Satellite, Model and In Situ Fusion: Characterizing Global $PM_{2.5}$ Exposure

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$PM_{2.5}$ affects human health and longevity

Life expectancy increases 7 months per 10 μg/m^3 decrease in long-term exposure

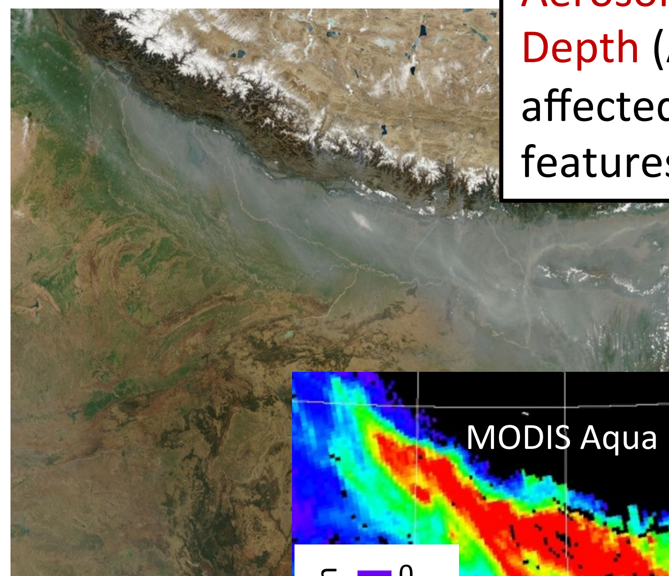
Initial versions of the Global Burden of Disease report were limited by insufficient ground-level observations of fine Particulate Matter ($PM_{2.5}$)

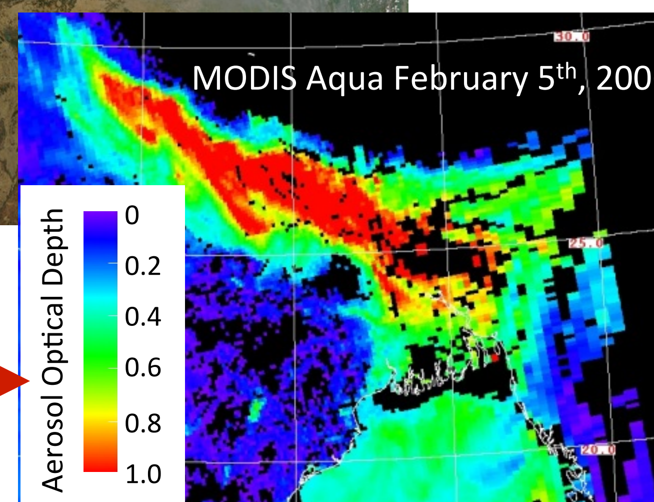
GBD2013 estimates $PM_{2.5}$ in urban and rural areas causes:

- 3 million premature deaths
- 10% of all risk factors (such as malnutrition, dietary risks)
- 36% environmentally-related (such as unsafe water, sanitation, other air pollutants)

Forouzanfaret al., 2015

Aerosol Optical Depth (AOD) affected by aerosol features at surface





Remote sensing of $PM_{2.5}$ versus AOD

Global monitoring of air pollution over land from the Earth Observing System-Terra Moderate Resolution Imaging Spectroradiometer (MODIS)

D. A. Chu,[1,2] Y. J. Kaufman,[2] G. Zibordi,[3] J. D. Chern,[4] Jietai Mao,[5] Chengcai Li,[5] and B. N. Holben[6]

"The derivation of PM concentration from satellite measurements may be possible once we know the detailed aerosol vertical distribution."

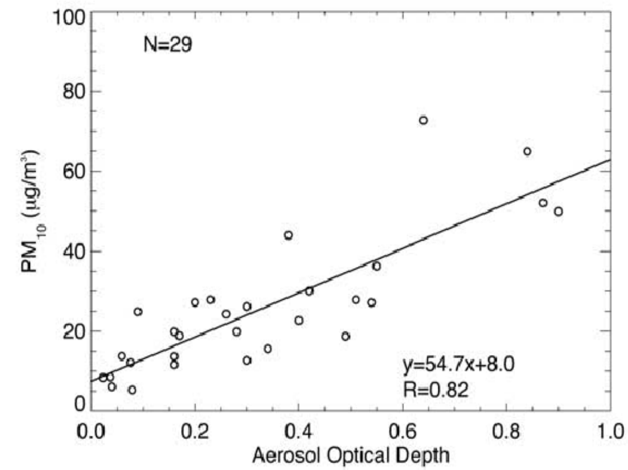
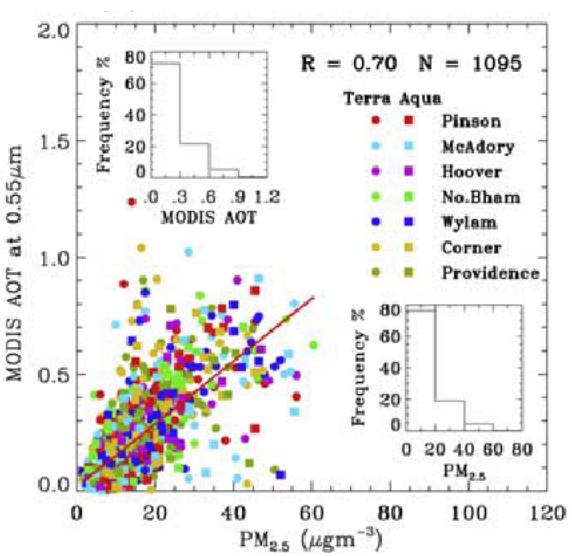


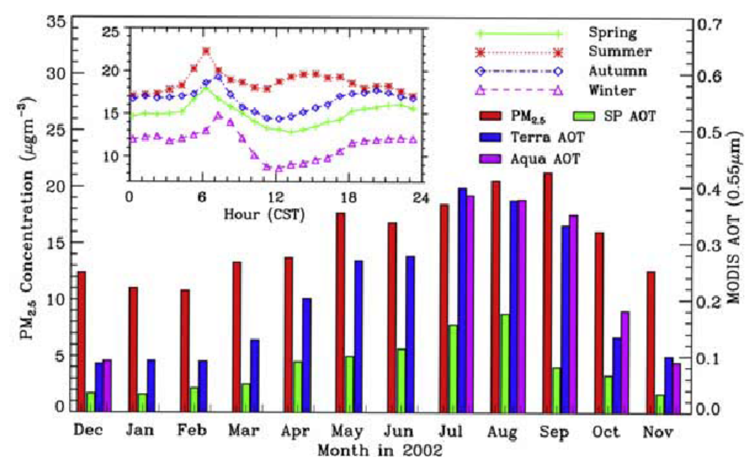
Figure 14. Relationship between 24-hour PM_{10} concentrations and daily averaged AERONET τ_a measurements from August to October 2000 in northern Italy.



Intercomparison between satellite-derived aerosol optical thickness and $PM_{2.5}$ mass: Implications for air quality studies

Jun Wang and Sundar A. Christopher

"There is excellent agreement between the monthly mean PM2.5 and MODIS AOD (R > 0.9) [in Jefferson county, Alabama]…"



Chu et al., JGR, 2003; Wang and Christopher, GRL, 2003

Remote sensing of $PM_{2.5}$ versus AOD

Qualitative and quantitative evaluation of MODIS satellite sensor data for regional and urban scale air quality

Jill A. Engel-Cox[a,c,*], Christopher H. Holloman[b], Basil W. Coutant[b], Raymond M. Hoff[c]

"The use of satellite sensor data… has significant potential to enhance air quality monitoring…"

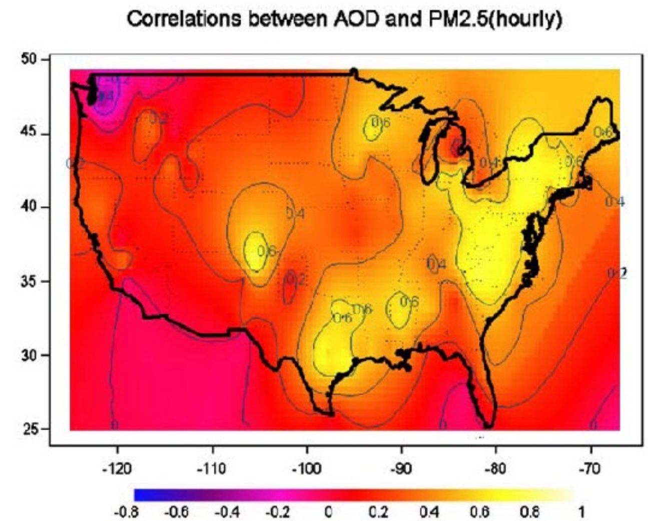
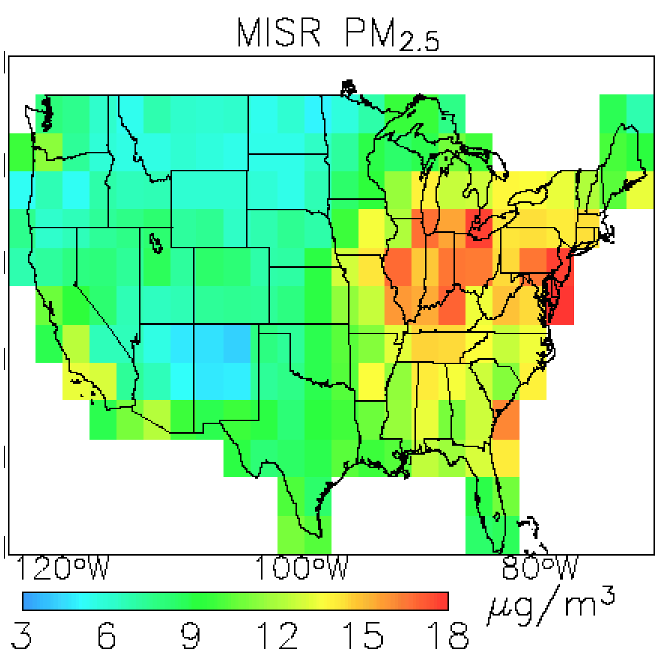


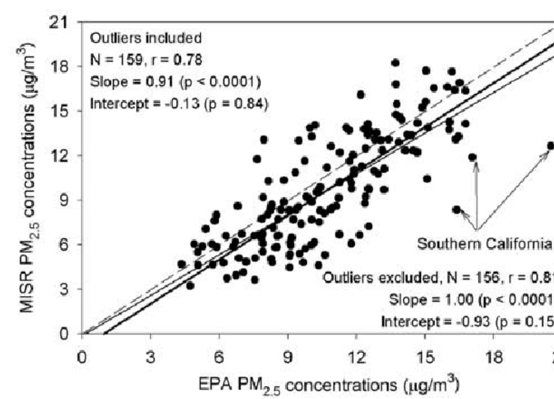
Fig. 7. Correlations between AOD and hourly $PM_{2.5}$ readings across the US.



