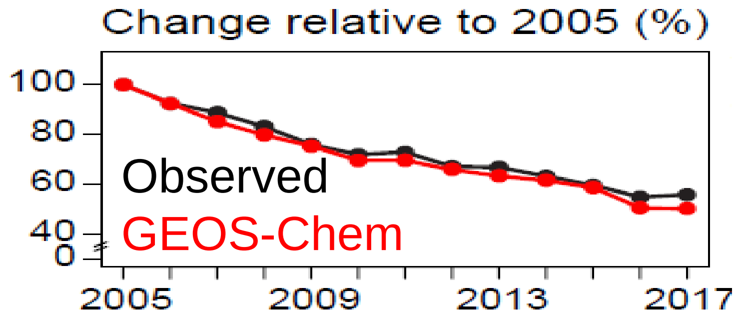
GEOS-Chem driven by EPA emission trend does not reproduce flat OMI trend after 2011



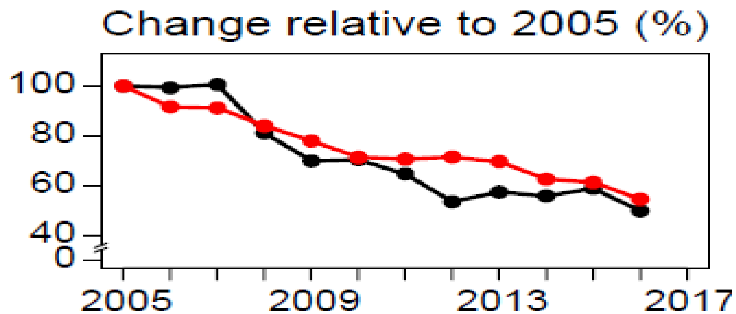
Silvern et al., ACPD 2019

2005-2017 trends in surface data

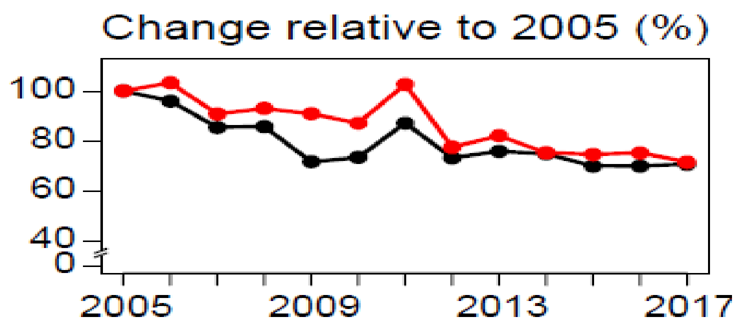
AQS NO_2 (urban)



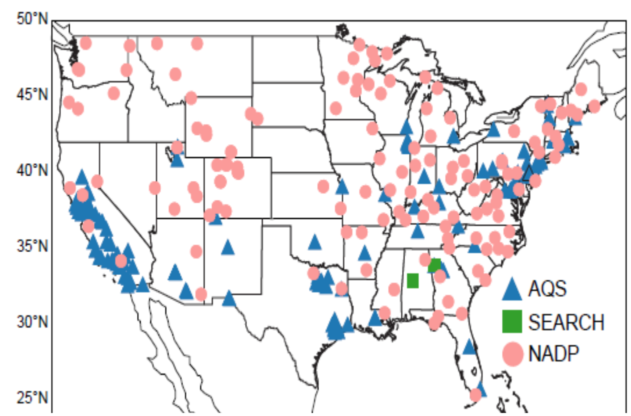
SEARCH NO_2 (2 rural sites)



NADP nitrate wet deposition



Surface sites with continuous annual records for 2005-2017



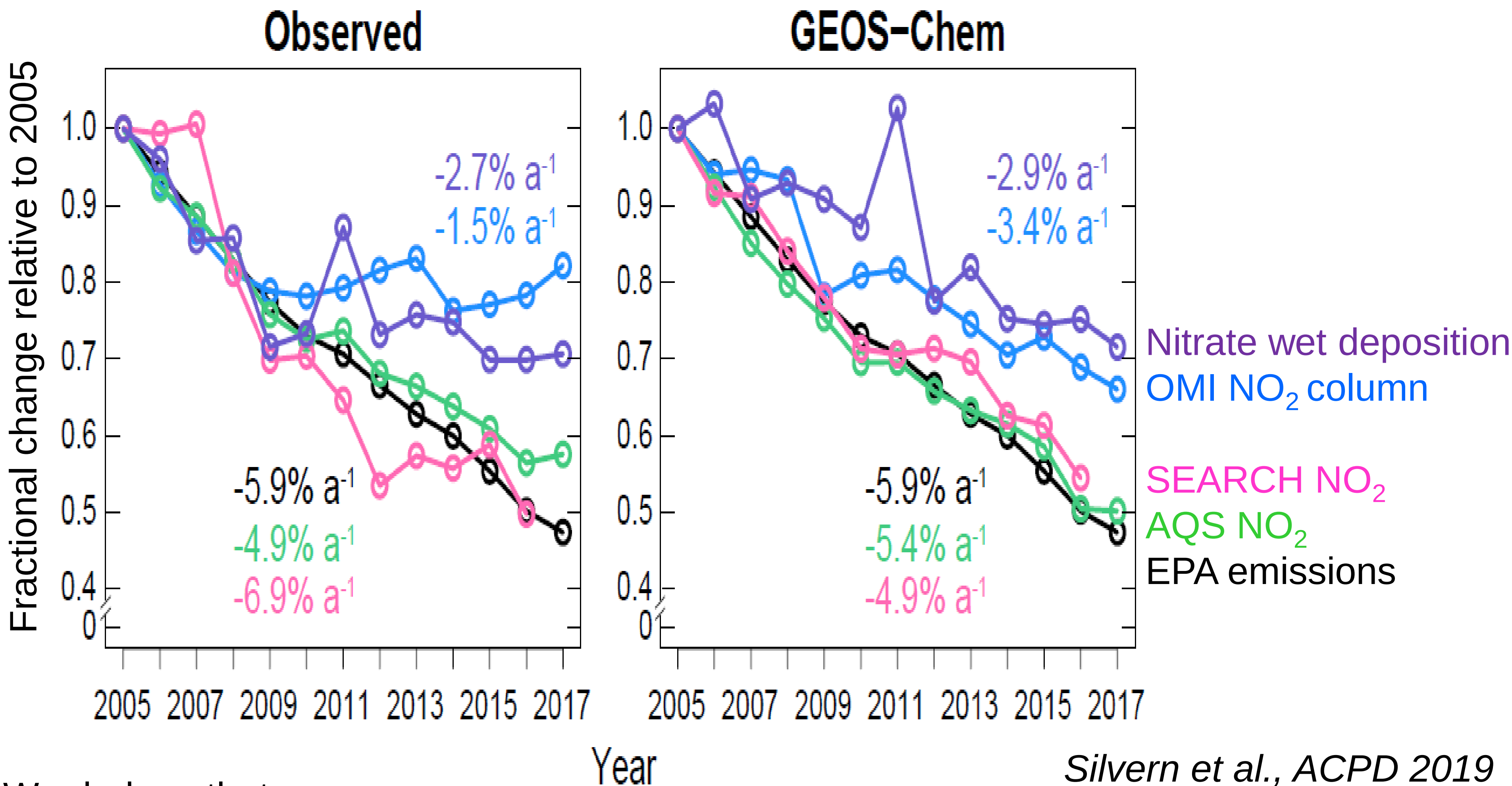
Silvern et al., ACPD 2019

GEOS-Chem matches the observed relative trends:

- surface NO_2 is most sensitive to anthropogenic emissions
- nitrate deposition is sensitive to background (soils, lightning, transport from outside US)

US anthropogenic sources contribute only 50% of nitrate wet deposition in 2005, 31% in 2017

Comparing 2005-2017 relative trends for different US quantities



Silvern et al., ACPD 2019

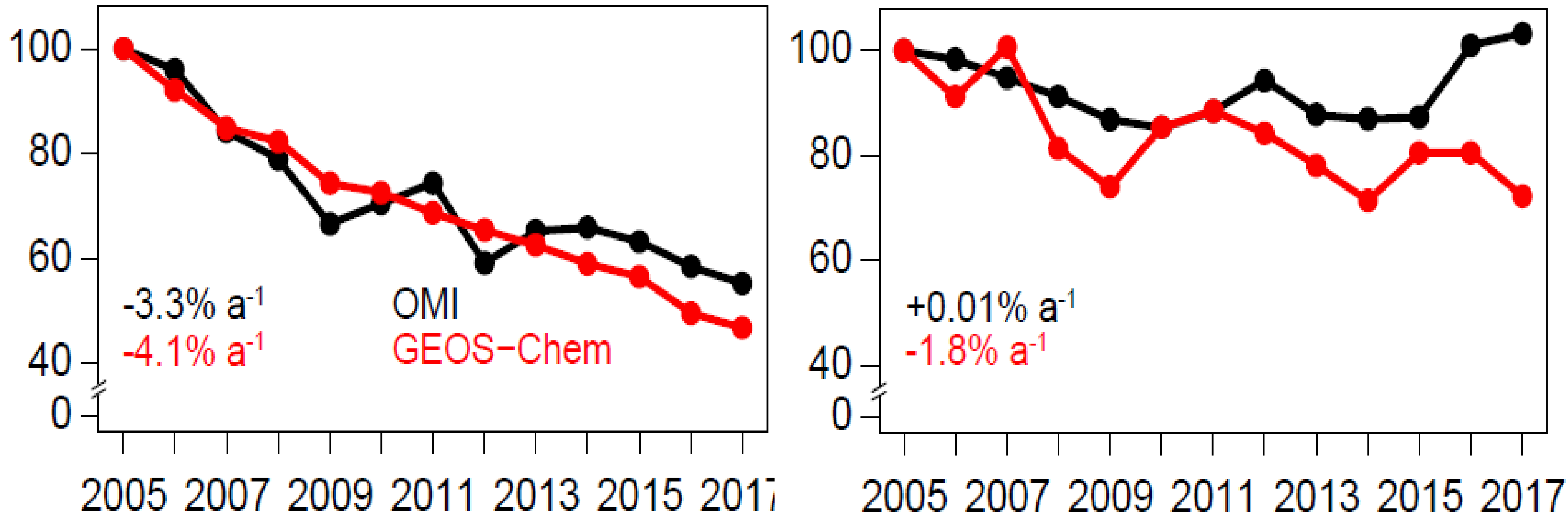
We deduce that:

- EPA 2005-2017 trend in NO_x emissions is correct
- OMI NO_2 columns have strong background influence
- GEOS-Chem underestimates free tropospheric background NO_2

