Combining the Attributes of Satellite Observations and a Chemical Transport Model to Estimate $PM_{2.5}$

Randall Martin

with contributions from

Brian Boys, Kacie Conrad, Daniel Cunningham, Jeff Geddes, Chris Gordon, Mark Gibson, Sajeev Philip, Yvonne Ritchie, Graydon Snider, Crystal Weagle, Aaron van Donkelaar, Junwei Xu, Matthew Zwicker

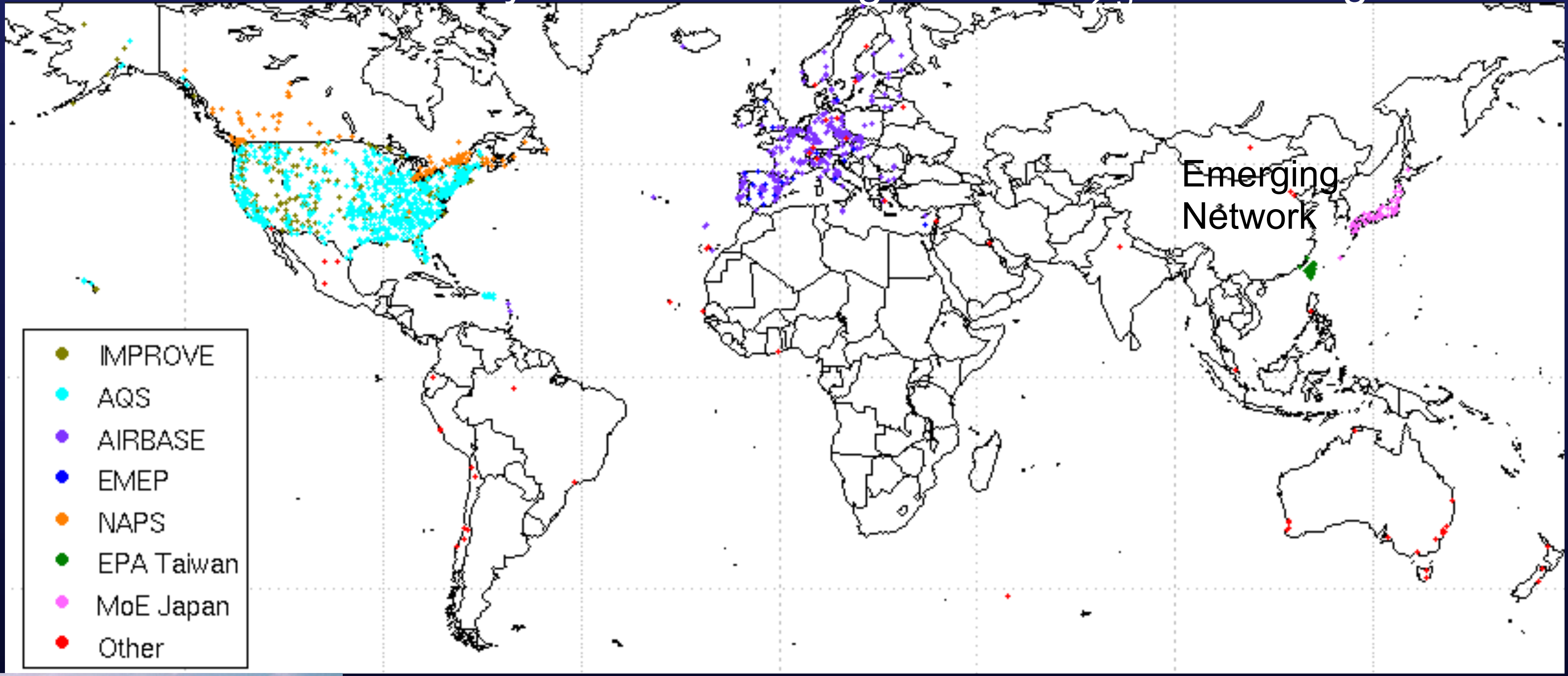
DALHOUSIE UNIVERSITY
Inspiring Minds

Michael Brauer (UBC), Rick Burnett (Health Canada), Myungie Choi (Yonsei), Aaron Cohen (HEI), Dan Crouse (Health Canada), Brent Holben (NASA), Christina Hsu (NASA), Jhoon Kim (Yonsei), Rob Levy (NASA), Yang Liu (Emory), Ralph Kahn (NASA), Vanderlei Martins (AirPhoton), Adam Pasch (STI), James Szykman (NASA/EPA), Qiang Zhang (Tsinghua)

ARSET Air Quality Webinar
22 October 2015

Vast Regions Have Insufficient $PM_{2.5}$ Measurements for Exposure Assessment

Locations of Publicly Accessible Long-Term $PM_{2.5}$ Monitoring Sites



Monitor locations can be driven by compliance objectives

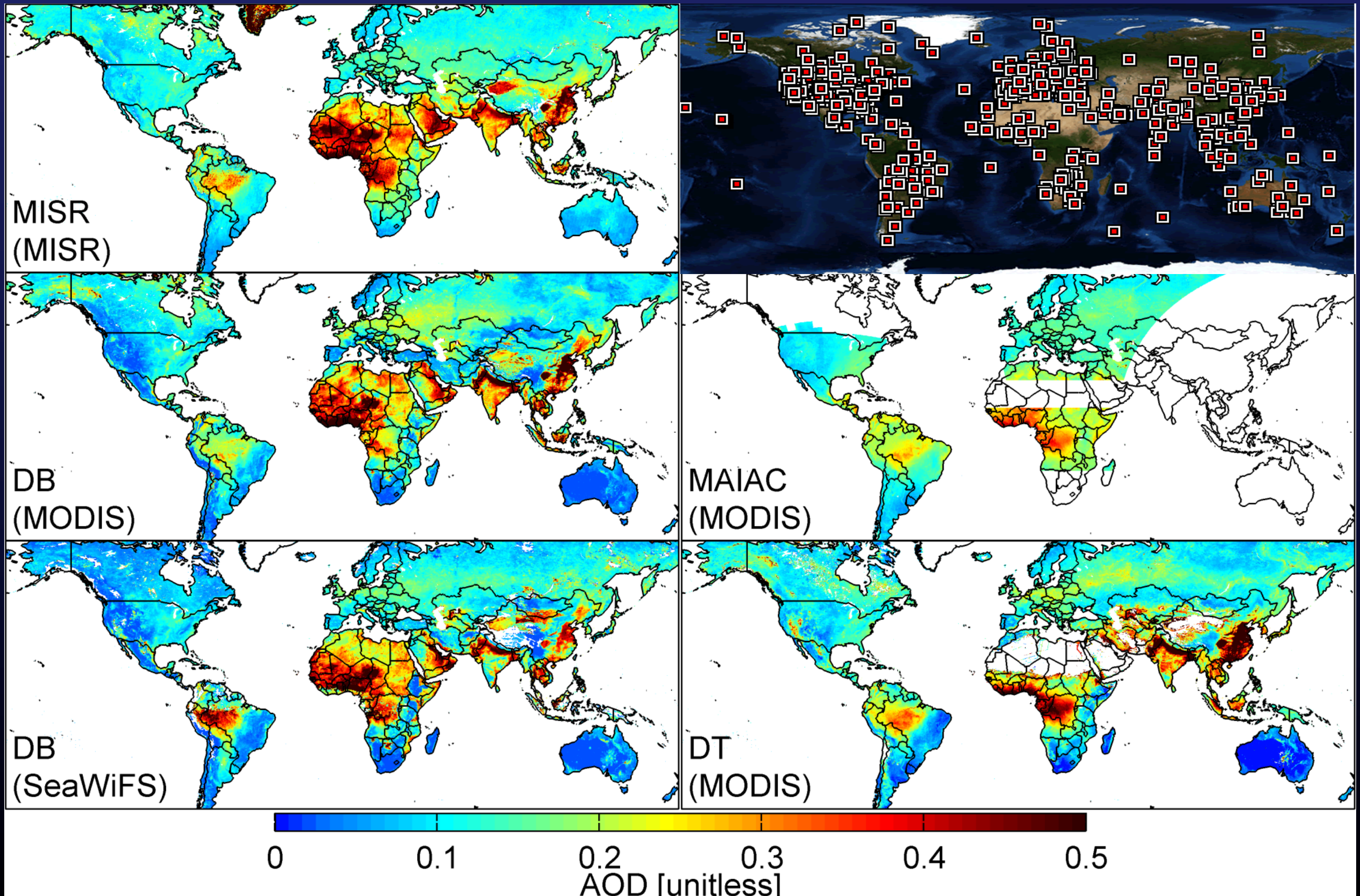
~1 site / 10,000 km^2 in continental US & southern Canada

Plagued early Global Burden of Disease efforts

Lack of Canadian long-term $PM_{2.5}$ guideline at start of work

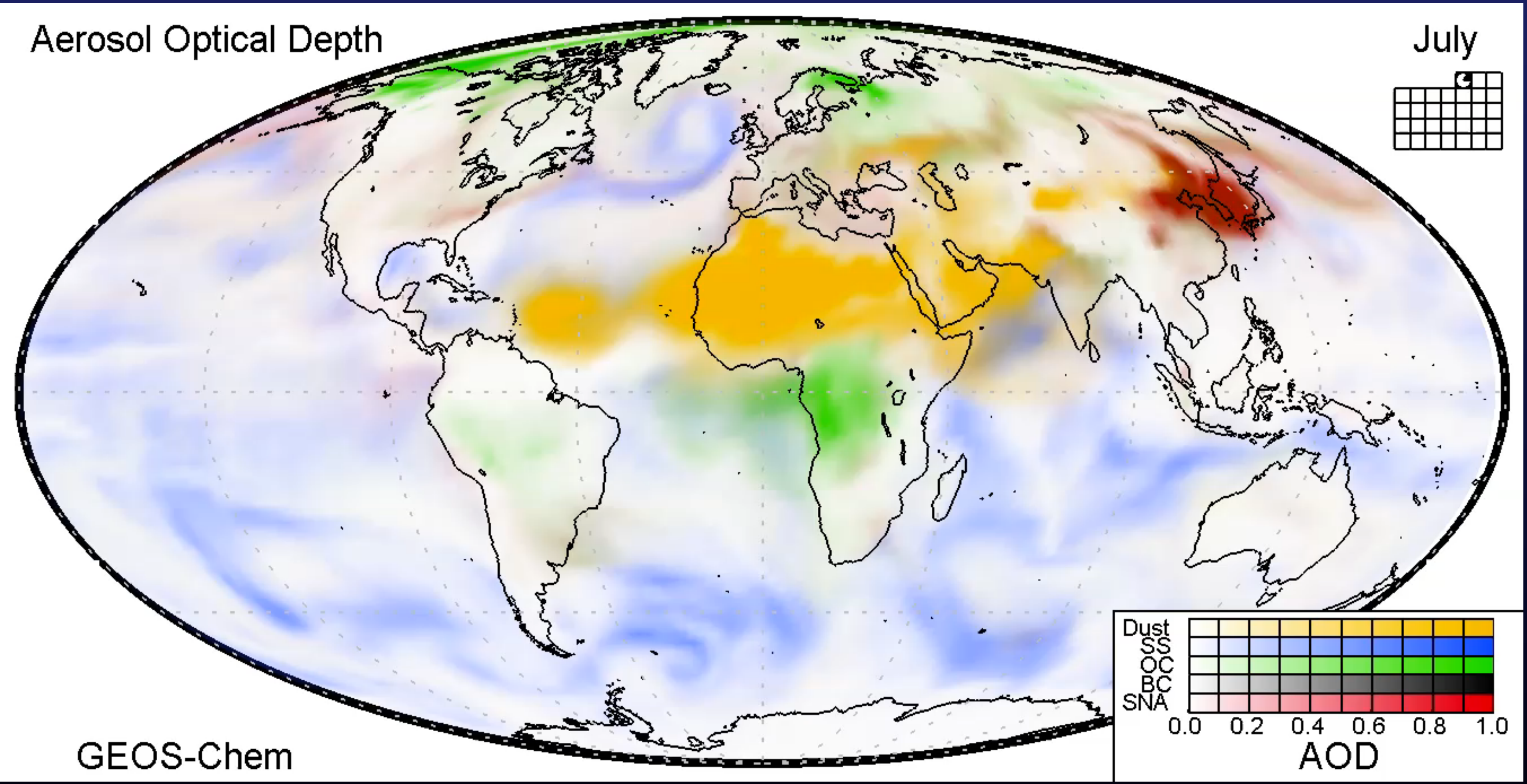
Long-Term (2001-2010) Aerosol Optical Depth (AOD)

Use AERONET AOD to Assess Relative Accuracy & Combine



van Donkelaar et al., in prep

Apply Chemical Transport Model (GEOS-Chem) to Calculate AOD/$PM_{2.5}$ for Each Observation



