

# Taking a wider view of NO<sub>2</sub> pollution: Estimating NO<sub>2</sub>'s health impacts from local to global scales

Susan Anenberg and Dan Goldberg (George Washington University)  
Michael Brauer (Institute for Health Metrics and Evaluation)

Additional support from the Health Effects Institute

[sanenberg@gwu.edu](mailto:sanenberg@gwu.edu)

**HAQAST2020**  
**WEBINAR SERIES**



# Speakers

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Susan Anenberg, PhD  
George Washington University



Michael Brauer, PhD  
Institute for Health Metrics and  
Evaluation  
University of British Columbia



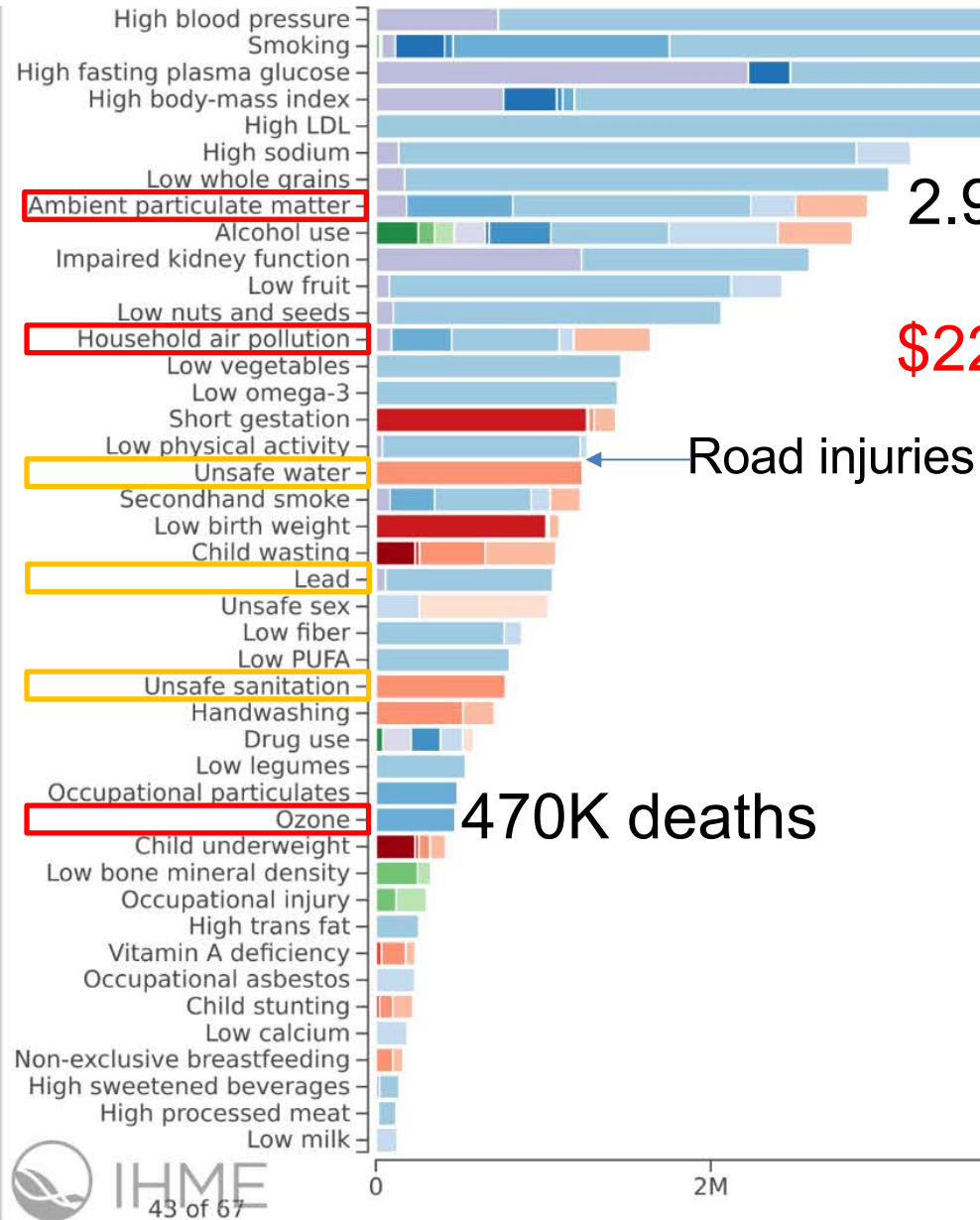
Dan Goldberg, PhD  
George Washington University  
Argonne National Laboratory

# Agenda

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- Overview of the Global Burden of Disease and air pollution
- Estimating NO<sub>2</sub> disease burdens from local to global scales
- Satellite remote sensing of NO<sub>2</sub> using OMI and TROPOMI
- Questions

# Air pollution is a major risk factor for global health



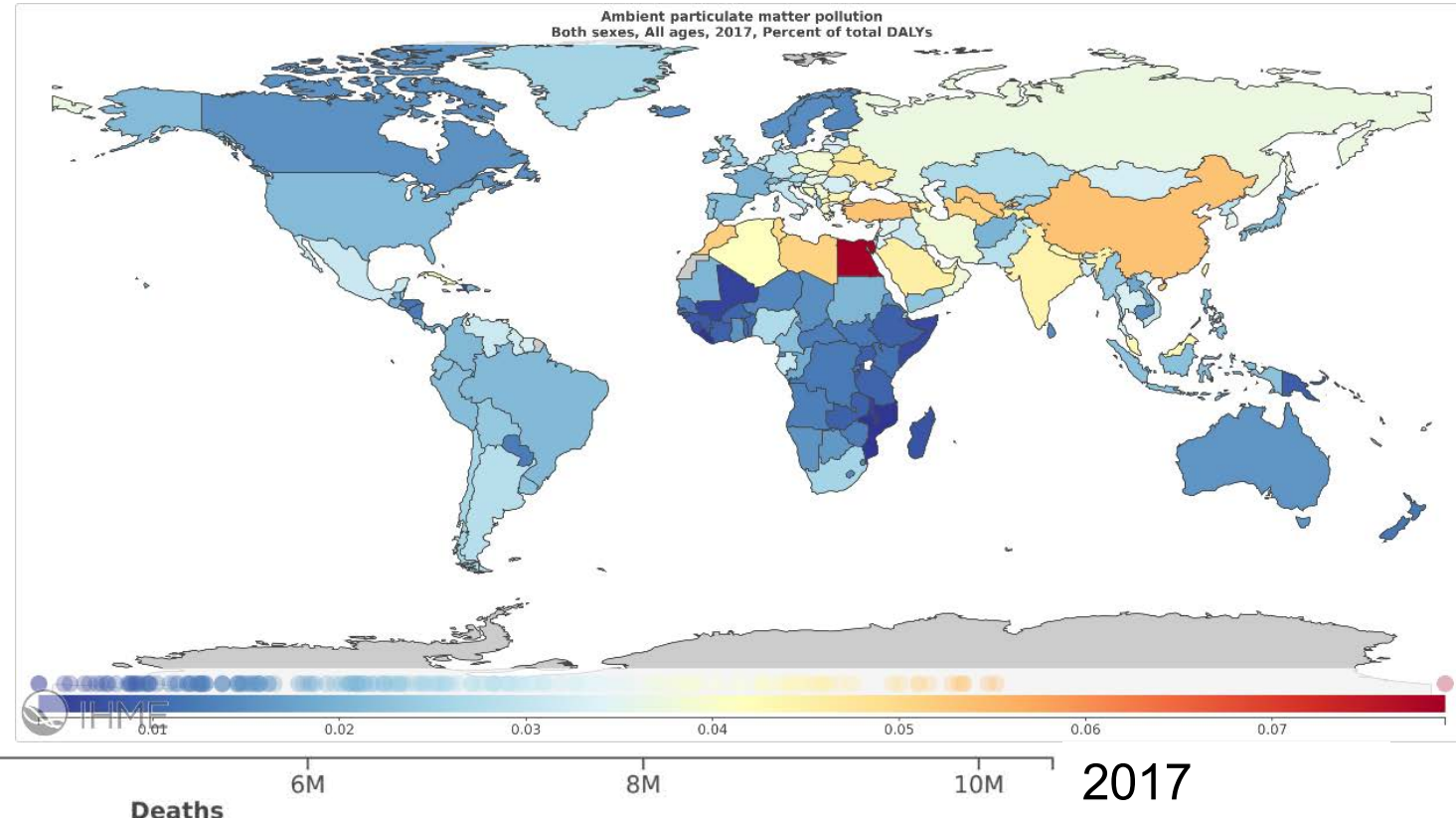
2.9 M deaths ~9% of all deaths

\$5 trillion/yr welfare losses

\$225 billion/yr lost labour income

Road injuries

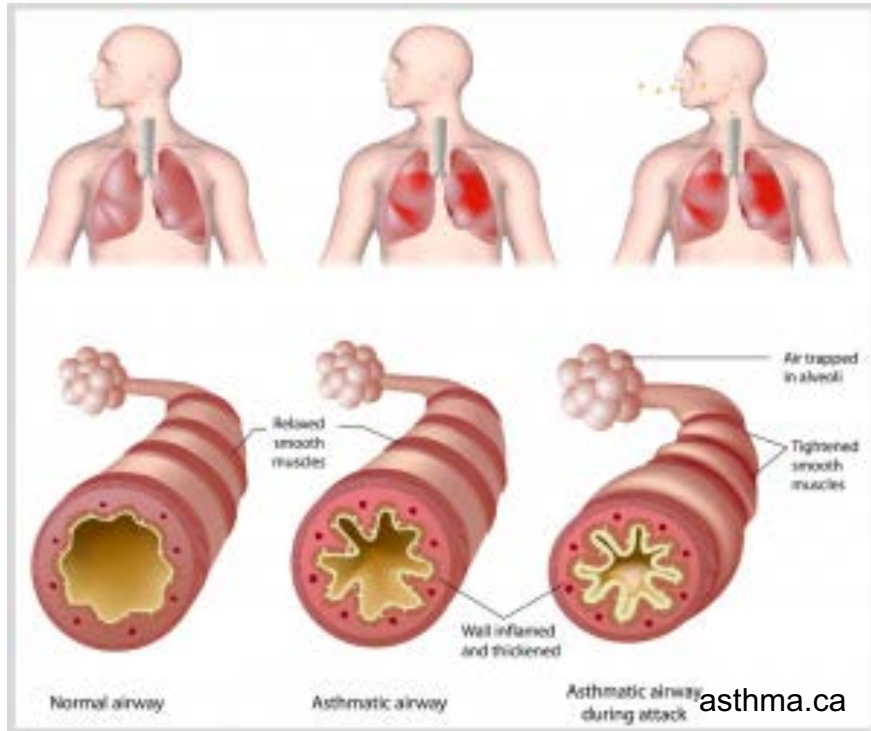
470K deaths





# What's missing?

- Current air pollution risks ( $\text{PM}_{2.5}$ ,  $\text{O}_3$ ) don't fully characterize urban air pollution (especially related to motor vehicle exhaust)
- Currently, no accounting for impacts on asthma



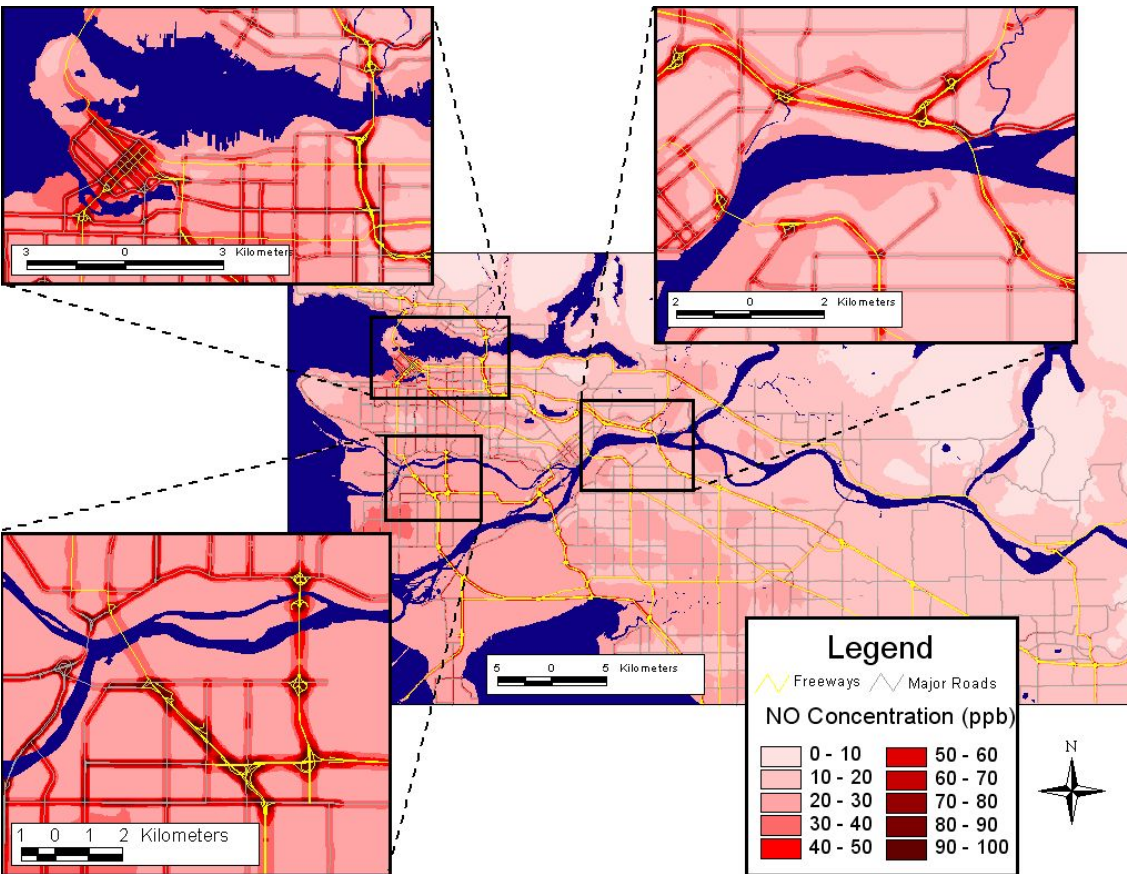
## Four of world's biggest cities to ban diesel cars from their centres

Paris, Madrid, Athens and Mexico City will ban the most polluting cars and vans by 2025 to tackle air pollution