Separating OMI trends by urban vs. rural, winter vs. summer

Trends in NO_2 columns relative to 2005 (%)

urban winter rural summer



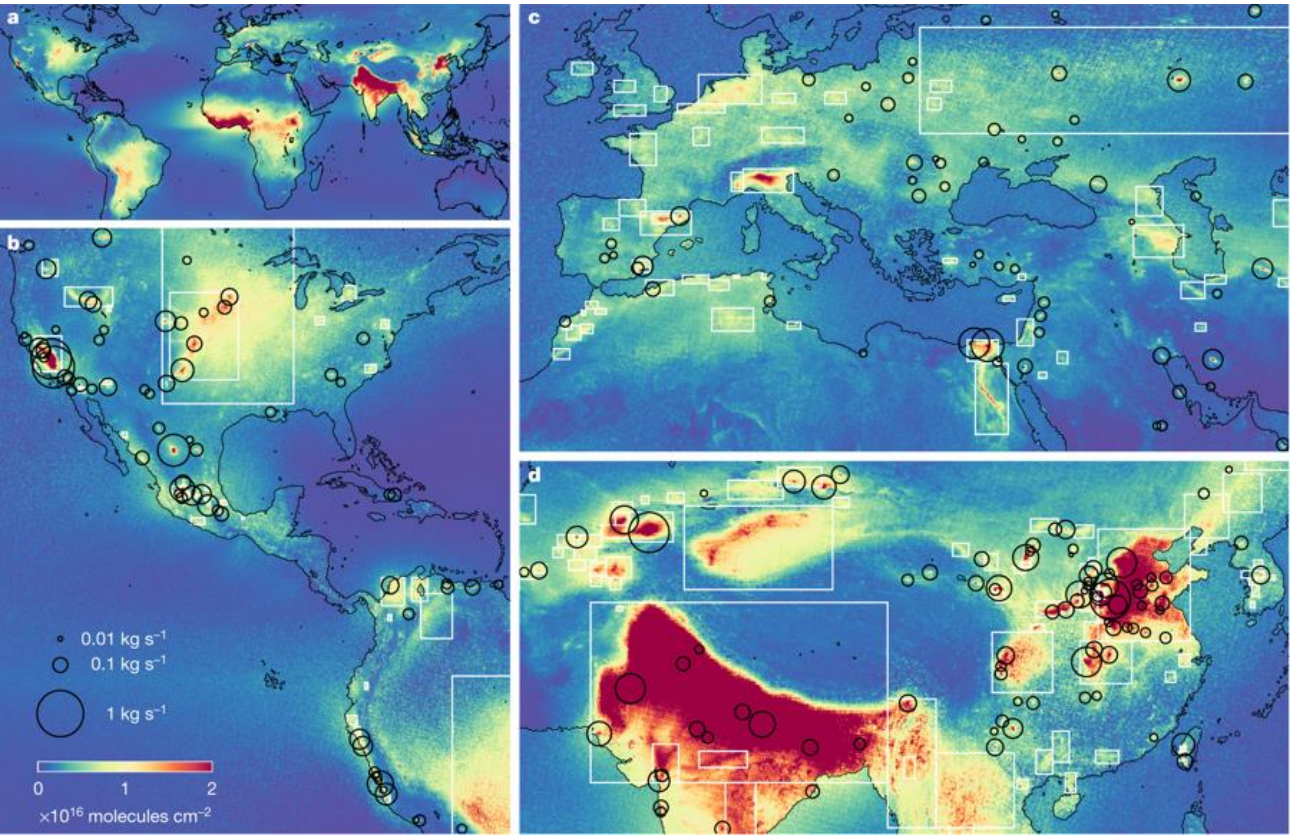
OMI shows:

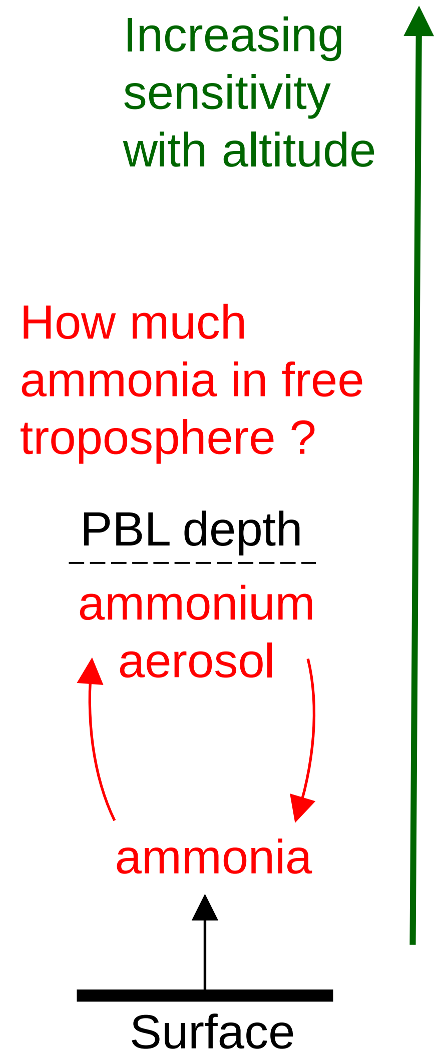
- steady decrease in urban winter where background is relatively low
- no trend in rural summer where background is relatively high

OMI NO_2 is useful to detect hotspots and plumes,
but inference of regional emissions is far more uncertain

Silvern et al., ACPD 2019

Observing ammonia from space (IASI)



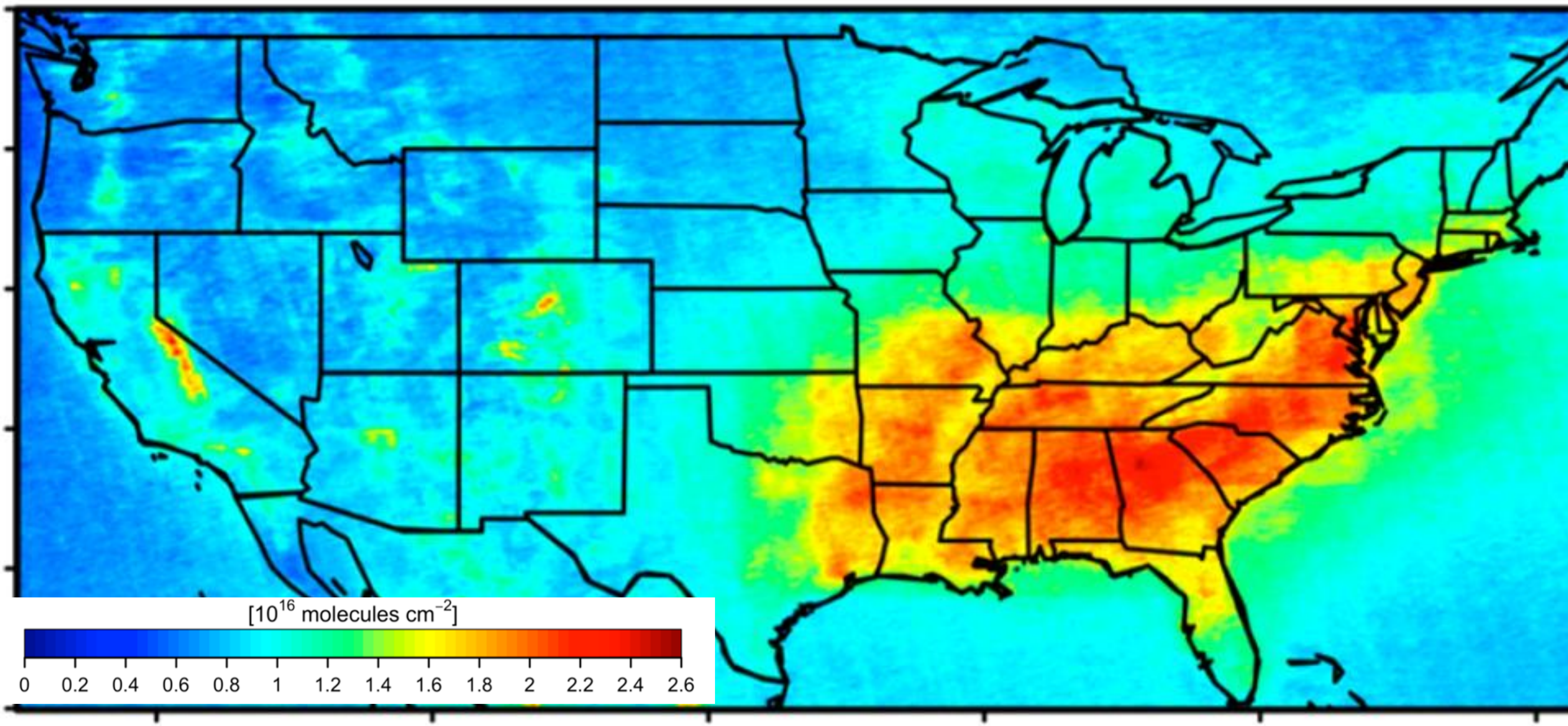


IASI/CrIS ammonia is useful to detect hotspots and plumes, but inference of regional emissions is far more uncertain

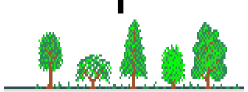
Van Damme et al., Nature 2018

Formaldehyde over US: tracer of reactive VOC emissions, mainly isoprene

OMI formaldehyde columns, JJA 2005-2016



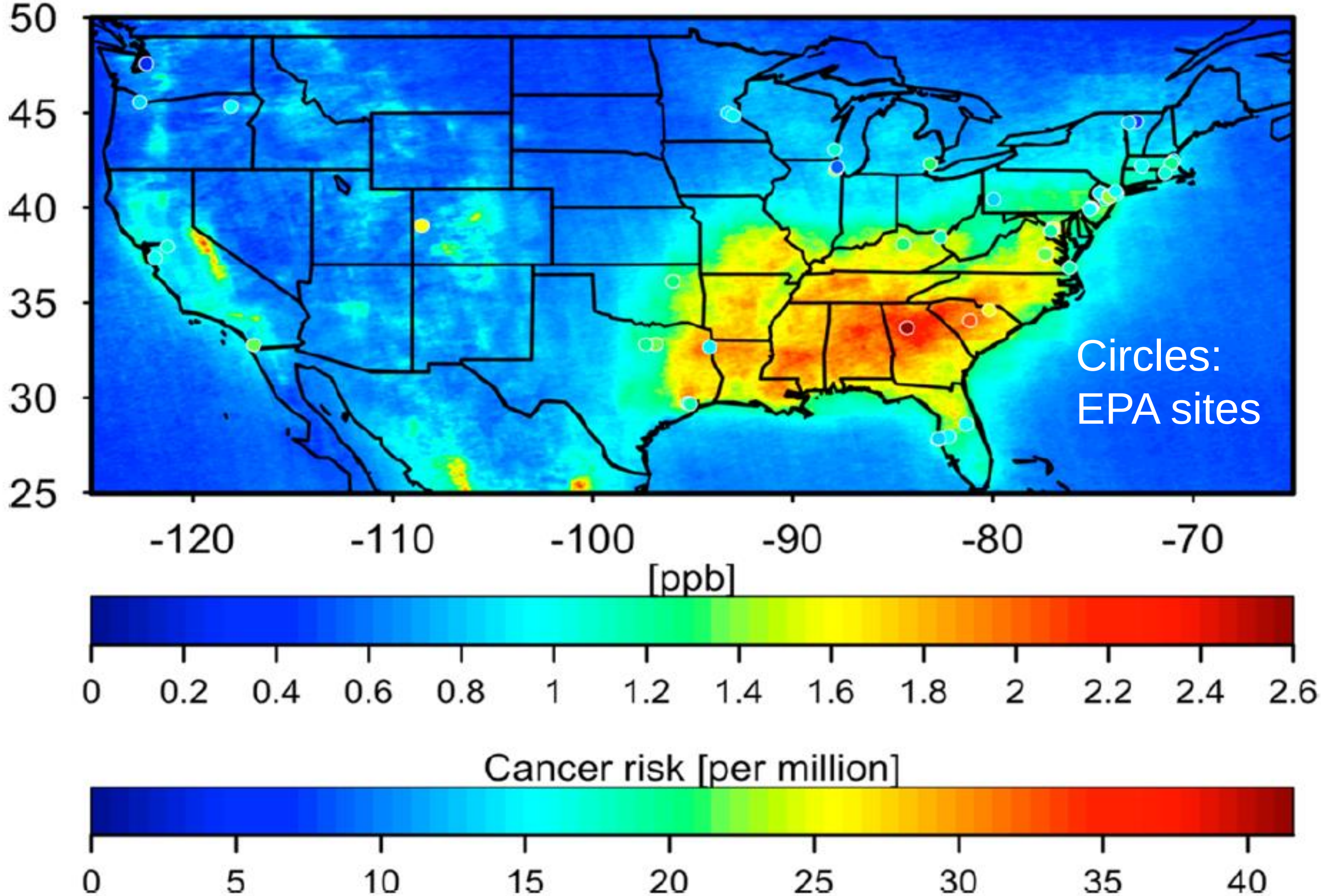
isoprene $\xrightarrow[\text{1 h}]{\text{oxidation}}$ formaldehyde $\xrightarrow[\text{2 h}]{\text{photolysis, oxidation}}$