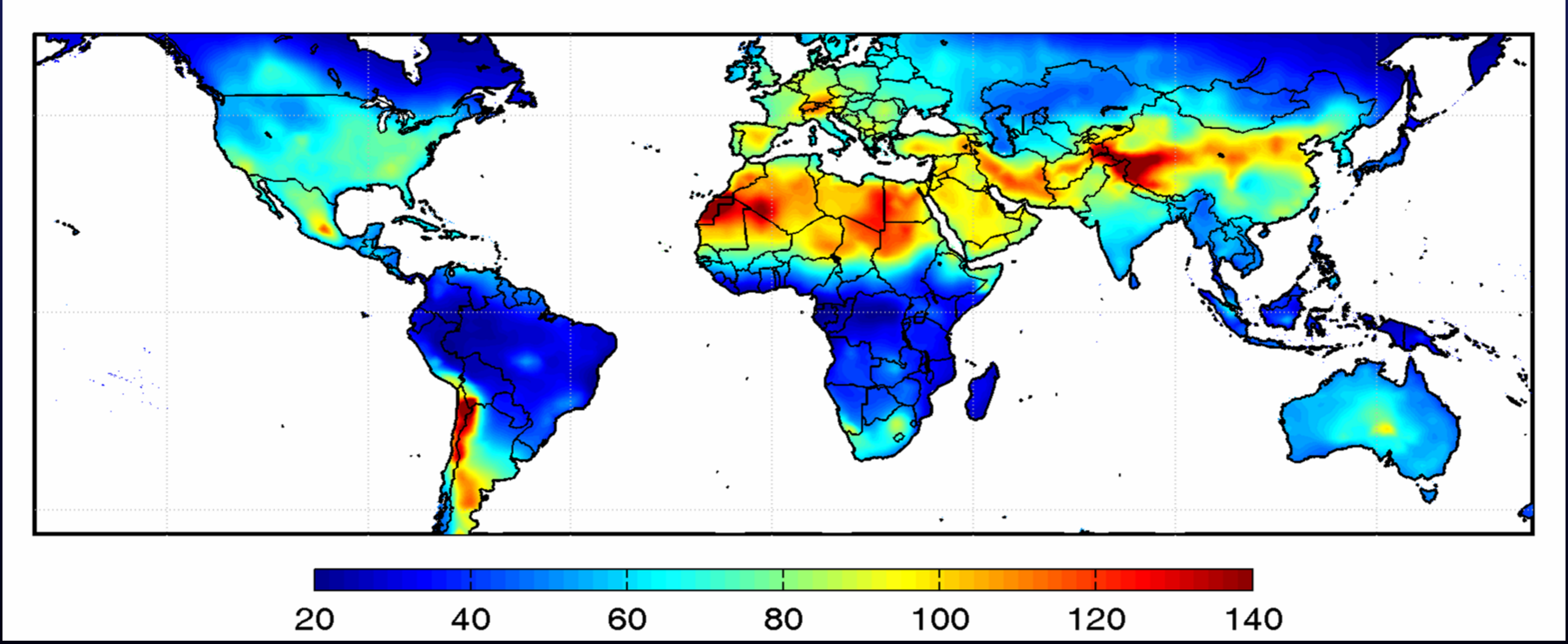
www.geos-chem.org

Aaron van Donkelaar

Long-Term "Dry" $PM_{2.5}$ to AOD Relation

Affected by vertical structure, aerosol properties, relative humidity
Model sampled coincidently with MODIS and MISR observations

GEOS-Chem Simulation of $PM_{2.5}$ / AOD for 2001-2006

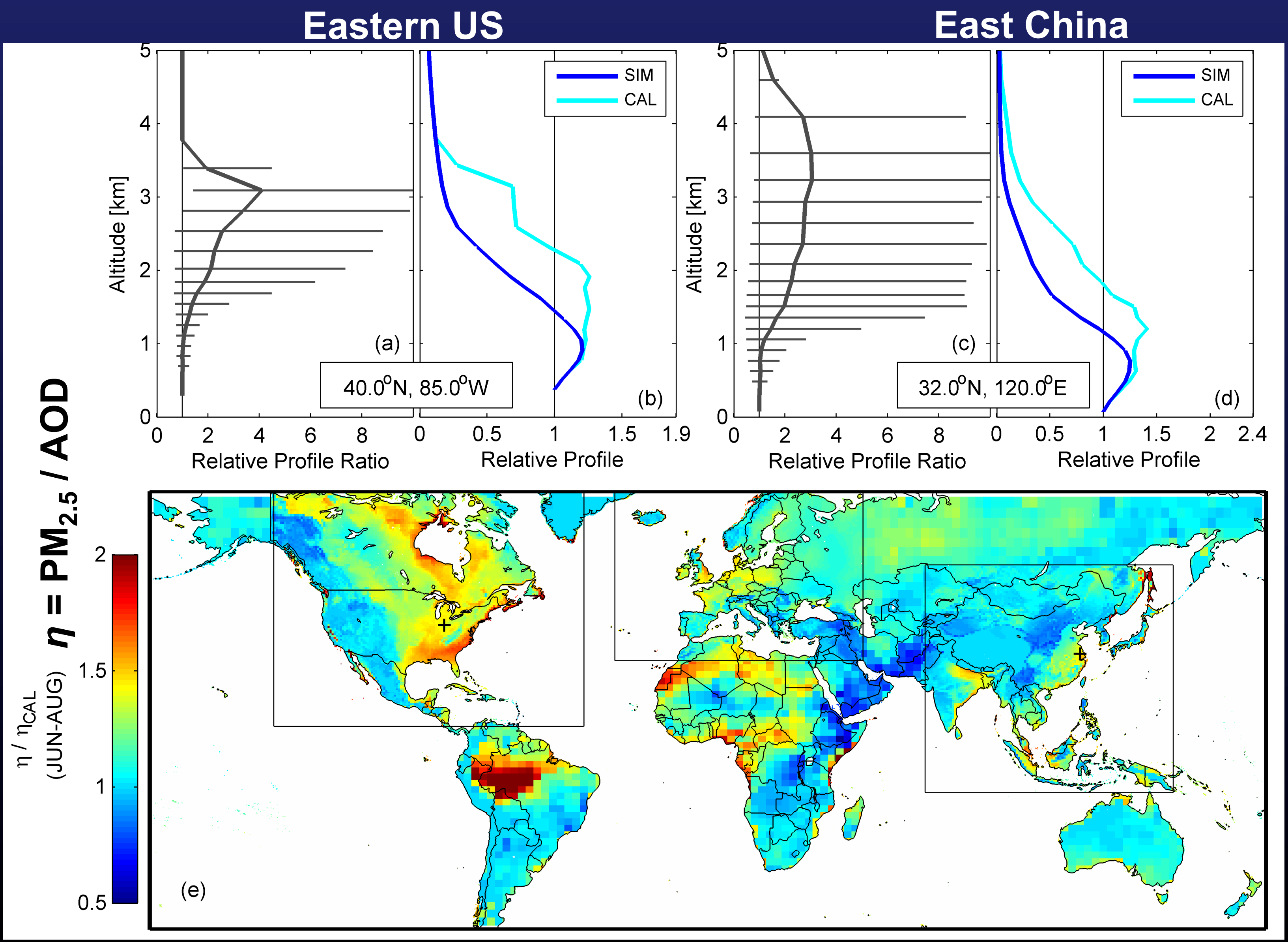


$PM_{2.5}$ / AOD ($\mu g\ m^{-3}$)

$PM_{2.5}$ calculated at 35% RH

van Donkelaar et al., EHP, 2010

Use CALIOP Observations (2006-2011) to Correct Seasonal Bias in Simulated Aerosol Extinction



van Donkelaar et al., JGR, 2013

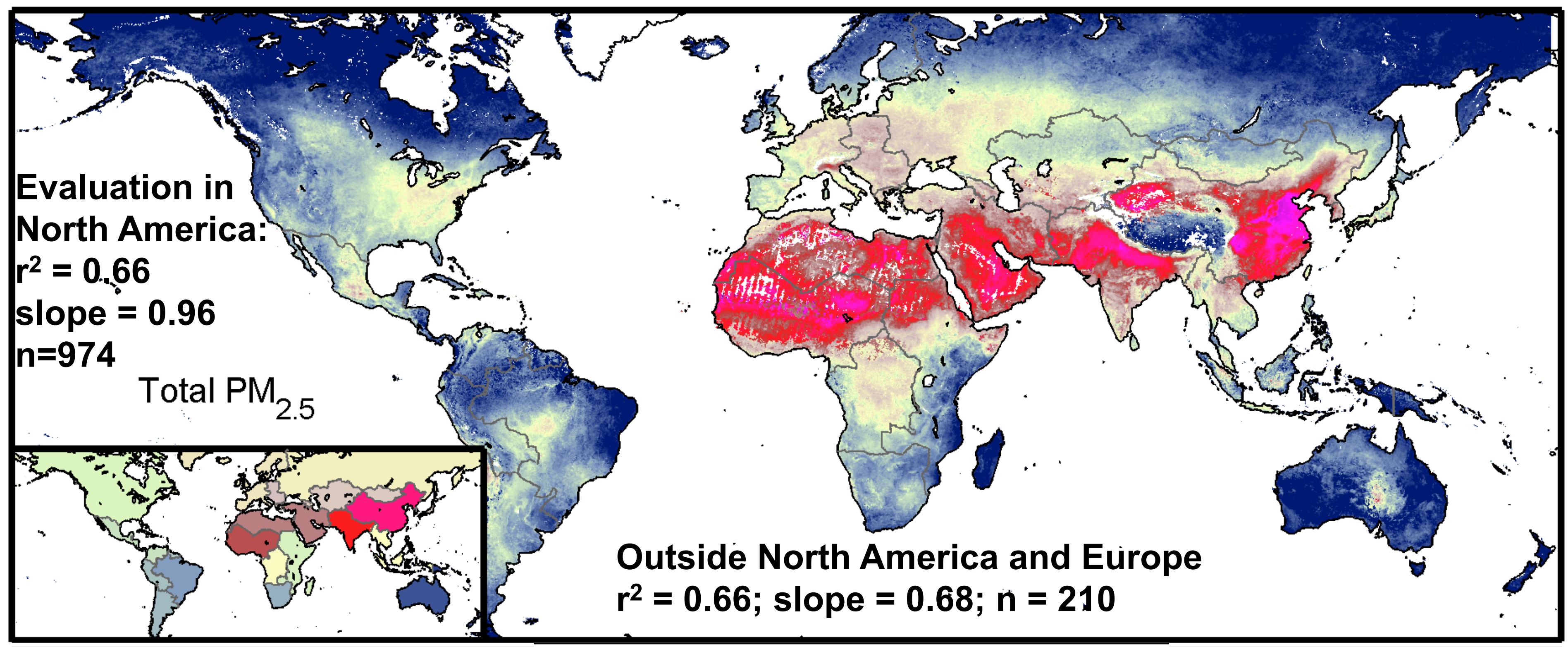
Comments on the Inference of $PM_{2.5}$ from AOD

May sound deceptively easy.

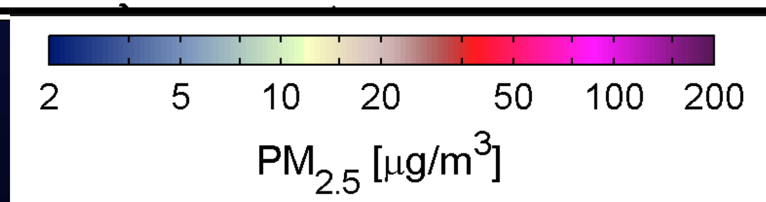
Valuable to:

- Mitigate error sources affecting satellite AOD retrievals
- Sample model coincidently with satellite observations (level 2)
- Evaluate and develop simulation capability for the numerous processes affecting relation of ground-level $PM_{2.5}$ at specified RH (e.g. 35%) with column AOD at ambient RH

Climatology (2001-2010) of Satellite-Derived $PM_{2.5}$



Spatial Resolution 10km x 10km



van Donkelaar et al., EHP, 2015

Information source for:

- Global Burden of Disease Assessments
- OECD Regaional Well Being Index
- Yale-Columbia Environmental Performance Index
- World Bank
- World Development Indicators

Contributed to:

Global Burden of Disease 2010

$PM_{2.5}$ Causal Role in

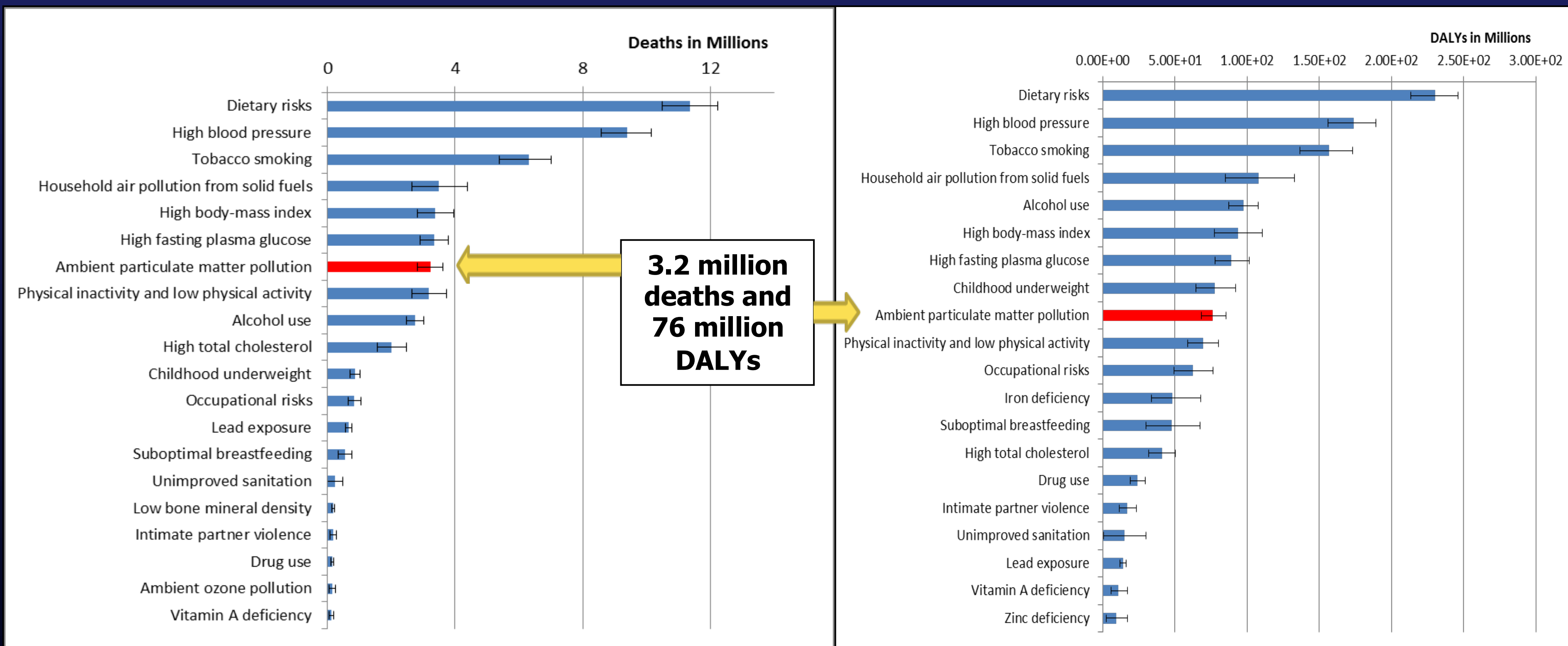
70 Million Disability Adjusted Life Years (~3%)