Mapping annual mean ground-level $PM_{2.5}$ concentrations using Multiangle Imaging Spectroradiometer aerosol optical thickness over the contiguous United States

Yang Liu[1,2], Rokjin J. Park,[3] Daniel J. Jacobs,[3] Qinbin Li,[3] Vasu Kilaru,[4] and Jeremy A. Sarnat[5]

"Using simulated aerosol vertical profiles… helps to reduce the uncertainty in estimated $PM_{2.5}$ concentrations…



Engel-Cox et al., AE, 2004; Liu et al., JGR, 2004

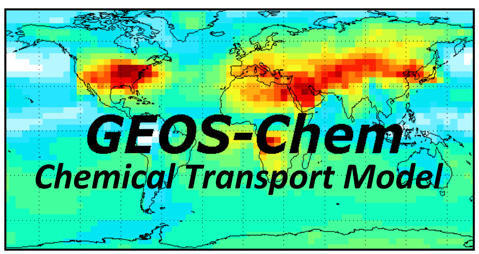
Global ground-based monitoring is sparse

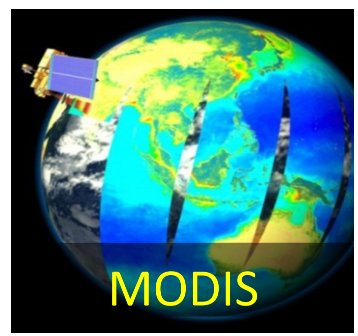
We relate satellite-based retrievals of *aerosol optical depth* (AOD) to $PM_{2.5}$
using a global chemical transport model

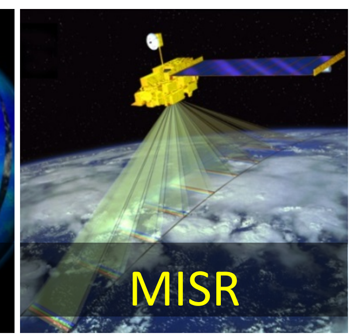
$$PM_{2.5} = \frac{PM_{2.5}}{AOD} \times AOD$$

$\frac{PM_{2.5}}{AOD}$
- relative vertical profile
- aerosol type
- meteorological effects

AOD
- total column of aerosol
- many instruments/sources
- many different retrievals







Many AOD sources are available

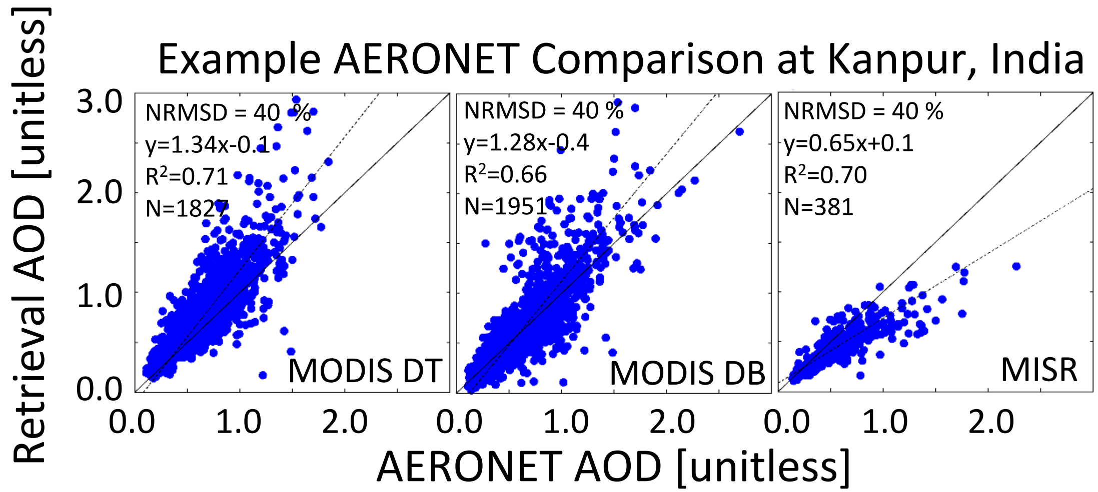
- Many advances in available retrievals: Dark Target, Deep Blue, MAIAC, MISR
- Bringing multiple AOD sources together
  - Consistent definition of uncertainty
  - comparison with AERONET
- Globally extend NDVI-specific NRMSD and bias correction via proximity (d^{-2}) and Land Cover Similarity (LCS^{-1})

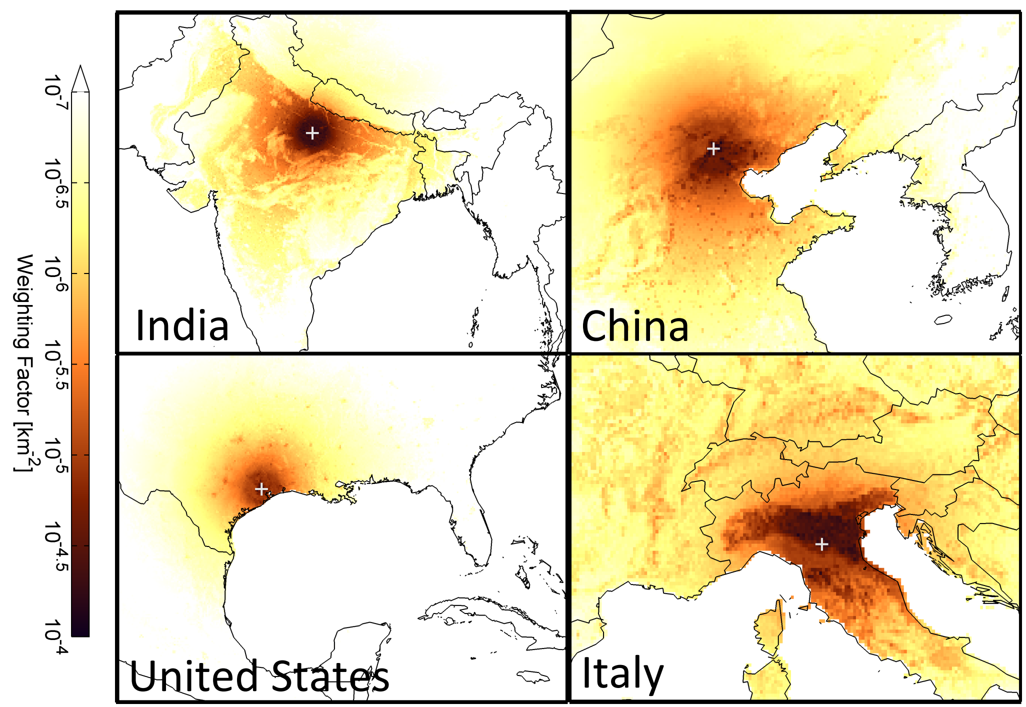
Land Cover Similarity

$$LCS_{i,j,k} = \sum_{n=1}^{N_{LT}} \left| LT_{i,j,n} - LT_{k,n} \right|$$

Land Type [%]

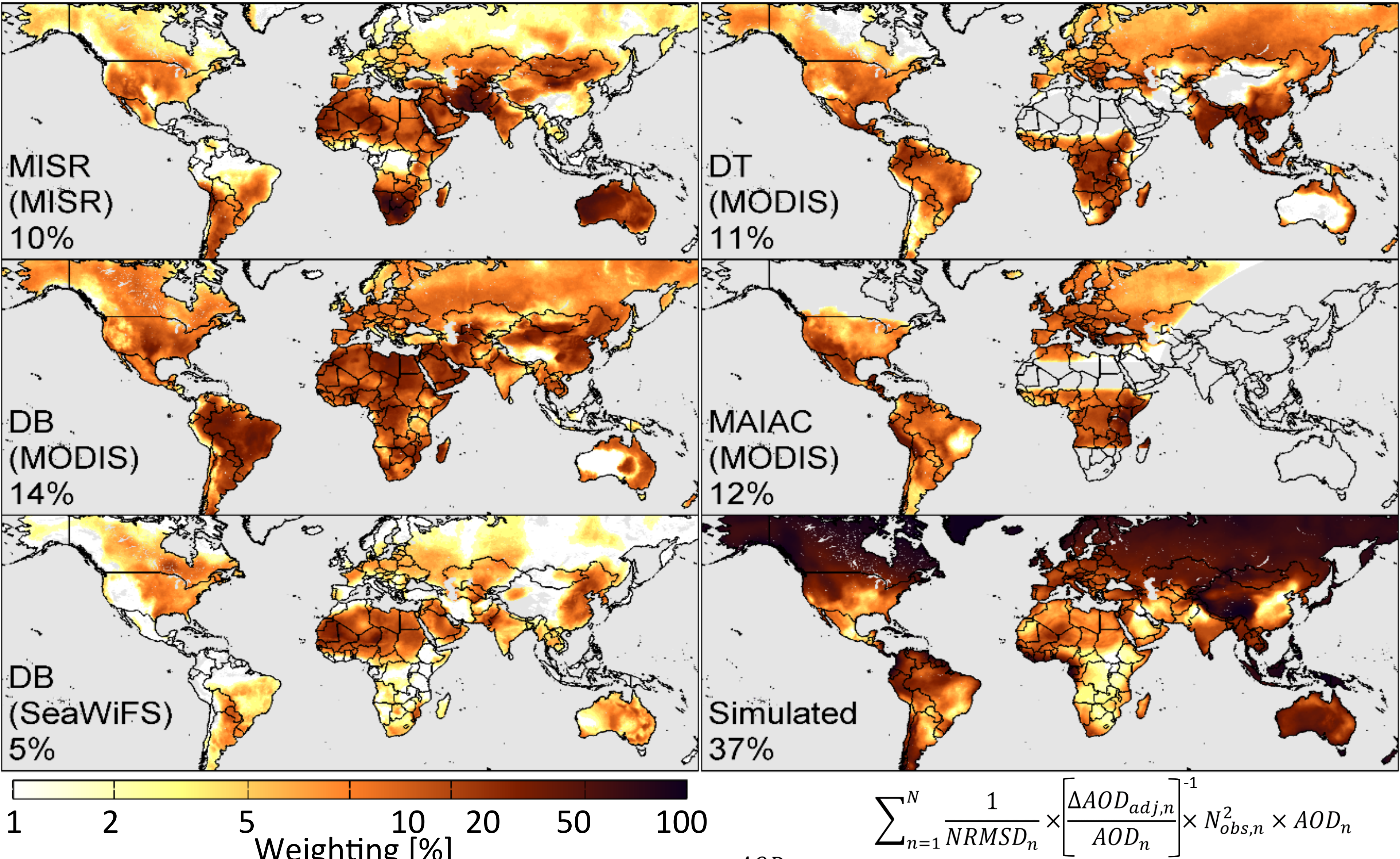
- Similar approach can be used to include simulated AOD