Zhu et al., ES&T 2017

Inferring formaldehyde surface concentrations and cancer risks from OMI data

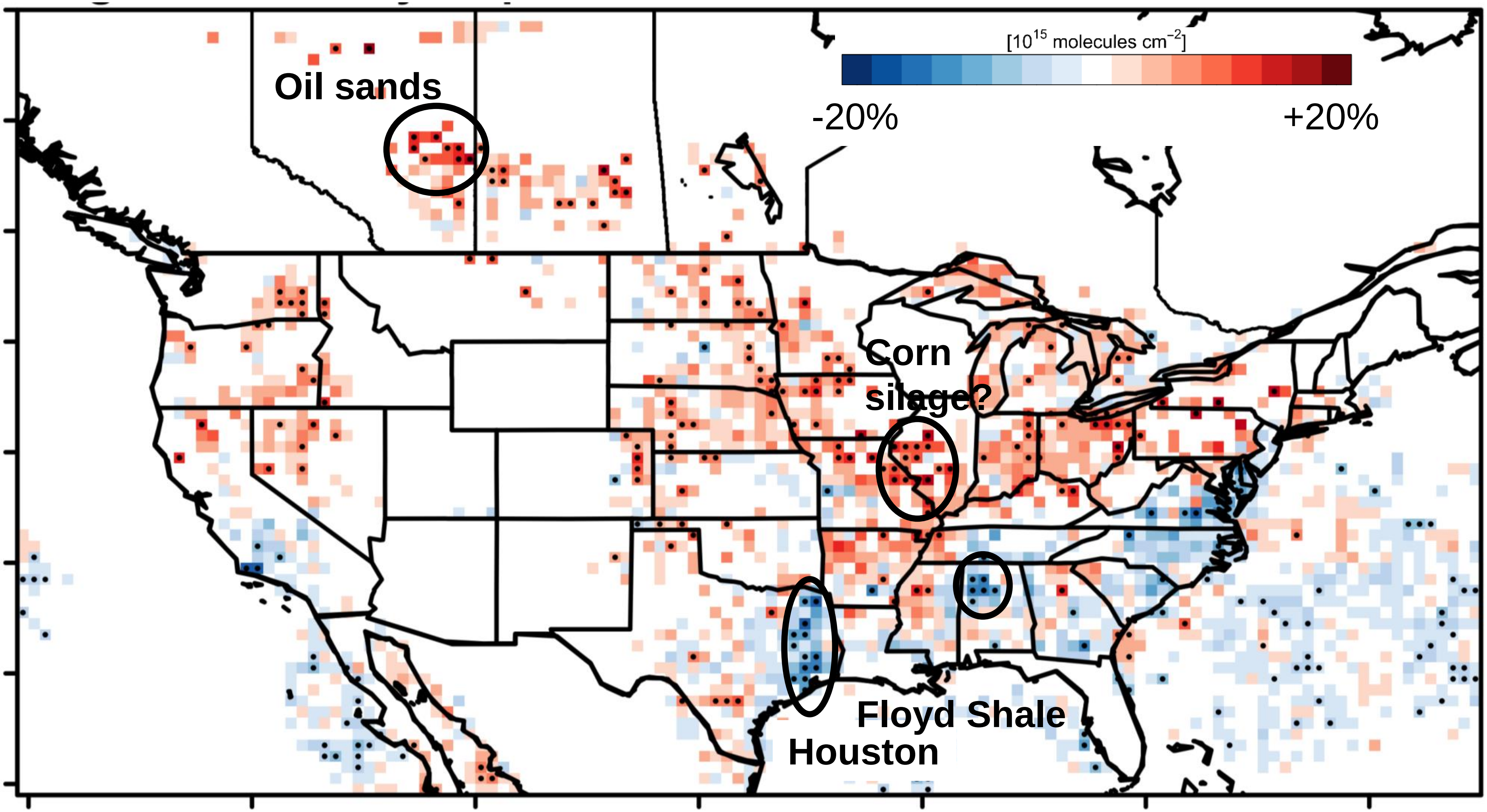
Annual mean OMI-derived surface formaldehyde, 2005-2016



6000-12000 people in US to develop cancer over their lifetimes from HCHO exposure

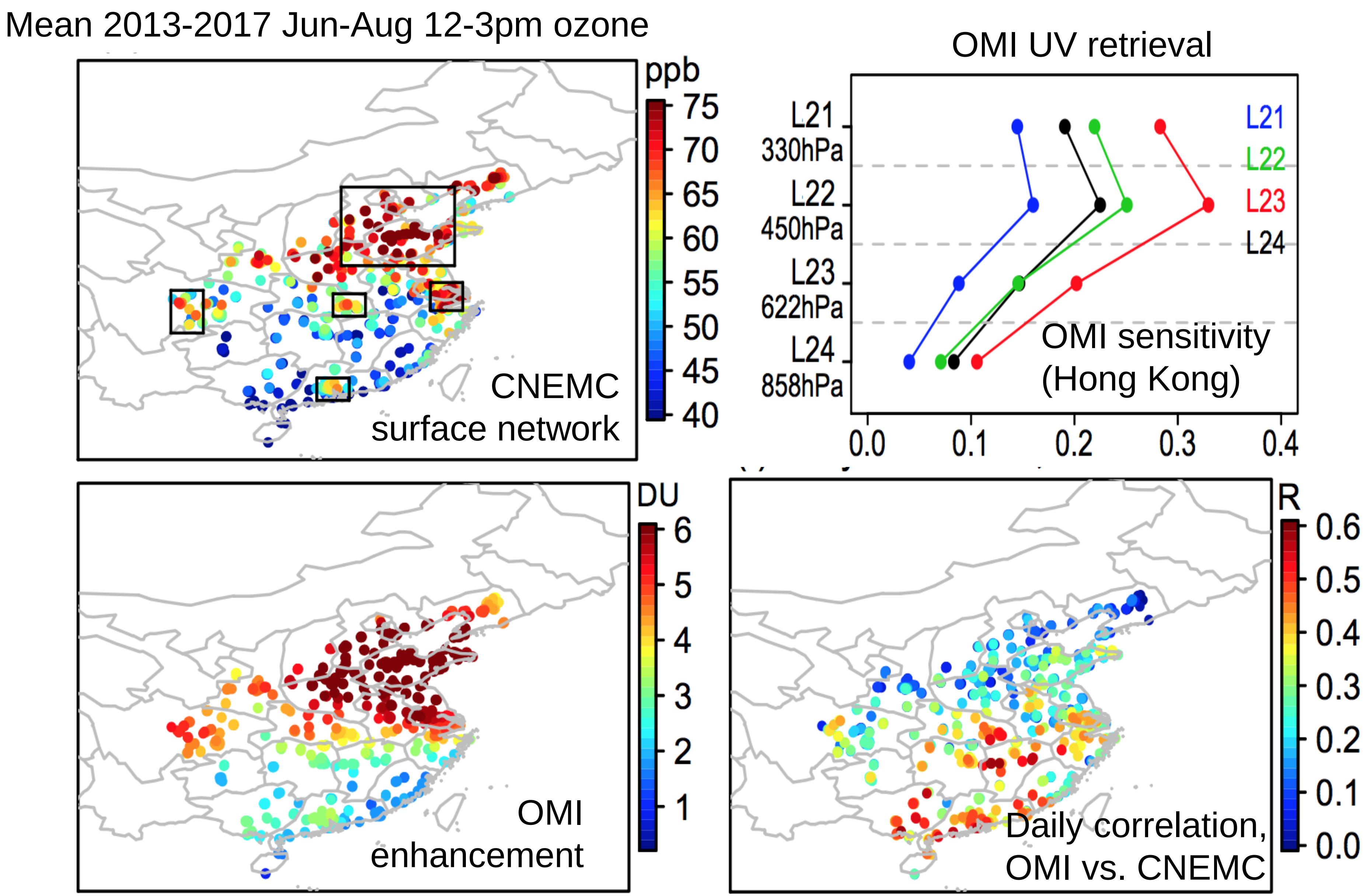
Zhu et al., ES&T 2017

OMI trends in formaldehyde columns, 2005-2009 to 2010-2014



Zhu et al., GRL 2017

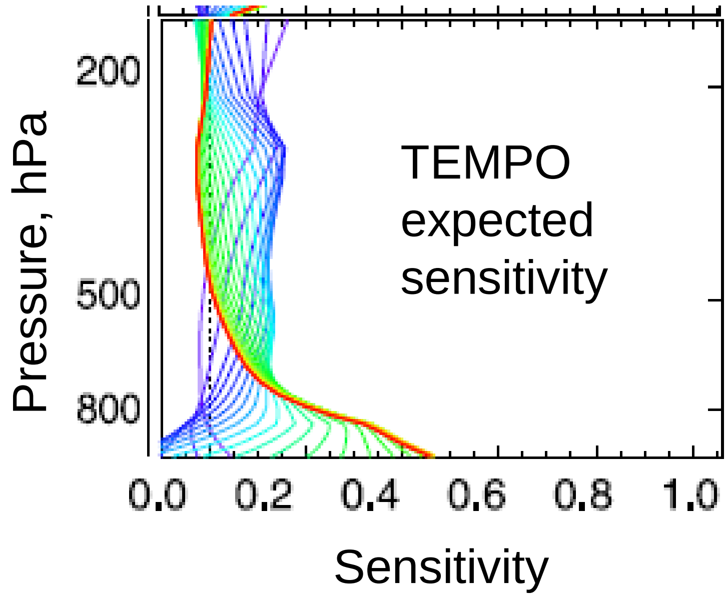
OMI detects surface ozone over China…but only because it's so high