>3 Million Excess Deaths (~5%)

Three-fold increase over GBD 2000

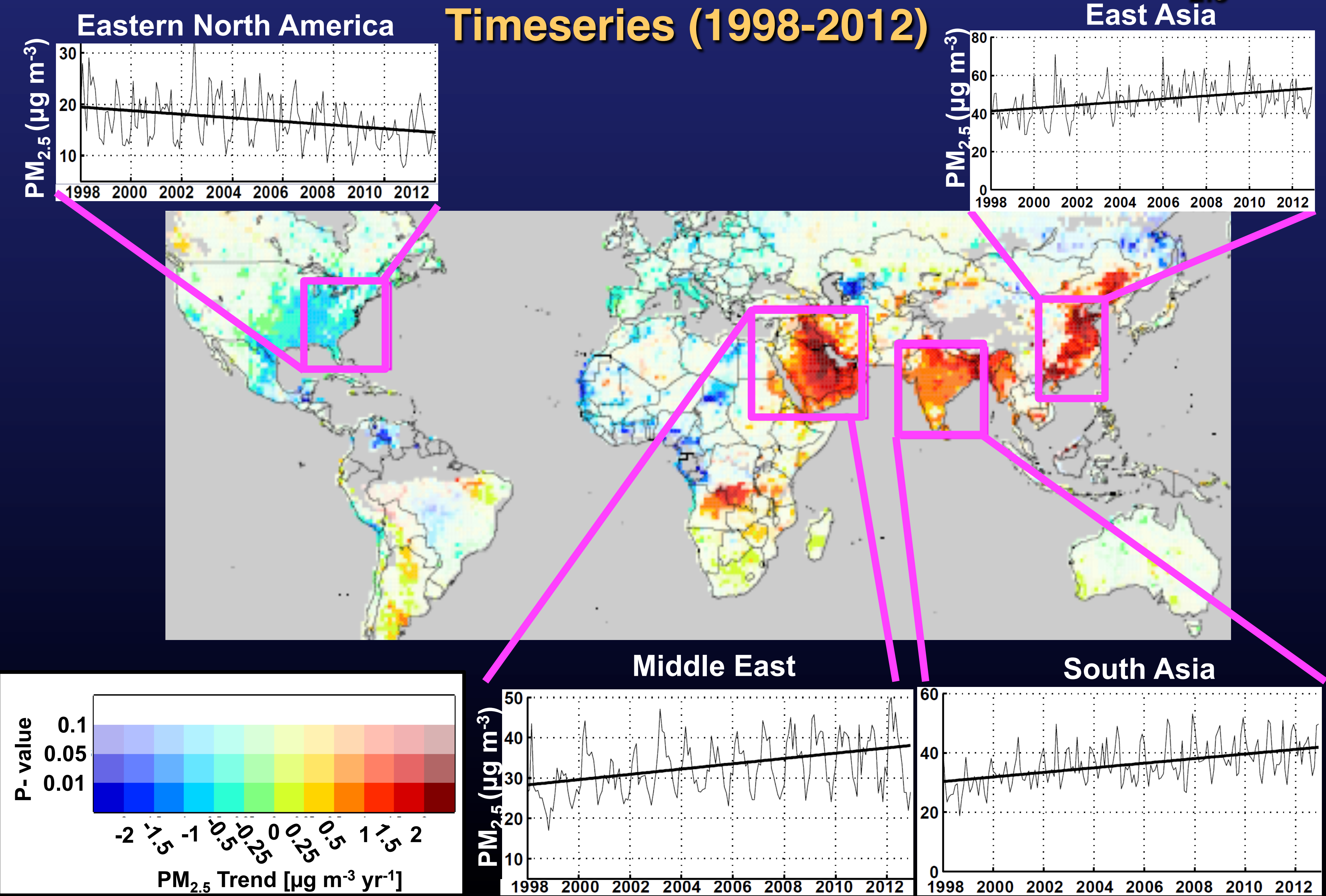
Lim et al., Lancet, 2012

Risk Factors for Global Premature Deaths and Disability Adjusted Life Years (DALYs) in 2010



Lim et al., Lancet, 2012

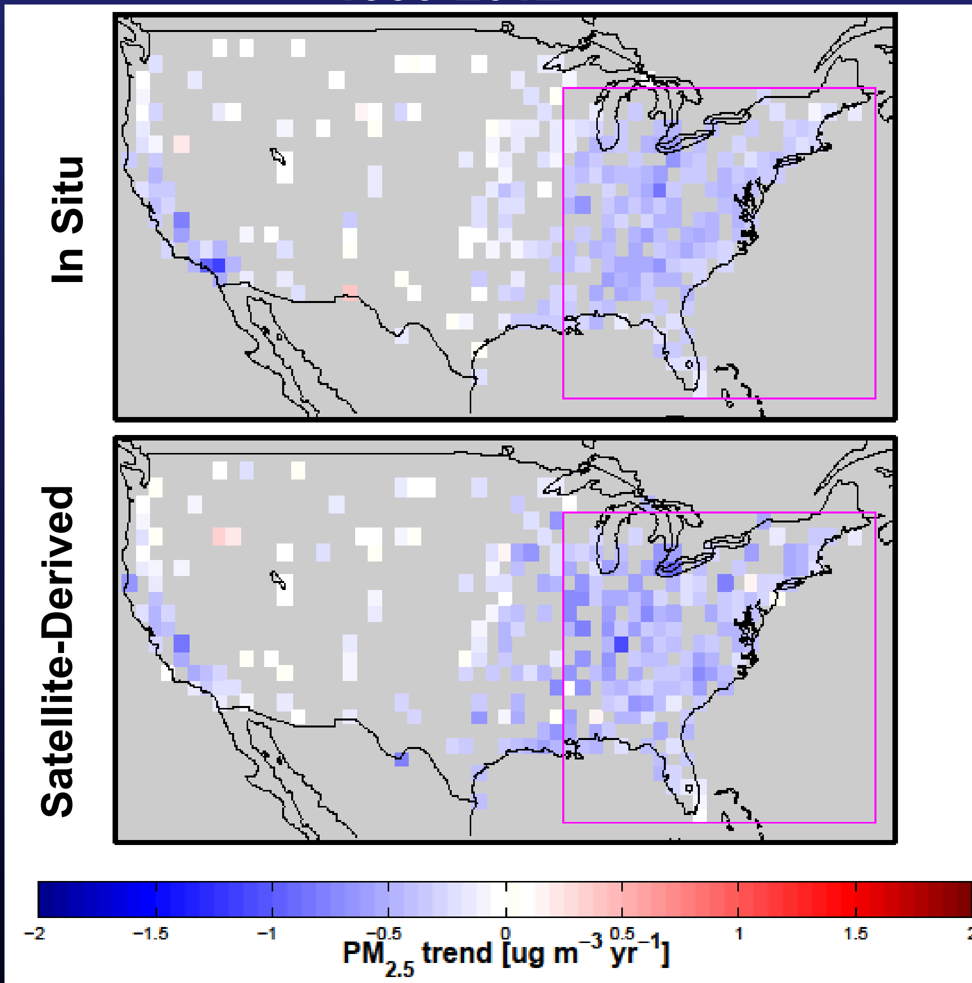
Combine SeaWifs & MISR to Calculate 15-Year $PM_{2.5}$ Timeseries (1998-2012)



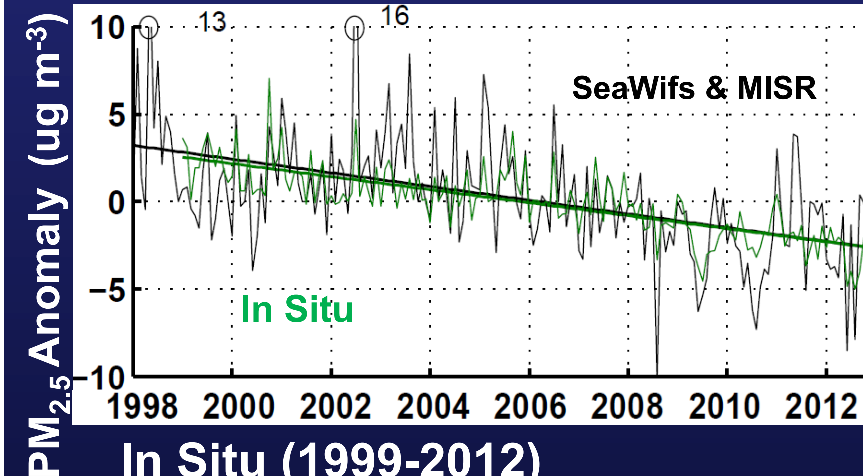
Boys et al., ES&T, 2014

Consistent Trends in Satellite-Derived and In Situ $PM_{2.5}$

1999-2012



Eastern US



In Situ (1999-2012)

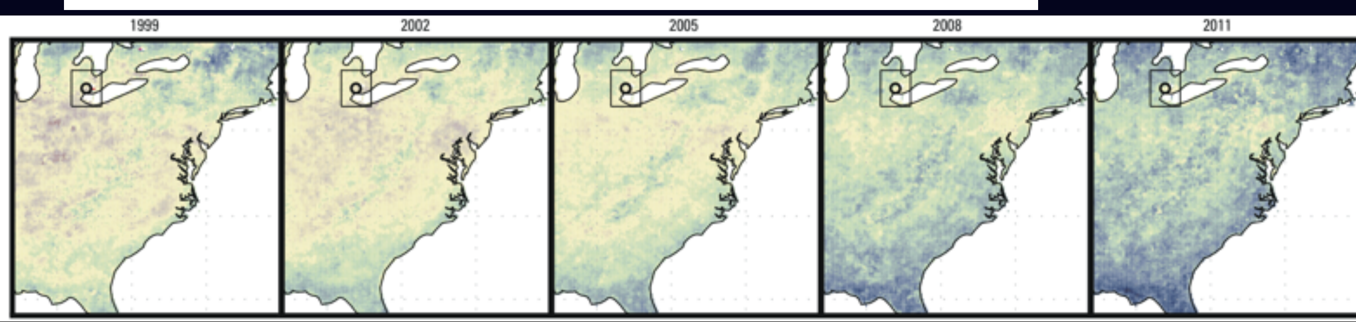
0.37 ± 0.06 μg m^{-3} yr^{-1}

Satellite-Derived (1999-2012)