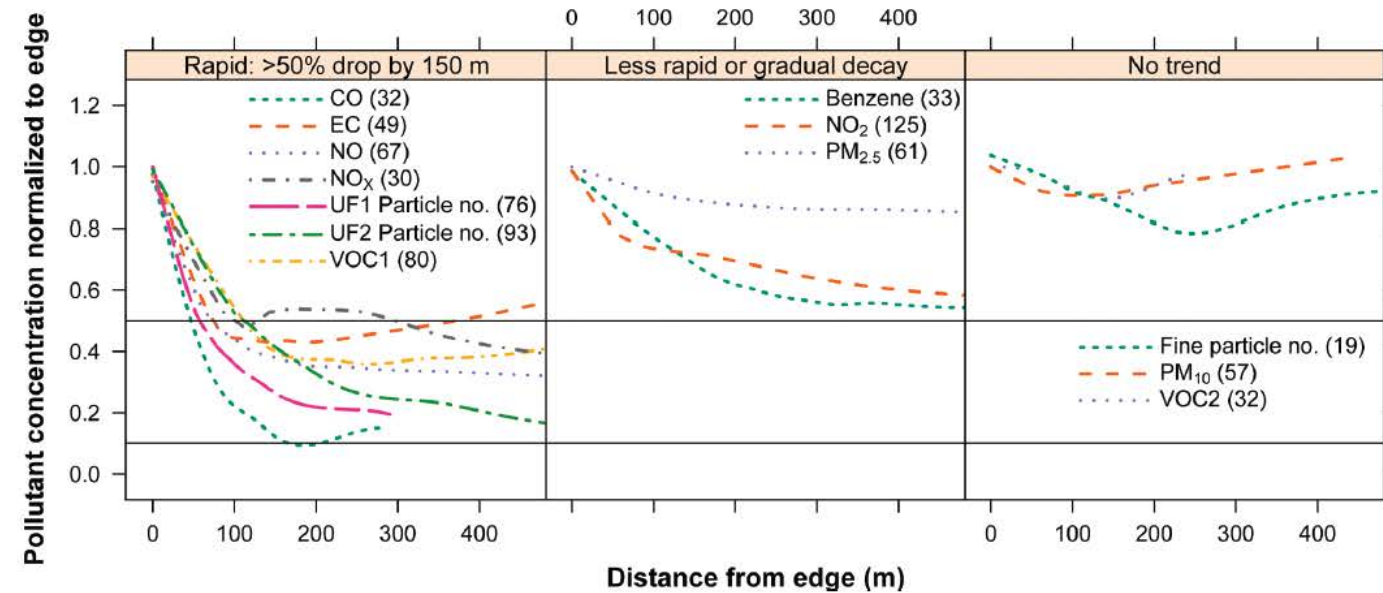


Cars sit in traffic in Mexico City, Mexico. Photograph: Brett Gundlock/Getty Images

# Traffic-related air pollution (TRAP)



Henderson SB et al. Environmental Science and Technology. 2007; 41 (7):2422 -2428



Karner et al. (2010) Environ. Sci. Technol. 44, 5334

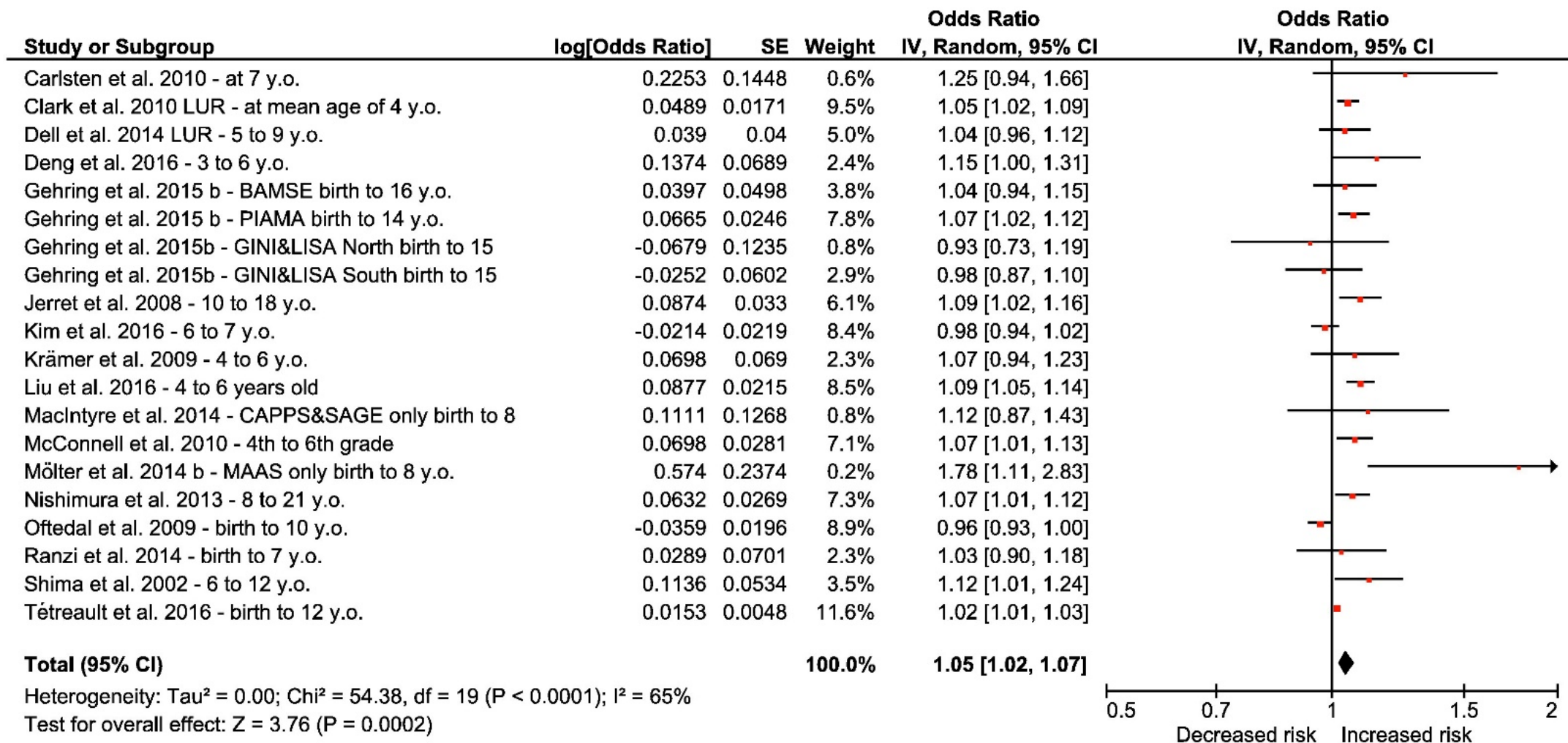
**Traffic influence zones** (<500m from highway or <100m from major road)

# Background

- Multiple meta analyses indicate associations between TRAP exposure, as characterized by high resolution nitrogen dioxide ( $\text{NO}_2$ ), and pediatric asthma.



# NO<sub>2</sub> and asthma



(per 4 µg/m<sup>3</sup>; birth – 21 yrs)

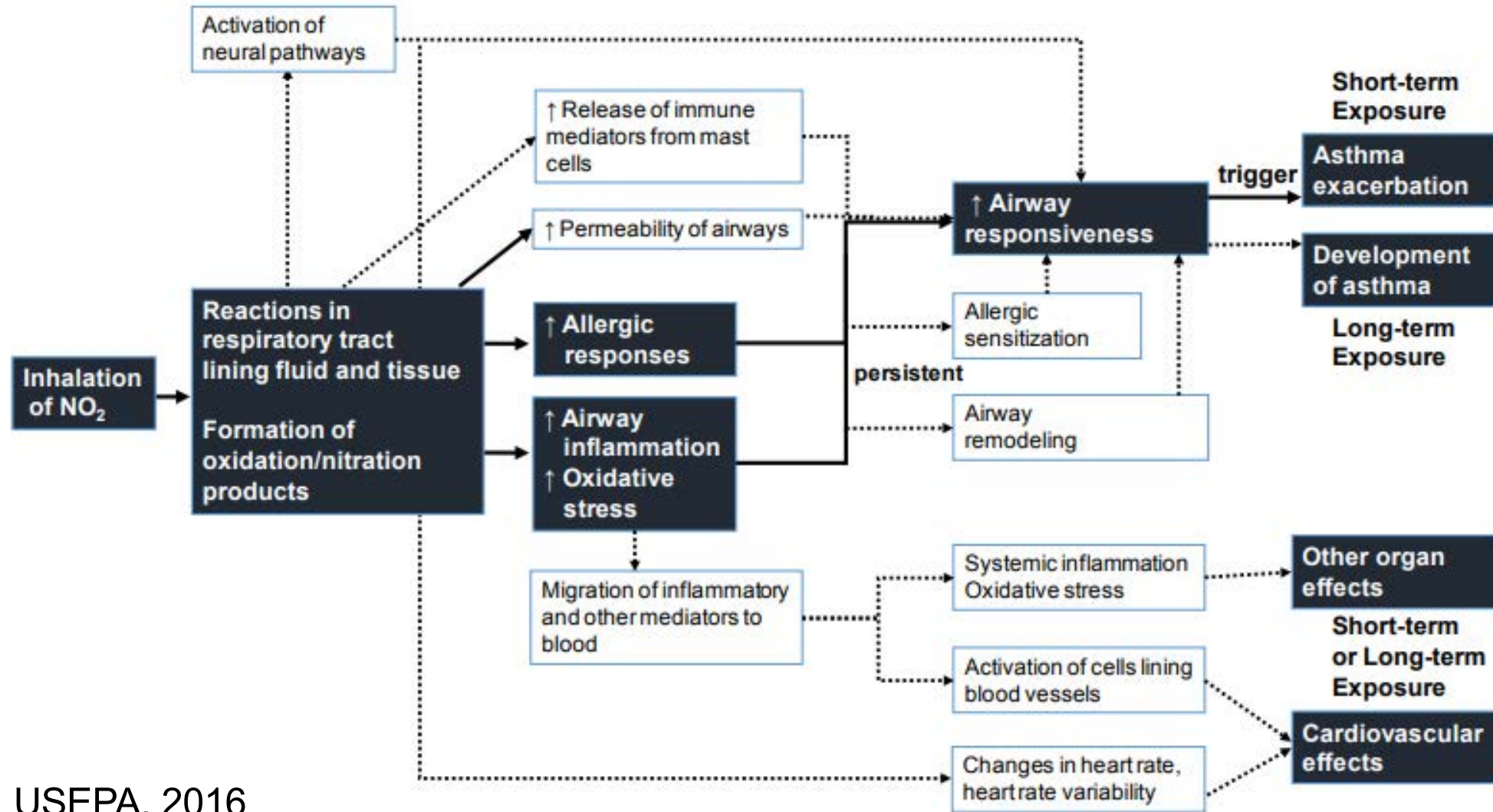
Khreis H, et al. Environ Int. 2017. doi: 10.1016/j.envint.2016.11.012;



# Background

- Multiple meta analyses indicate associations between TRAP exposure, as characterized by high resolution nitrogen dioxide ( $\text{NO}_2$ ), and pediatric asthma.
  - Biological plausibility

# Biological Pathways



USEPA, 2016



# Background

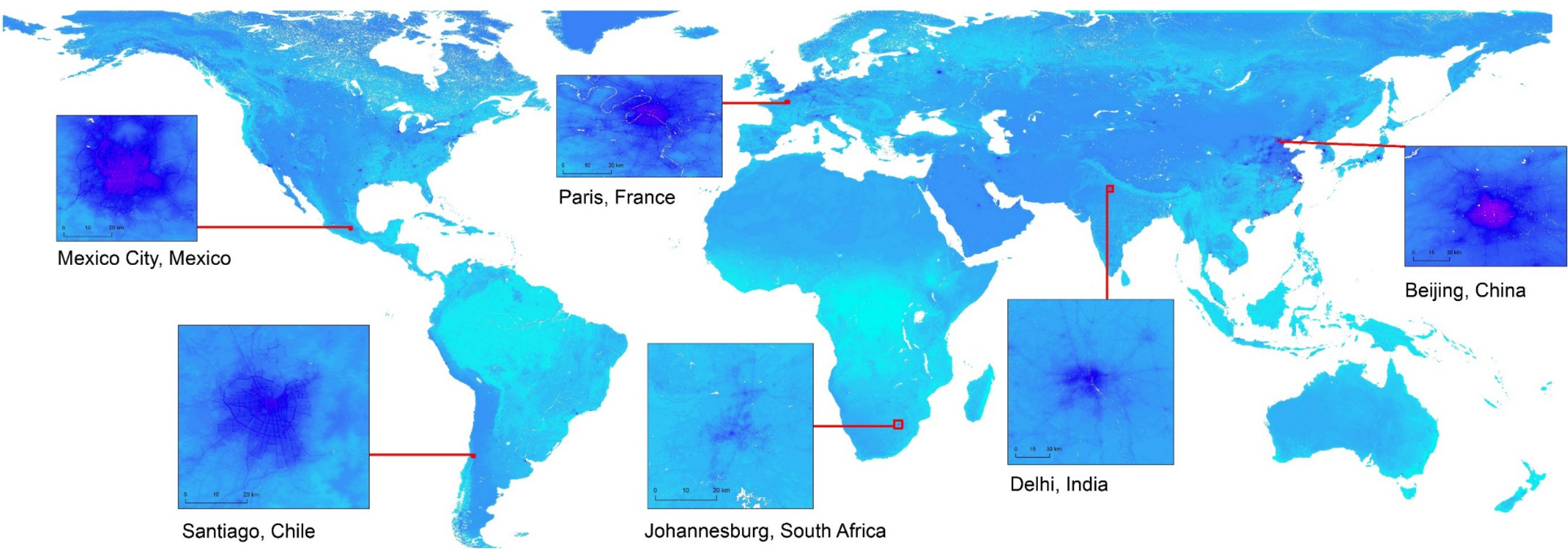
- Multiple meta analyses indicate associations between TRAP exposure, as characterized by high resolution nitrogen dioxide ( $\text{NO}_2$ ), and pediatric asthma.
  - Biological plausibility
  - US EPA, 2016; Health Canada, 2016: **Likely a causal** relationship between long-term  $\text{NO}_2$  exposure and pediatric asthma development.
- Global exposure estimation at required spatial resolution

# Background

- Multiple meta analyses indicate associations between TRAP exposure, as characterized by high resolution nitrogen dioxide ( $\text{NO}_2$ ), and pediatric asthma.
  - Biological plausibility
  - US EPA, 2016; Health Canada, 2016: **Likely a causal** relationship between long-term  $\text{NO}_2$  exposure and pediatric asthma development.
- Global exposure estimation at required spatial resolution



# Exposure: Global high resolution (100m) NO<sub>2</sub> model



Larkin A, Geddes J, Martin RV, Xiao Q, Liu Y, Marshall JD, Brauer M, Hystad P. A Global Land Use Regression Model for Nitrogen Dioxide Air Pollution. Environmental Science & Technology. 2017



# Estimating global NO<sub>2</sub> disease burdens

## Research

A Section 508-compliant HTML version of this article is available at <https://doi.org/10.1289/EHP3766>.

## Estimates of the Global Burden of Ambient PM<sub>2.5</sub>, Ozone, and NO<sub>2</sub> on Asthma Incidence and Emergency Room Visits

Susan C. Anenberg,<sup>1</sup> Doven K. Henge,<sup>2</sup> Veronica Tinney,<sup>1</sup> Patrick L. Kinney,<sup>3</sup> Willem Raich,<sup>4</sup> Neal Fann,<sup>5</sup> Chris S. Malley,<sup>6</sup> Henry Roman,<sup>4</sup> Lok Lamsal,<sup>7</sup> Bryan Duncan,<sup>8</sup> Randall V. Martin,<sup>9,10</sup> Aaron van Donkelaar,<sup>1</sup> Michael Brauer,<sup>10,11</sup> Ruth Doherty,<sup>12</sup> Jan Eilof Jonson,<sup>13</sup> Yanko Davila,<sup>2</sup> Kengo Sudo,<sup>14,15</sup> and Johan C.J. Kuylenstierna<sup>6</sup>

<sup>1</sup>Milken Institute School of Public Health, George Washington University, Washington, District of Columbia, USA  
<sup>2</sup>University of Colorado Boulder, Boulder, Colorado, USA  
<sup>3</sup>School of Public Health, Boston University, Boston, Massachusetts, USA  
<sup>4</sup>Industrial Economics, Inc., Cambridge, Massachusetts, USA  
<sup>5</sup>Office of Air and Radiation, U.S. Environmental Protection Agency, Research Triangle Park, North Carolina, USA  
<sup>6</sup>Stockholm Environment Institute, York, UK  
<sup>7</sup>NASA Goddard Space Flight Center, Greenbelt, Maryland, USA  
<sup>8</sup>Dalhousie University, Halifax, Nova Scotia, Canada  
<sup>9</sup>Sinclairian Astrophysical Observatory, Cambridge, Massachusetts, USA  
<sup>10</sup>School of Population and Public Health, University of British Columbia, Vancouver, British Columbia, Canada  
<sup>11</sup>Institute for Health Metrics and Evaluation, University of Washington, Seattle, Washington, USA  
<sup>12</sup>University of Edinburgh, Edinburgh, UK  
<sup>13</sup>Norwegian Meteorological Institute, Oslo, Norway  
<sup>14</sup>Graduate School of Environmental Studies, Nagoya University, Nagoya, Japan  
<sup>15</sup>Japan Agency for Marine-Earth Science and Technology (JAMSTEC), Yokohama, Japan

**BACKGROUND:** Asthma is the most prevalent chronic respiratory disease worldwide, affecting 358 million people in 2015. Ambient air pollution is a major risk factor for asthma and may also contribute to new-onset asthma.