van Donkelaar, ES&T, 2016

Different AOD sources have different strengths

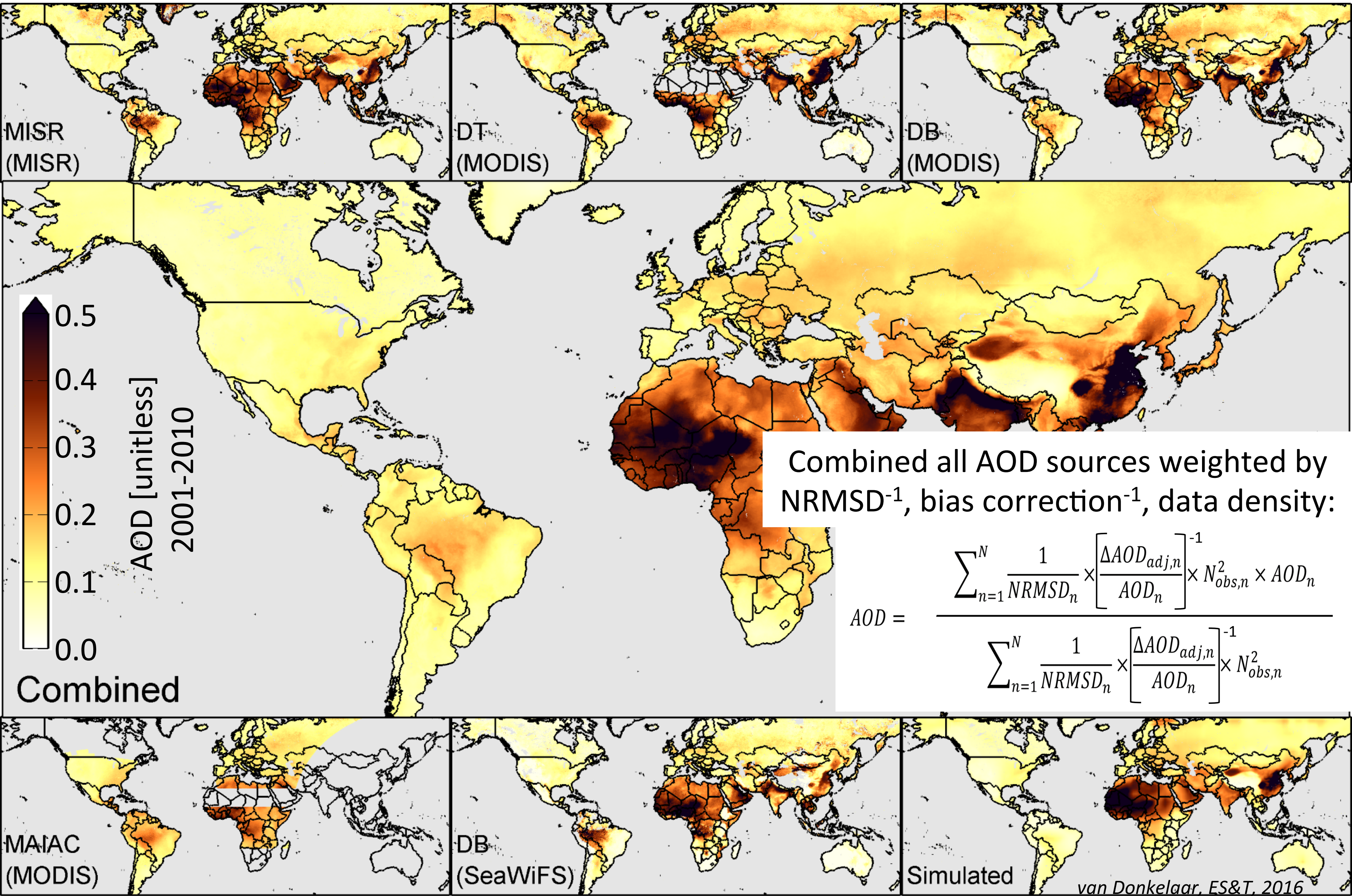


Combined all AOD sources weighted by NRMSD^{-1}, bias correction^{-1}, data density:

$$AOD = \frac{\sum_{n=1}^{N} \frac{1}{NRMSD_n} \times \left[\frac{\Delta AOD_{adj,n}}{AOD_n}\right]^{-1} \times N_{obs,n}^2 \times AOD_n}{\sum_{n=1}^{N} \frac{1}{NRMSD_n} \times \left[\frac{\Delta AOD_{adj,n}}{AOD_n}\right]^{-1} \times N_{obs,n}^2}$$

van Donkelaar, ES&T, 2016

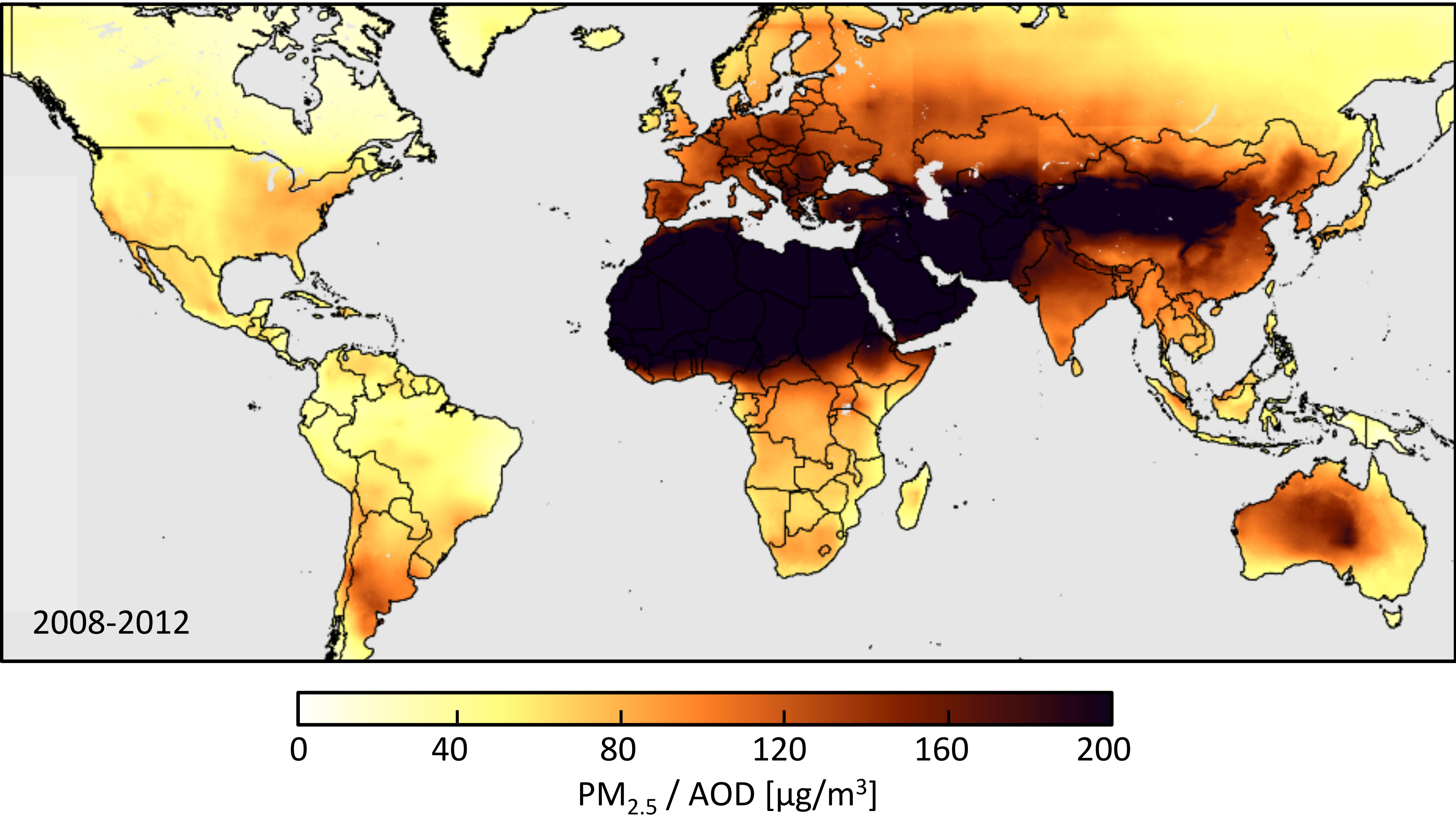
Consistent uncertainty allows for global combined AOD



Combined all AOD sources weighted by $NRMSD^{-1}$, bias correction^{-1}, data density:

$$AOD = \frac{\sum_{n=1}^{N} \frac{1}{NRMSD_n} \times \left[\frac{\Delta AOD_{adj,n}}{AOD_n}\right]^{-1} \times N_{obs,n}^2 \times AOD_n}{\sum_{n=1}^{N} \frac{1}{NRMSD_n} \times \left[\frac{\Delta AOD_{adj,n}}{AOD_n}\right]^{-1} \times N_{obs,n}^2}$$

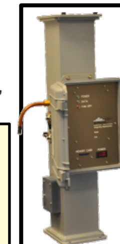
CTMs simulate the AOD to $PM_{2.5}$ relationship



Direct evaluation of *f*(x,y,t,AOD) requires collocation

- Few prior publicly available cases
- SPARTAN network
  - collocate $PM_{2.5}$ with existing AOD measurements
  - nephelometer and speciated filter-based measurements
  - IGAC endorsed
  - contributing ground-system for NASA's MAIA mission

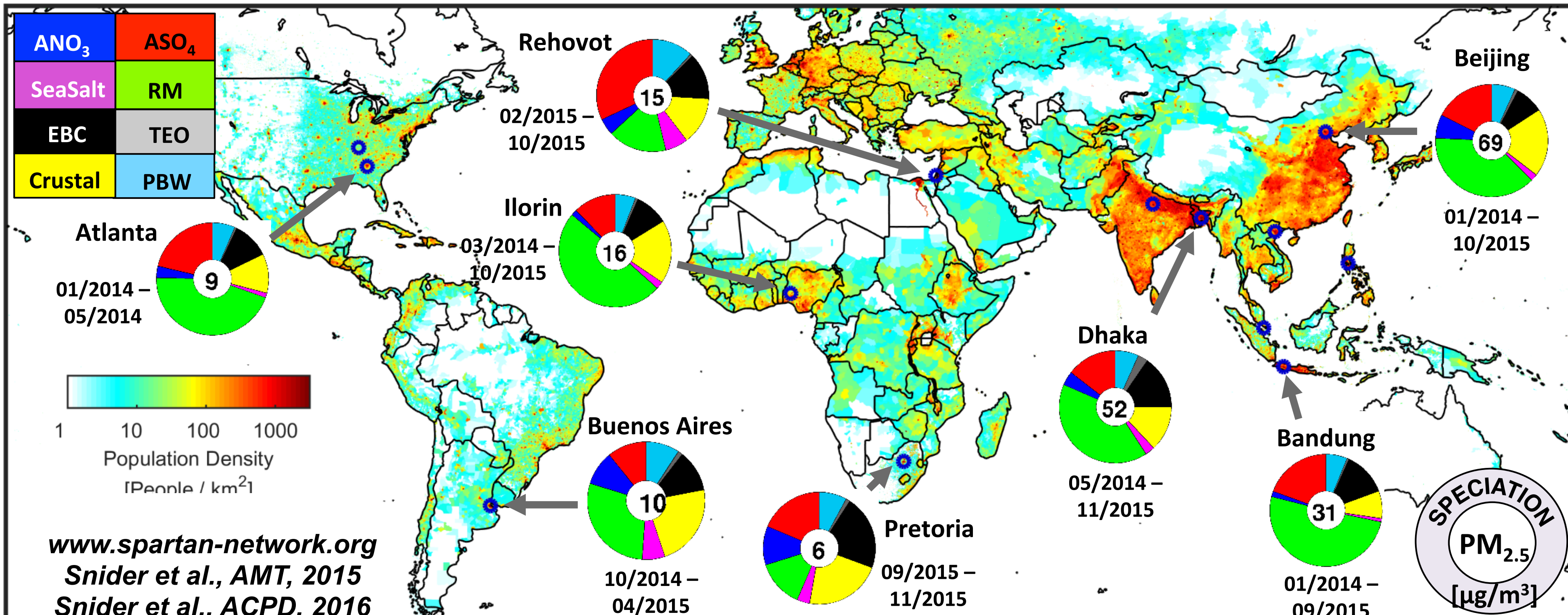
Site Selection Criteria
- population
- uncertainty
- availability



Airphoton $PM_{2.5}$

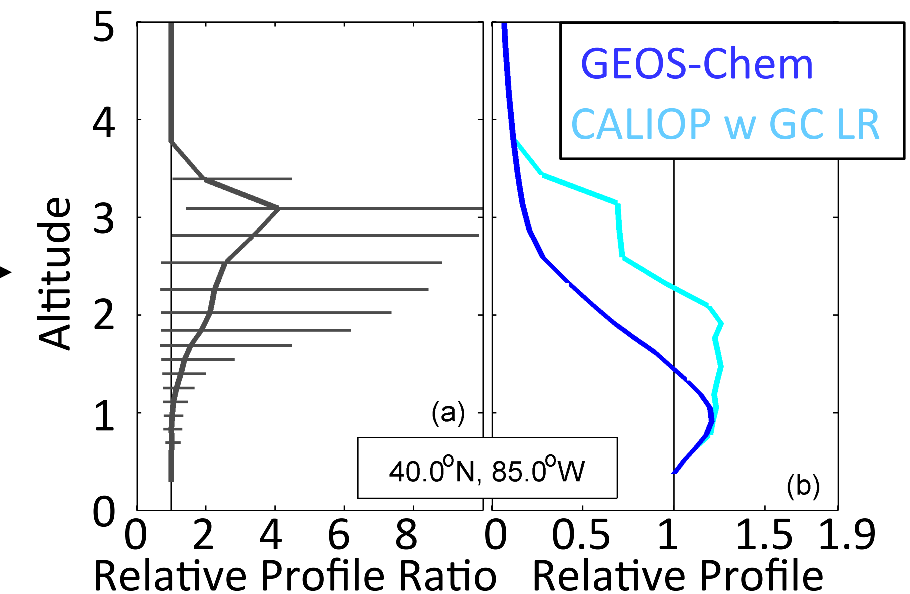
Filter $PM_{2.5}$
Filter PM_{10}
3-λ Nephelometer