0.36 ± 0.13 μg m^{-3} yr^{-1}

If constant $PM_{2.5}$ / AOD, trend degrades: 0.22 ± 0.09 μg m^{-3} yr^{-1}

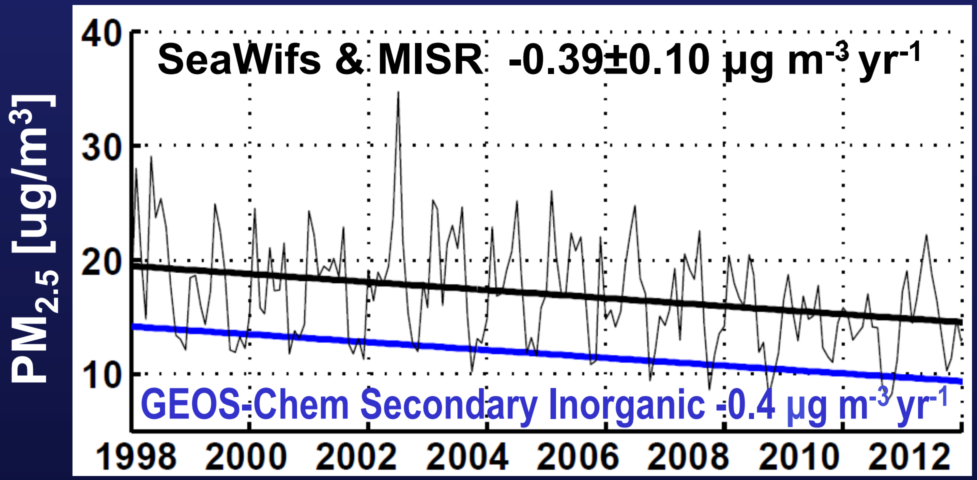
Boys et al., ES&T, 2014



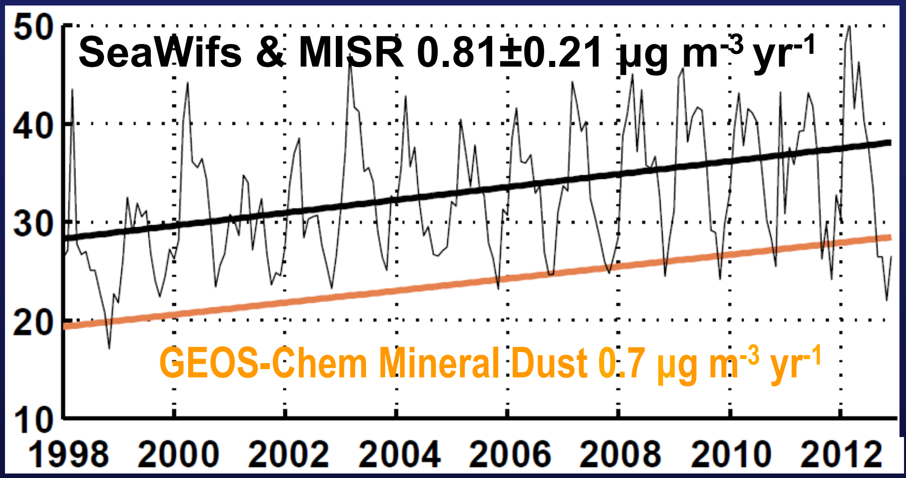
van Donkelaar et al., EHP, 2015

Interpret Satellite-derived $PM_{2.5}$ Trends with GEOS-Chem

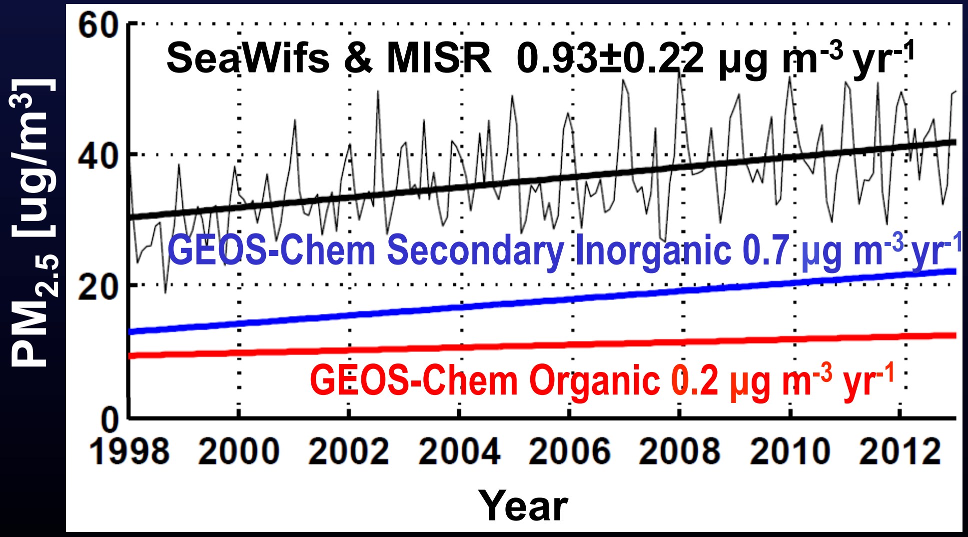
Eastern North America



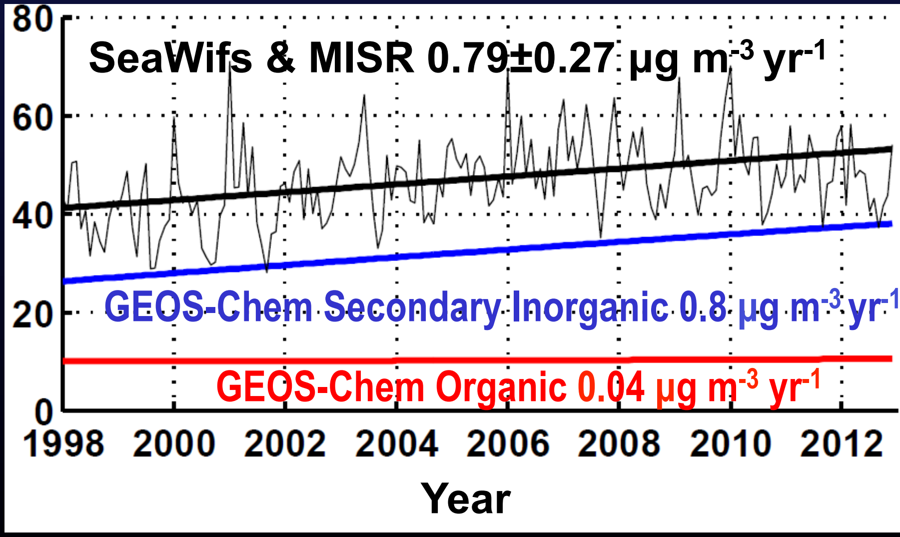
Middle East



South Asia



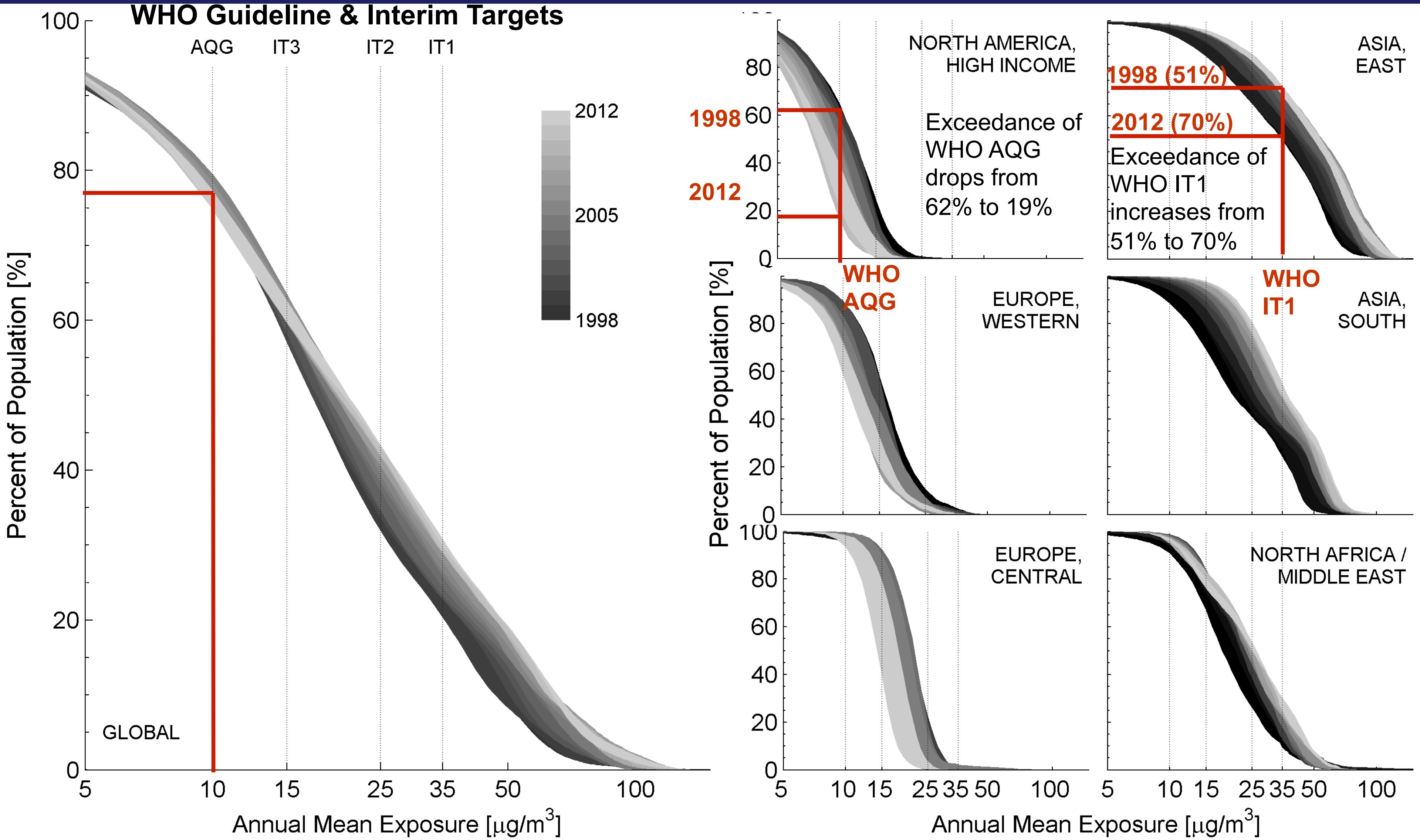
East Asia



Boys et al., ES&T, 2014

Changes in Long-term Population-Weighted Ambient $PM_{2.5}$

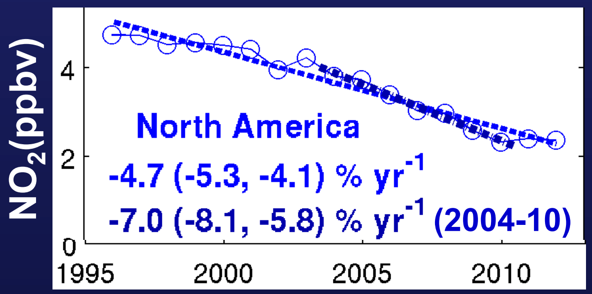
Clean Areas are Improving; High $PM_{2.5}$ Areas are Degrading

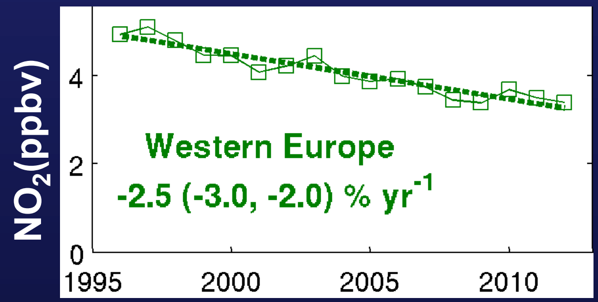


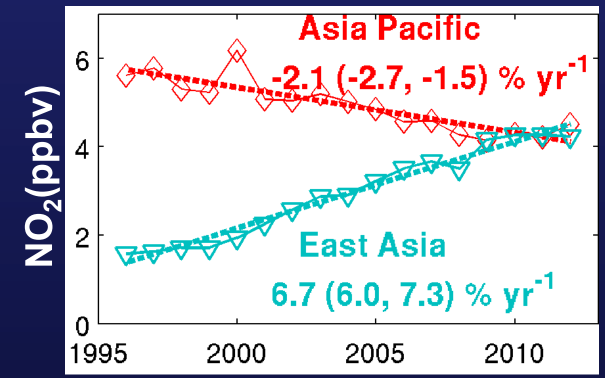
van Donkelaar et al., EHP, 2014

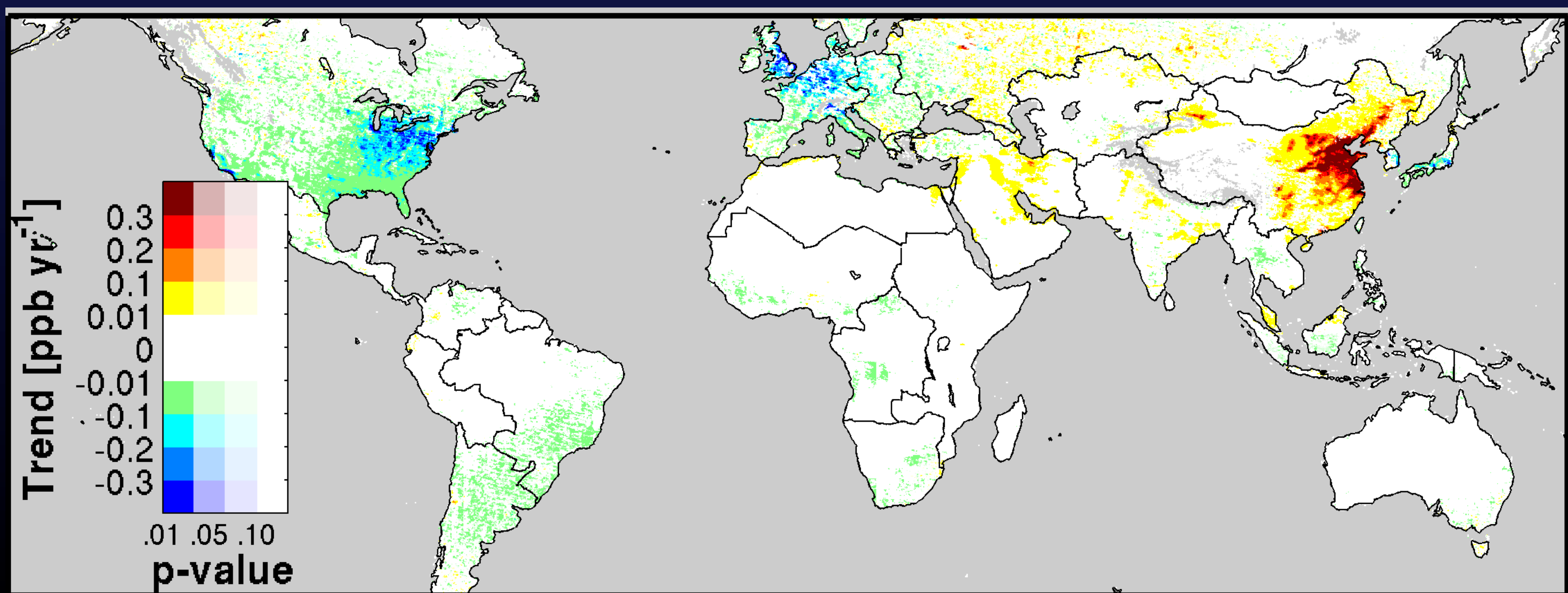
Surface NO_2 Trends over 1996-2012 from GOME, SCIAMACHY, GOME-2

Similarities with $PM_{2.5}$ Trends where Driven by Secondary Inorganics
Differences Elsewhere







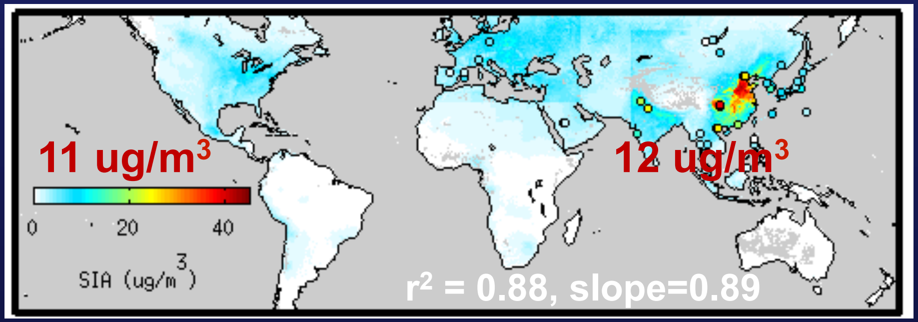


Geddes et al., EHP, 2015

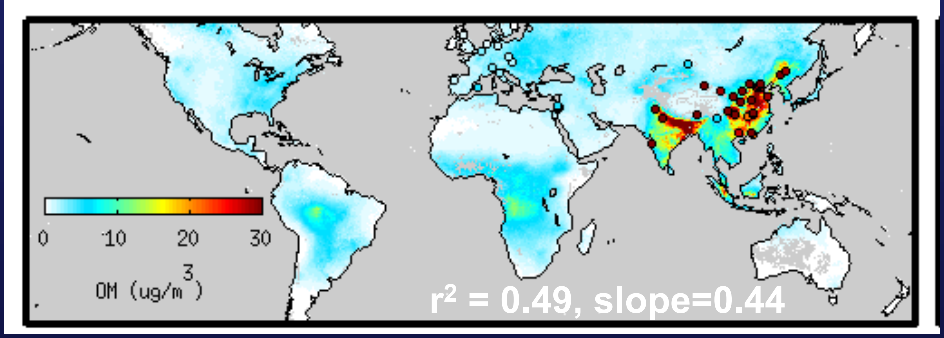
Population Weighted $PM_{2.5}$ Composition

