Assessment of human exposures to air pollution using satellite-based remote sensing and spatiotemporal models

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and

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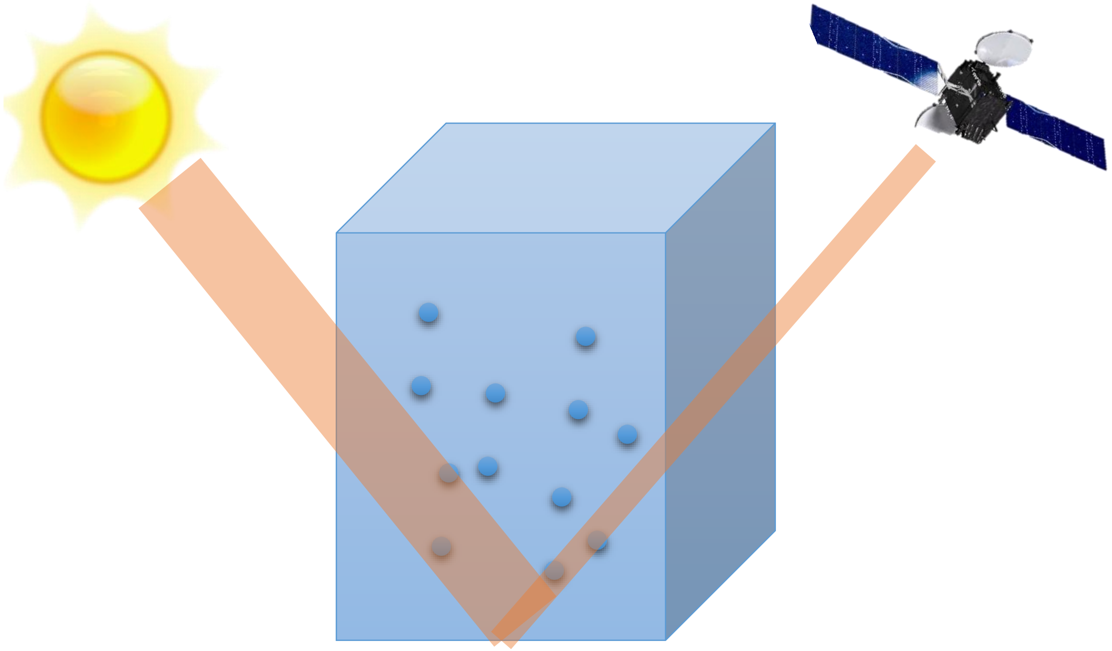
2002-2017

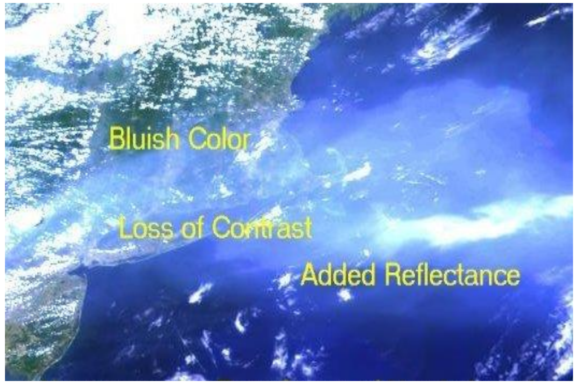
Aerosol Optical Depth

Loss of light by scattering and absorption
due to the presence of particles



Earlier applications of satellite-based remote sensing

- Characterization of air pollution across space and time, especially in areas with sparse monitoring networks or those not accessible to humans
- Applications increased over time due to the increasing number of satellite platforms collecting data with better accuracy, spatiotemporal coverage, and accessibility
- The concomitant increase of computing power made it easier to access, manage, and analyze remote sensing data.