AOD from CIMEL Sunphotometer (e.g. AERONET)



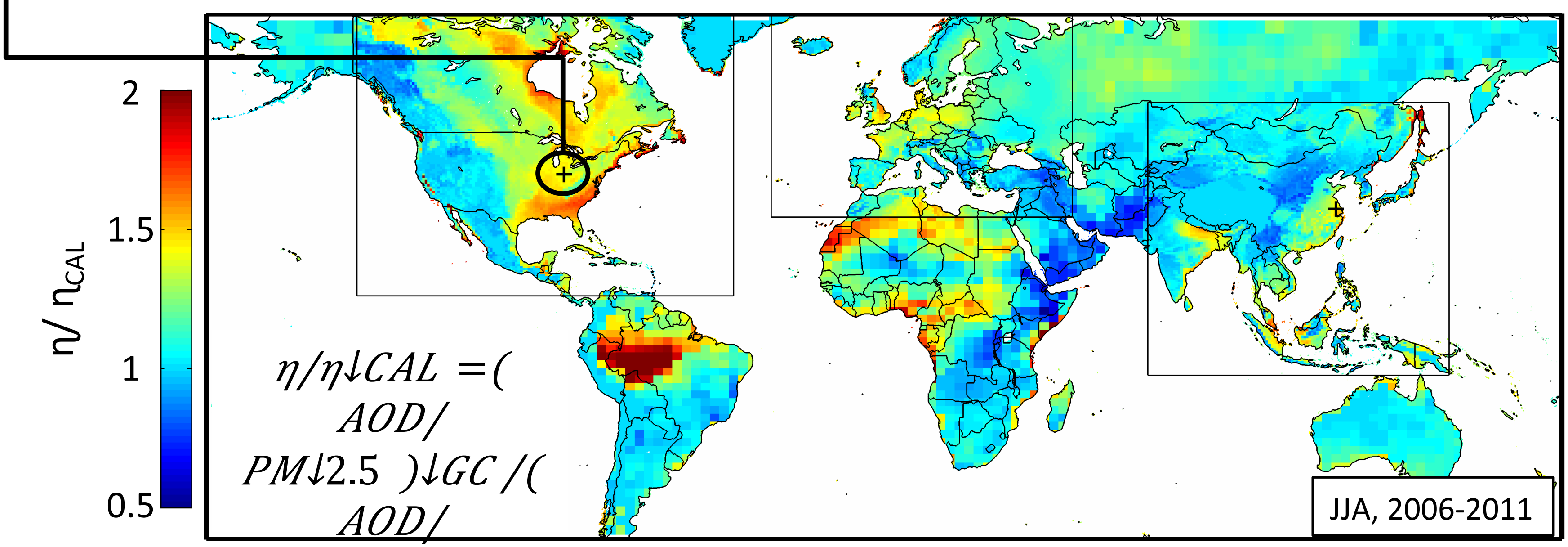
www.spartan-network.org
Snider et al., AMT, 2015
Snider et al., ACPD, 2016

Alternatives exist to direct AOD to $PM_{2.5}$ evaluation



CALIOP

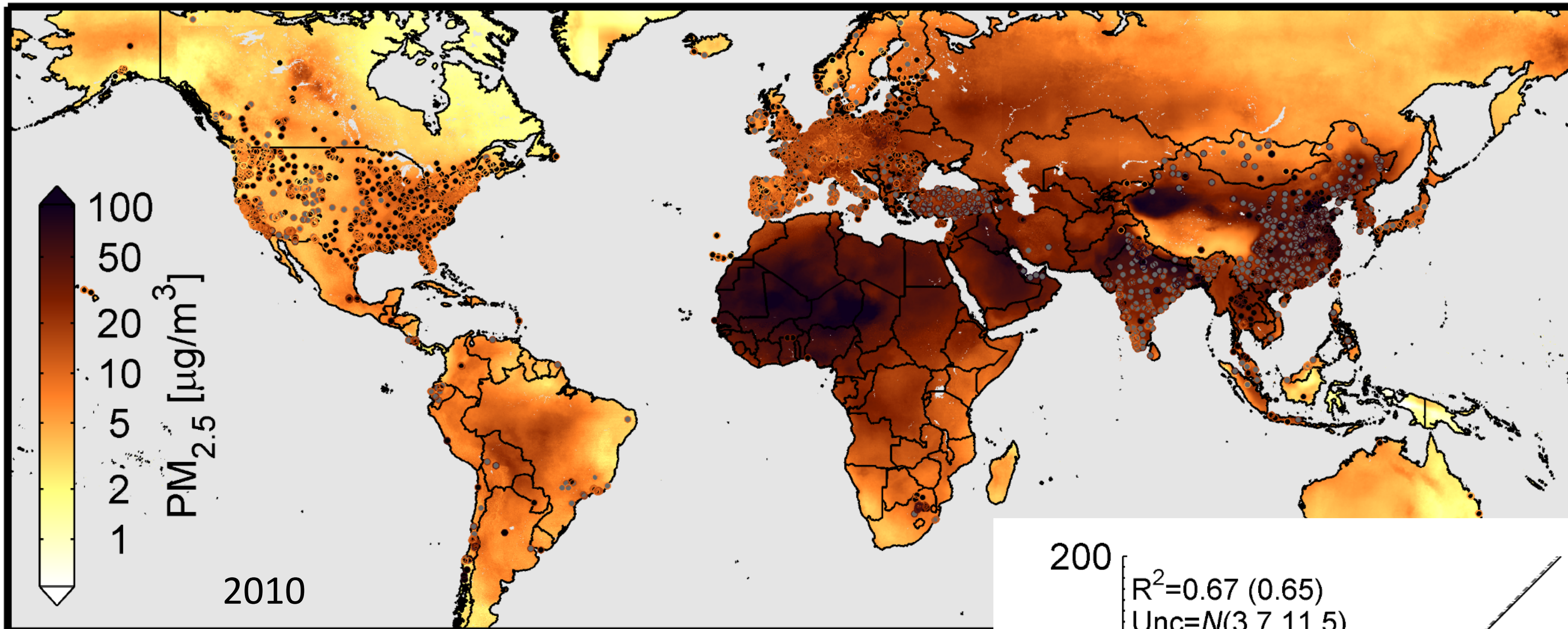
- Comparison of extinction profile
- Match optical properties
- Long-term (2006-2011), monthly comparison

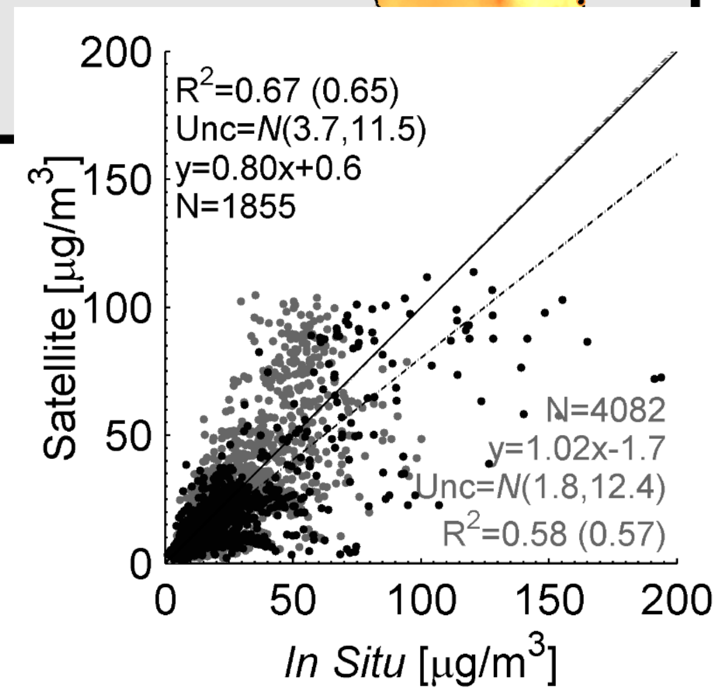


$$\eta/\eta_{CAL} = (AOD/PM_{2.5})_{GC} / (AOD/PM_{2.5})_{CAL}$$

van Donkelaar, JGR, 2013

Significant agreement with global measurements

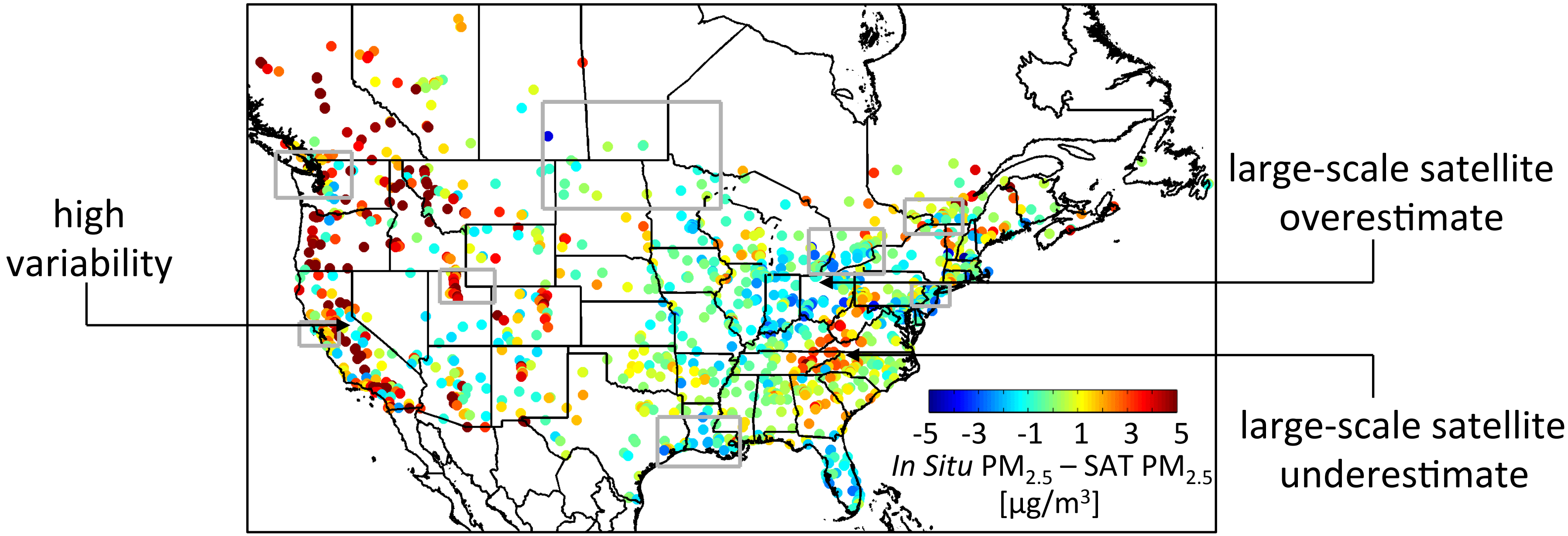




- Comparison of annual average values
  - includes sampling effects
  - includes of PM_{10}-based estimates
- Removal of CTM reduces agreement (R^2=0.45)
- Individual AODs further reduce agreement (R^2=0.32-0.39)

van Donkelaar, ES&T, 2016

How can we understand the remaining bias?