Use GEOS-Chem to Partition Satellite AOD into $PM_{2.5}$ Composition

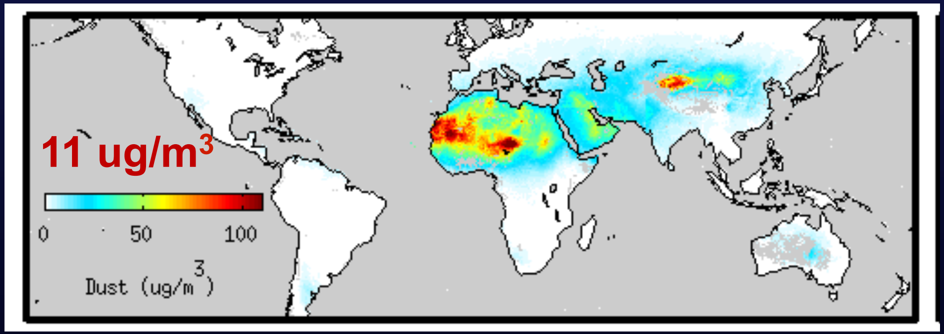
Secondary Inorganic Aerosols (SIA)

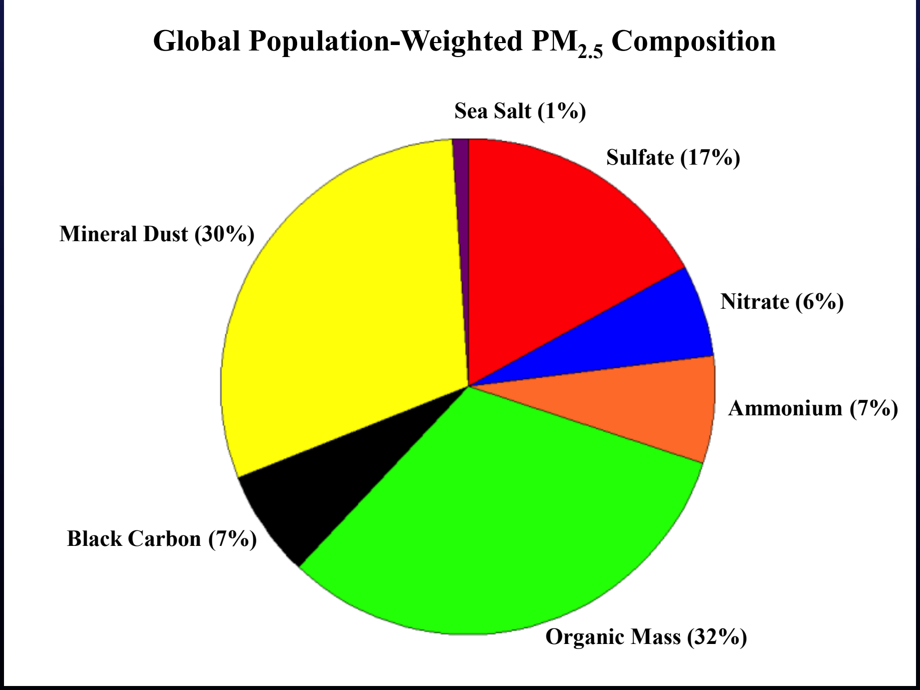


Particulate Organic Matter (OM)



Mineral Dust





Satellite-Model outperforms pure model. Examples:

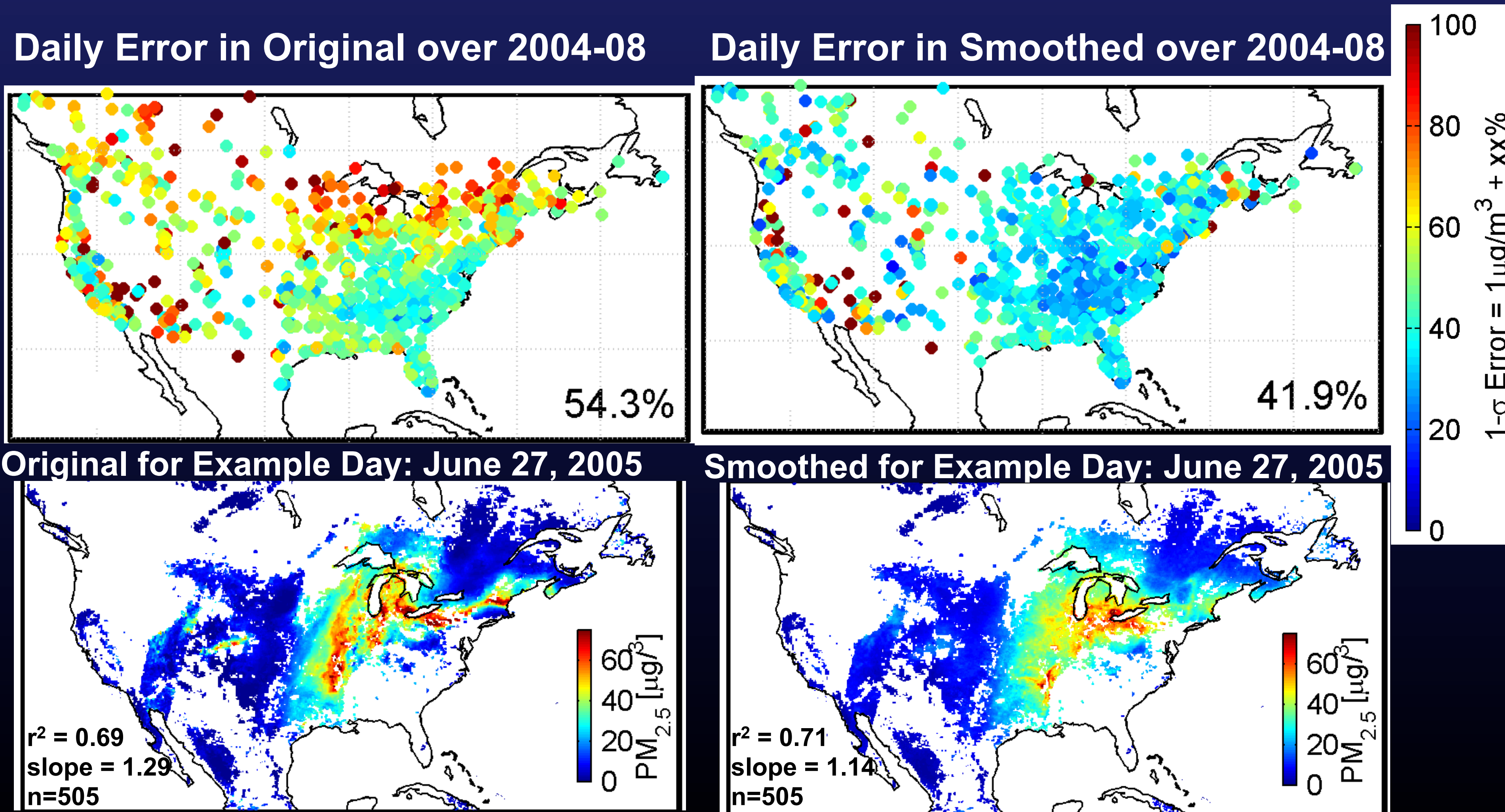
Slope GEOS-Chem SIA = 0.65 (vs 0.93 with sat)

GEOS-Chem OM: $r^2 = 0.37$ (vs $r^2 = 0.49$ with sat)

Philip et al., ES&T, 2014

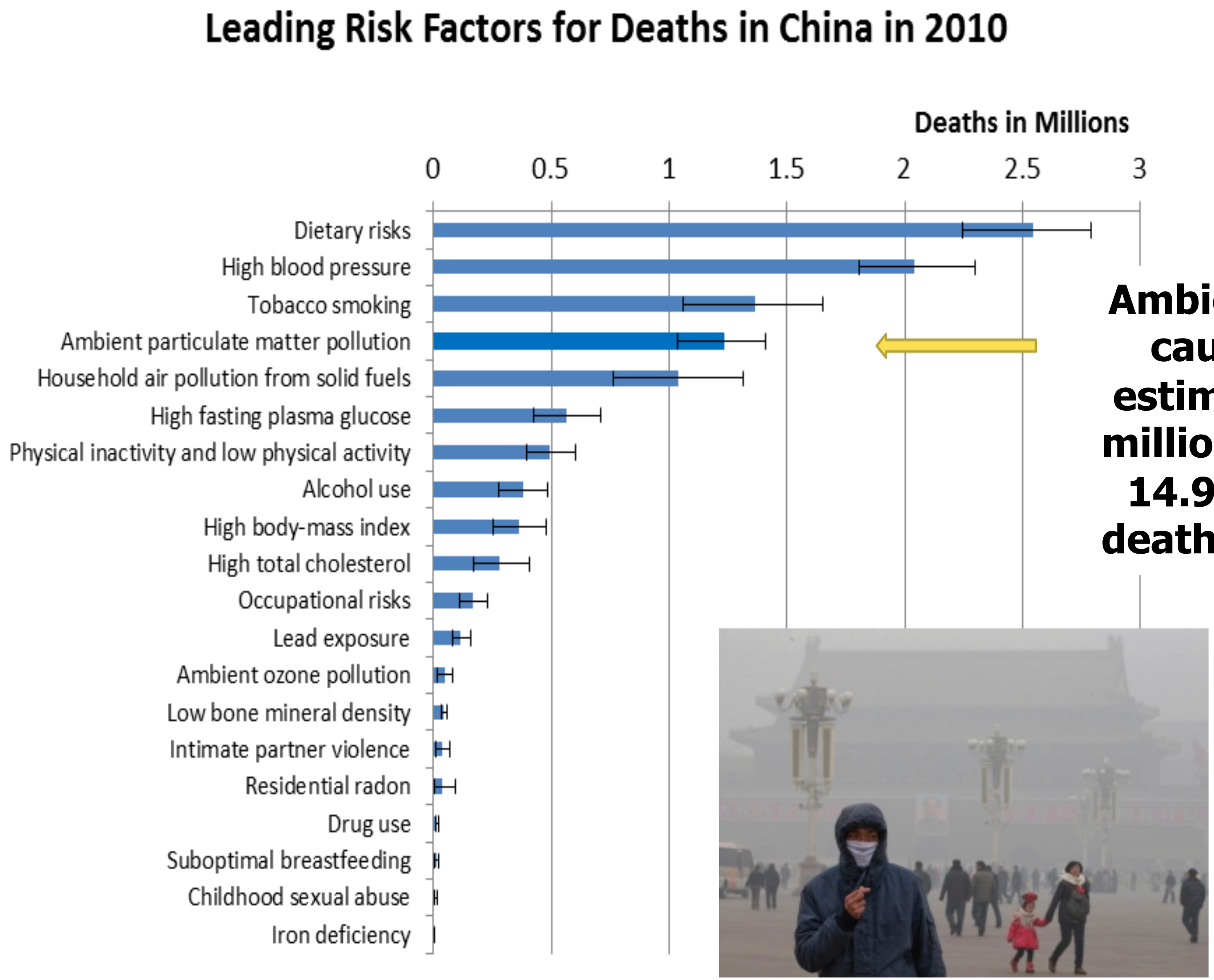
AirNow Satellite Data Processor

Daily Errors in MODIS-Derived $PM_{2.5}$ Reduced by Spatial Smoothing



van Donkelaar et al., ES&T, 2012

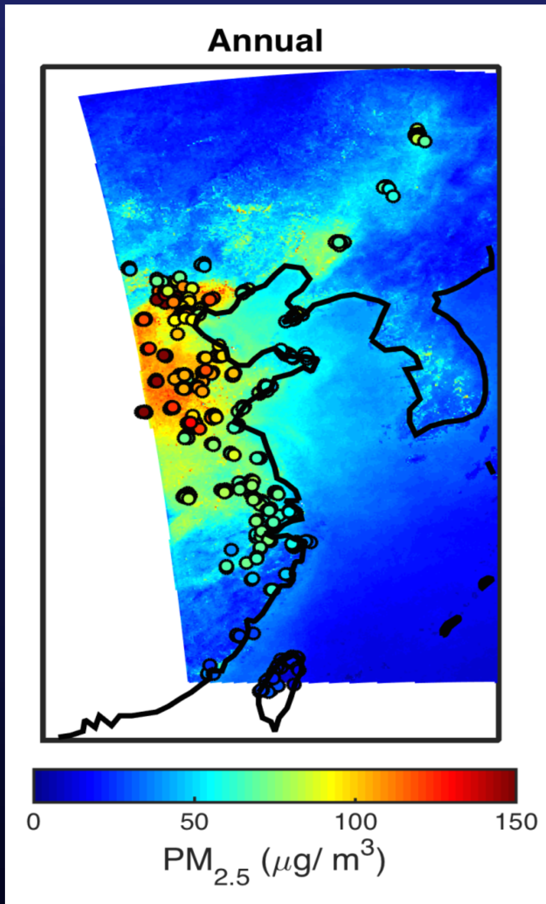
Top Mortality Risk Factors in China in 2010