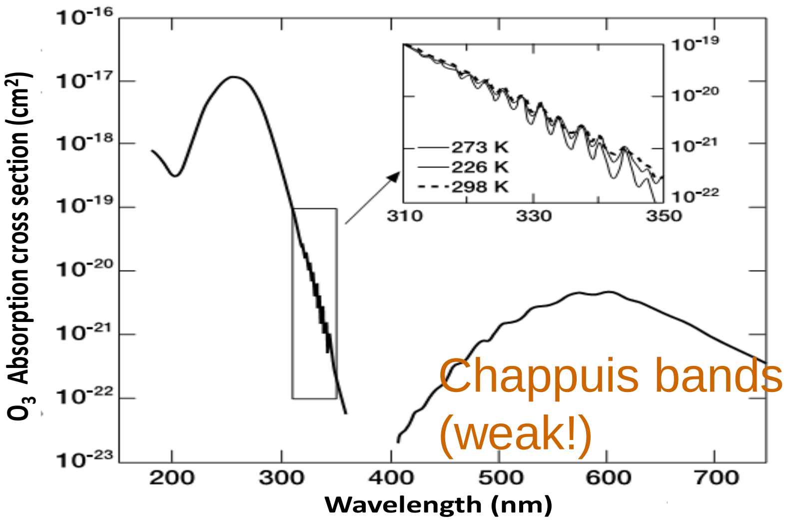
Shen et al., ACPD 2019

US surface ozone is too low for OMI…but TEMPO could help

TEMPO will have a visible channel for ozone observations



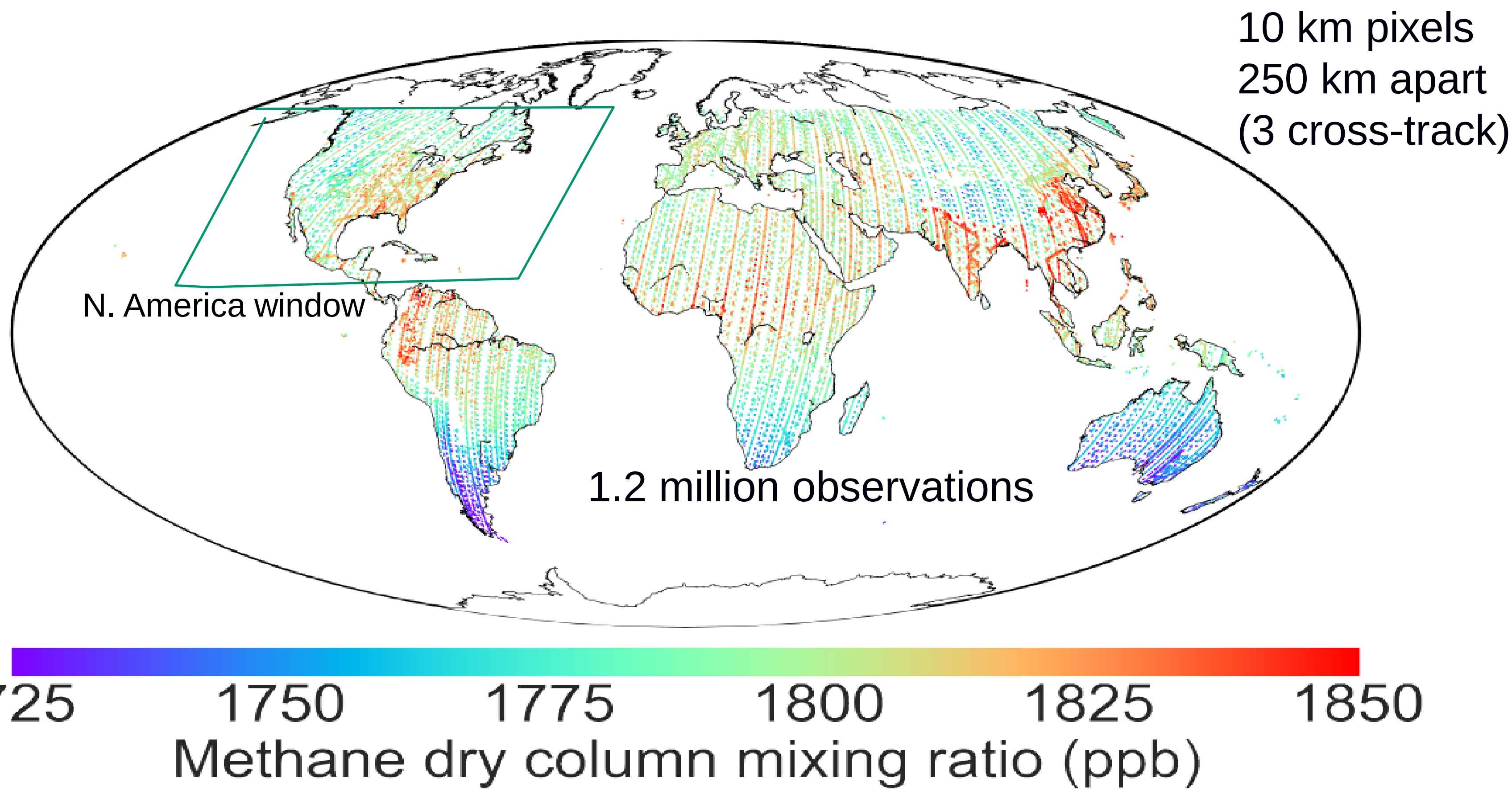
Ozone absorption spectrum



Don't count on TEMPO for ozone monitoring – but it should be very useful for

- recognizing exceptional events (such as stratosphere intrusion)
- observing long-range transport
- chemical data assimilation
- initializing air quality forecasts

Methane: mean GOSAT observations, 2010-2015

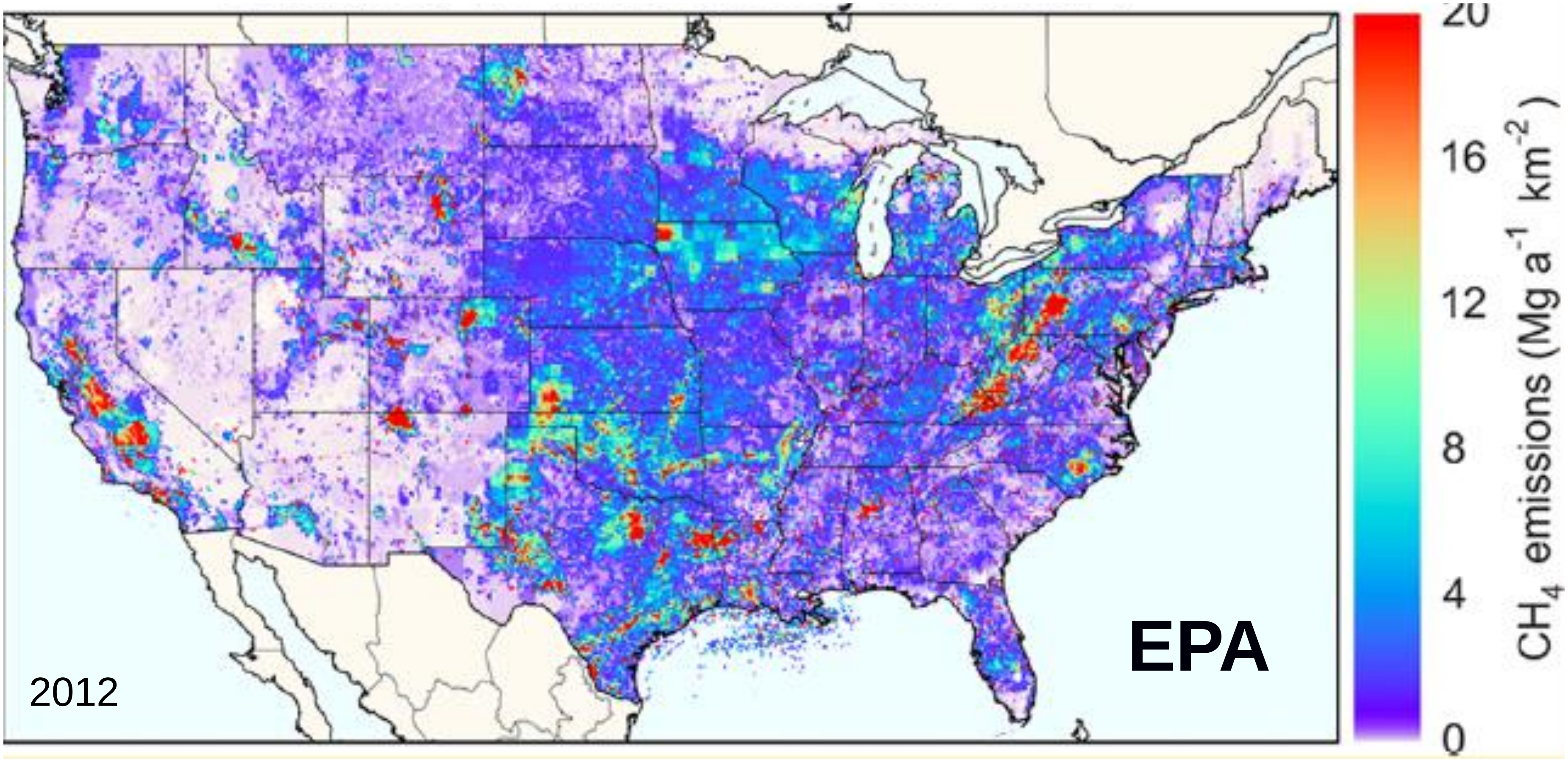


Emissions can be inferred from the data by inversion of an atmospheric transport model

Maasakkers et al., ACPD 2019

Spatially resolved version of EPA US methane inventory

EPA inventory distributed on 0.1°x0.1° grid with scale-dependent error characterization

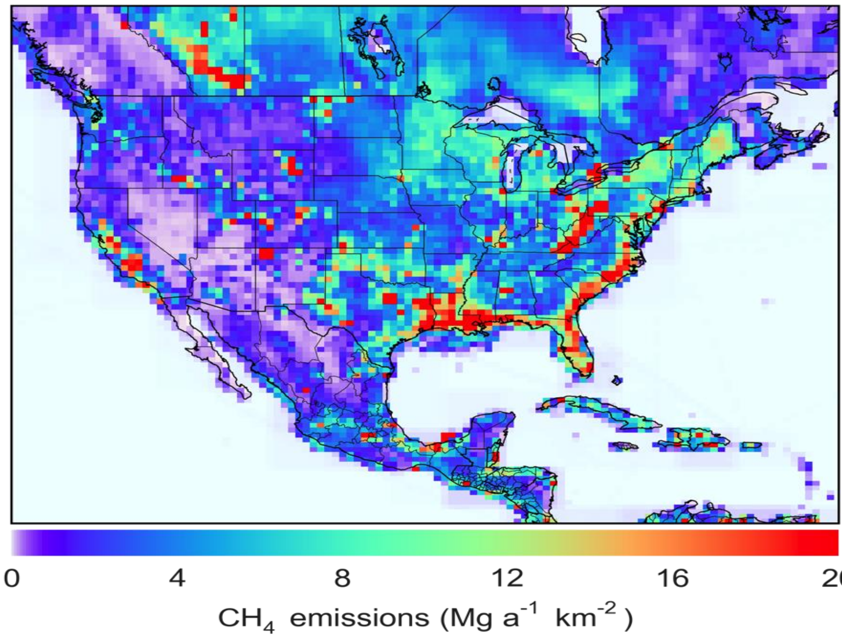


Use as prior estimate for the inversion

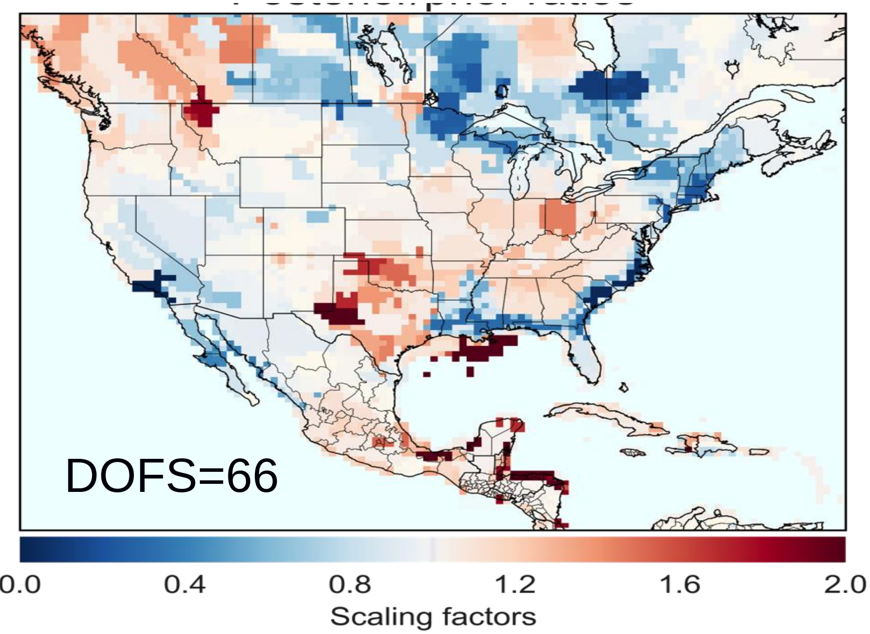
Maasakkers et al. , ES&T 2016

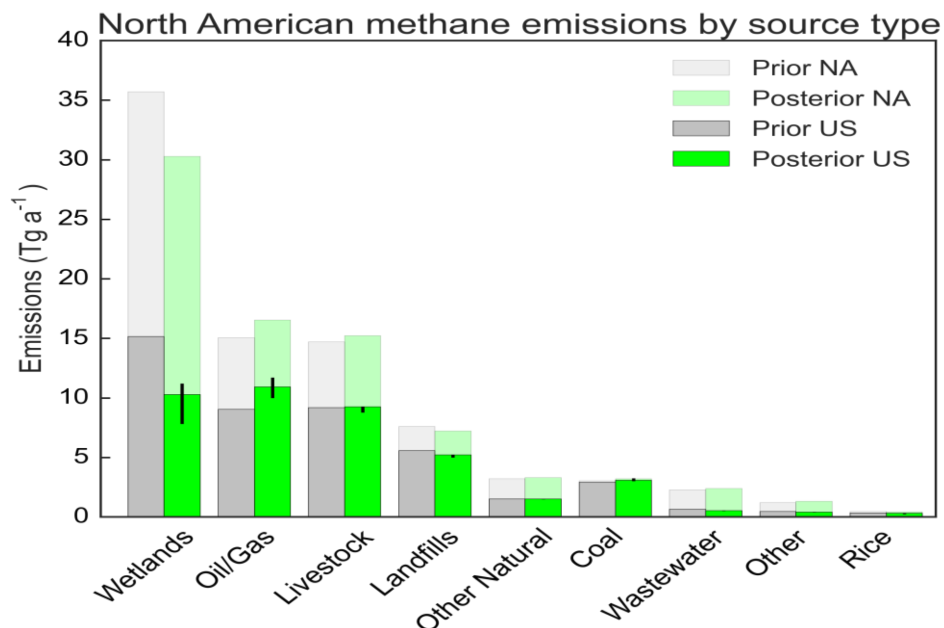
High-resolution inversion for North America