**OBJECTIVES:** We aimed to estimate the number of asthma emergency room visits and new-onset asthma cases globally attributable to ambient air pollution (PM<sub>2.5</sub>, ozone, and nitrogen dioxide (NO<sub>2</sub>) concentrations).

**METHODS:** We used epidemiological health impact functions combined with data describing population, baseline asthma incidence, and pollutant concentrations. We constructed a new dataset of national and regional emergency room visit rates among people with asthma.

**RESULTS:** We estimated that 9–23 million and 5–10 million annual asthma emergency room visits globally in 2015 could be attributed to PM<sub>2.5</sub>, respectively, representing 8–20% and 4–9% of the annual number of global visits, respectively. The range reflects the uncertainty in risk estimates from different epidemiological meta-analyses. Anthropogenic emissions were responsible for ~37% and 73% of ozone and PM<sub>2.5</sub> impacts, respectively. Remaining impacts were attributable to naturally occurring ozone precursor emissions (e.g., from vegetation, lightning) and PM<sub>2.5</sub> (e.g., dust, sea salt), though several of these sources are also influenced by humans. The largest impacts were estimated in China and India.

**CONCLUSIONS:** These findings estimate the magnitude of the global asthma burden that could be avoided by reducing ambient air pollution. We also identified key uncertainties and data limitations to be addressed to enable refined estimation. <https://doi.org/10.1289/EHP3766>

## Introduction

Approximately 358 million people worldwide were estimated to have had asthma in 2015 (GBD 2015 Chronic Respiratory Disease Collaborators 2017), including about 14% of the world's children (Global Asthma Network 2014). Asthma prevalence is considered the fourth leading cause of years lived with disability (YLDs) for children ages 5–14 globally, and the 16th leading cause of YLDs for all ages (GBD 2015 Chronic Respiratory Disease Collaborators 2017). Asthma is among the top causes of YLDs among children ages 5–14 across all sociodemographic index categories, affecting both high- and low-income populations. Economic costs are substantial and include both direct (e.g., inpatient care, emergency room visits (ERVs), physician visits, diagnostic tests, and medica-

tion) and indirect costs (e.g., school and work days lost; Bahaduri et al. 2009). Epidemiological and clinical experimental studies have shown over decades that exposure to air pollution is a key risk factor for asthma exacerbation and may also contribute to new-onset asthma (Giamberini and Balme 2014; Toskala and Kennedy 2015).

Ambient fine particulate matter (PM<sub>2.5</sub>) exposure, currently considered the leading environmental risk factor globally, is estimated to be associated with 4.2 million premature deaths and 103 million Disability Adjusted Life Years (DALYs; YLDs plus Years of Life Lost) in 2015 (Cohen et al. 2017). Updated for 2016, the PM<sub>2.5</sub> disease burden estimate includes 4.1 million deaths and 106 million DALYs (GBD 2016 Risk Factors Collaborators 2017). This global burden attributable to PM<sub>2.5</sub> accounts for 27% of all DALYs from chronic obstructive pulmonary disease (COPD; an additional 6% are attributable to ambient ozone); 20% of those from ischemic heart disease; 16% of those from stroke; 17% of those from tracheal, bronchus, and lung cancer; and 31% from child acute lower respiratory infections (GBD 2016 Risk Factors Collaborators 2017). The Global Burden of Disease Study 2016 estimated that smoking and occupational asbestosis were each responsible for 10% of DALYs from asthma in 2016 (GBD 2015 Chronic Respiratory Disease Collaborators 2017).

The contribution of air pollution to asthma exacerbation and new asthma incidence remains unquantified and has not been included in global burden of disease studies (Cohen et al. 2017;

Surface NO<sub>2</sub> from OMI satellite retrieval plus GMI-Replay model

- 0.1° resolution
- 1:45pm → 24hr avg

Surface NO<sub>2</sub> from land use regression

- 100m resolution
- Average 2010-2012
- GOME2 and SCIAMACHY satellite retrievals

## Global, national, and urban burdens of paediatric asthma incidence attributable to ambient NO<sub>2</sub> pollution: estimates from global datasets

Pattarun Achakulwinat, Michael Brauer, Perry Hystad, Susan C. Anenberg

**Summary** Background Paediatric asthma incidence is associated with exposure to traffic-related air pollution (TRAP), but the TRAP-attributable burden remains poorly quantified. Nitrogen dioxide (NO<sub>2</sub>) is a major component and common proxy of TRAP. In this study, we estimated the annual global number of new paediatric asthma cases attributable to NO<sub>2</sub> exposure at a resolution sufficient to resolve intra-urban exposure gradients.

**Methods** We obtained 2015 country-specific and age-group-specific asthma incidence rates from the Institute for Health Metrics and Evaluation for 194 countries and 2015 population counts at a spatial resolution of 250 × 250 m from the Global Human Settlement population grid. We used 2010–12 annual average surface NO<sub>2</sub> concentrations derived from land-use regression at a resolution of 100 × 100 m, and we derived concentration-response functions from relative risk estimates reported in a multinational meta-analysis. We then estimated the NO<sub>2</sub>-attributable burden of asthma incidence in children aged 1–18 years in 194 countries and 125 major cities at a resolution of 250 × 250 m.

**Findings** Globally, we estimated that 4.0 million (95% uncertainty interval [UI] 1.8–5.2) new paediatric asthma cases could be attributable to NO<sub>2</sub> pollution annually; 64% of these occur in urban centres. This burden accounts for 13% (6–16) of global incidence. Regionally, the greatest burdens of new asthma cases associated with NO<sub>2</sub> exposure were estimated for Andean Latin America (340 cases per year, 95% UI 150–440), high-income Asia Pacific (300, 140–370). Within cities, the greatest burdens of new asthma cases attributable to NO<sub>2</sub> pollution ranged from 5.6% (95% UI 2.4–7.4) in Ordu, China. This contribution exceeded 20% of new asthma cases in 92 cities. We also estimated that the burden of paediatric asthma incidence attributable to NO<sub>2</sub> exposure occurred in areas with annual average NO<sub>2</sub> concentrations lower than the WHO guideline of 21 parts per billion.

Reducing NO<sub>2</sub> exposure could help prevent a substantial portion of new paediatric asthma cases developing countries, and especially in urban areas. Traffic emissions should be a target for policy. The adequacy of the WHO guideline for ambient NO<sub>2</sub> concentrations might need to be re-evaluated.

non University.

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Asthma prevalence has increased globally, and asthma is now the most common chronic disease among children in many countries, and the variability of TRAP mixture appears to be well characterised by NO<sub>2</sub>.<sup>1,2</sup> Results from four meta-analyses of TRAP exposure and paediatric asthma incidence all indicated consistent associations with NO<sub>2</sub>, but results were mixed for associations with fine particulate matter (PM<sub>2.5</sub>; appendix).<sup>3–6</sup> Reviews<sup>7,8</sup> done by the US Environmental Protection Agency and Health Canada, published in 2016, also concluded that the overall evidence indicated that a causal relationship probably exists between TRAP exposure and paediatric asthma incidence.



Lancet Planet Health 2019  
April 10, 2019  
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See Online/Comment  
[http://dx.doi.org/10.1016/S2542-5196\(19\)30046-4](http://dx.doi.org/10.1016/S2542-5196(19)30046-4)

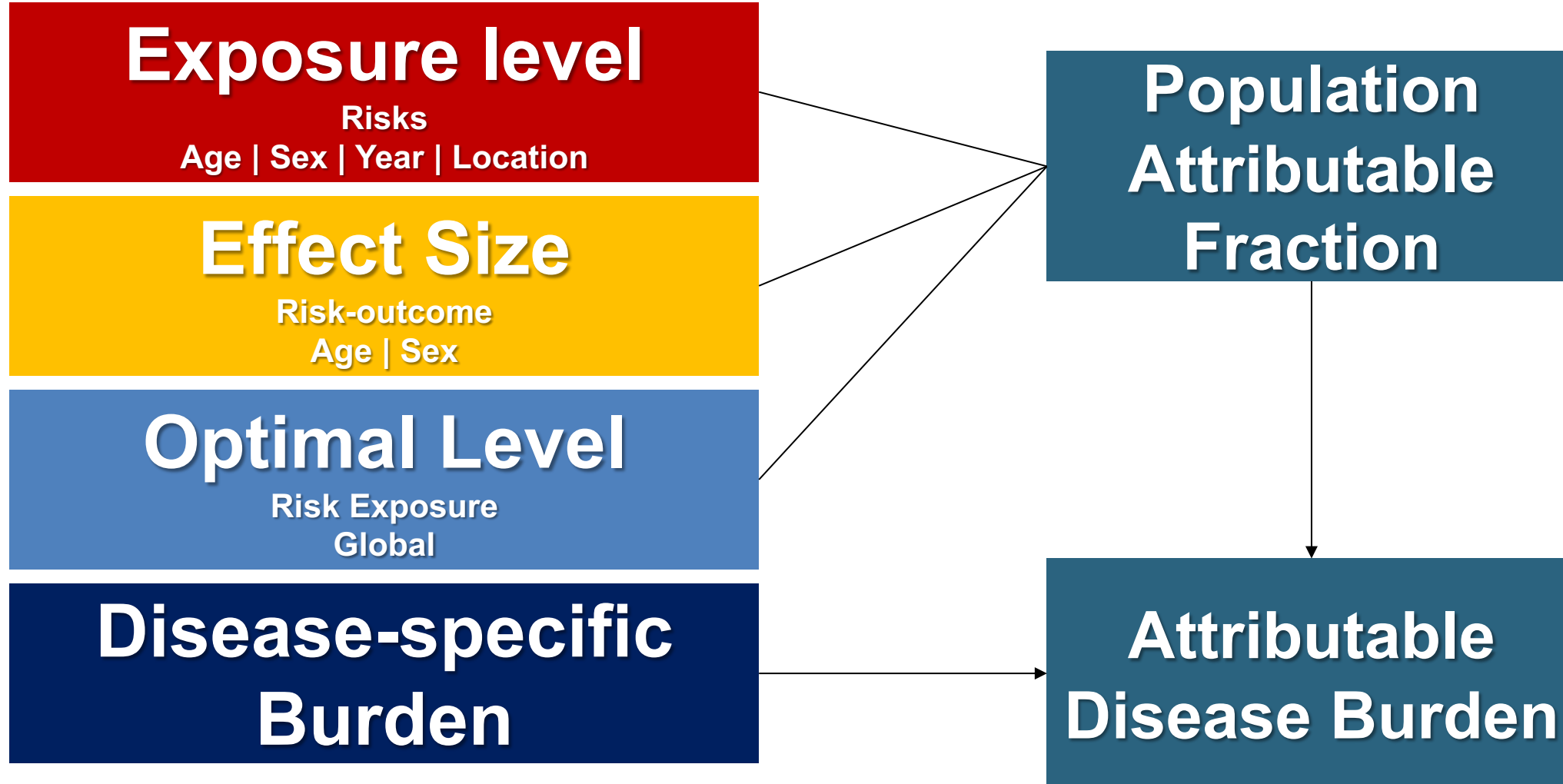
Milken Institute School of Public Health, George Washington University, Washington, DC, USA  
(P. Achakulwinat PhD), School of Population and Public Health, The University of British Columbia, Vancouver, BC, Canada (Prof M. Brauer MD), Institute for Health Metrics and Evaluation, Seattle, WA, USA (Prof M. Brauer), and College of Public Health and Human Sciences, Oregon State University, Corvallis, OR, USA (P. Hystad PhD)

Correspondence to: Dr Susan C. Anenberg, Milken Institute School of Public Health, George Washington University, Washington, DC 20052, USA. [sanenberg@gwu.edu](mailto:sanenberg@gwu.edu)