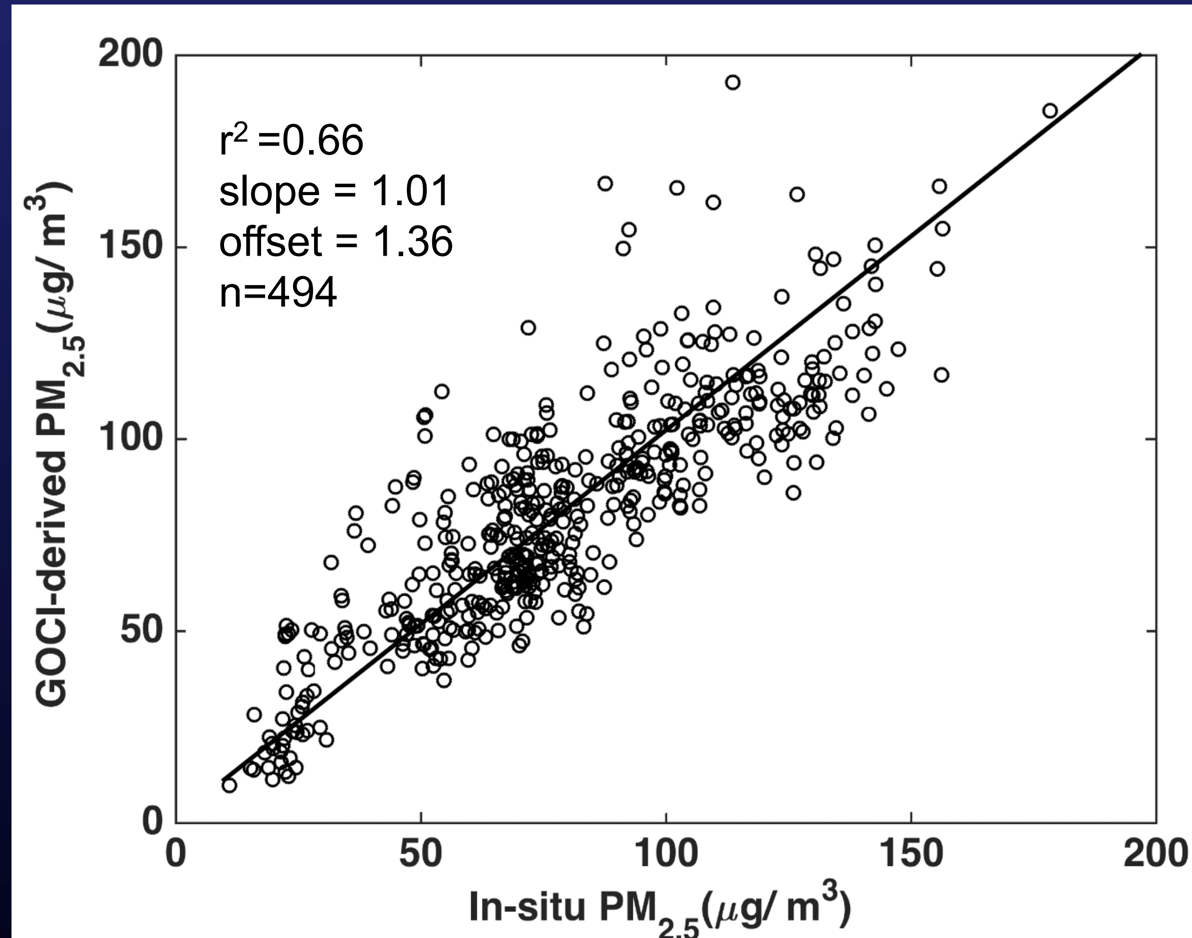


Ambient $PM_{2.5}$ caused an estimated 1.2 million deaths; 14.9% of all deaths in 2010

Lim et al., 2012

Geostationary (GOCI) Instrument Offers High Temporal and Spatial Resolution for Inference of $PM_{2.5}$





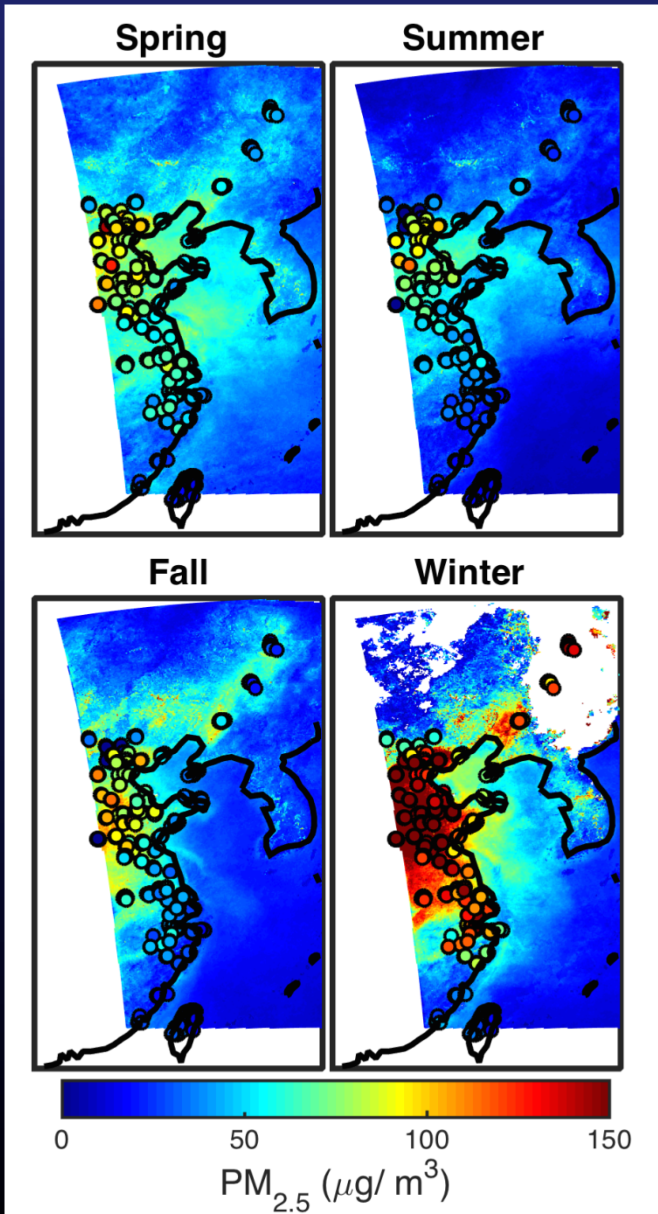
In Situ $PM_{2.5}$ better represented by GOCI-derived $PM_{2.5}$ (slope = 1.01) than by GEOS-Chem (slope = 0.68)

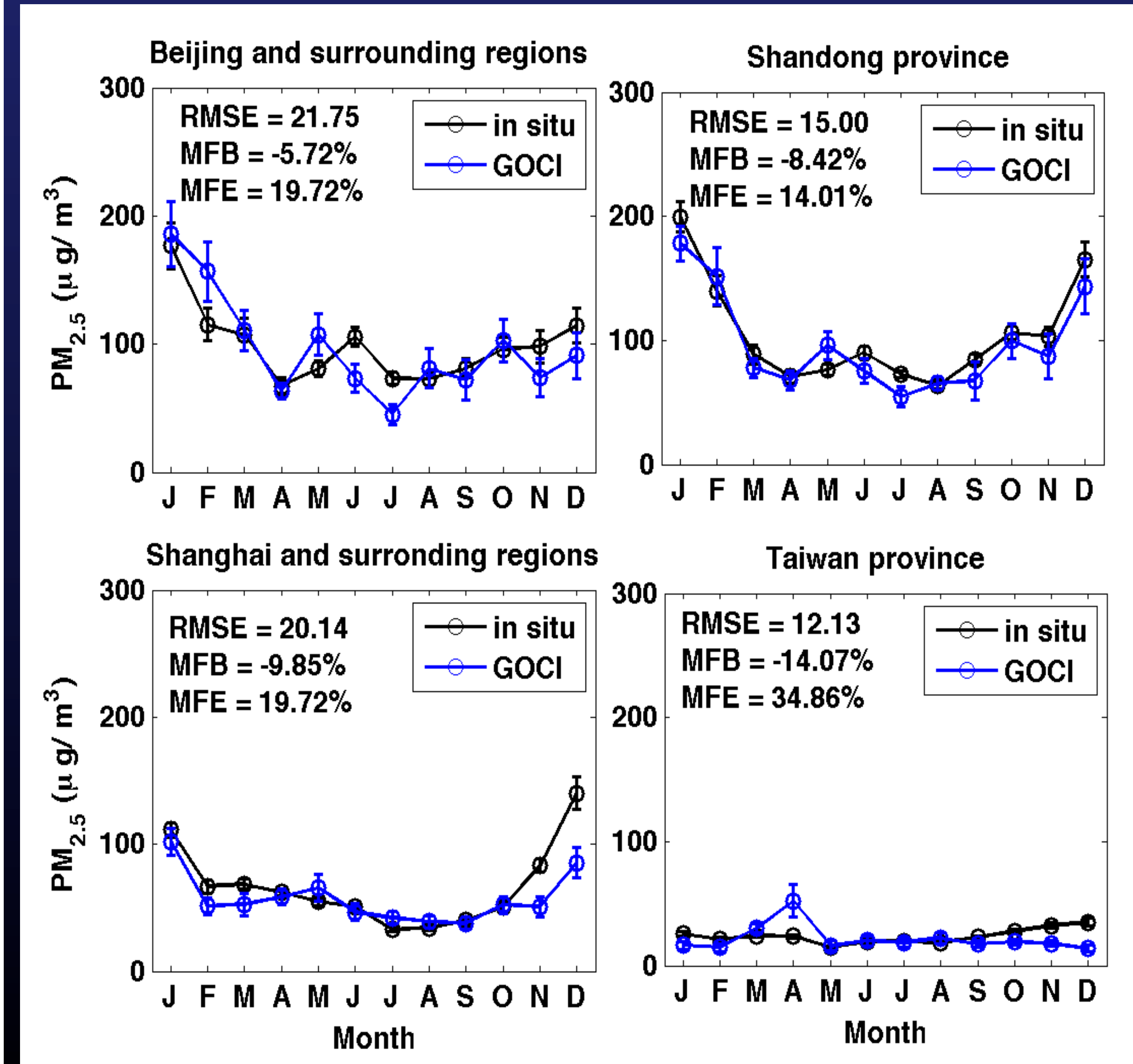
Also better than from MODIS (r^2 = 0.64, slope = 1.3)