US EPA emissions + WetCHARTS wetlands



Correction factors from the inversion

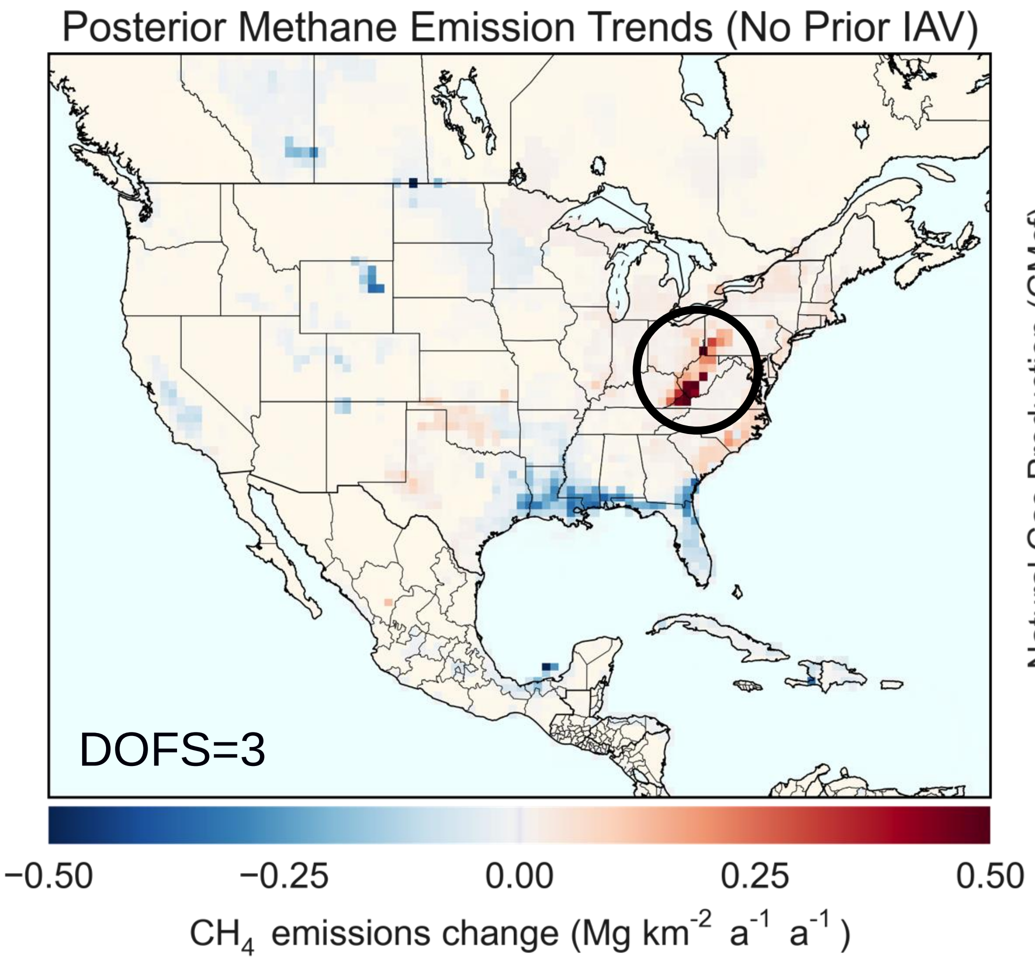


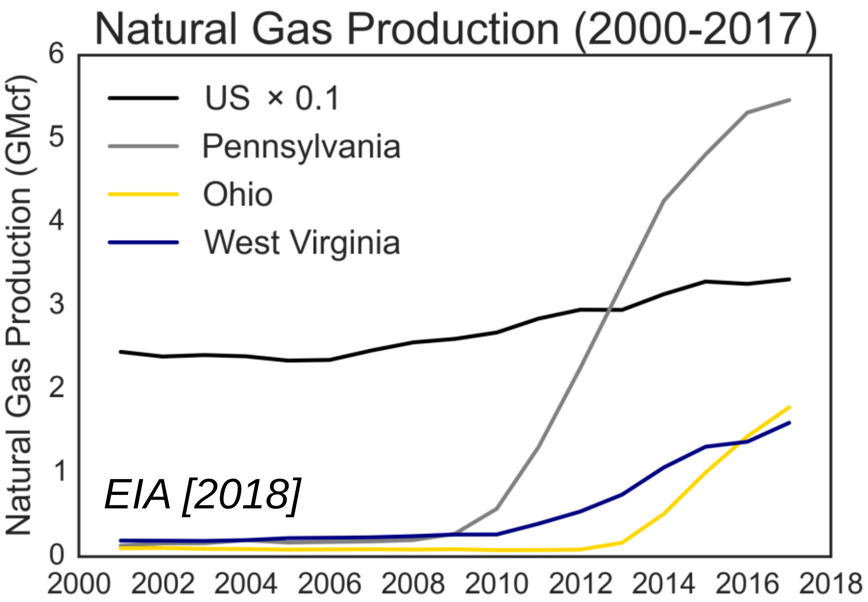


- WetCHARTS emission from US coastal wetlands are too high
- US EPA inventory has 20% low bias for oil/gas (mainly oil production),
- no bias for other sources

Maasakkers et al., in prep.

GOSAT-inferred North American emission trends, 2010-2015



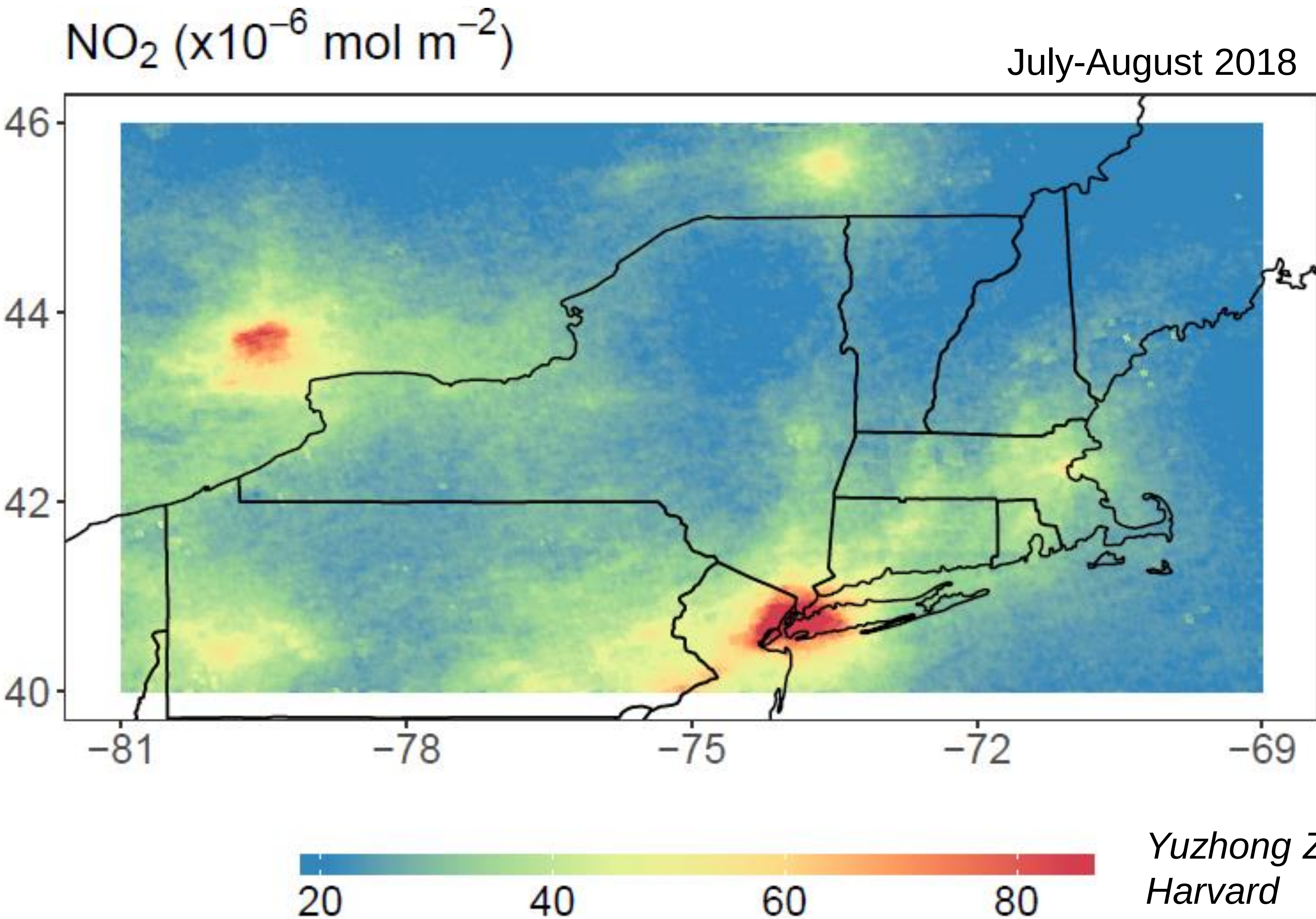


Increasing emissions from fracking in Midwest

Maasakkers et al., in prep.