$PM_{2.5}$-AOD Linear Regression Model Fit

$R^2 = 0.43$, $N = 1,315$

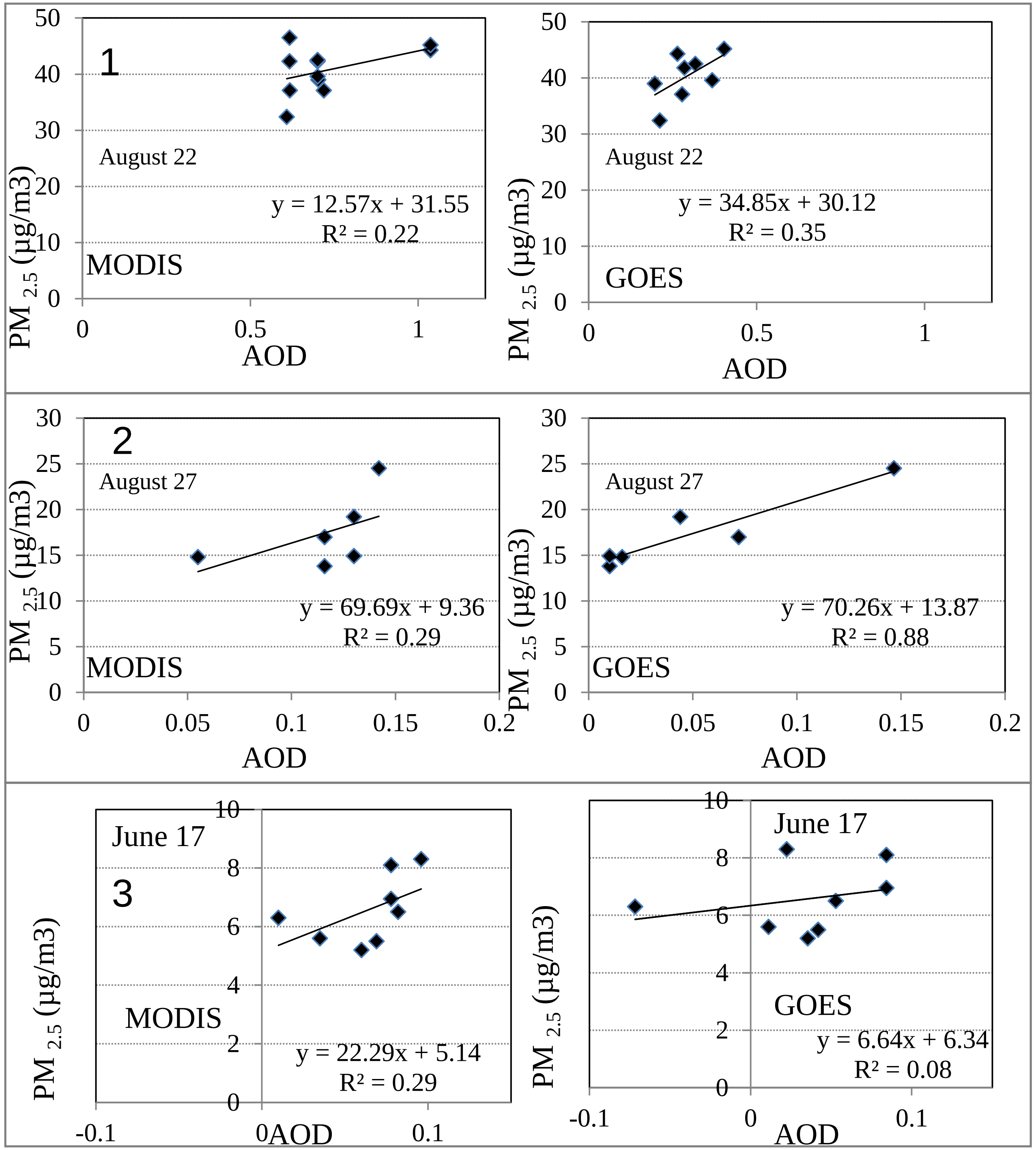
Variables	Estimates	Std Error	p value	CI factor
RH	-0.63	0.11	< 0.0001	$e^{-0.63 \times RH}$
Power of AOT	0.45	0.02	< 0.0001	$AOT^{0.45}$
Power of *h*	-0.36	0.02	< 0.0001	$h^{-0.36}$