Xu et al., ACPD, 2015

AOD from Jhoon Kim

Seasonal Variation Well Resolved with GOCI-derived $PM_{2.5}$

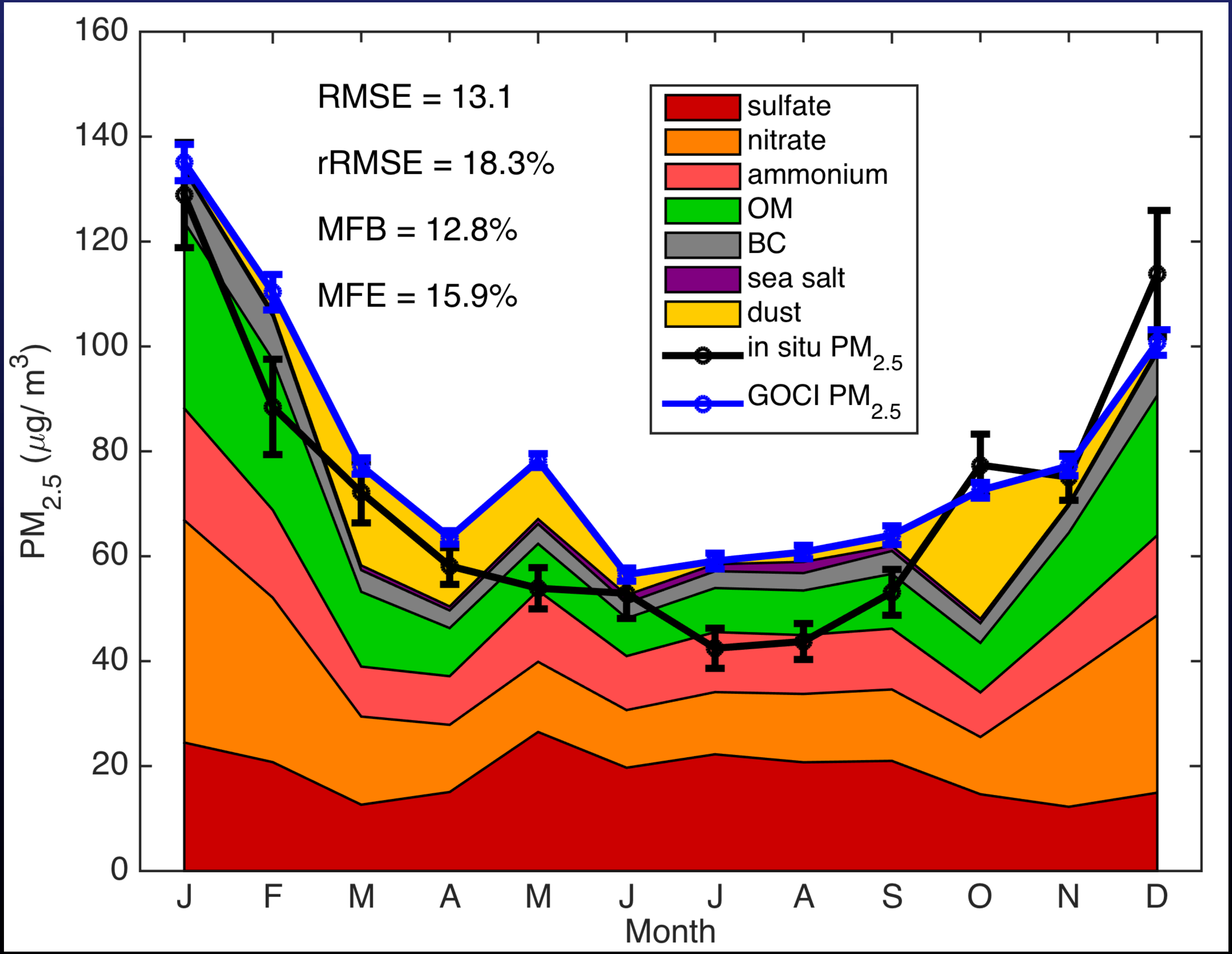




Xu et al., ACPD, 2015

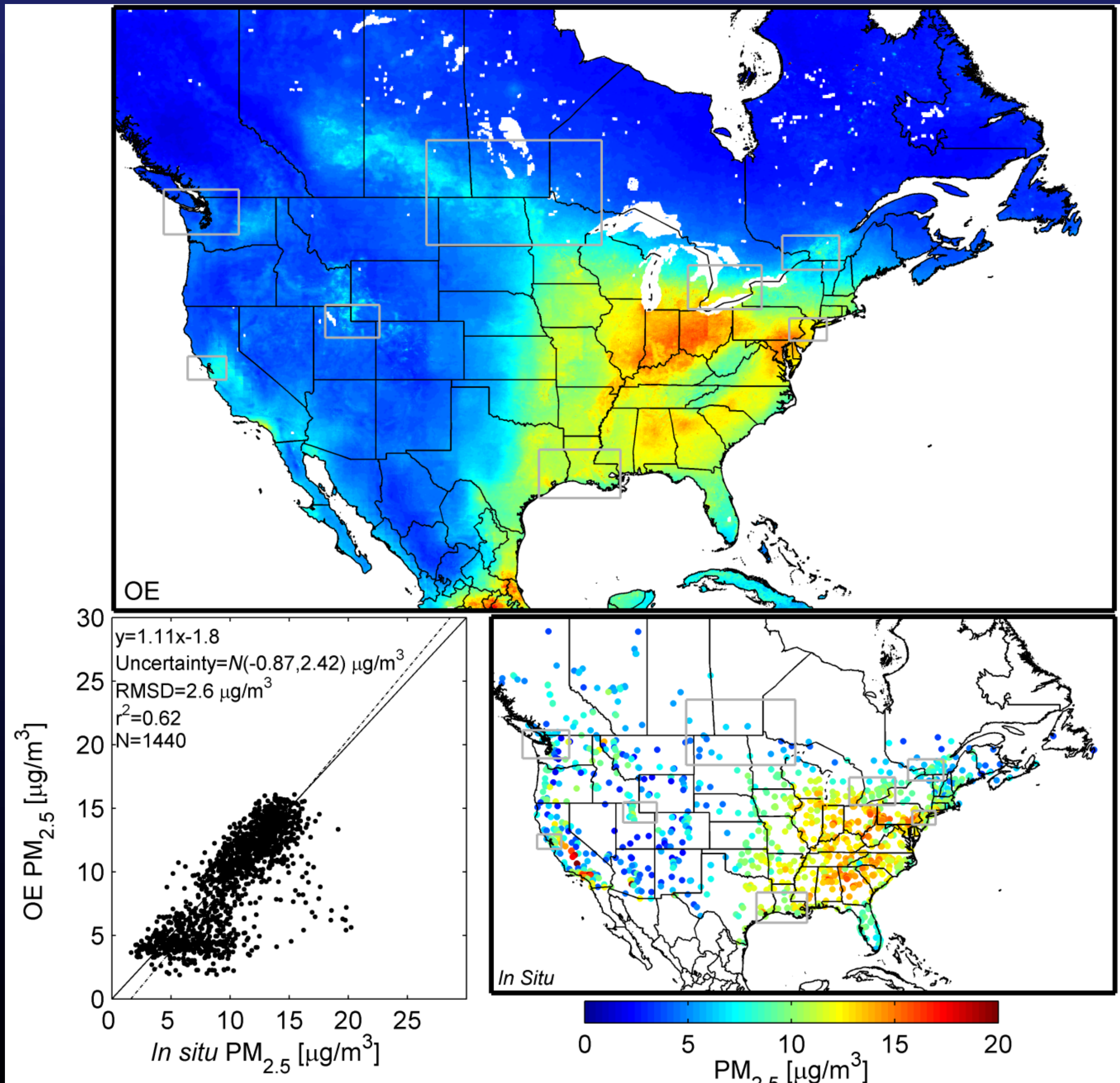
Interpret GOCI-derived $PM_{2.5}$ using GEOS-Chem

Seasonal Variation Driven by Nitrate and Biofuel Organics



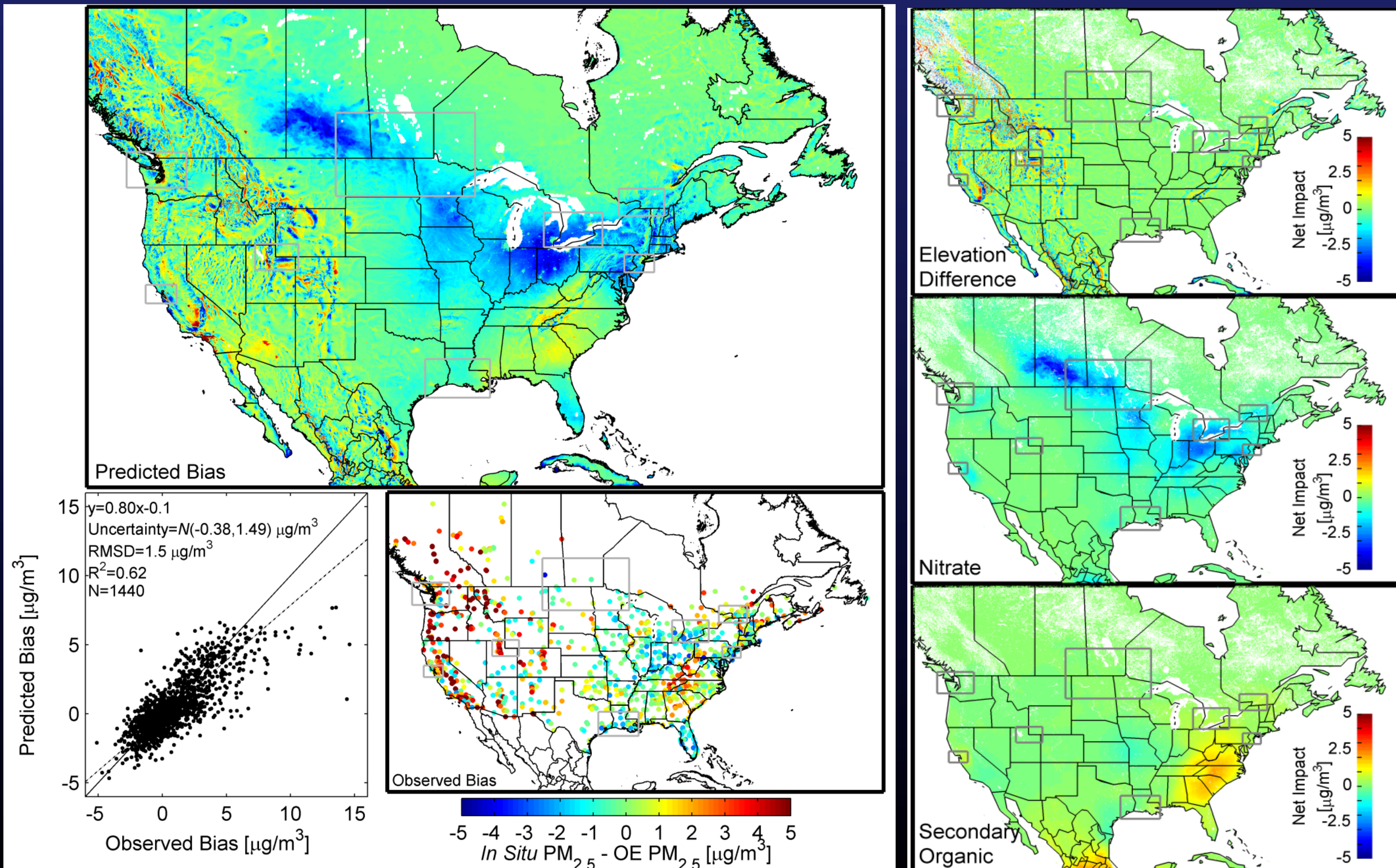
Xu et al., ACPD, 2015

Satellite-Derived $PM_{2.5}$ Over North America (2004-2008)



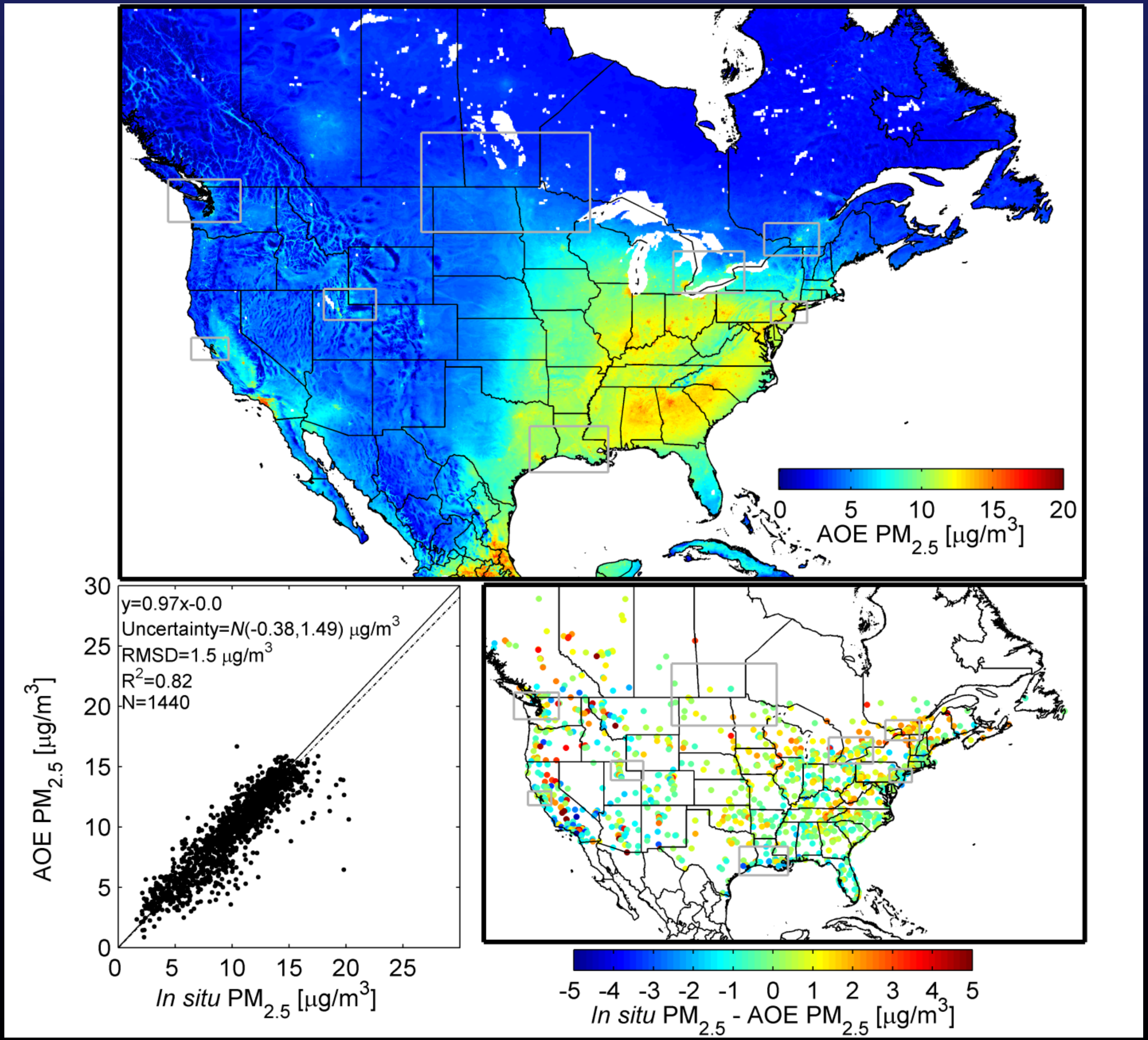
van Donkelaar et al., ES&T, 2015

Geographic Weighted Regression (GWR) Offers Insight into Bias of Satellite-Derived $PM_{2.5}$ vs Ground Monitors (2004-2008)



Combined Geophysical and Statistical Approach Improves Consistency with Ground-based Monitors

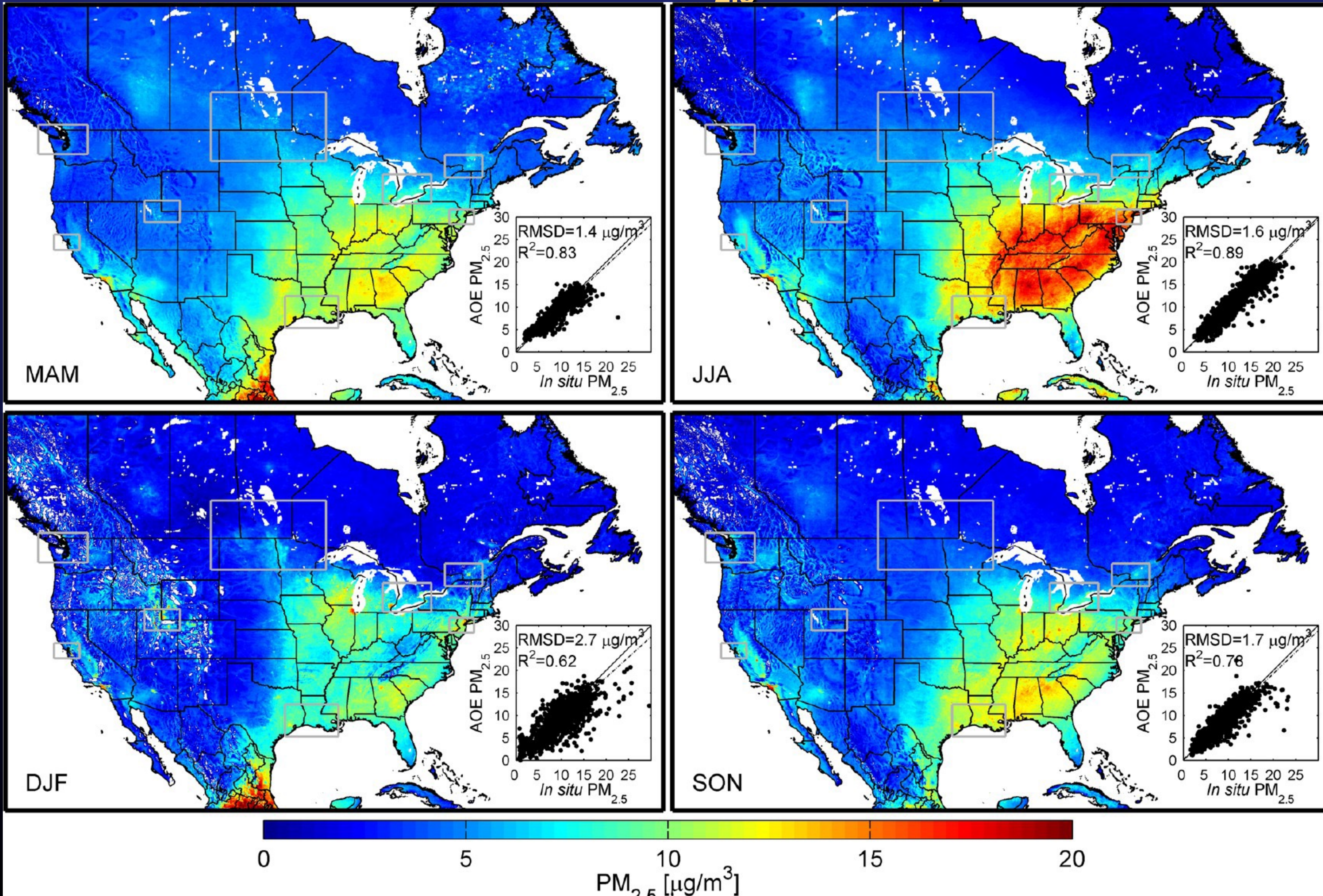
Performance remains high (R^2=0.78) even when most (70%) sites withheld for cross-validation