Geographically Weighted Regression (GWR) provides a spatially varying, linear regression to:

$$(\textit{in situ}\ PM_{2.5} - \text{Satellite}\ PM_{2.5}) = \beta_1 U + \beta_2 ED + \beta_3 NIT + \beta_4 PC + \beta_5 SOA$$

U: Percent Urban

ED: Local Elevation Difference with GEOS-Chem grid

NIT: Nitrate

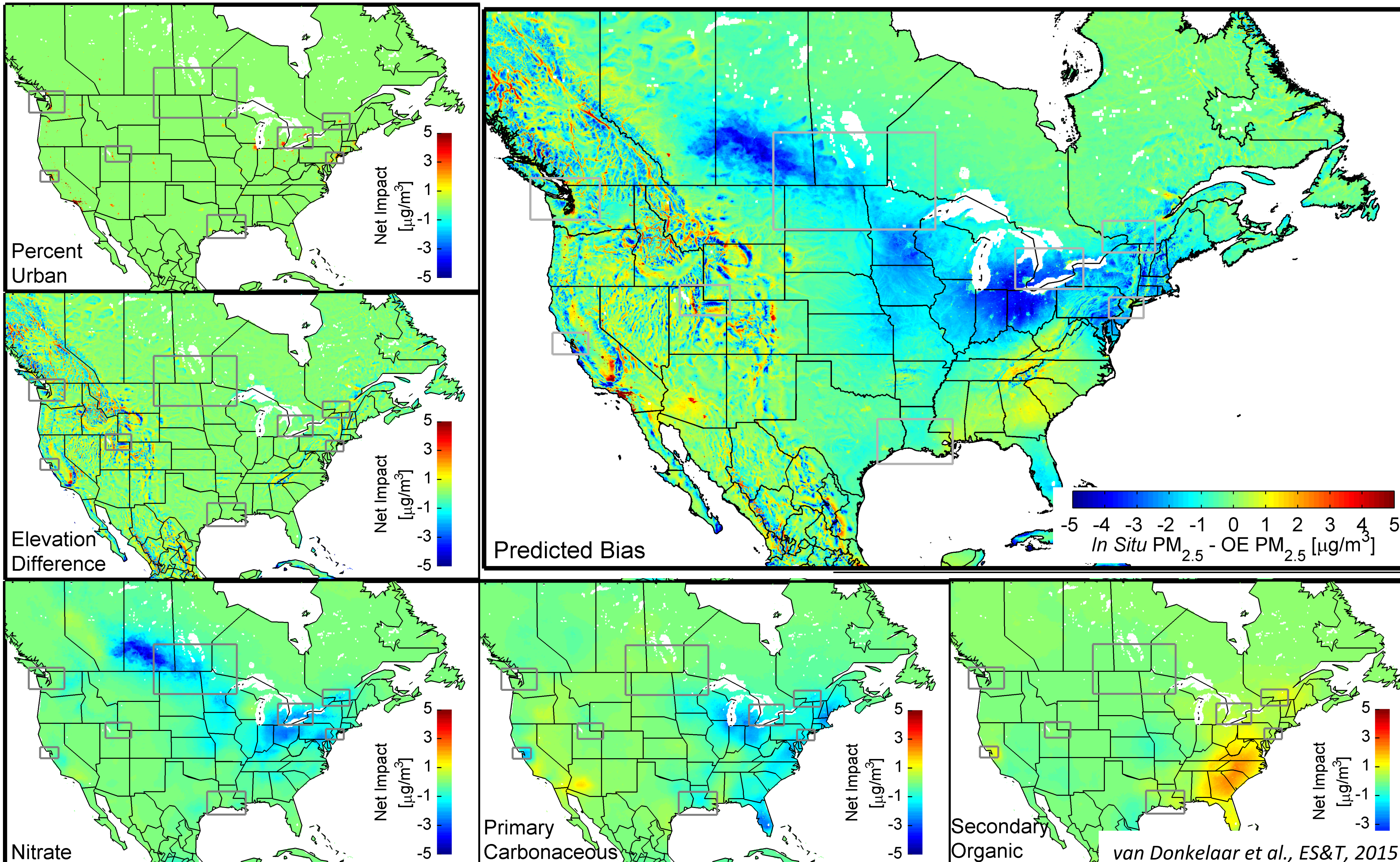
PC: Primary Carbon (BC+OC)

SOA: Secondary Organic Aerosol

Apply simulated speciation to Satellite $PM_{2.5}$

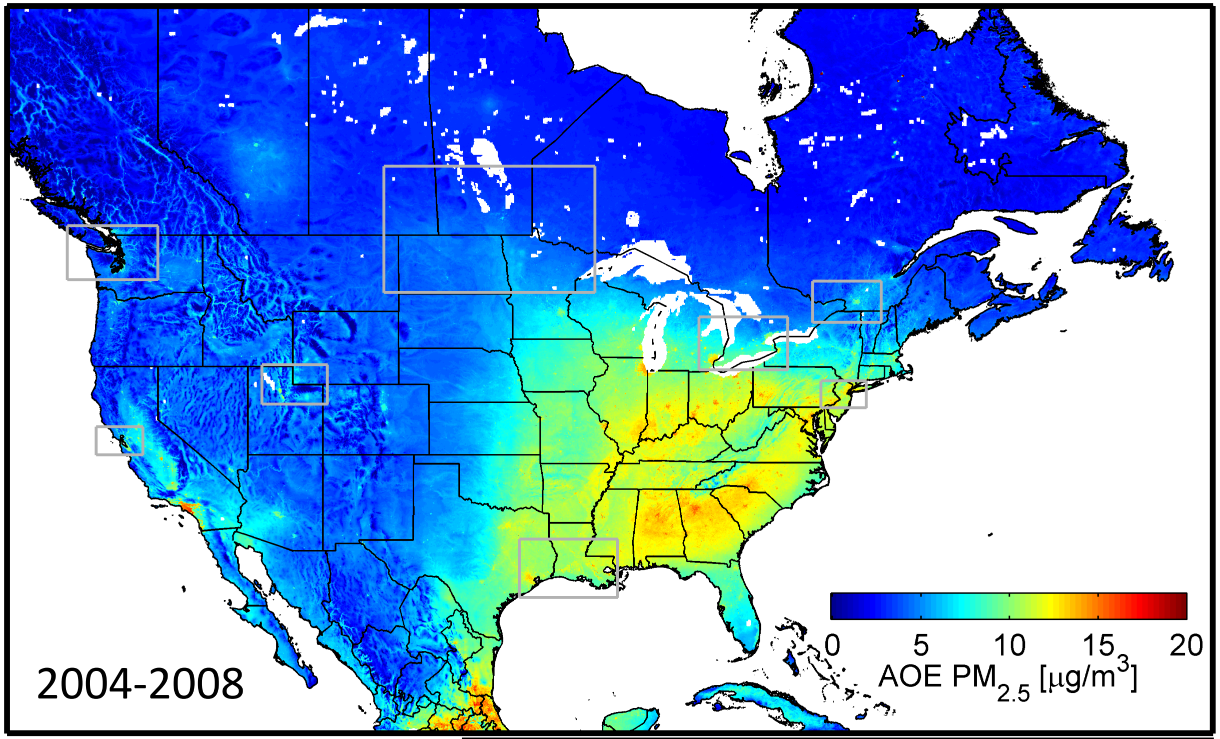
van Donkelaar et al., ES&T, 2015

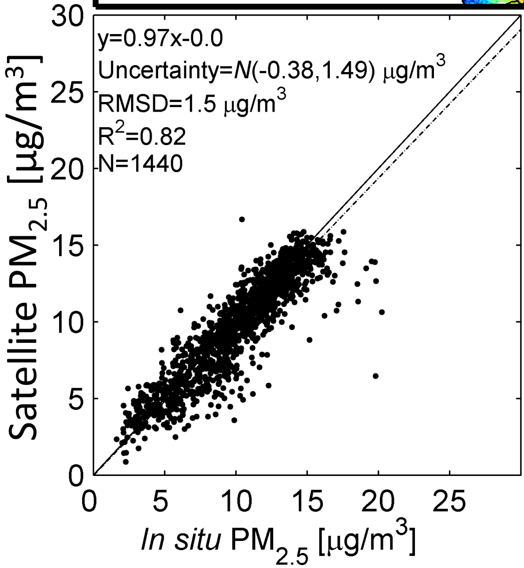
Geographically Weighted Regression can predict bias and provide physical insight

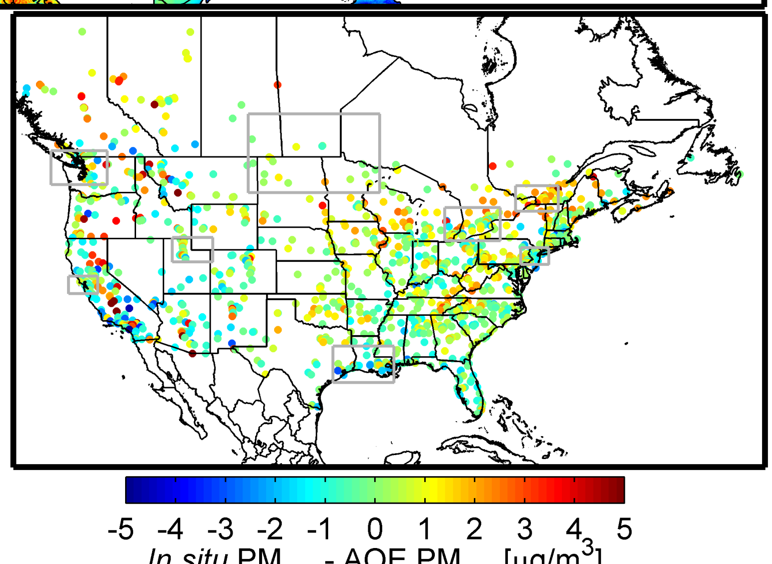


van Donkelaar et al., ES&T, 2015

GWR significantly improves performance







…and agreement is independent of resolution:

R^2 by resolution (no GWR)

Res	NA	ENA	WNA
0.01°	0.62	0.69	0.40
0.03°	0.62	0.70	0.40
0.05°	0.62	0.69	0.40
0.10°	0.62	0.69	0.39

R^2 by resolution (with GWR)