See Online for appendix

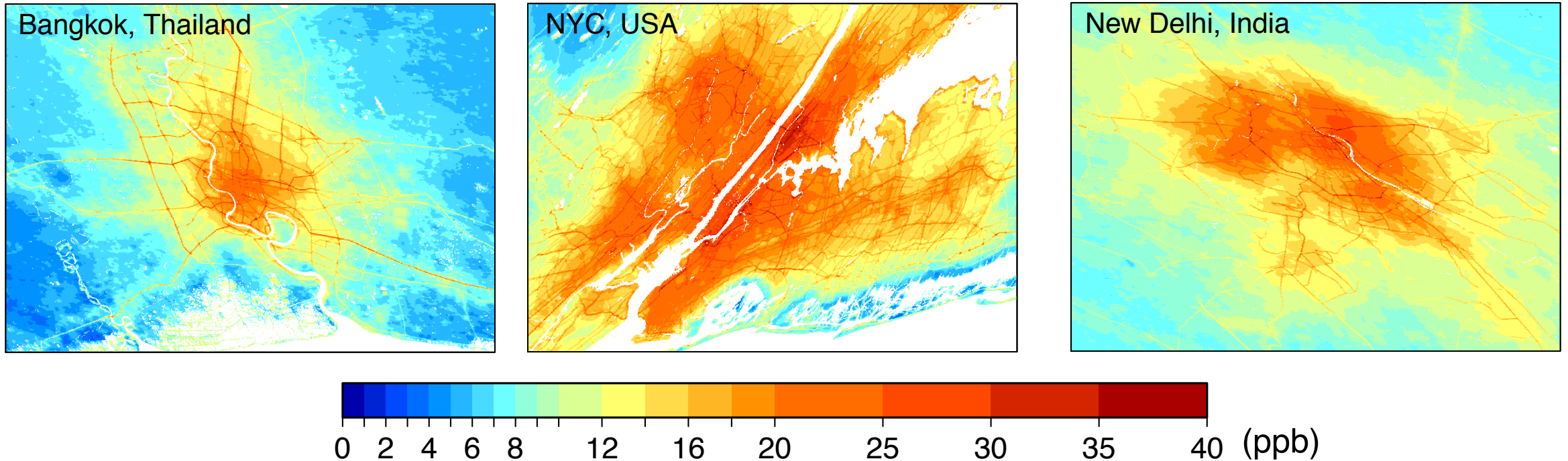


# Estimating (global) disease burden from air pollution



# Methods: Finding global datasets that can resolve intra-city and near-roadway exposures

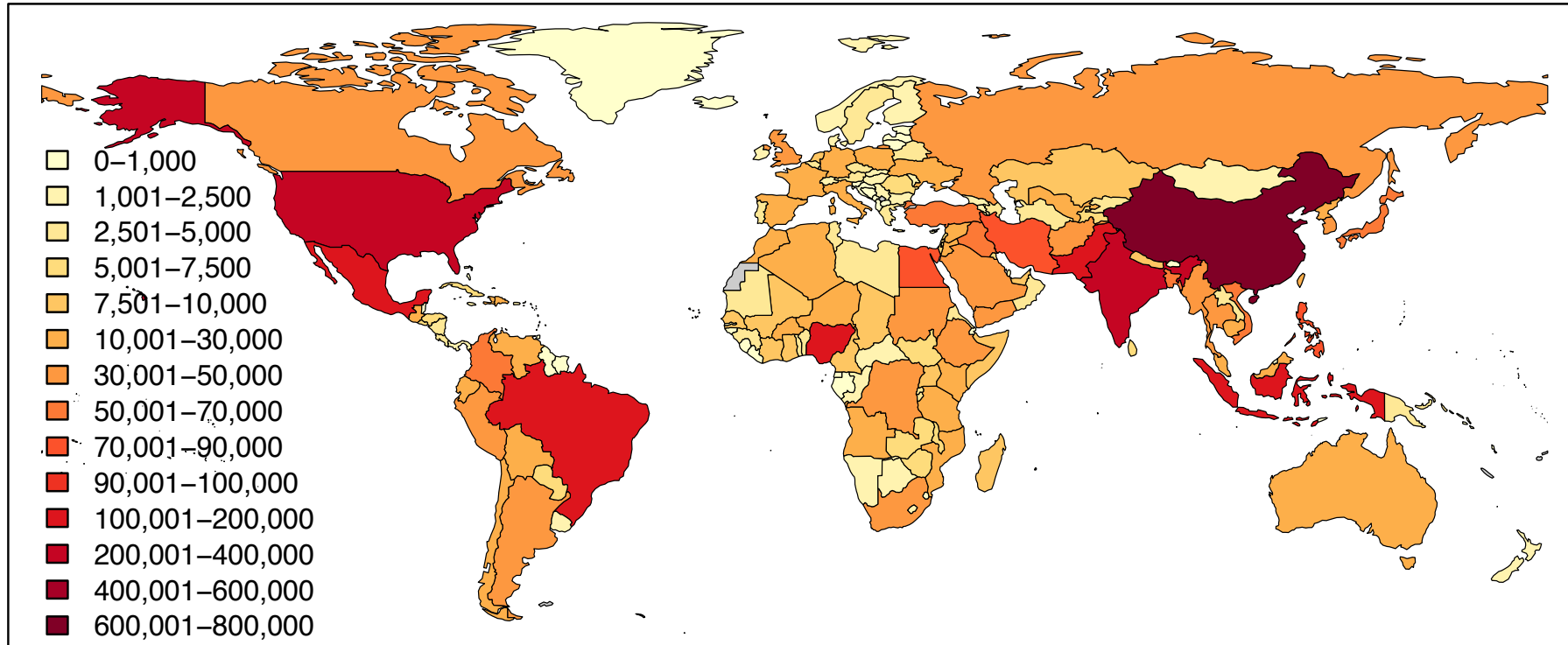
2010-2012 global surface NO<sub>2</sub> modeled by land-use regression at 100m x 100m (Larkin et al., 2017)



Traffic-related NO<sub>2</sub> generally declines to urban background levels at a distance beyond 300-500 m from roadways (HEI, 2010).

**Each year, 4 million (95% UI 1.8-5.2) children developed asthma due to NO<sub>2</sub> pollution, accounting for 13% (6-16) of the global annual burden (2010-2015)**

(a) Number of new asthma cases due to NO<sub>2</sub> exposure

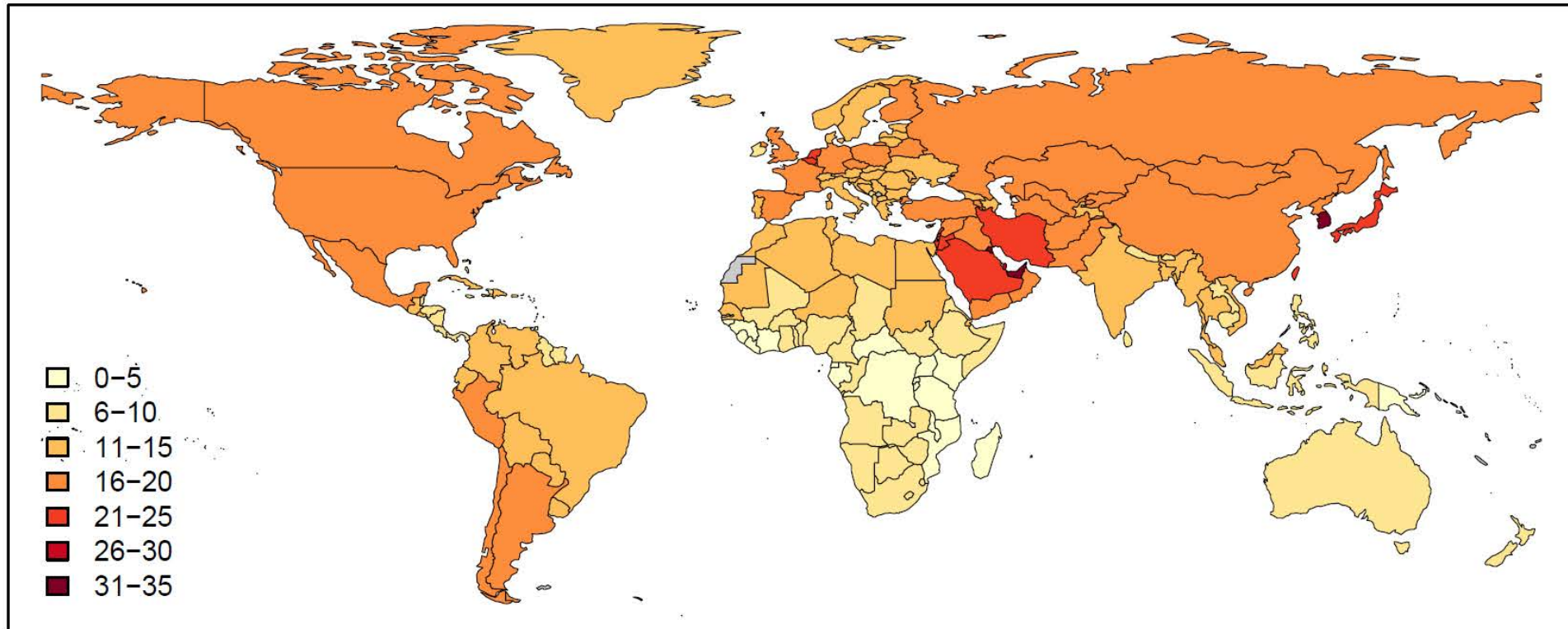


- Top national burdens (attributable cases/year): China (760,000), India (350,000), USA (240,000), Indonesia (160,000)
- We estimate that ~97% of children lived, and ~92% of NO<sub>2</sub>-attributable pediatric asthma incidence occurred, in areas below the current WHO guideline of 21 ppb for annual average NO<sub>2</sub>.



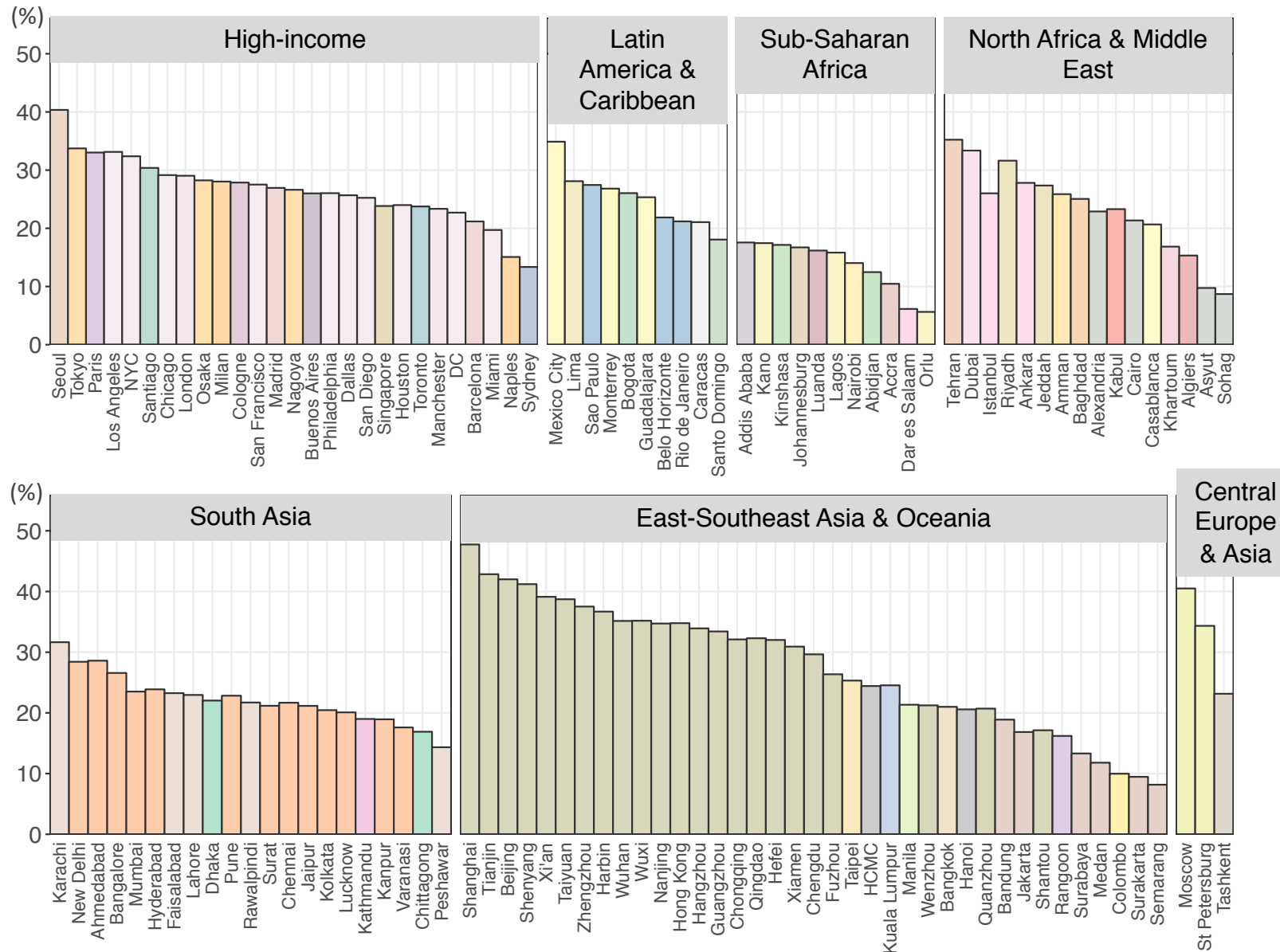
# Spatial pattern of NO<sub>2</sub>-attributable asthma impacts differs from PM<sub>2.5</sub> mortality

(c) Percent of new asthma cases due to NO<sub>2</sub> exposure



Achakulwisut et al., 2019, *Lancet Planetary Health* (2019)

# In both developed and developing cities, NO<sub>2</sub> pollution is an important risk factor for pediatric asthma incidence



Globally, 90% of NO<sub>2</sub>-attributable pediatric asthma incidence occurred in urban centers (including suburban areas)

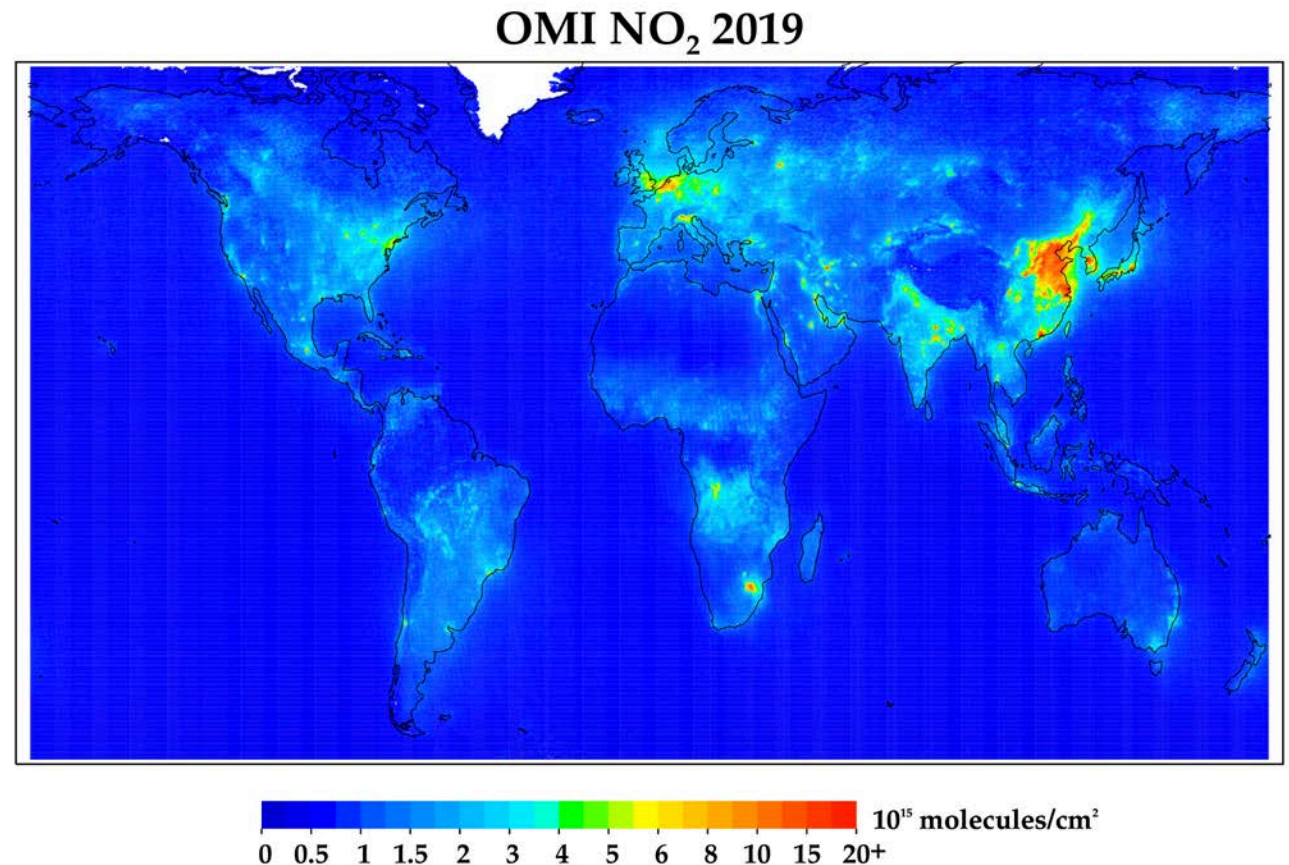
In 125 major cities, the percent of new pediatric asthma cases attributable to NO<sub>2</sub>:

- Ranged from 6% (Orlu, Nigeria) to 48% (Shanghai, China).
- Exceeded 20% in 92 cities, located in both developed and developing countries.