Adjusted Optimal Estimation (AOE) with Geophysical and Statistical Information

van Donkelaar et al., ES&T, 2015

Seasonal Variation in $PM_{2.5}$ Well Represented



van Donkelaar et al., ES&T, 2015

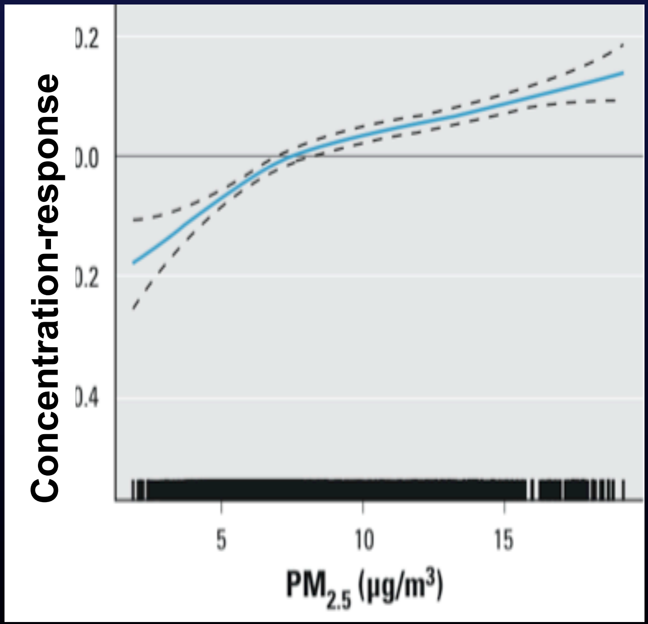
Inform Epidemiological Studies on Health Outcomes
Benefits from Large Statistical Power

- Global childhood asthma prevalence (Anderson et al., 2012)
- Lung cancer in Canada (Hystad et al., 2012)
- Air pollution and mortality in California (Jerrett et al., 2013)
- Diabetes (Brook et al., 2013; Chen et al., 2013)
- Hypertension (Chen et al., 2013)
- Global adverse birth outcomes (Fleischer et al., 2014)
- Pregnancy outcomes (Stieb et al., 2015)

Significant Association of Long-term $PM_{2.5}$ Exposure with Cardiovascular Mortality at Low $PM_{2.5}$

Evidence of No Threshold

Contributed to Canadian $PM_{2.5}$ Guideline



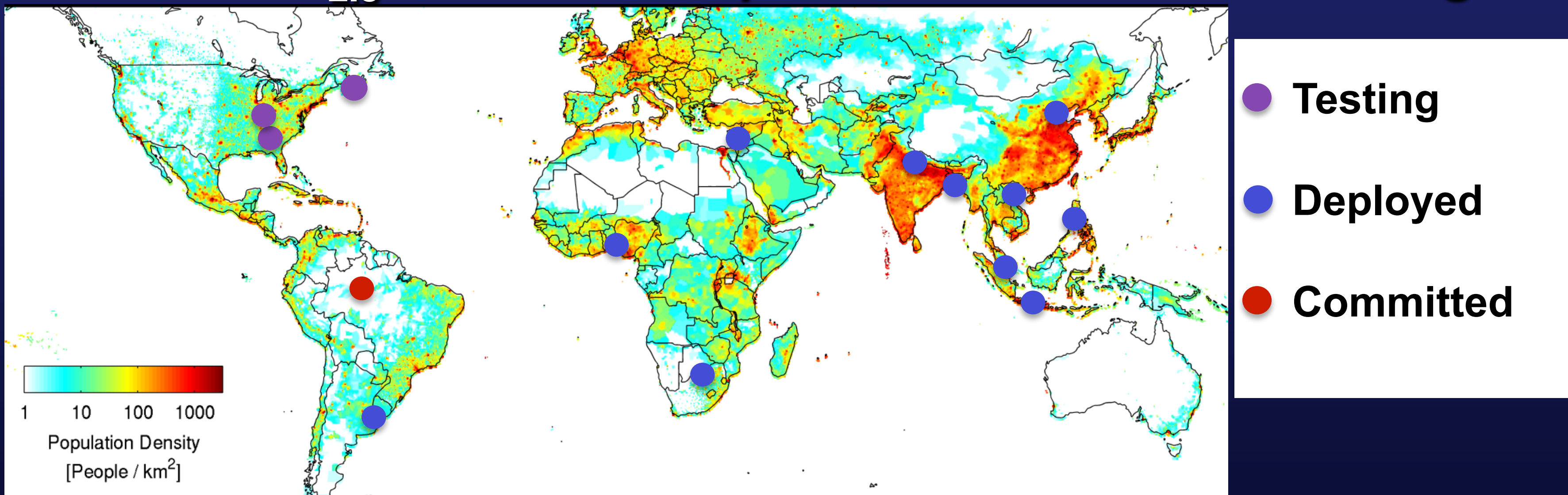
Crouse et al., EHP, 2012

Few Publicly Available Collocated Measurements of $PM_{2.5}$ & AOD to Evaluate those Calculations

Data for 2012

SPARTAN: An Emerging Global Network to Evaluate and Enhance Satellite-Based Estimates of $PM_{2.5}$

Measures $PM_{2.5}$ Mass & Composition at Sites Measuring AOD



Seeking Additional Collaborations to Develop Network

Semi-autonomous $PM_{2.5}$ & PM_{10} Impaction Sampling Station (AirPhoton)
Ions & metals

3-λ nephelometer for temporal resolution

AOD from CIMEL Sunphotometer (e.g. AERONET)

www.spartan-network.org

Snider et al., AMT, 2015

Spatial $PM_{2.5}$ to AOD Relation Driven by Scattering Vertical Profile & Mass Scattering Efficiency

Surface/Column — Diurnal — Mass Scattering Efficiency

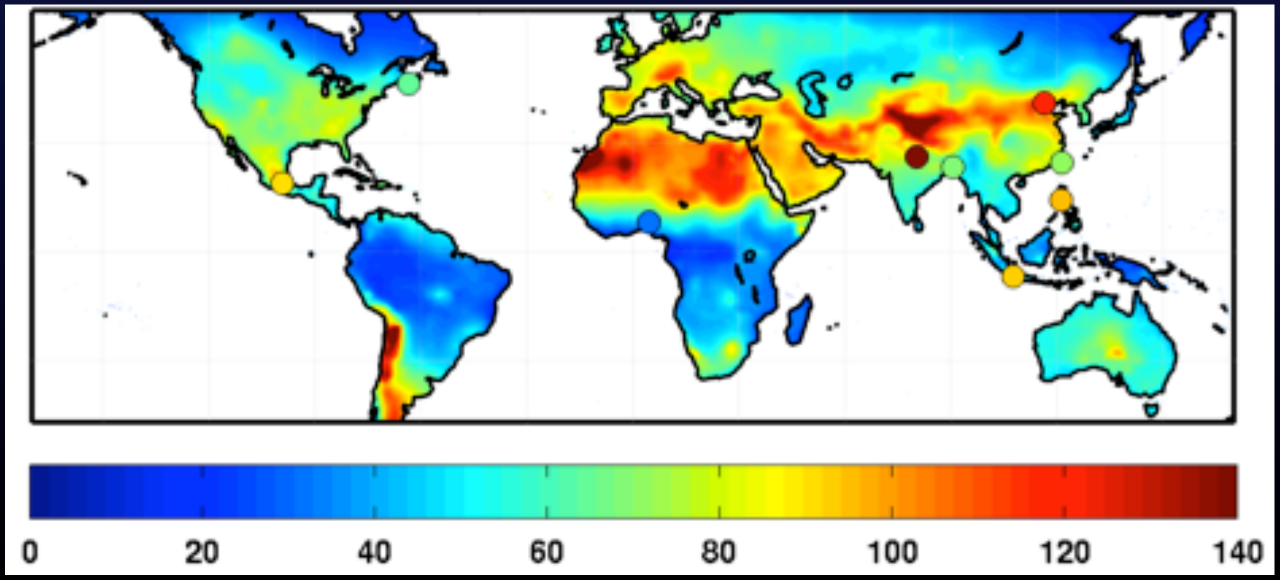
$$\frac{PM_{2.5}}{AOD} = \left(\frac{b_{sp,overpass}}{AOD_{overpass}}\right)\left(\frac{b_{sp,24h}}{b_{sp,overpass}}\right)\left(\frac{PM_{2.5,24h}}{b_{sp,24h}}\right)$$

Contribution to R^2: 0.59 -0.22 0.46

b_{sp} = nephelometer measurements of aerosol scatter

overpass = satellite overpass times (taken as 10am – 2pm)

Emerging Evidence that $PM_{2.5}$/AOD May be Larger: Increased Global $PM_{2.5}$ Burden



$PM_{2.5}$ / AOD (μg / m^3)

Consistent with slope < 1 vs monitors outside North America

van Donkelaar et al. (2010, 2015)

www.spartan-network.org

Snider et al., AMT, 2015

For More Information

- van Donkelaar, A., R.V. Martin, M. Brauer, R. Kahn, R. Levy, C. Verduzco, and P. Villeneuve, Global estimates of ambient fine particulate matter concentrations from satellite-based aerosol optical depth: Development and application, *Environ. Health Perspect.*, doi:10.1289/ehp.0901623, 2010.

- van Donkelaar, A., R.V. Martin, A.N. Pasch, J.J. Szykman, L. Zhang, Y. X. Wang, and D. Chen, Improving the accuracy of daily satellite-derived ground-level fine aerosol concentration estimates for North America, *Env. Sci. and Tech.*, 46: 11971–11978, 2012.

- Boys, B.L., Martin, R.V., van Donkelaar, A., MacDonell, R., Hsu, N.C., Cooper, M.J., Yantosca, R.M., Lu, Z., Streets,D.G., Zhang,Q., Wang,S., Fifteen-year global time series of satellite-derived fine particulate matter, *Env. Sci. Technol.*, doi: 10.1021/es502113p, 2014.

- Philip, S., R.V. Martin, A. van Donkelaar, J. Wai-Ho Lo, Y. Wang, D. Chen, L. Zhang, P. S. Kasibhatla, S. W. Wang, Q. Zhang, Z. Lu, D. G. Streets, S. Bittman, and D. J. Macdonald, Global chemical composition of ambient fine particulate matter for exposure assessment, *Environ. Sci. Technol.*, doi:10.1021/es502965b, 2014.

- Snider, G., Weagle, C. L., Martin, R. V., van Donkelaar, A., Conrad, K., Cunningham, D., Gordon, C., Zwicker, M., Akoshile, C., Artaxo, P., Anh, N. X., Brook, J., Dong, J., Garland, R. M., Greenwald, R., Griffith, D., He, K., Holben, B. N., Kahn, R., Koren, I., Lagrosas, N., Lestari, P., Ma, Z., Vanderlei Martins, J., Quel, E. J., Rudich, Y., Salam, A., Tripathi, S. N., Yu, C., Zhang, Q., Zhang, Y., Brauer, M., Cohen, A., Gibson, M. D., and Liu, Y.: SPARTAN: a global network to evaluate and enhance satellite-based estimates of ground-level particulate matter for global health applications, *Atmos. Meas. Tech.*, 8, 505-521, doi:10.5194/amt-8-505-2015, 2015.

- van Donkelaar, A., R. V. Martin, M. Brauer and B. L. Boys, Global fine particulate matter concentrations from satellite for long-term exposure assessment, *Environ. Health Perspec.*, doi:10.1289/ehp.1408646, 2015.

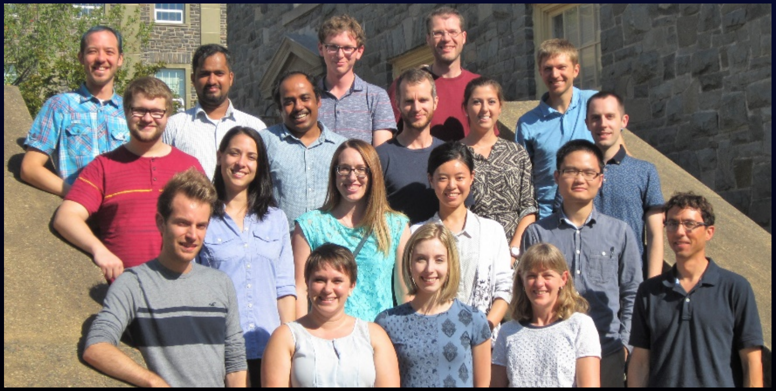
- van Donkelaar, A., R. V. Martin, R. J. D. Spurr and R. T. Burnett, High-resolution satellite-derived $PM_{2.5}$ from optimal estimation and geographically weighted regression over North America, *Environ. Sci. and Tech.*, doi 10.1021/acs.est.5b02076, 2015.

Satellite Observations Valuable Information for Air Quality
Numerous Opportunities to Develop Representation

Chemical Transport Model Plays a Valuable Role in Relating Retrieved (e.g. AOD) and Desired (e.g. $PM_{2.5}$) Quantity

Ongoing Challenge to Continue to Develop that Capability

www.spartan-network.org



http://fizz.phys.dal.ca/~atmos/martin/