Res	NA	ENA	WNA
0.01°	0.82	0.83	0.74
0.03°	0.81	0.83	0.71
0.05°	0.79	0.81	0.68
0.10°	0.76	0.78	0.63

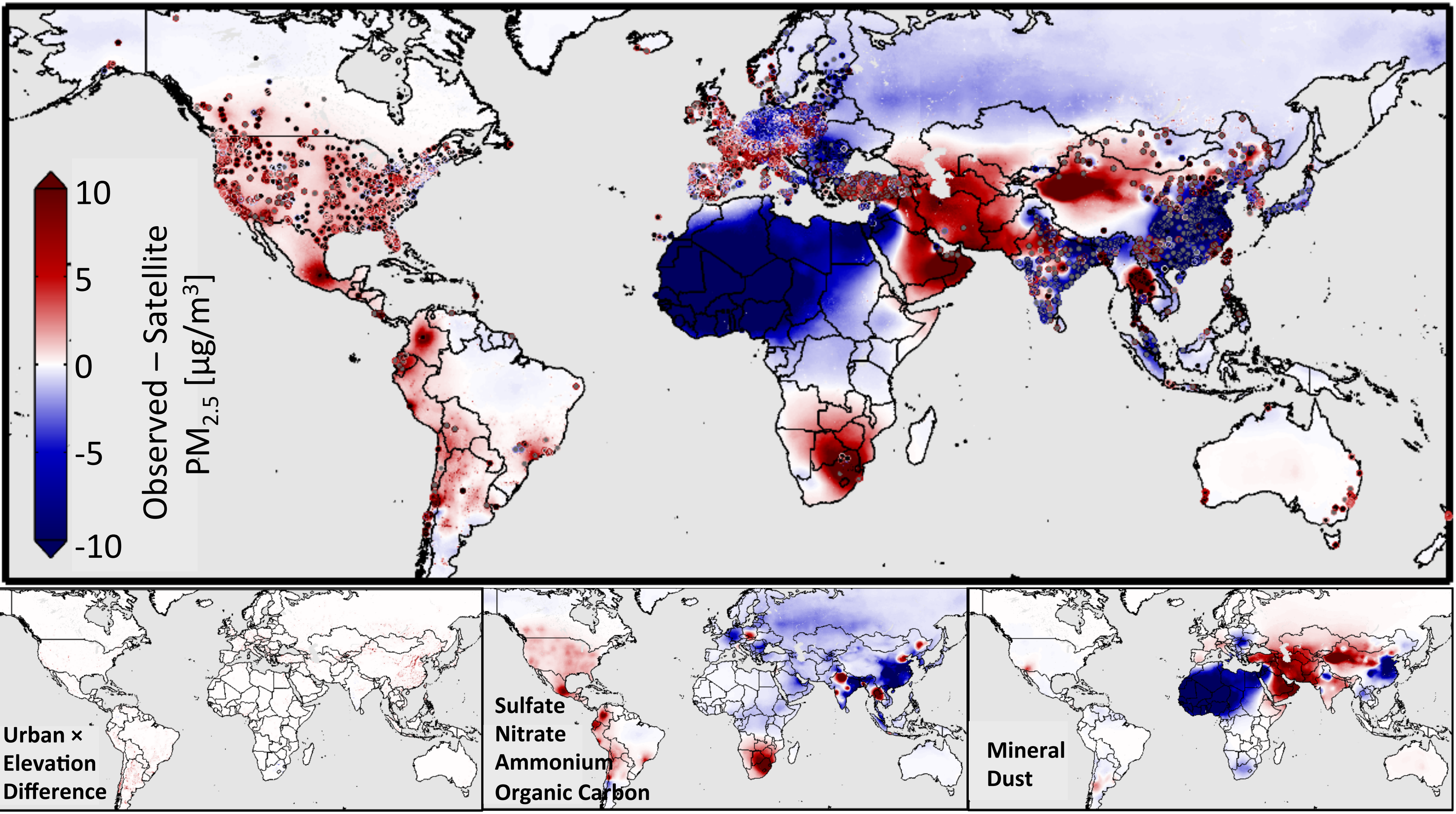
Consistent agreement at cross validation sites:

Percent CV	R^2
95%	0.73
90%	0.75
70%	0.78
50%	0.78
30%	0.79
10%	0.79

Can we use GWR globally?

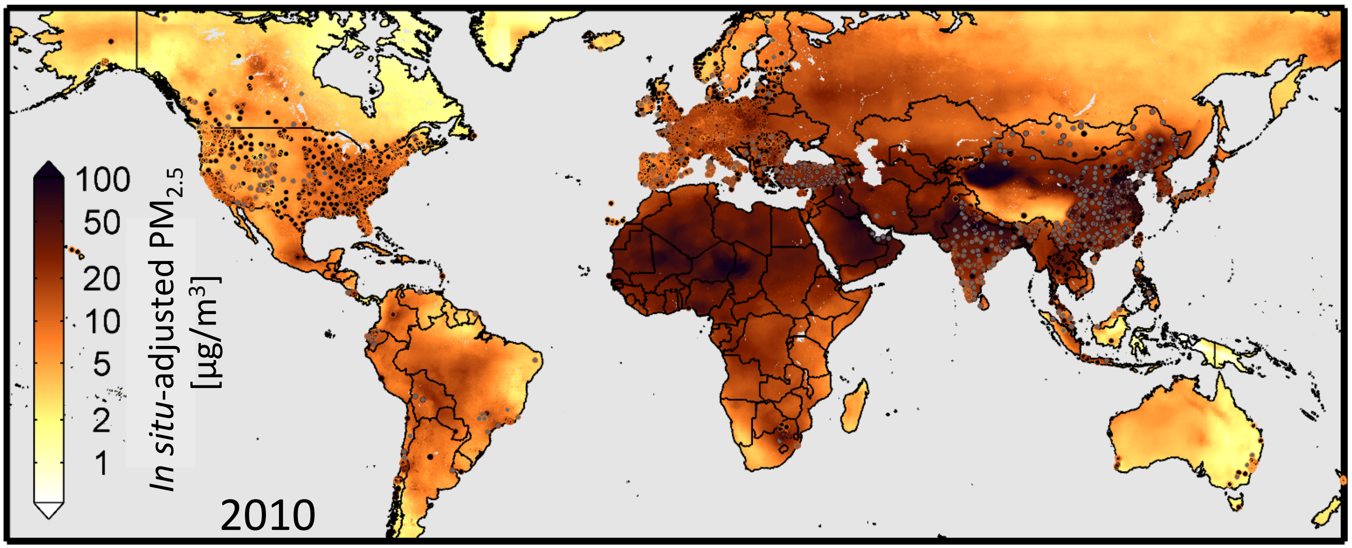
Modify predictors due to sparse monitors:

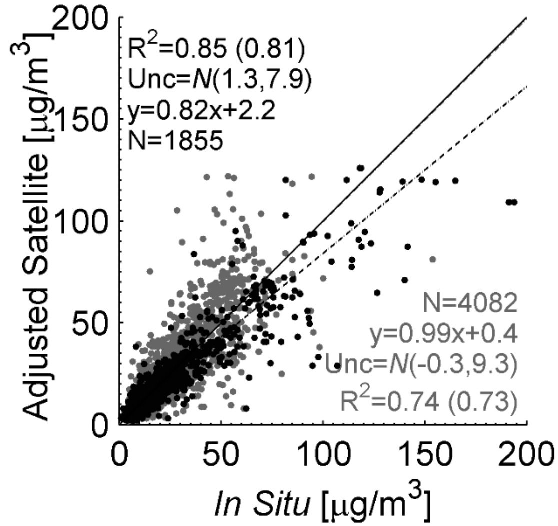
$$(\textit{in situ}\ PM_{2.5} - SAT\ PM_{2.5}) = \beta_1 U\times ED + \beta_2 DST + \beta_3(SNAO)$$

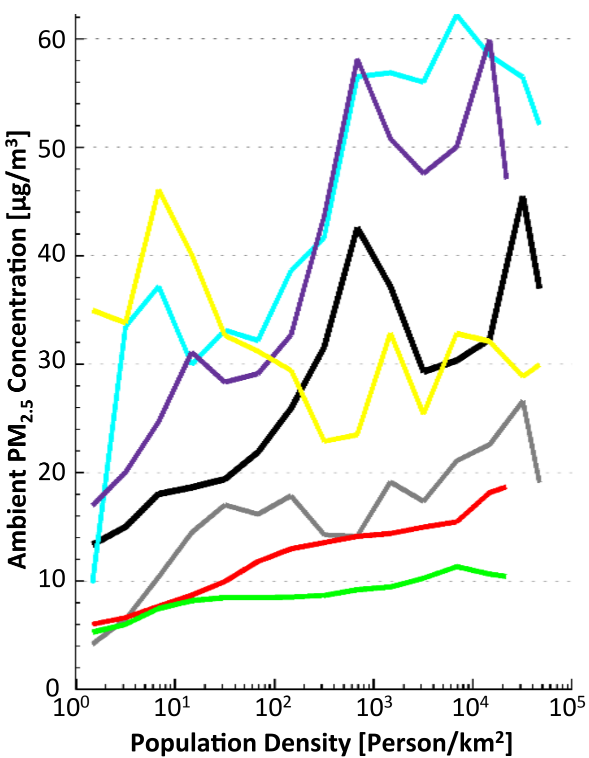


van Donkelaar, ES&T, 2016

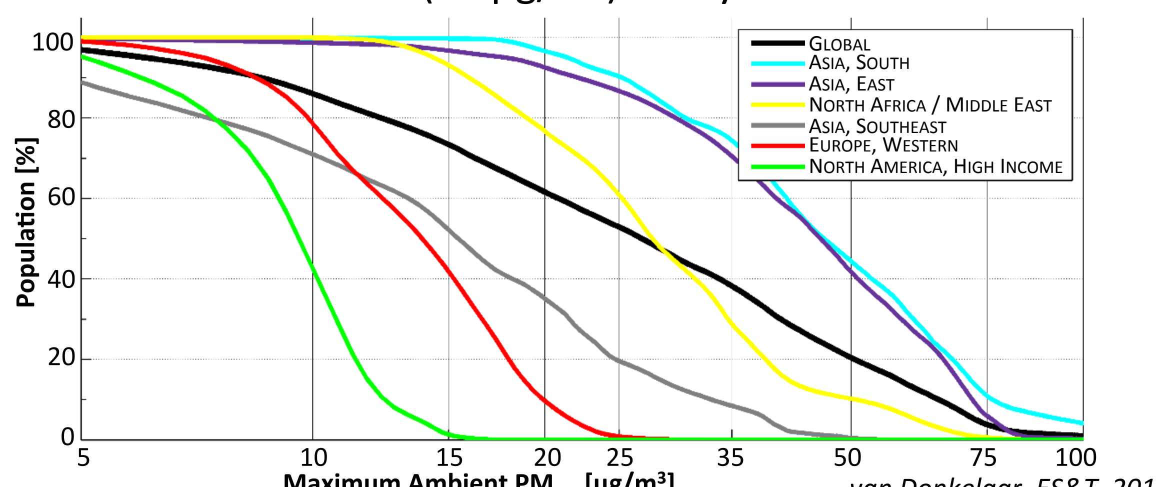
Large benefit to GWR, even on a global scale





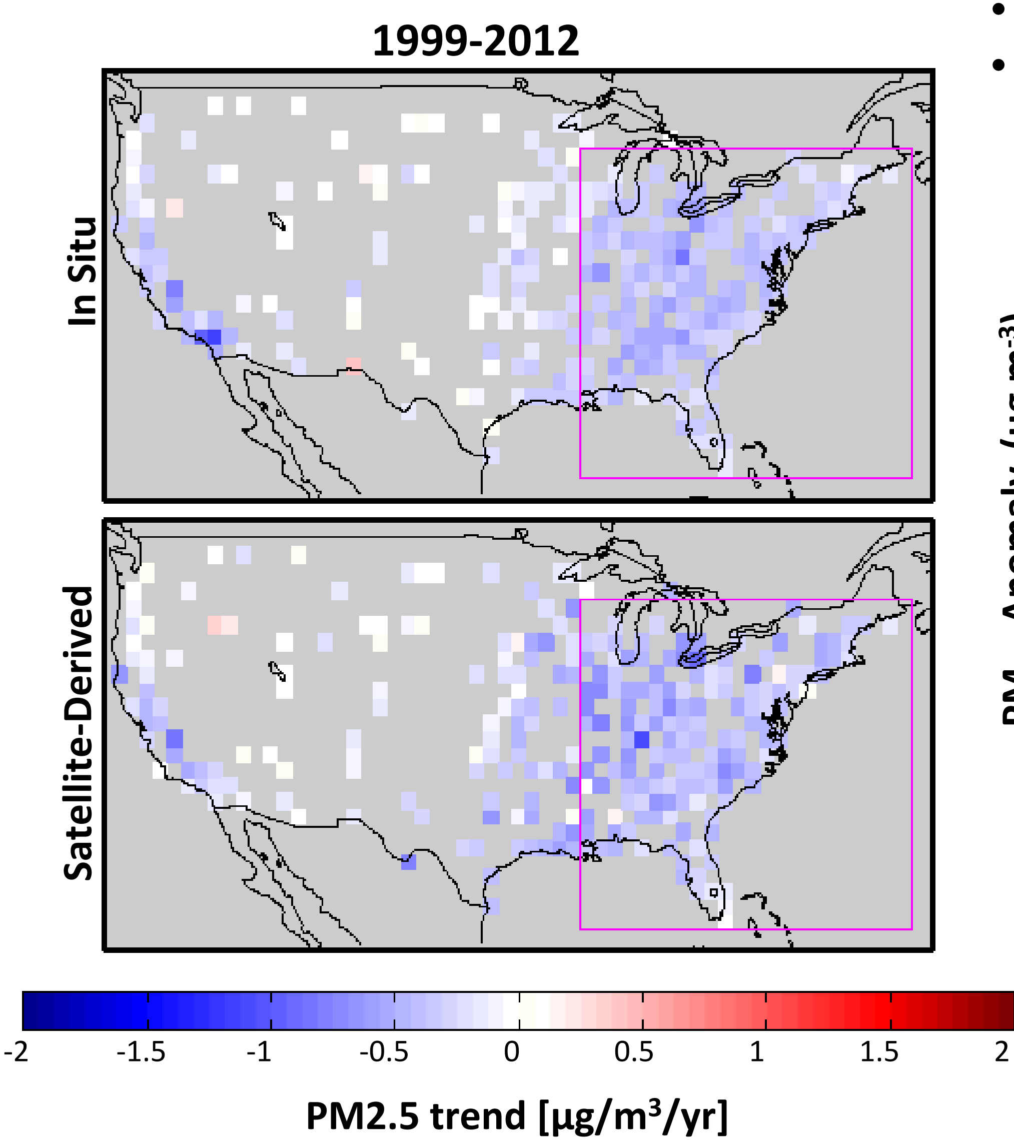


- Exposure generally increases with density
- Dense NA/EU populations have lower concentrations than sparse Asian populations
- WHO standard (10 μg/m^3) rarely met