(Liu et al. EST 2004)

Literature survey of P/A ratios, intercepts, and correlation coefficients (Hoff and Christofer 2009)

Author	Sensor	Date	Region	Number of Ground Monitors	$PM_{2.5}/PM_{10}$	Linear Regression	R
Wang[154]	MODIS (Terra)	2002	Alabama	7	$PM_{2.5}$ (24 hr)[a]	$77.0\tau - 0.23$	0.67
	MODIS (Aqua)	2002	Alabama	7	$PM_{2.5}$ (24 hr)[a]	$68.6\tau + 1.93$	0.76
	Average	2002	Alabama	7	$PM_{2.5}$ (24 hr)[a]	$72.3\tau + 0.85$	0.98
Chu[153]	MODIS	August–October 2000	Italy	1	PM_{10}	$54.7\tau + 8.0$	0.82
Engel-Cox[161]	MODIS	April–September 2002	United States	1338	$PM_{2.5}$	$22.6\tau + 6.4$	0.4
					$PM_{2.5}$ (24 hr)	$18.7\tau + 7.5$	0.43
Liu[208]	MISR	2003	St. Louis	22	$PM_{2.5}$	NA	0.8
Engel-Cox[163]	MODIS	July 1 to August 30, 2004	Baltimore	4	$PM_{2.5}$	$31.1\tau + 5.2$	0.65
					$PM_{2.5}$ (<PBL)	$48.5\tau + 6.2$	0.65
					$PM_{2.5}$ (24 hr)	$25.3\tau + 11.1$	0.57
					$PM_{2.5}$ (24 hr < PBL)	$64.8\tau + 1.76$	0.76
Liu[169]	MISR	2001	Eastern United States	346	$PM_{2.5}$		–
Al-Saadi[164]	MODIS	Review	United States		$PM_{2.5}$	62.0τ	NA
Gupta[171]	MODIS	2002 and July–November 2003	Global cities	26	PM_{10}[a]	$141.0\ \tau$	0.96
Koelemeijer[152]	MODIS	2003	Europe	88 ($PM_{2.5}$)	$PM_{2.5}$[a]	NA	0.63
					PM_{10}[a]	$214.0\tau - 42.3$	0.58
Kacenelenbogen[118]	POLDER	April–October 2003	France	28	$PM_{2.5}$	$26.6\tau + 13.2$	0.7
Gupta[173]	MODIS	February 2000 to December 2005	Southeastern United States	38	$PM_{2.5}$	$29.4\tau + 8.8$	0.62
					$PM_{2.5}$ (24 hr)	$27.5\tau + 15.8$	0.52
Hutchison[158]	MODIS	August–November 2003 and 2004	Texas	28	$PM_{2.5}$ (August)[a]	$68.8\tau - 39.9$	0.47
					$PM_{2.5}$ (September)[a]	$59.7\tau - 17.2$	0.98
Paciorek[177]	GOES-12	2004	United States	Not given	$PM_{2.5}$ (24 hr)	NA	0.5
					$PM_{2.5}$ (yearly)	NA	0.75
An[179]	MODIS	April 3–7, 2005	Beijing	6	PM_{10}[a]	$21.7\tau + 6.1$	0.92
					$PM_{2.5}$[a]	$31.1\tau + 5.1$	0.92
Schaap[180]	MODIS	August 2006 to May 2007	Cabauw, Netherlands	1	$PM_{2.5}$	$120\tau + 5.1$	0.72

Notes: [a]Slope and intercept converted from an AOD to PM (A/P) ratio. The P/A ratio is the slope of $PM_{2.5}$ to AOD in a linear regression model.