Achakulwisut et al., 2019, *Lancet Planetary Health* (2019)

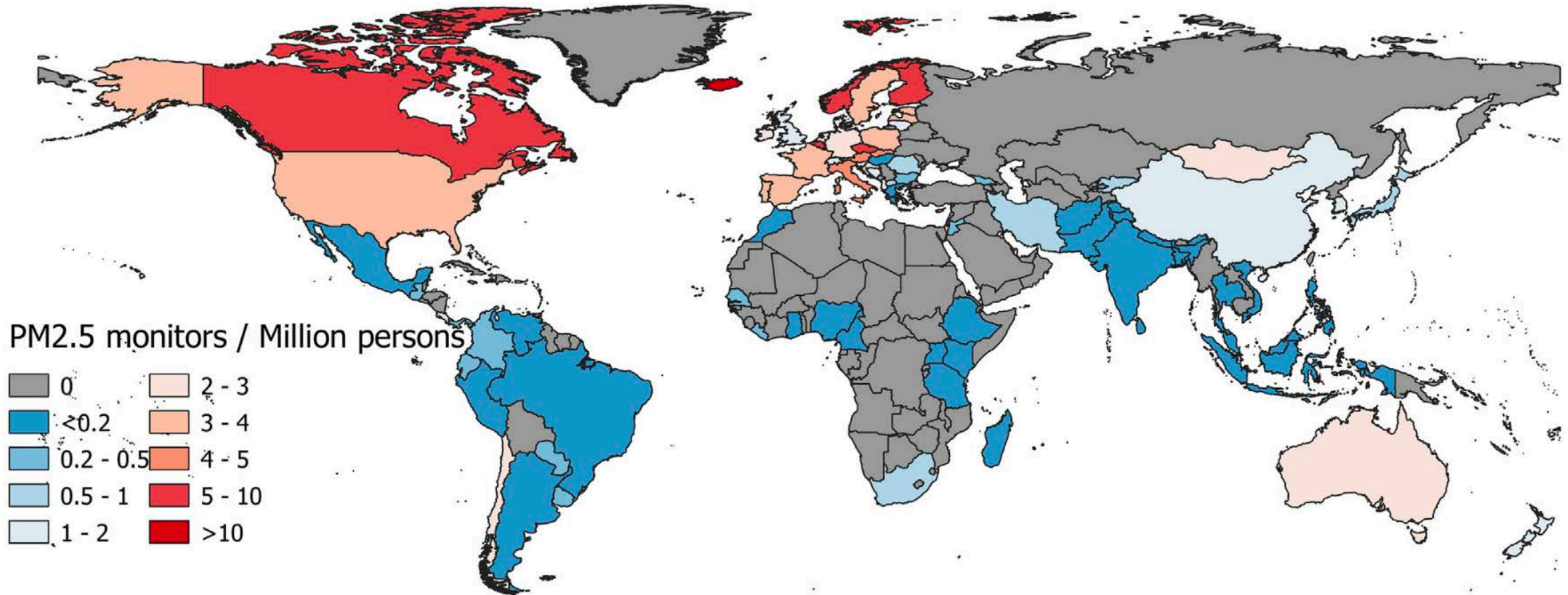
# How can satellites help us improve estimates of the global burden of NO<sub>2</sub> on asthma?

- Consistency with GBD comparative framework
  - Full global coverage
  - Temporal trends
- High spatial resolution
  - Urban vs rural
  - Capture near roadway concentrations





# Number of AQ monitors globally are sparse



**Fig. 1.** Number of PM<sub>2.5</sub> monitors per million inhabitants by country for any of the years 2010–2016.

From Martin et al., 2019: “No one knows which city has the highest concentration of fine particulate matter”

# NO<sub>2</sub> from satellite instruments: 101

Names of the satellite instruments:

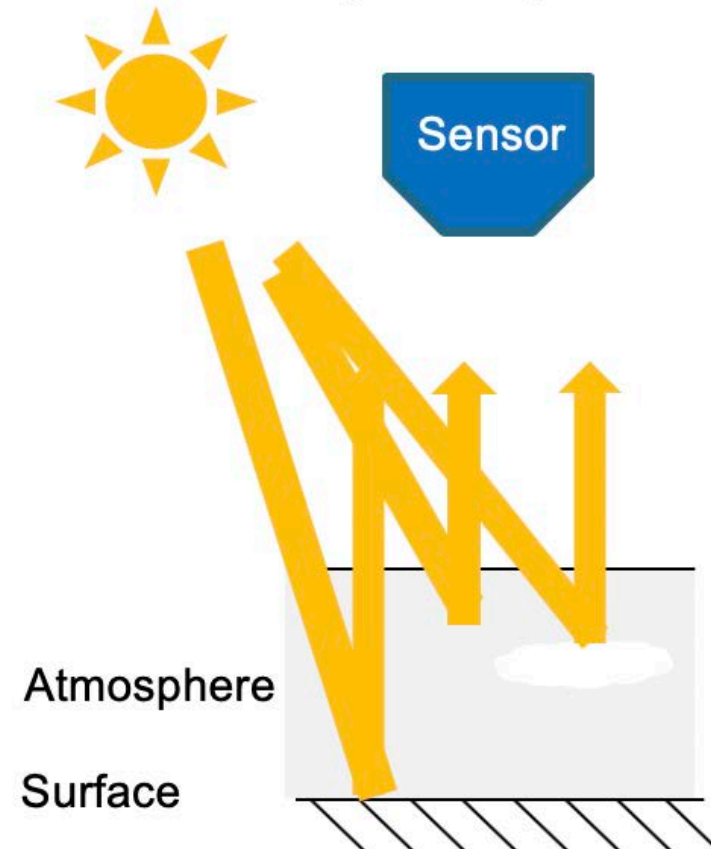
- **OMI** (Ozone Monitoring Instrument) (pixels are  $\sim 13 \times 24 \text{ km}^2$ )
- **TROPOMI** (Tropospheric Monitoring Instrument) (pixels are  $\sim 3.5 \times 5.5 \text{ km}^2$ )

Key points:

- Polar-orbiting; global coverage once per day
- Quantities reported are *column contents* between surface and  $\sim 12 \text{ km}$  in altitude
- Units: molecules per  $\text{cm}^2$
- Measures during the mid-afternoon only ( $\sim 1:30 \text{ PM}$  local time)

## Passive Optical

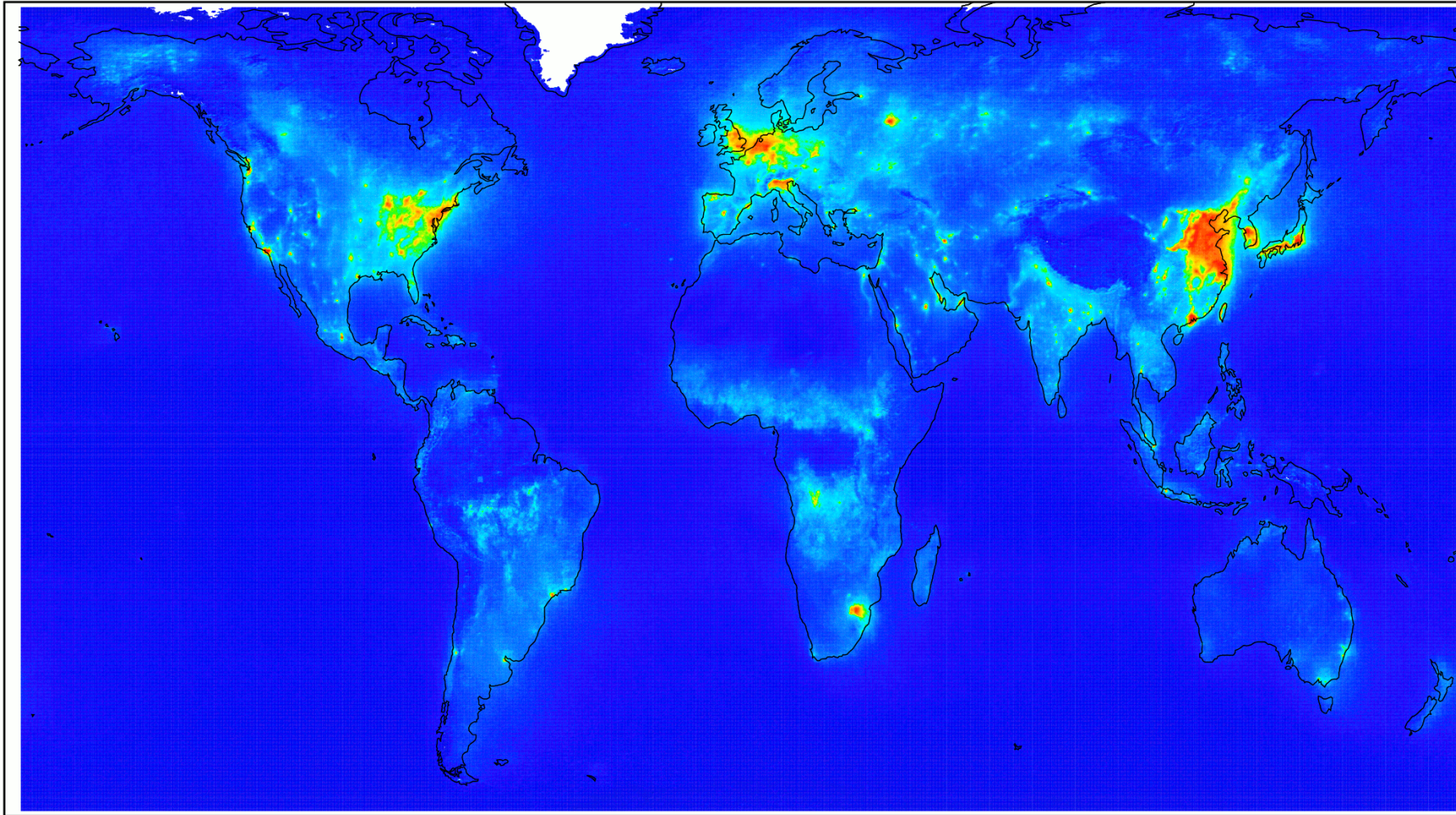
- UV and Visible light
- Daytime only





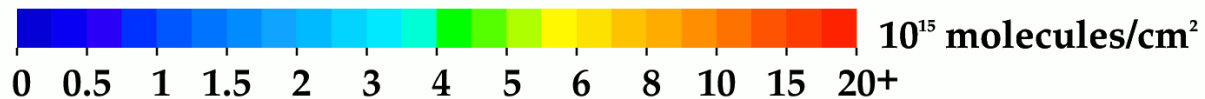
# Trends of NO<sub>2</sub> using satellite (OMI) data

## OMI NO<sub>2</sub> 2005



OMI = Ozone Monitoring Instrument, launched July 2004

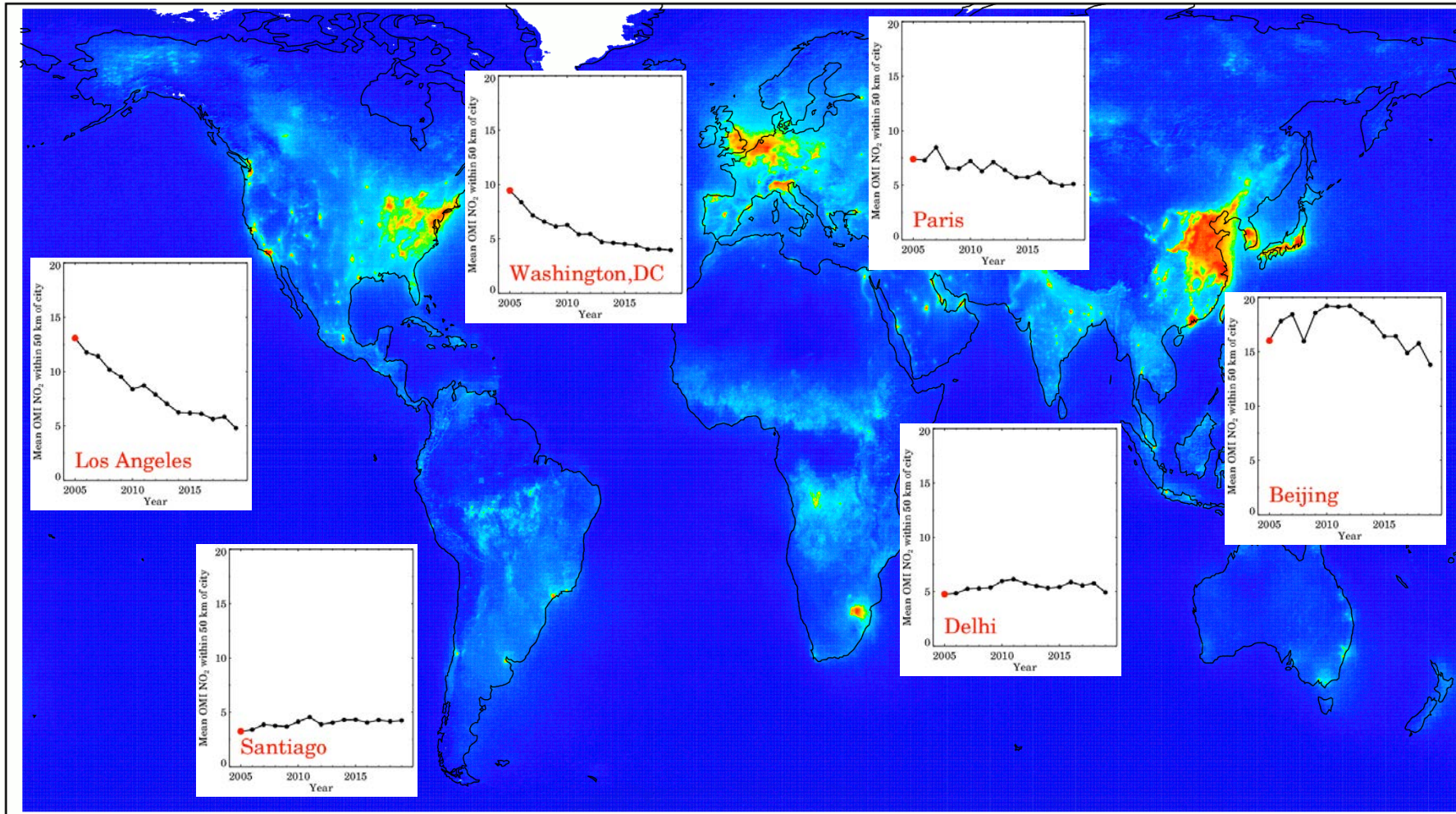
- Largest regional decreases since 2005 are in the United States
- Moderate decreases in Europe
- Increase in China between 2005 and 2012, then decrease since then
- General increases in India (with the exception of Delhi itself)