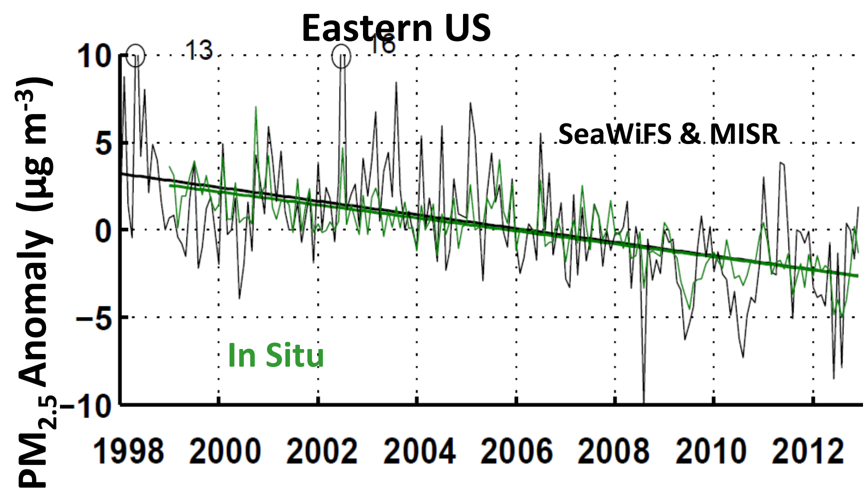


van Donkelaar, ES&T, 2016

SeaWiFS and MISR AOD give insight into $PM_{2.5}$ trend



- Both instruments radiometrically stable
- CALIOP unavailable before 2006
  - cannot use on long-term AOD-$PM_{2.5}$ relationship



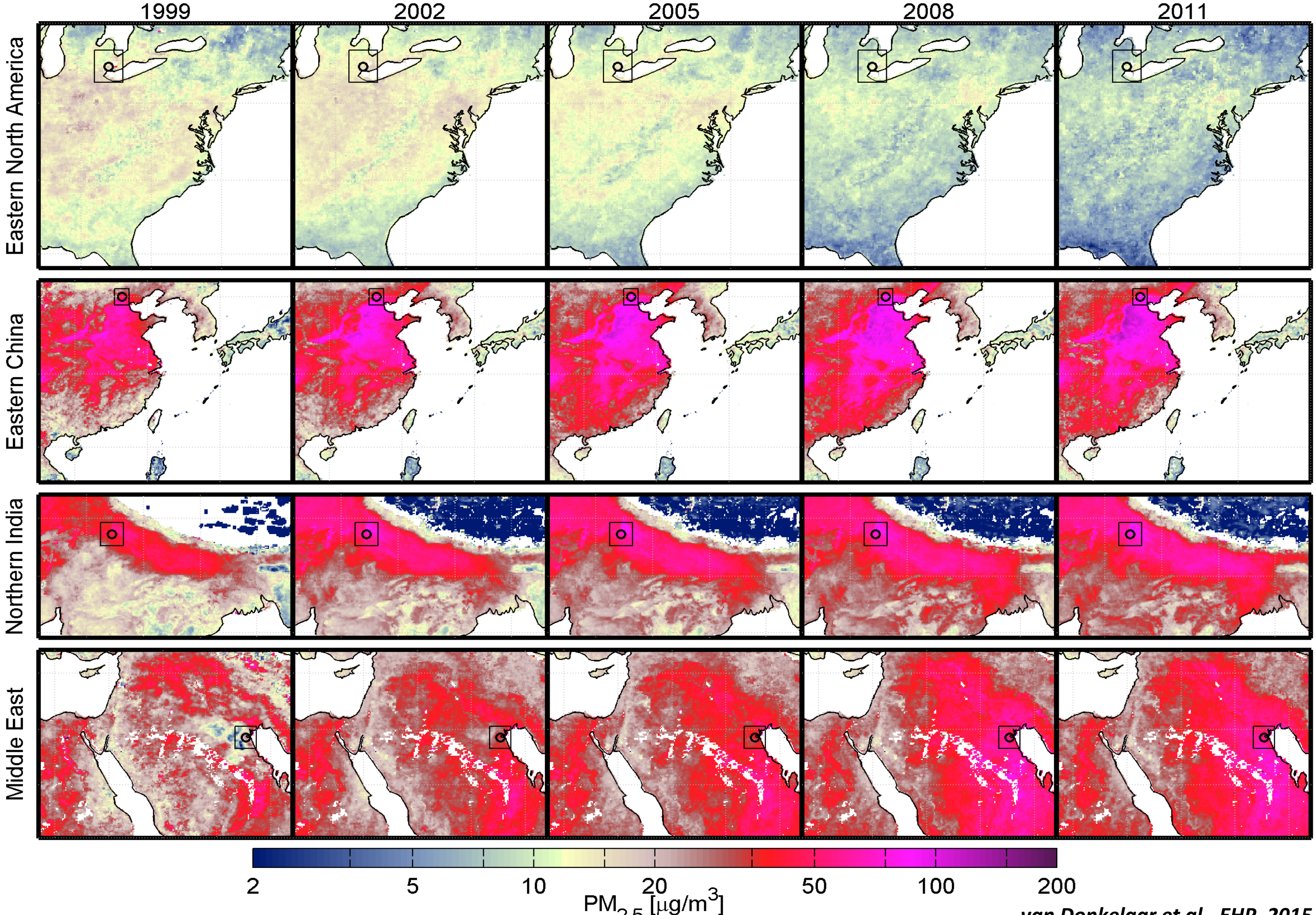
In Situ (1999-2012): 0.37 ± 0.06 µg m^{-3} yr^{-1}

Satellite-Derived (1999-2012): 0.36 ± 0.13 µg m^{-3} yr^{-1}

- Apply relative change to 2001-2010 mean $PM_{2.5}$
  → consistent magnitude and trend

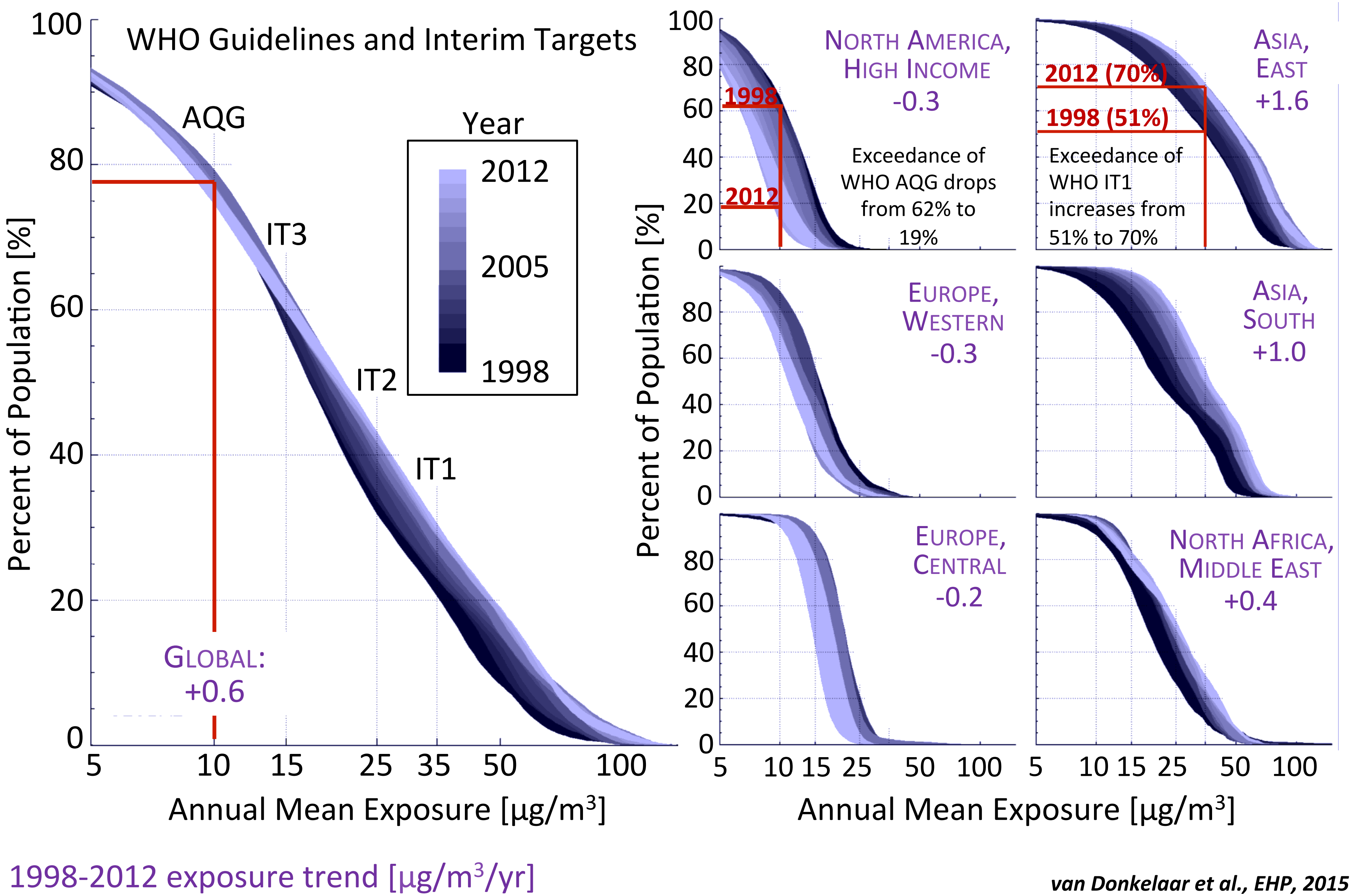
Boys et al., ES&T, 2014

Time series highlight significant global changes



van Donkelaar et al., EHP, 2015

Changes in Long-term Population-Weighted Ambient $PM_{2.5}$
Clean Areas are Improving; High $PM_{2.5}$ Areas are Degrading



van Donkelaar et al., EHP, 2015

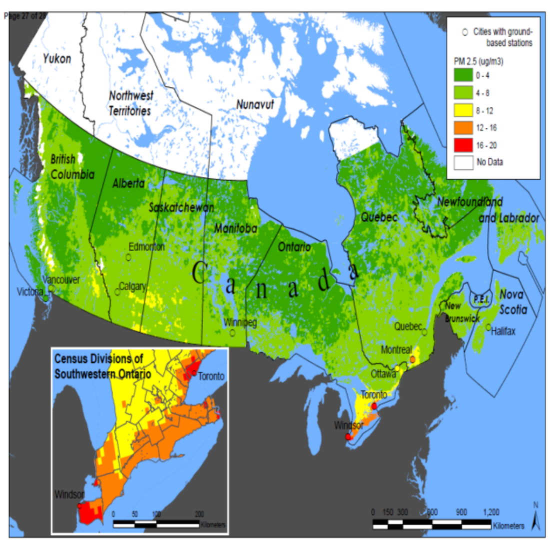
Global impact of global data

Global Burden of Disease

- 488 authors from 303 institutions in 50 countries
- $PM_{2.5}$ causal role in 3 million deaths per year