TROPOMI instrument launched in October 2017:

Global daily mapping of NO_2, formaldehyde, ozone, SO_2, CO, methane for 3.5x7 km^2 or 7x7 km^2 nadir pixels



Yuzhong Zhang, Harvard

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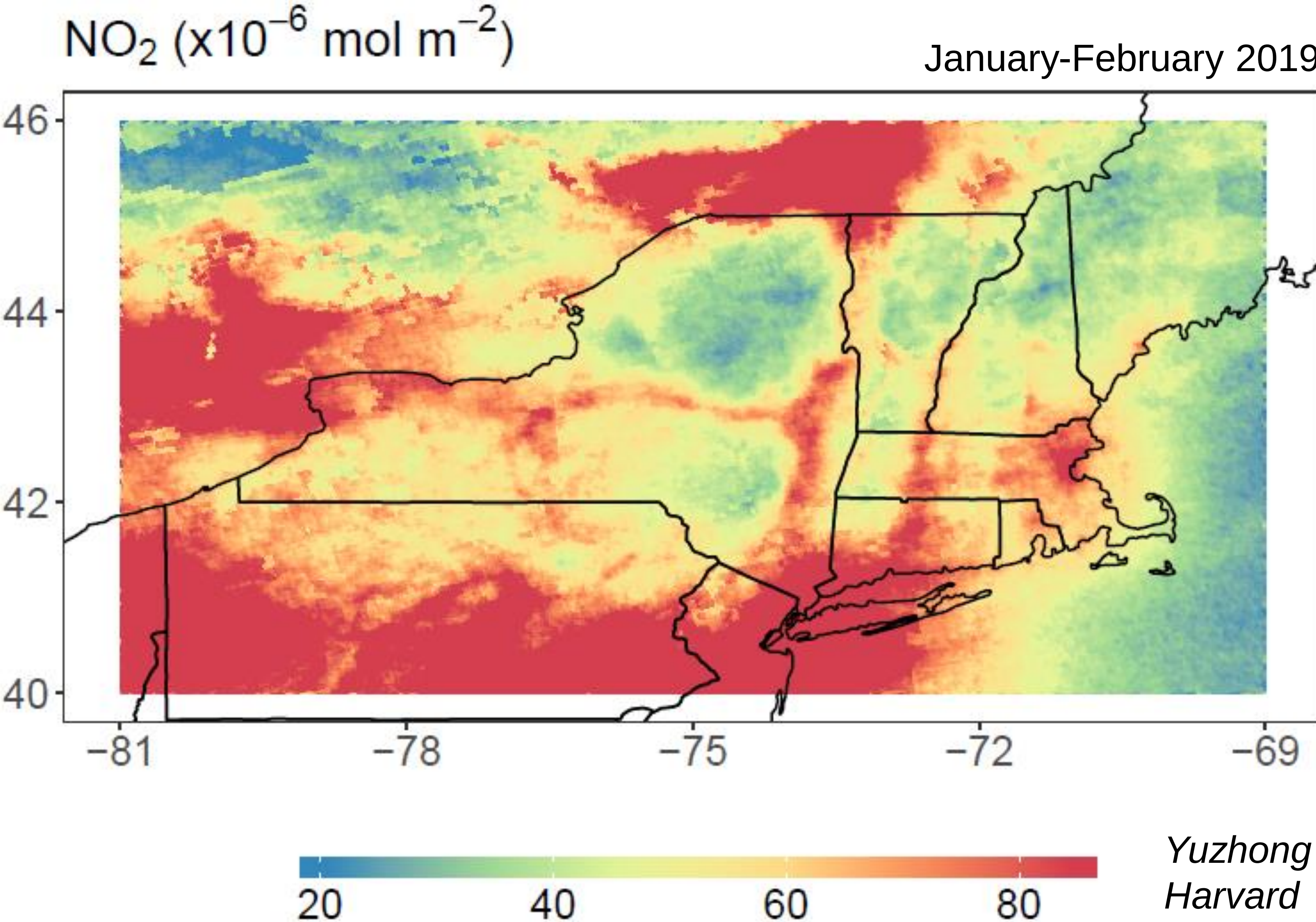

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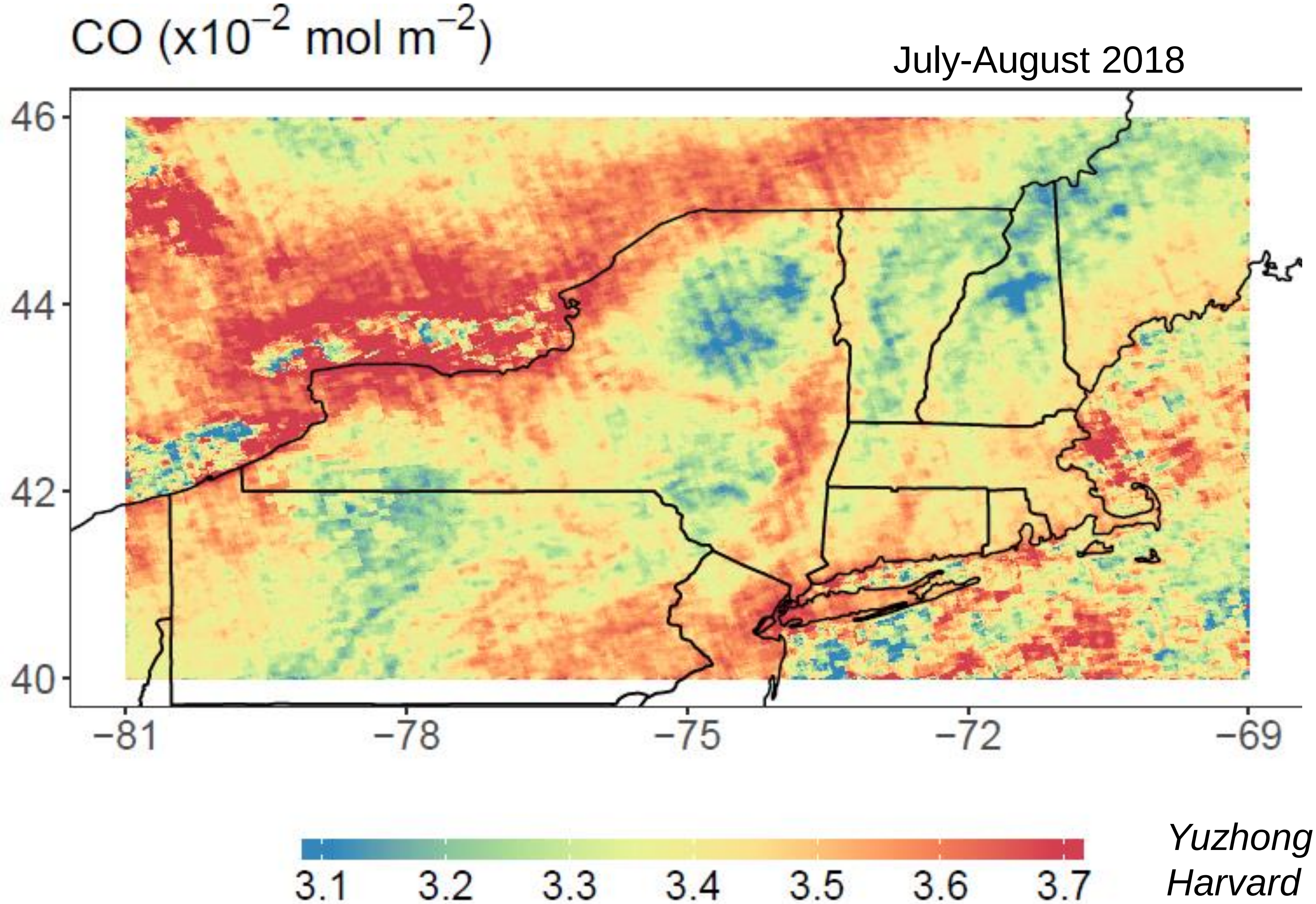

Yuzhong Zhang, Harvard

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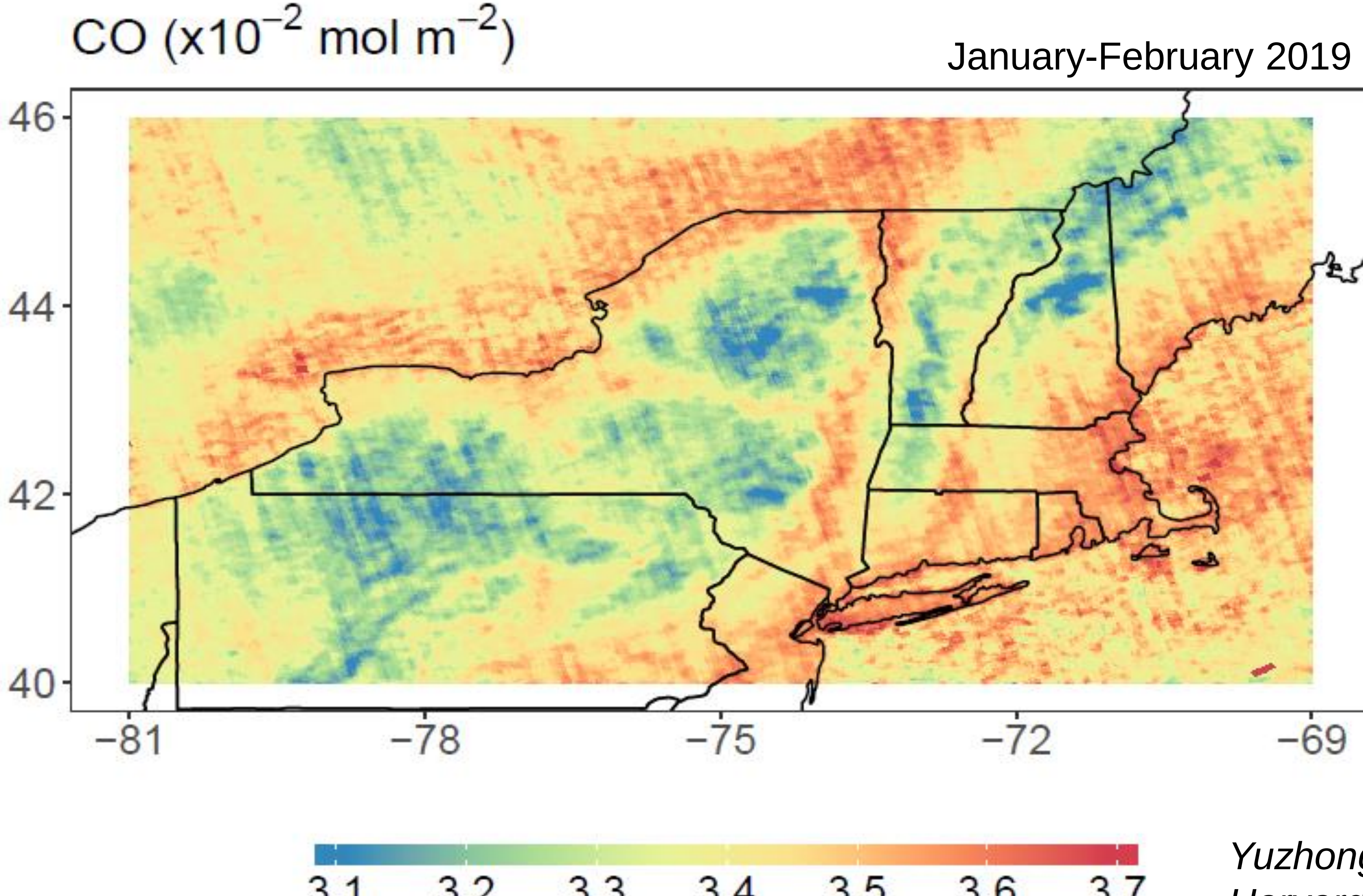