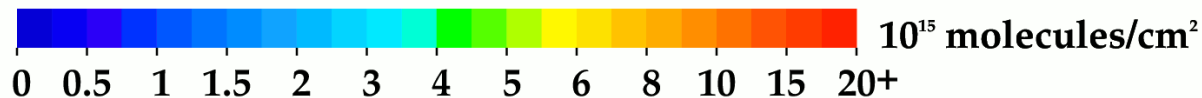
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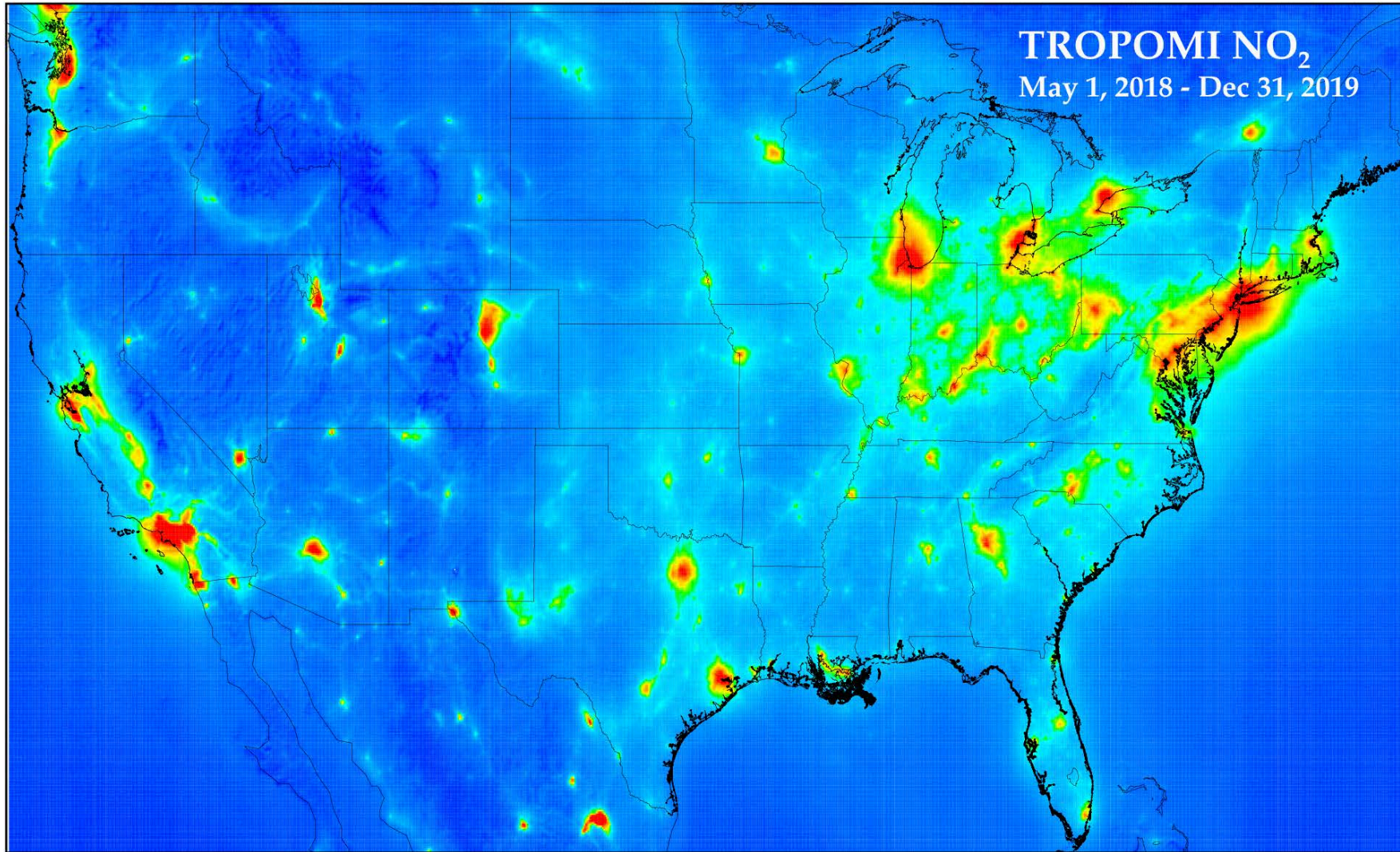
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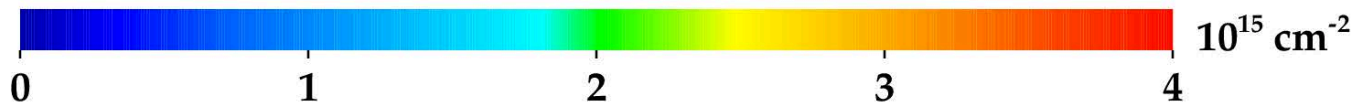


# Using TROPOMI NO<sub>2</sub> to quantify urban/rural gradients



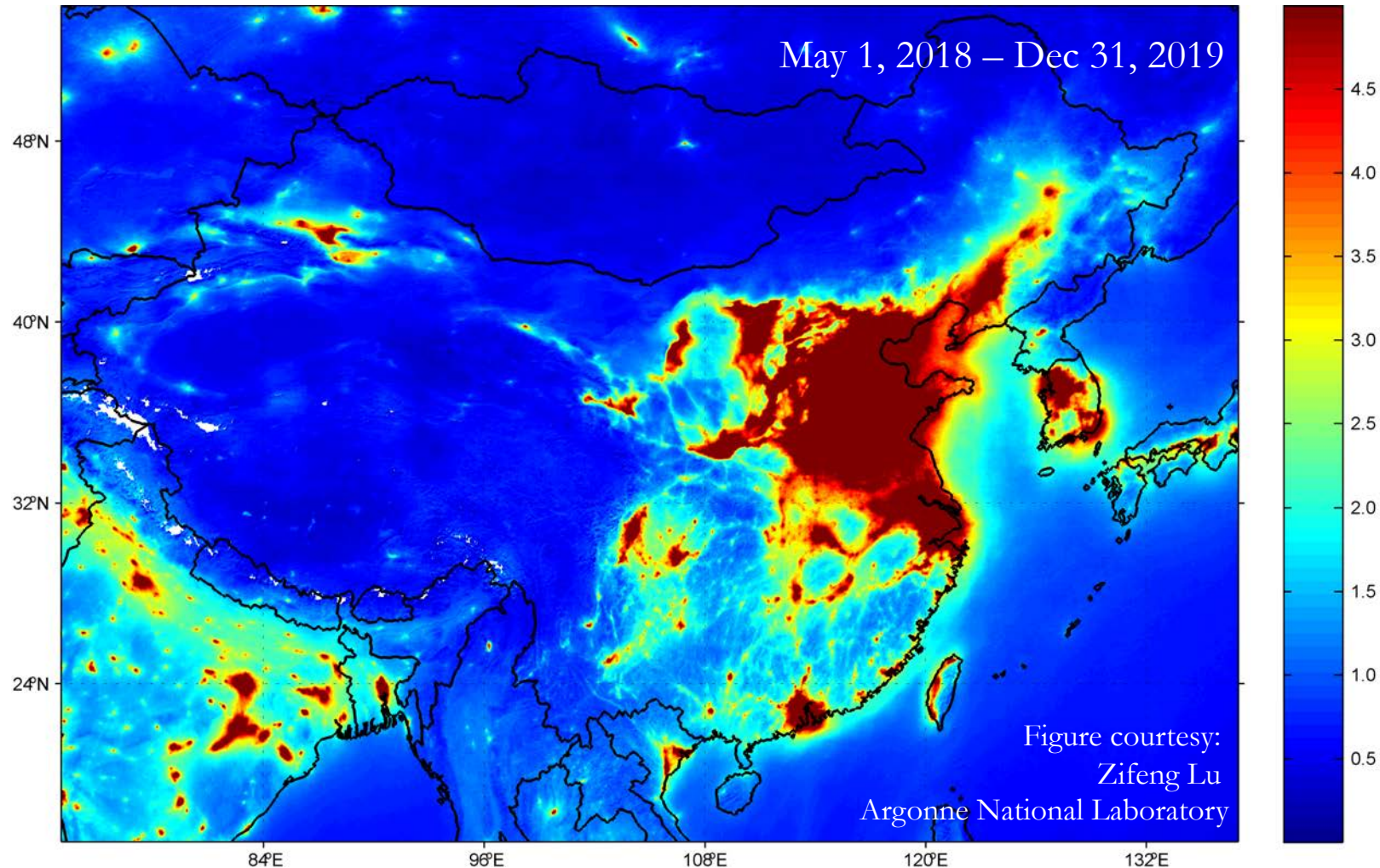
Largest values encompass cities, but other small scale features can be seen:

- Power plants in Ohio River Valley and rural western US
- Roadway networks (e.g., Idaho and Montana)
- Oil & gas operations including Permian basin (Texas), Uintah Basin (Utah), Bakken (North Dakota)
- Airports (e.g., Dulles)
- Cement kilns (e.g., Mexico)
- Copper mining operations (Utah & Arizona)
- Steel mills (e.g., E Chicago)





# Using TROPOMI NO<sub>2</sub> to quantify urban/rural gradients



## China

- Trending downward since 2012
- All large power plants have controls
- NO<sub>x</sub> originating from other sources (transportation / residential / industrial, etc.)

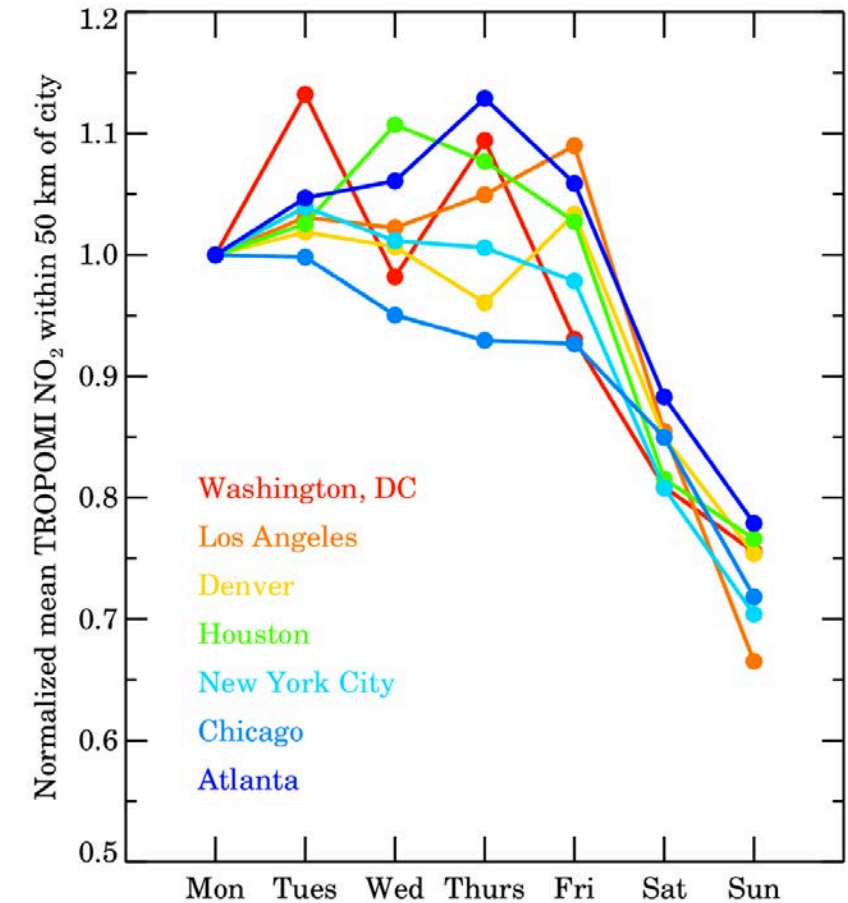
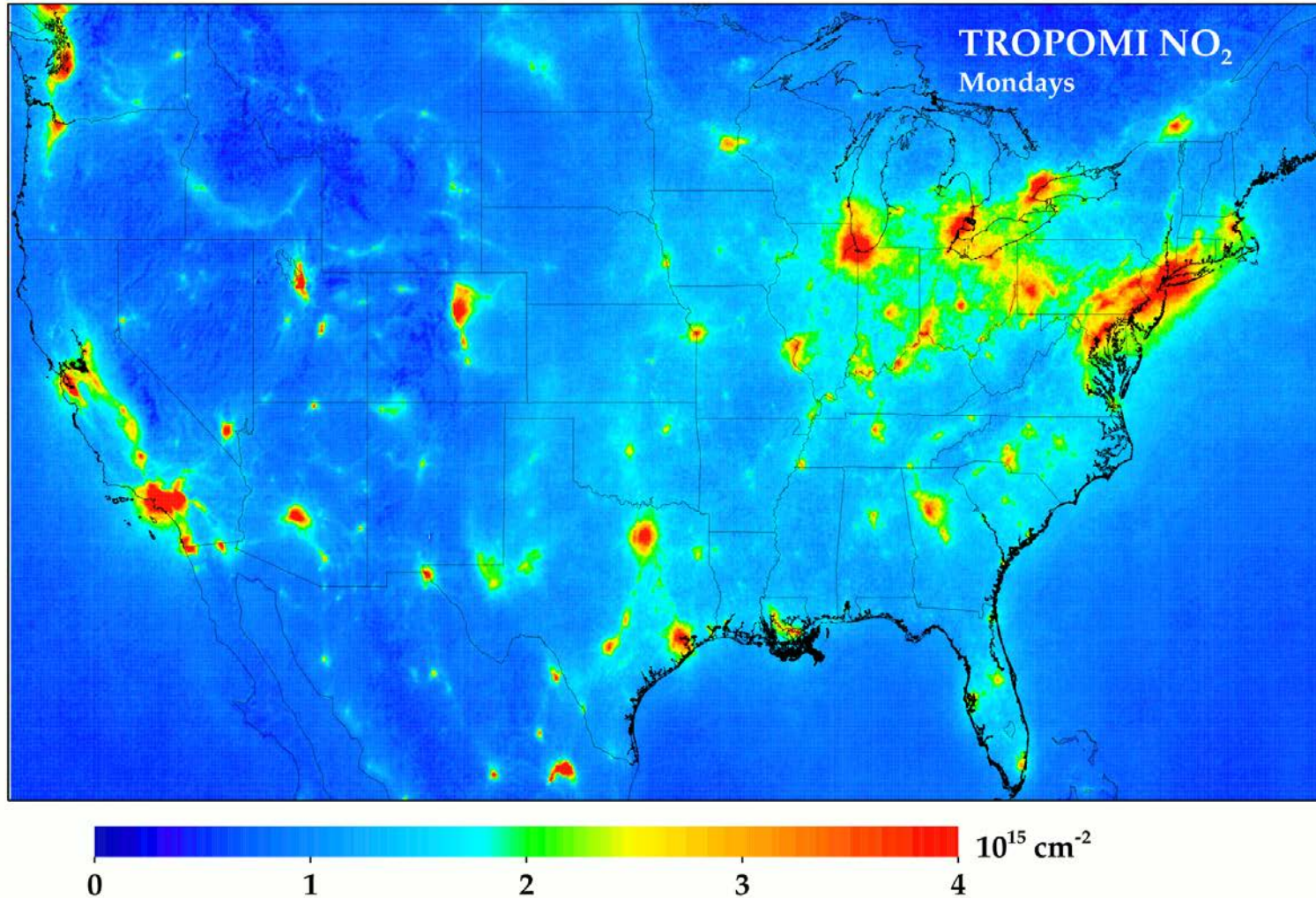
## India

- Still trending up in most communities
- Very few power plants have full NO<sub>x</sub> controls

Check out Fei Liu's work (Bryan Duncan HAQAST PI) if you want information on how precautions due to COVID-19 is affecting air quality in China: <https://www.earthobservatory.nasa.gov/images/146362/airborne-nitrogen-dioxide-plummets-over-china>