Lim et al., Lancet, 2012
Forouzanfar et al., Lancet, 2015

Inform Epidemiological Studies:



Crouse et al., EHP, 2012

- Global childhood asthma (Anderson et al., 2012)
- Lung cancer in Canada (Hystad et al., 2012)
- Mortality in California (Jerrett et al., 2013)
- Diabetes (Brook et al., 2013; Chen et al., 2013)
- Global adverse birth outcomes (Fleischer et al., 2014)
- Hypertension (Chen et al., 2013)
- Low $PM_{2.5}$ effects (Crouse et al., 2012; Pinault et al., 2016)
- Changes in Health Impacts (Steib et al., 2015)

Conclusions

- AOD provides observationally-based basis for global $PM_{2.5}$ estimation
- Multi-retrieval approaches draw on the strengths of all available sources
  - Consistent, spatially-varying error important
- Space-based extinction profiles can constrain AOD to $PM_{2.5}$ relational uncertainties
- Even sparse ground-based observations of significant value
- Long-term estimates capture regional changes

Alternatives exist to direct AOD to $PM_{2.5}$ evaluation

- Indirect validation
- Aircraft campaigns
  - non-global
  - sparse coverage
- CALIOP
  - global coverage
  - challenging near-surface retrieval
  - LIDAR ratio dependencies

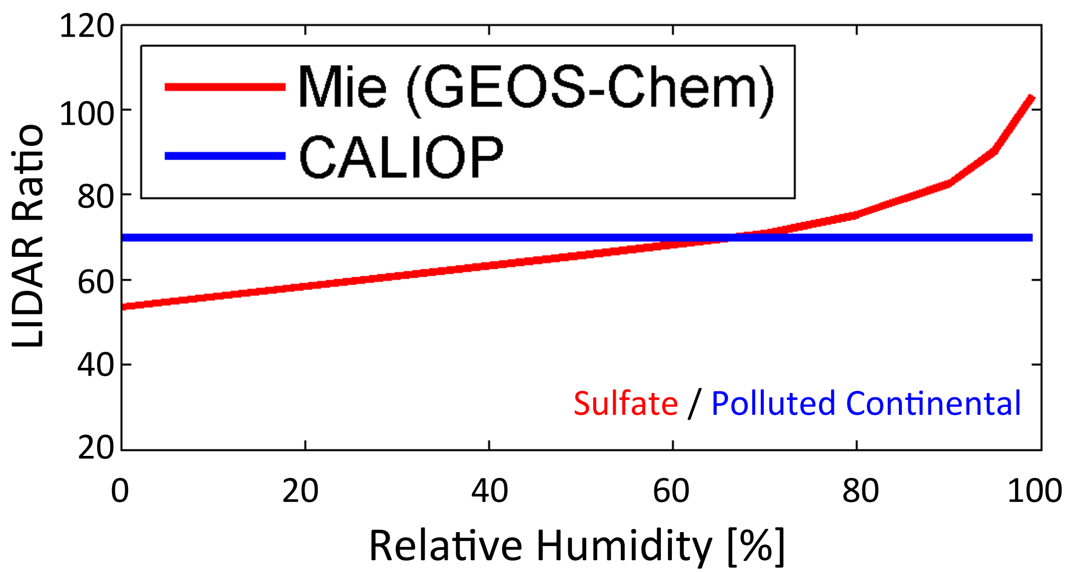
CALIOP LIDAR Ratio

- from field studies
- fixed for each species
- species from observed properties and location

GEOS-Chem Optical Properties

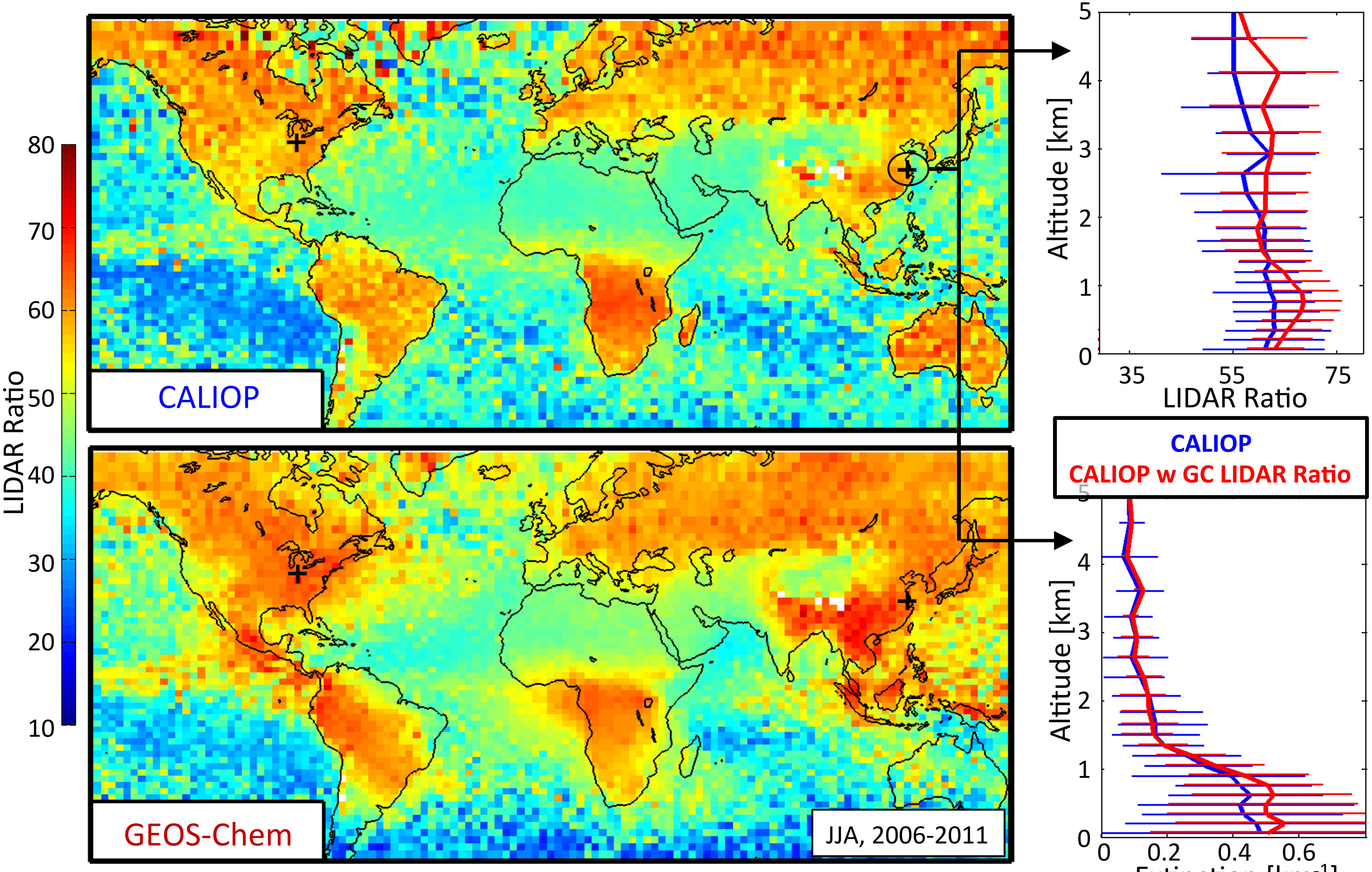
- from Mie calculation
- hydrophillic species vary as a function of RH
- species from emissions, chemistry, processing, etc.

$$\text{LIDAR Ratio} = \frac{\text{Particulate extinction}}{\text{Particulate backscatter}}$$



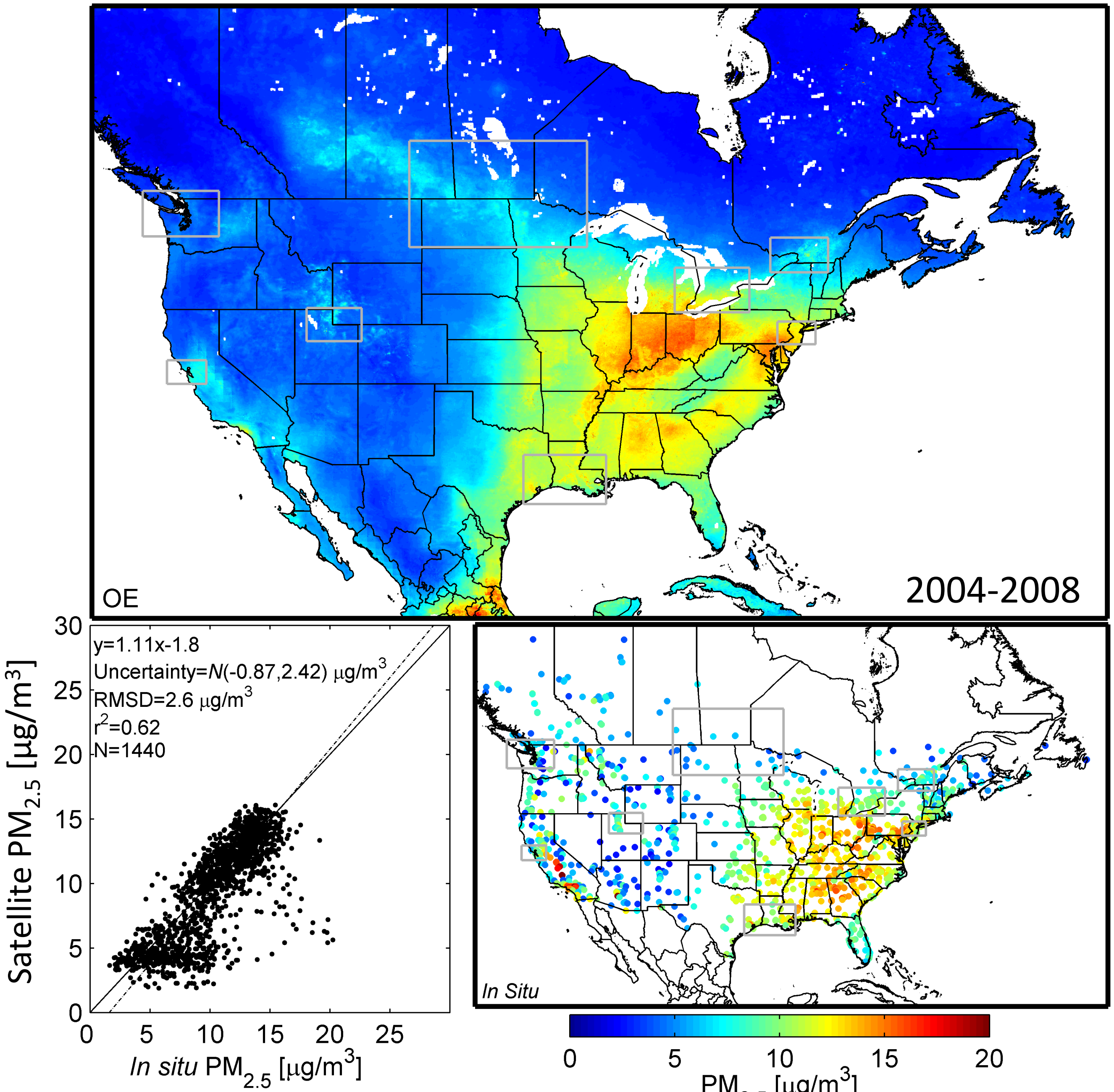
van Donkelaar, JGR, 2013

Optical properties affect profile comparison



van Donkelaar, JGR, 2013

Global and NA agreement is consistent



van Donkelaar, ES&T, 2015