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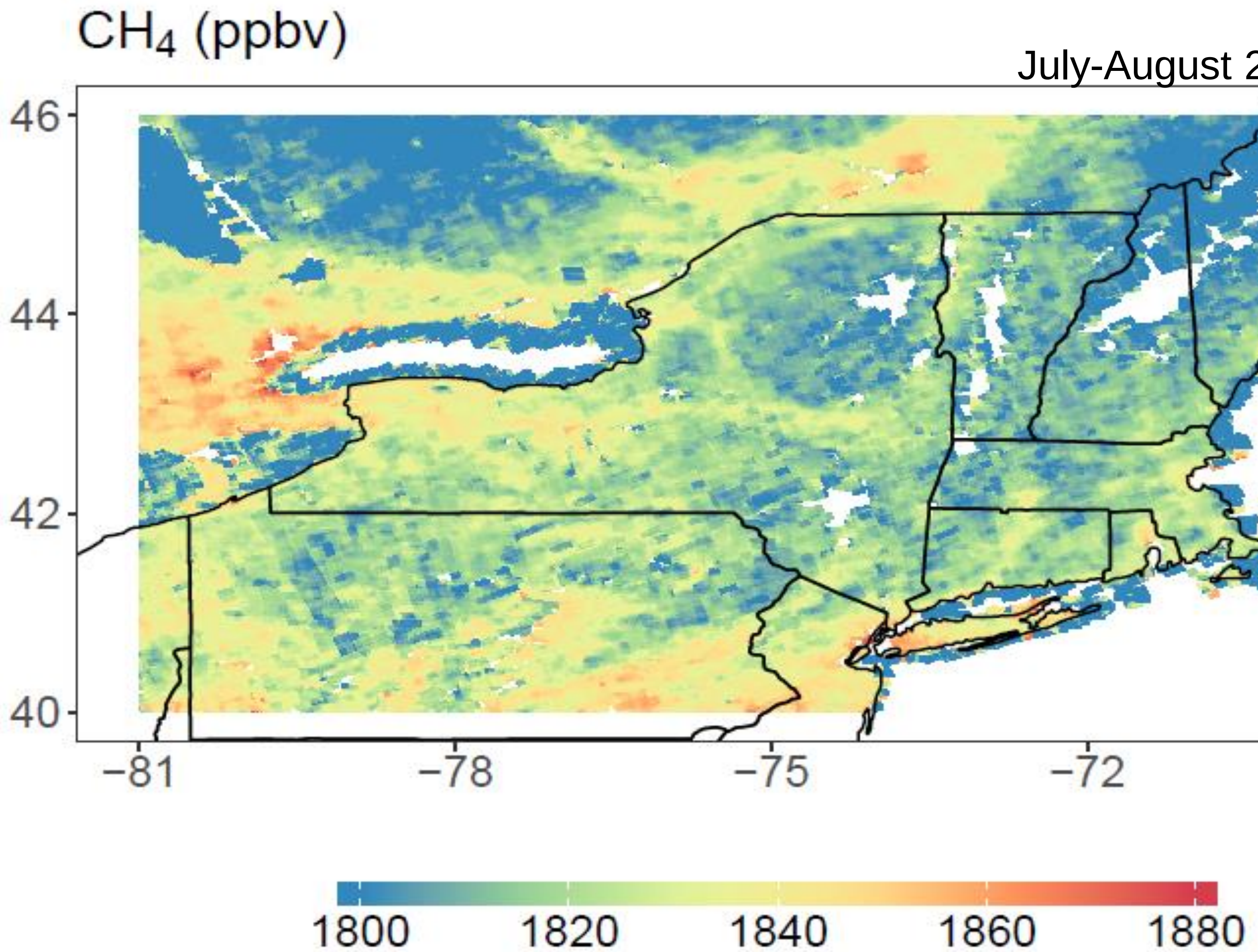

Yuzhong Zhang, Harvard

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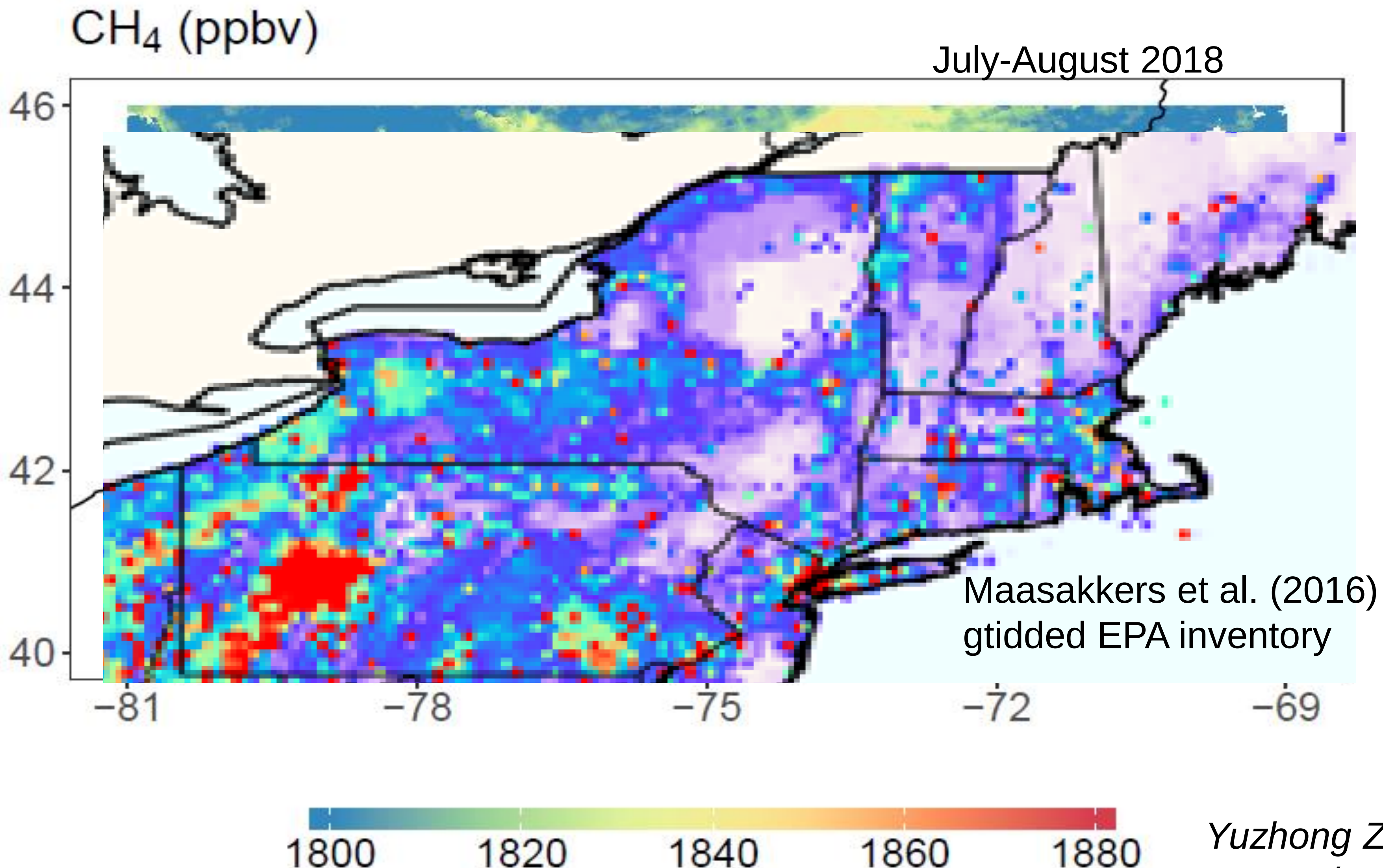

Yuzhong Zhang, Harvard

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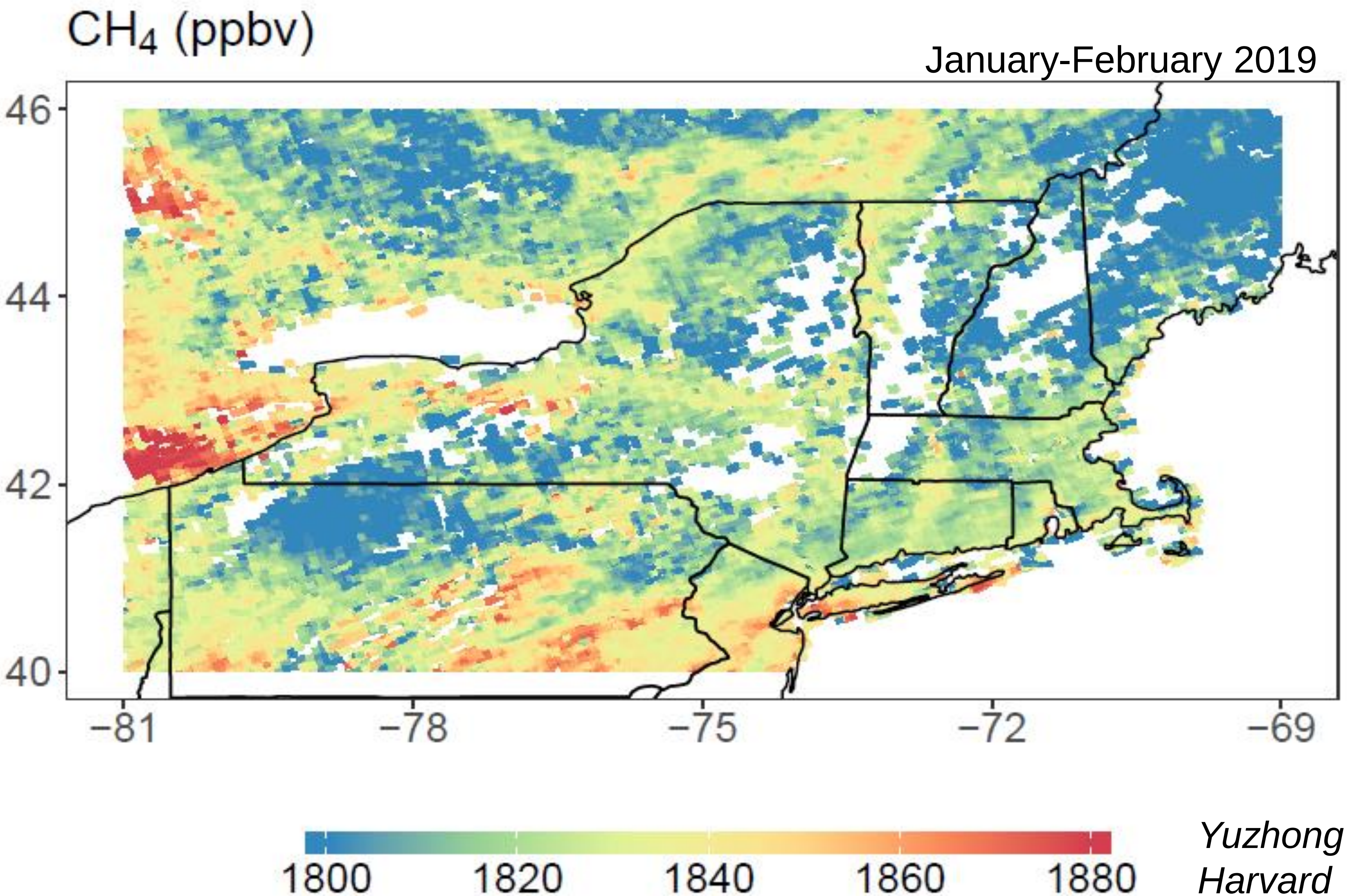
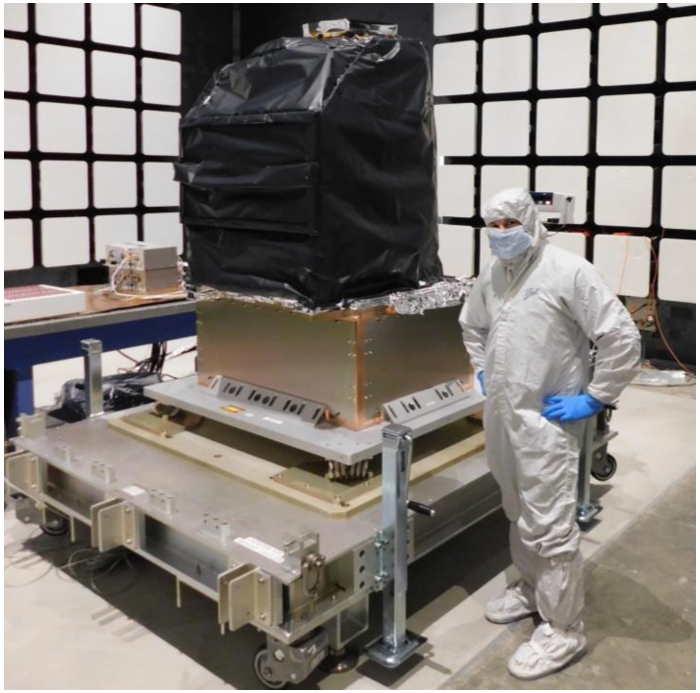