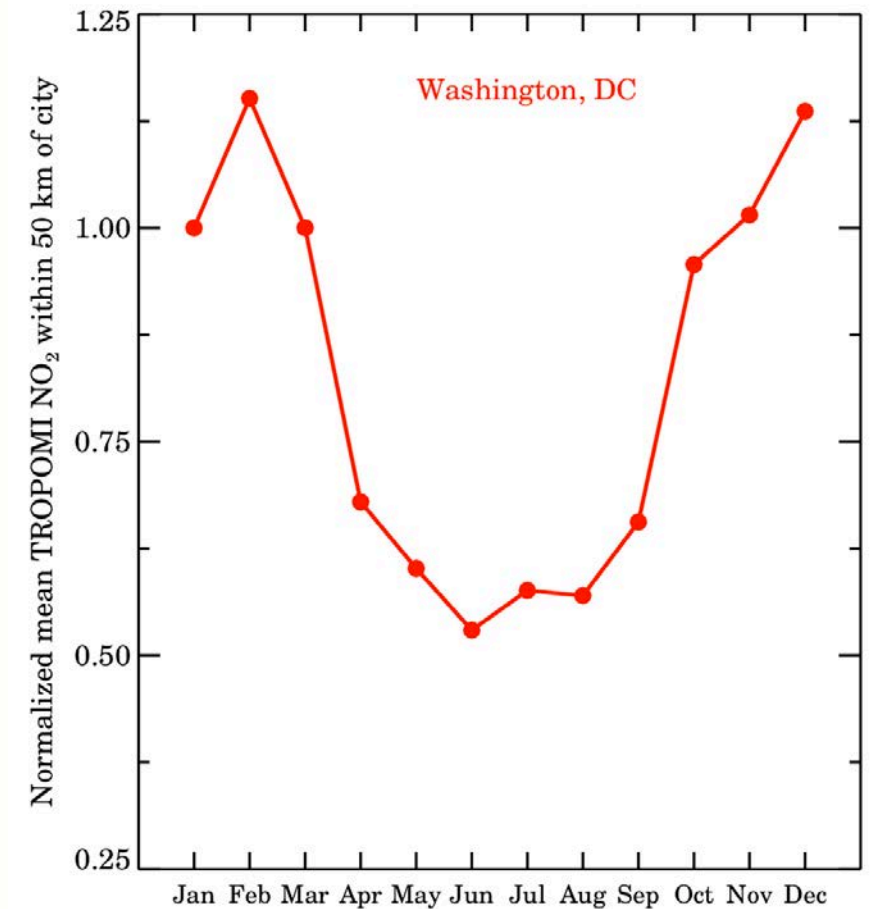
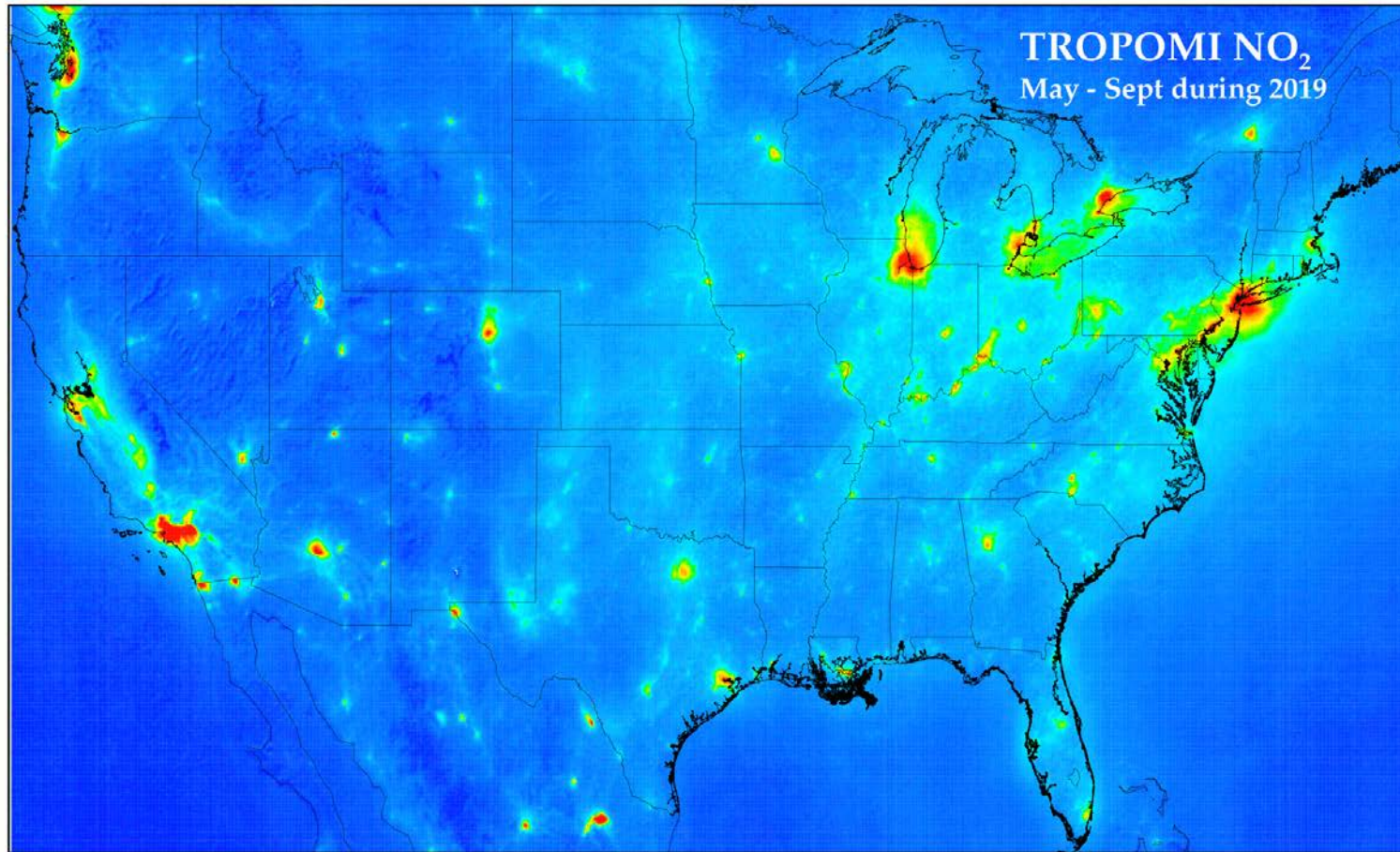
# Weekday / Weekend Cycles of Air Pollution



- NO<sub>2</sub> highest on weekdays; lower on Saturdays; lowest on Sundays
- Some interesting unexpected city-specific trends

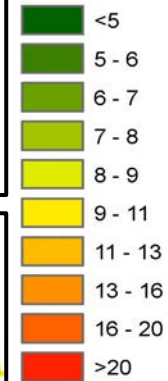
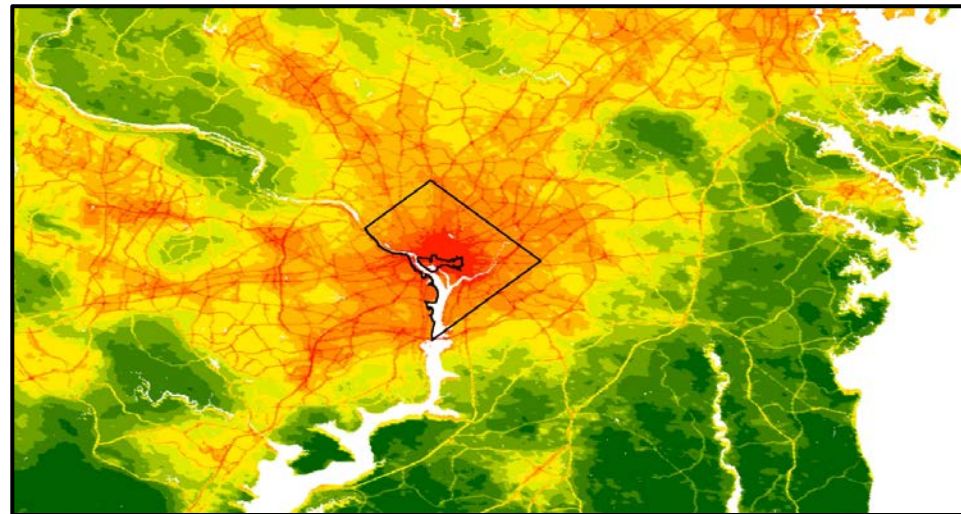
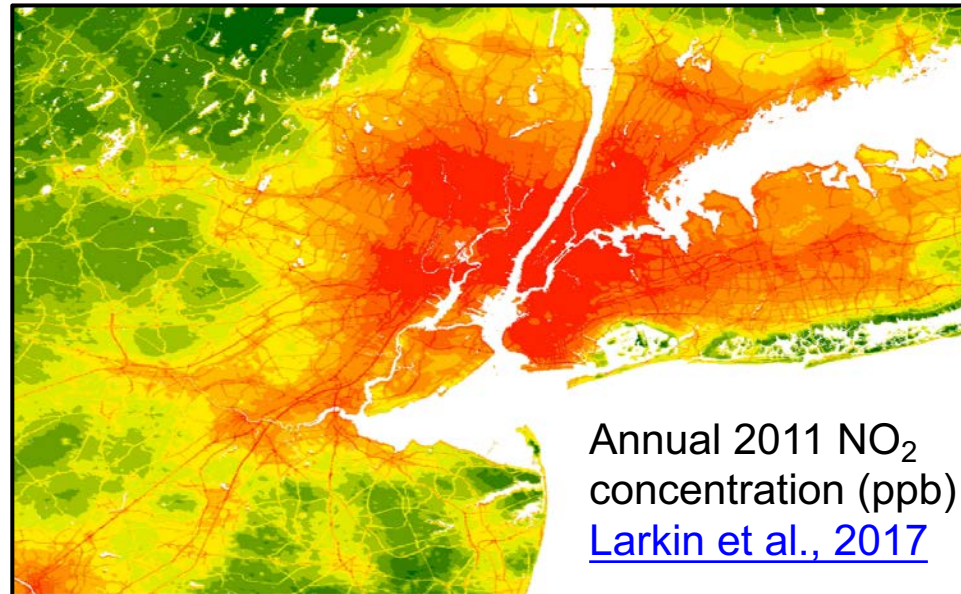


# Seasonal Cycles of Air Pollution



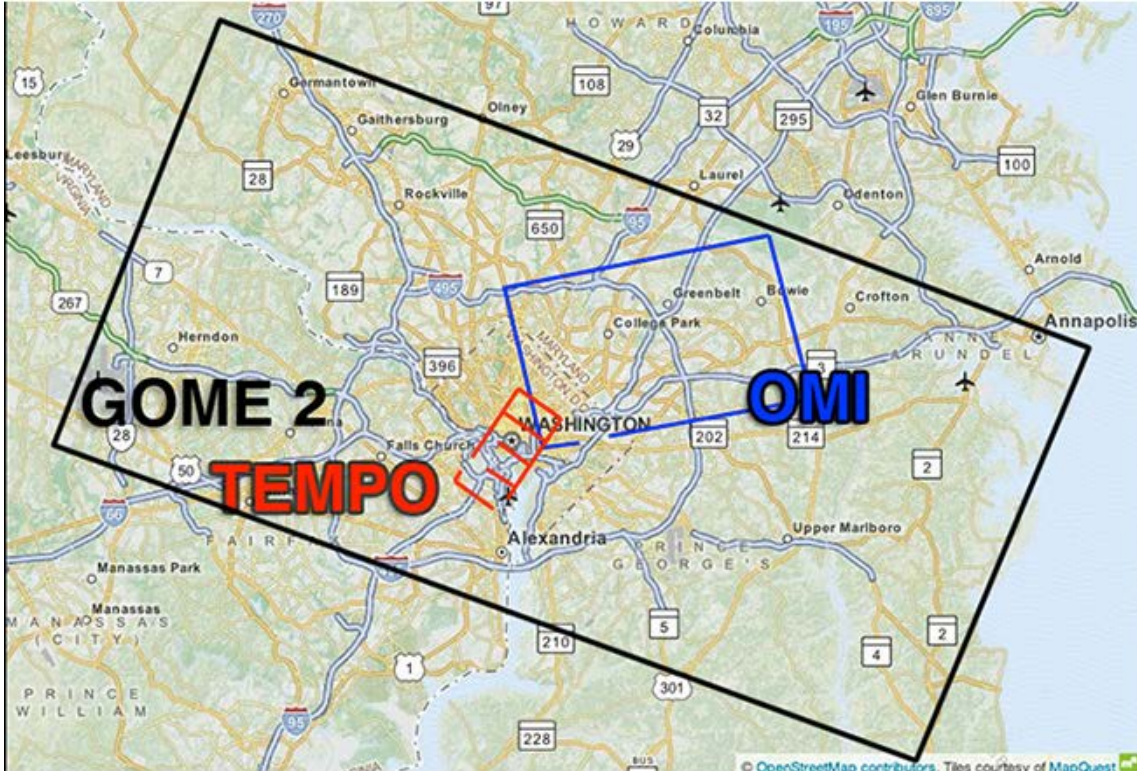
- NO<sub>2</sub> is larger during winter (longer NO<sub>2</sub> lifetime) even though emissions are likely larger during summer.
- NO<sub>2</sub> concentrations  $\neq$  NO<sub>x</sub> emissions. In many cases, NO<sub>2</sub> concentrations  $\sim$  NO<sub>x</sub> emissions, but make sure you are comparing similar months or seasons!

# Annual Surface NO<sub>2</sub> concentrations





# The future is now! TEMPO & GEMS



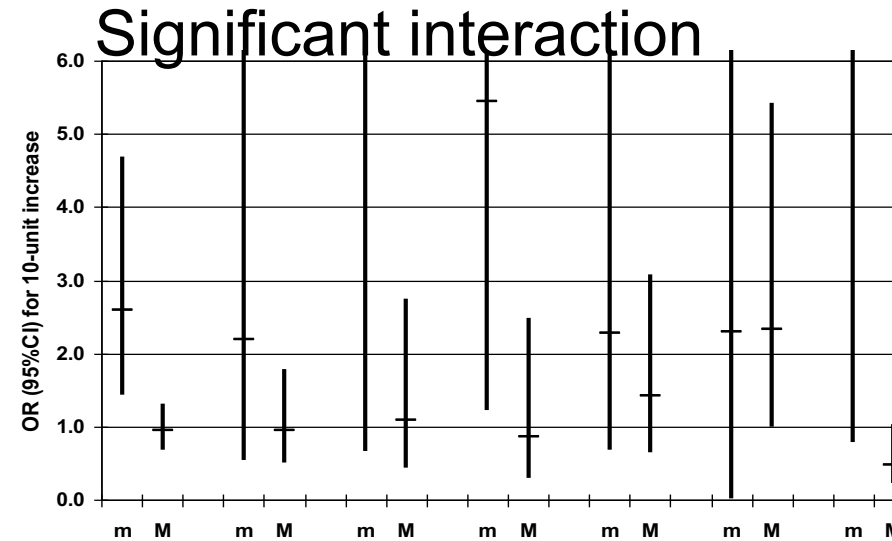
## Characteristics:

- Geostationary orbit
  - TEMPO: North America
  - GEMS: East Asia
- Hourly resolution that can show diurnal variability of emissions!
- Spatial resolution:
  - TEMPO: 2 km x 4.5 km
  - GEMS: 7 km x 8 km

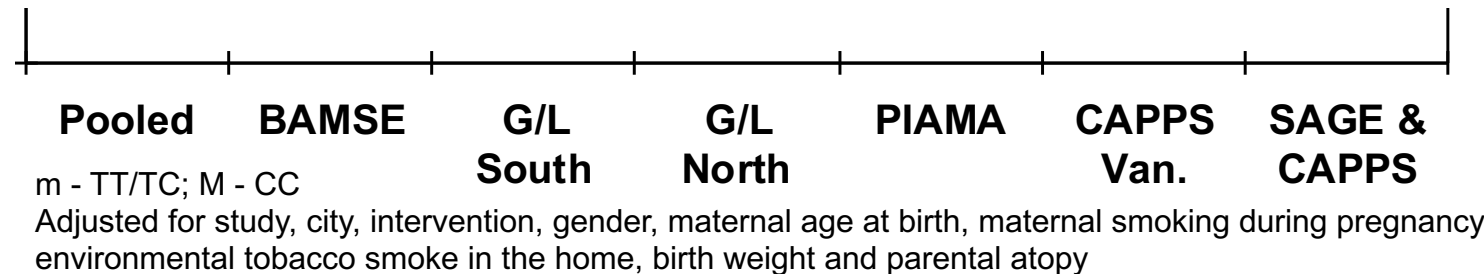
# Traffic pollution, Asthma Genetics (TAG)



NO<sub>2</sub> - Asthma, by GSTP1  
rs1138272



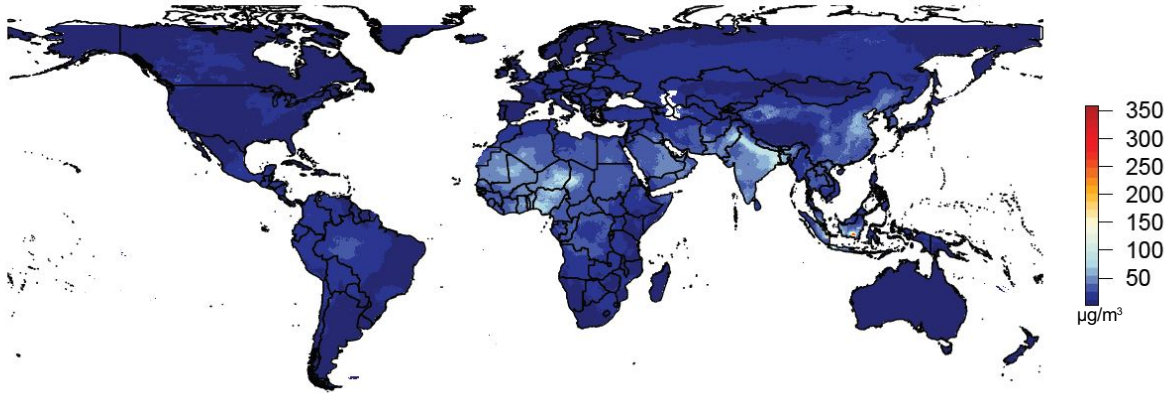
[GSTP1 and TNF Gene variants and associations between air pollution and incident childhood asthma: the traffic, asthma and genetics \(TAG\) study.](#) MacIntyre EA, Brauer M, Melén E, Bauer CP, Bauer M, Berdel D, Bergström A, Brunekreef B, Chan-Yeung M, Klümper C, Fuertes E, Gehring U, Gref A, Heinrich J, Herbarth O, Kerkhof M, Koppelman GH, Kozyrskyj AL, Pershagen G, Postma DS, Thiering E, Tiesler CM, Carlsten C; TAG Study Group. Environ Health Perspect. 2014 Apr;122(4):418-24. doi: 10.1289/ehp.1307459.



# Combining satellite and ground monitoring to estimate exposure

Bayesian Hierarchical Model (DIMAQ2)

Raw PM<sub>2.5</sub> Exposure, 2019



$$\log(PM_{2.5st}) = \beta_{0st} + \beta_{1st} \log(SAT_s) + \beta_{3..P} X_{st} + \varepsilon_{st}$$

**Spatially varying determinants of AOD-PM<sub>2.5</sub> relationship (from chemical transport model, other) + hierarchical random effects**

Ground measurements

**N = 10,408 unique locations**, from 116 countries

~11 x 11 km resolution, annual average

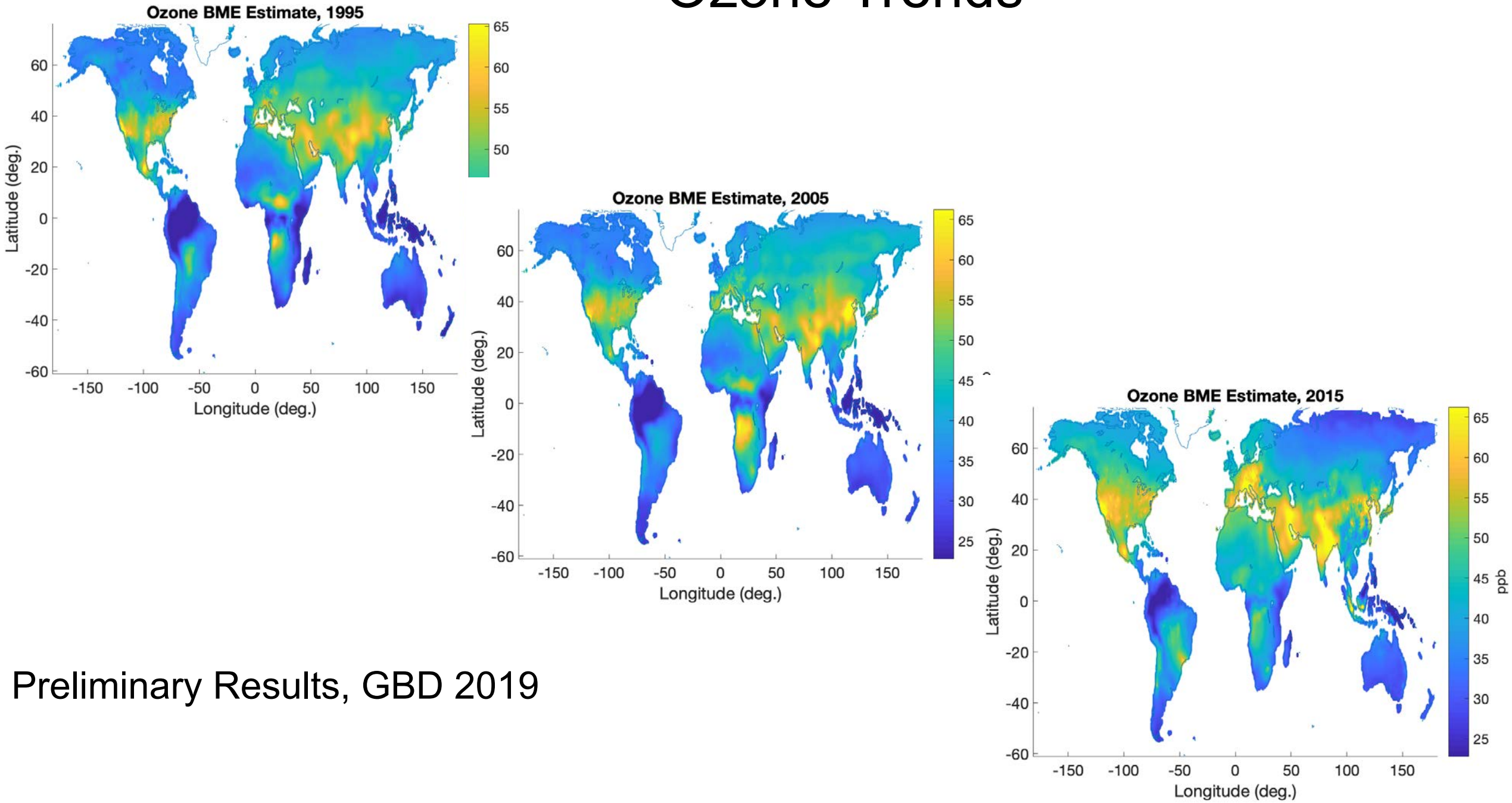
Median  $R^2 = 0.9$

Median Pop-weighted RMSE = 10.1  $\mu\text{g}/\text{m}^3$

- Shaddick et al. 2018. Data integration model for air quality: a hierarchical approach to the global estimation of exposures to ambient air pollution. J. R. Stat. Soc. C, 67: 231–253.
- Shaddick et al. 2018. Data Integration for the Assessment of Population Exposure to Ambient Air Pollution for Global Burden of Disease Assessment. Environ Sci Technol. 2018 Aug 21;52(16):9069-9078.



# Ozone Trends



Preliminary Results, GBD 2019

# Methods: Quantifying the global, national, and urban burdens of pediatric asthma incidence attributable to ambient NO<sub>2</sub>

$$Burden = Inc_{c,a} \times \sum_{i,j} Pop_{i,j,a} \times (1 - e^{-\beta X_{i,j}})$$

2015 national incidence rates from IHME (for 1-4, 5-9, 10-14, 15-18 year age groups)

2015 gridded population at 250 m x 250 m from the European Commission Joint Research Center GHS-POP + gridded age-group fractions from 2010 NASA CIESIN GPWv4

Relative risk from Khreis et al. (2017)

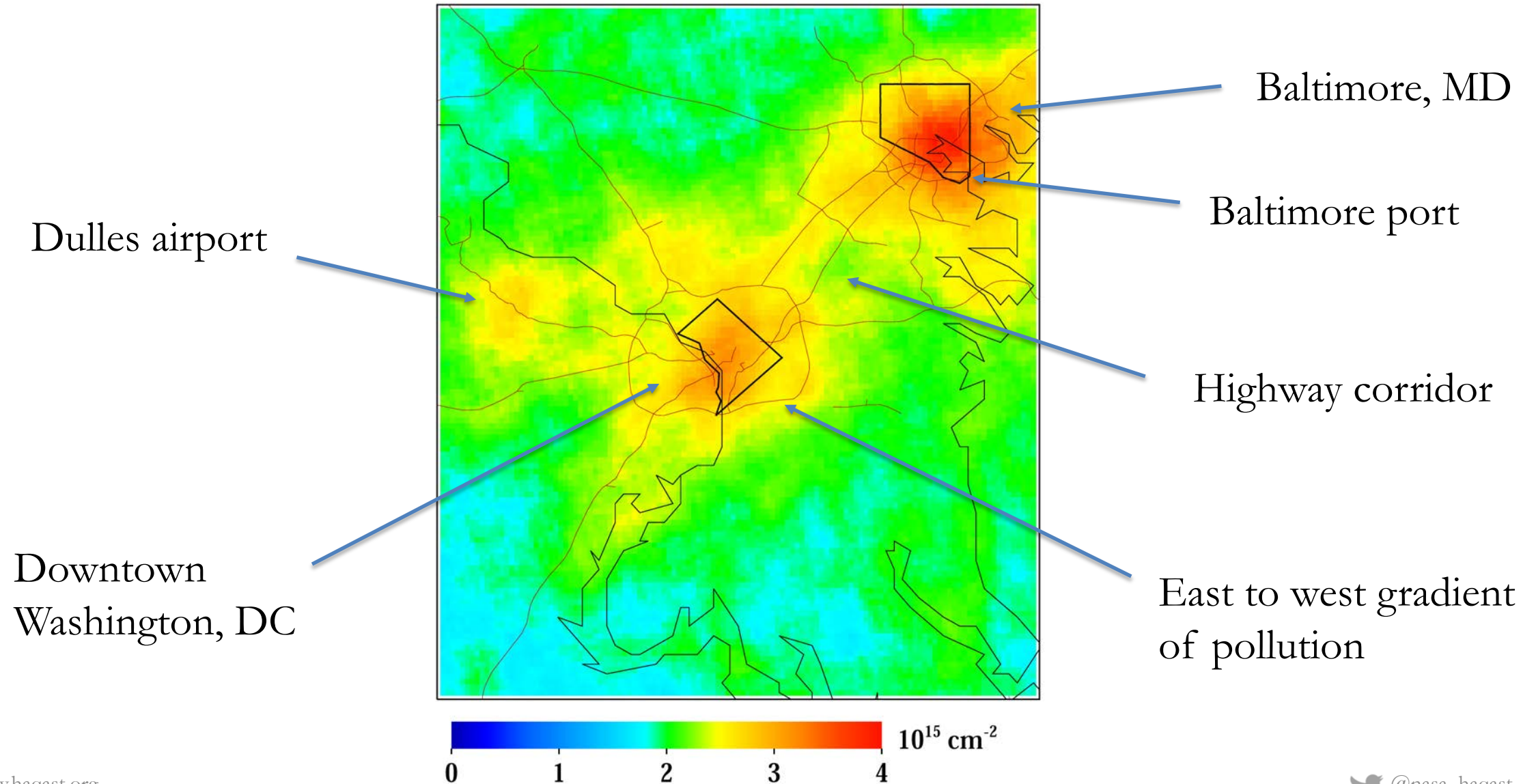
2010-2012 gridded surface NO<sub>2</sub> (100 m x 100 m) from Land Use Regression modeling by Larkin et al. (2017) → aggregated to 250 m x 250 m

We apply the health impact function in each 250 m x 250 m grid cell globally, and sum results over 21 regions, 194 countries, and 125 major cities – assuming counterfactual concentrations of 0, 2, and 5 ppb.

City extents from the GHS-SMOD (defined as any contiguous cells with ≥50,000 people and a population density of ≥1,500 inhabitants/km<sup>2</sup> or a density of built-up >50%.)

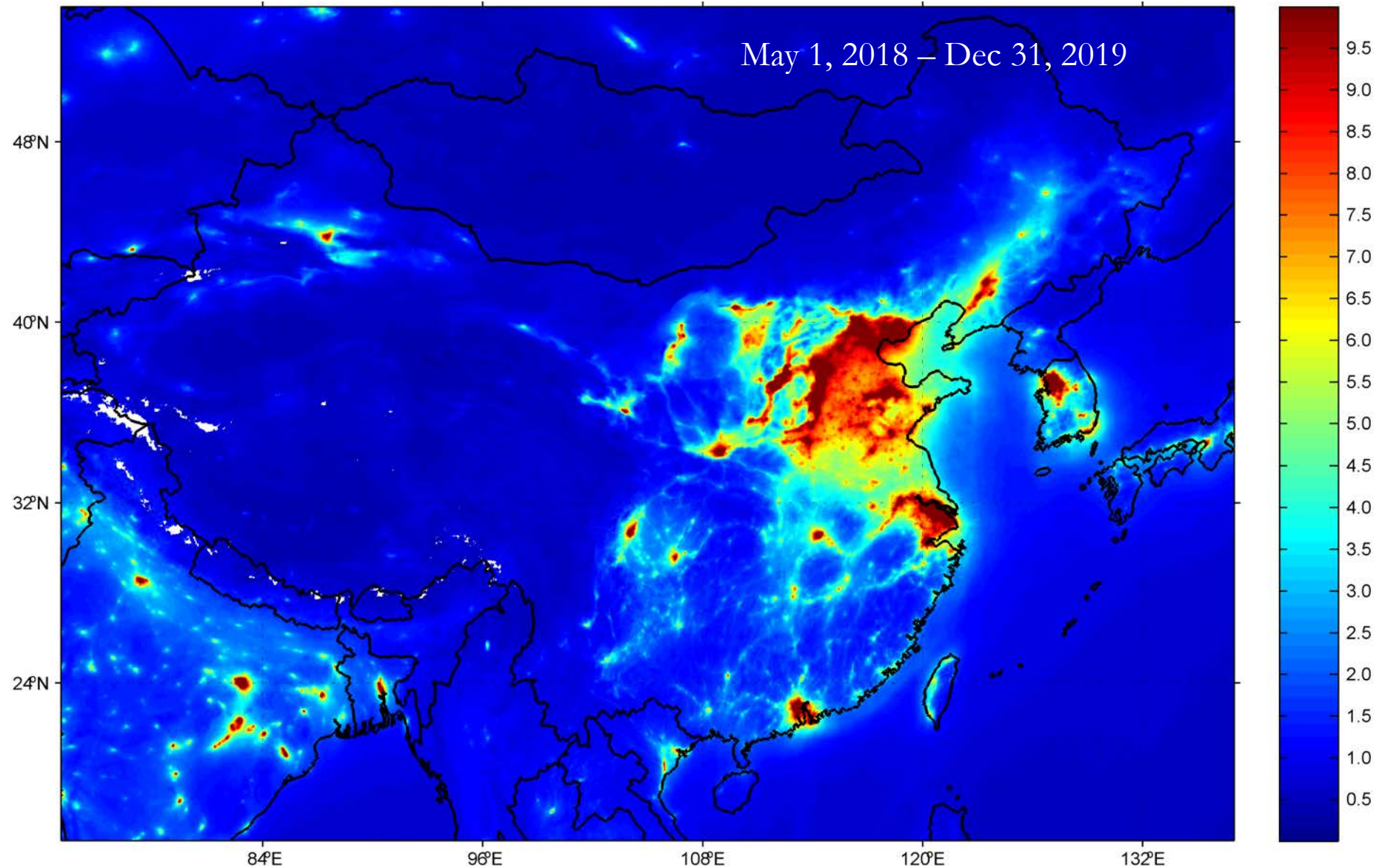
# Using TROPOMI NO<sub>2</sub> to quantify urban/rural gradients

Washington, DC & Baltimore, MD (May – Sept 2019)





# Using TROPOMI NO<sub>2</sub> to quantify urban/rural gradients



# Using TROPOMI NO<sub>2</sub> to quantify urban/rural gradients