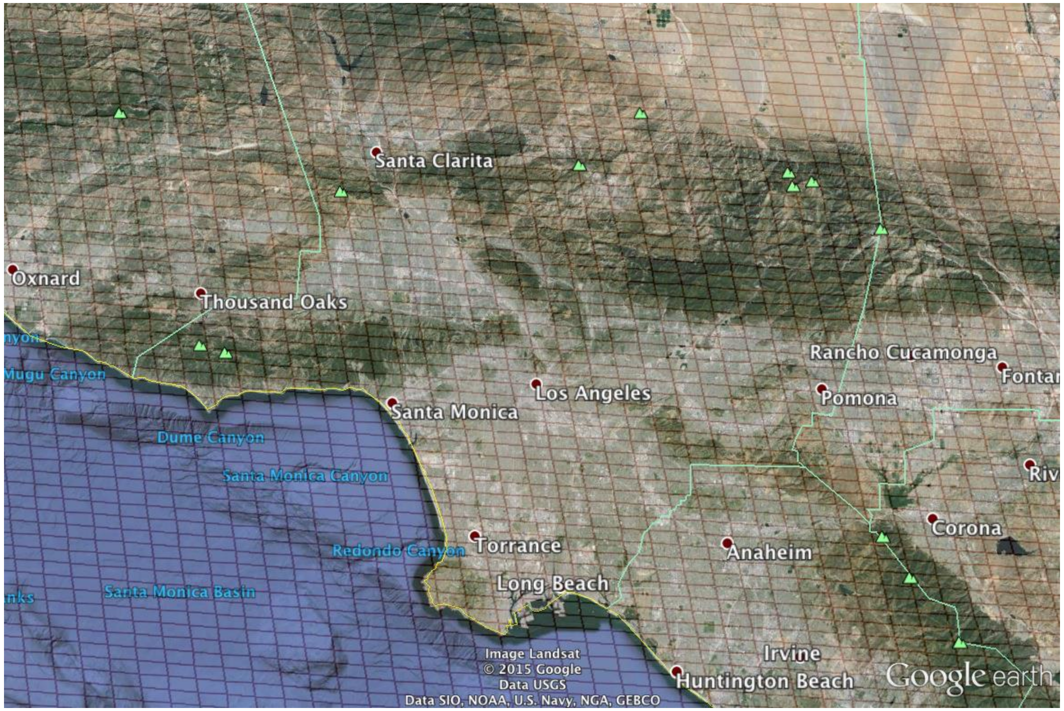
Yuzhong Zhang, Harvard

What to expect from TEMPO?

Instrument is built and in storage
Waiting for ride in 2020-2022

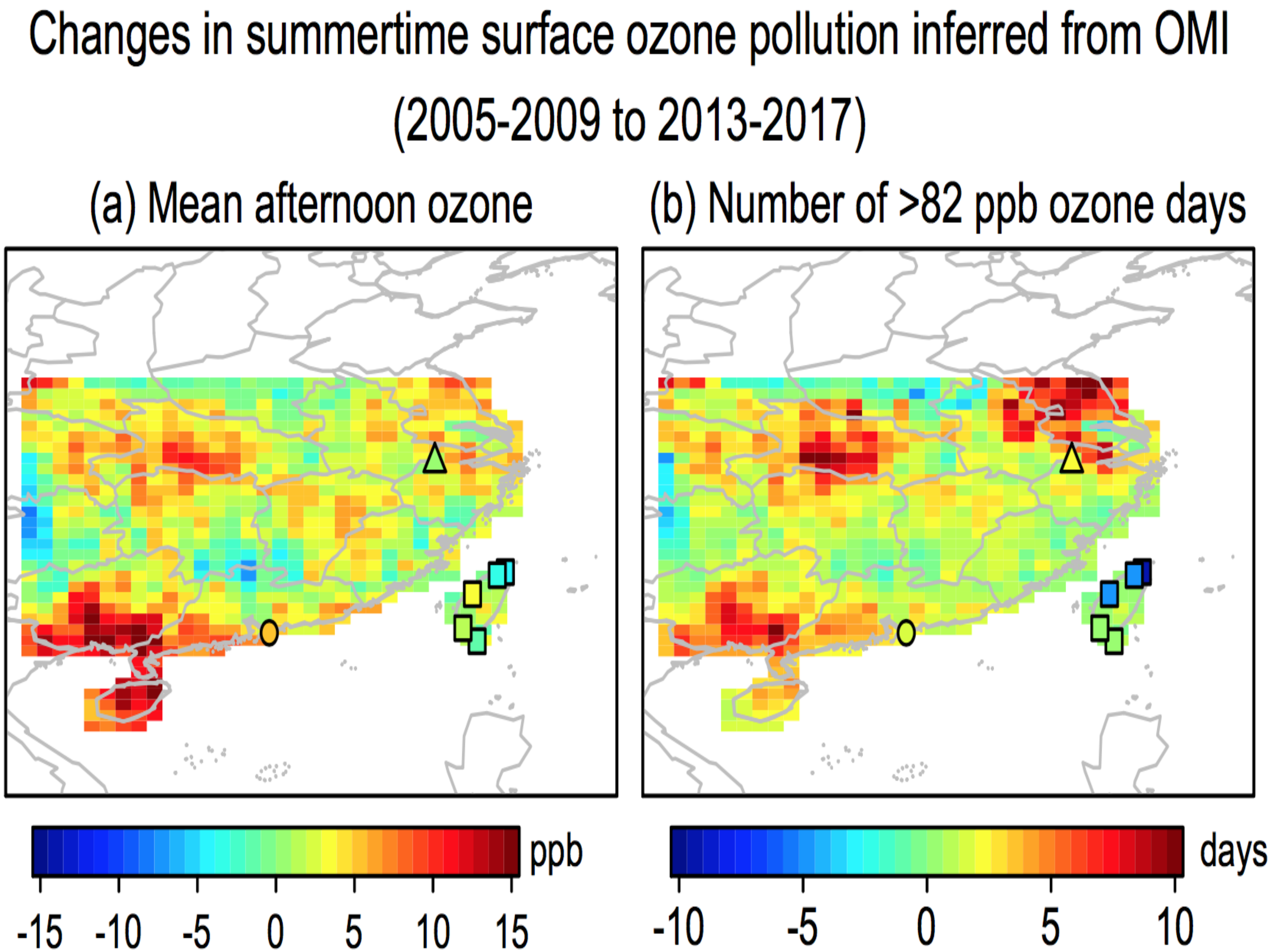


Geostationary orbit, 2x5 km^2 pixels over N. America,
hourly frequency



Spectral bands: 290-490 + 540-740 nm
Species: ozone (including 2-level vertical profile), NO_2, formaldehyde, SO_2

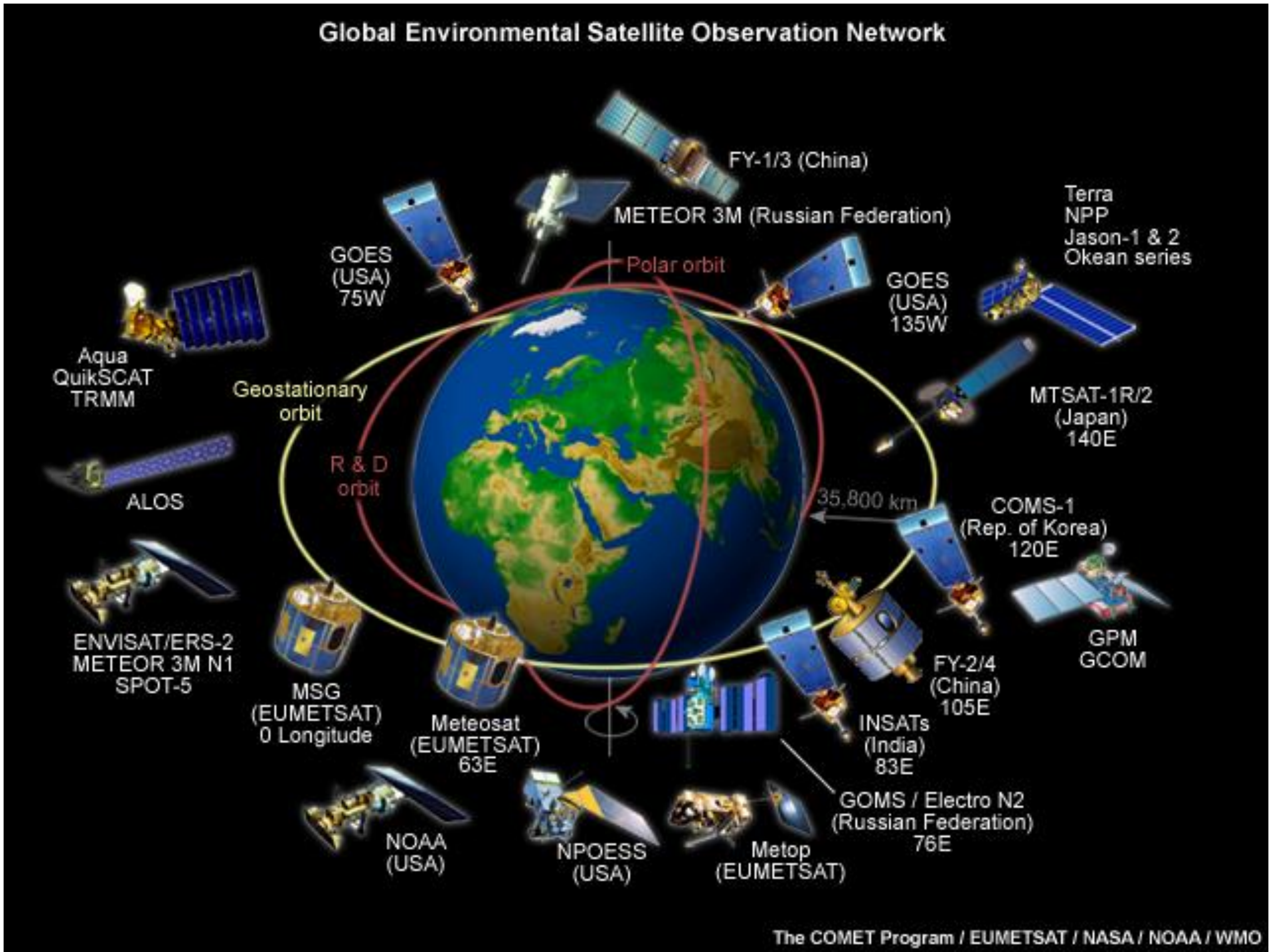
Using OMI to infer long-term trends of surface ozone in China



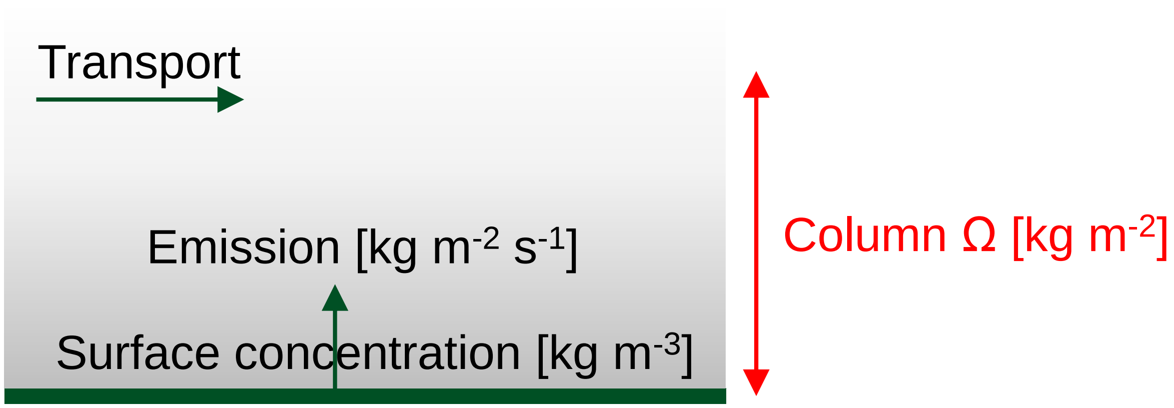
Symbols:
long-term stations

Shen et al., ACPD 2018

Satellites have transformed Earth Science from data-poor to data-rich over past 30 years



Why observe air pollution from space?



- Map surface concentrations (data assimilation)
- Infer emissions (inversion)
- Identify hotspots
- Monitor trends
- Inform air pollution meteorology: long-range transport, mixing depths…