Different slopes and intercepts

Daily Calibration Method of AOD

- There is an inherent day-to-day variability in the AOD-$PM_{2.5}$ relationship which depends on time varying parameters such as <u>particle optical properties, concentration vertical mixing and ground surface reflectance among others</u>
- A daily calibration technique is applied to AOD data to accurately predict $PM_{2.5}$ concentrations within the study region
- This method requires data from multiple ground sites within the study region **[SENSORS]**

Statistical Approach

A mixed effects model with random intercepts and slopes:

$$PM_{ij} = (\alpha + u_j) + (\beta_1 + v_j) \times AOD_{ij} + \varepsilon_{ij}$$

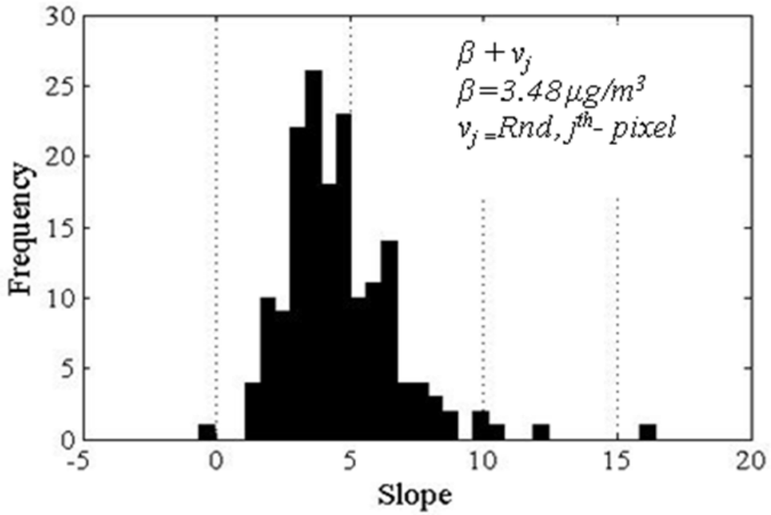
$$(u_j \; v_j) \sim [(0 \; 0), \Sigma_\beta]$$

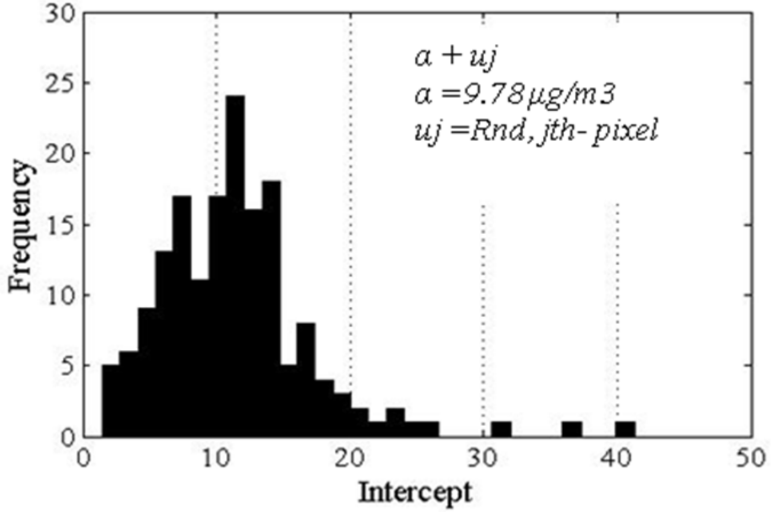
where PM_{ij} is the $PM_{2.5}$ concentration at a spatial site i on a day j; AOD_{ij} is the AOD value in the grid cell corresponding to site i on a day j; a and u_j are the fixed and random intercepts, respectively; β_1 and v_j are the fixed and random slopes, respectively; w is the random slope of site i; and Σ_β is the variance-covariance matrix for the random effects

Lee HJ et al. (2011). *Atmospheric Chemistry and Physics* (2011)

Lee HJ et al. (2012). Environmental Research (2012)

Frequency distribution of slopes and intercepts resulted from the mixed effect model estimations





The relationship between $PM_{2.5}$ and AOD – before (a) and after (b) the daily calibrations

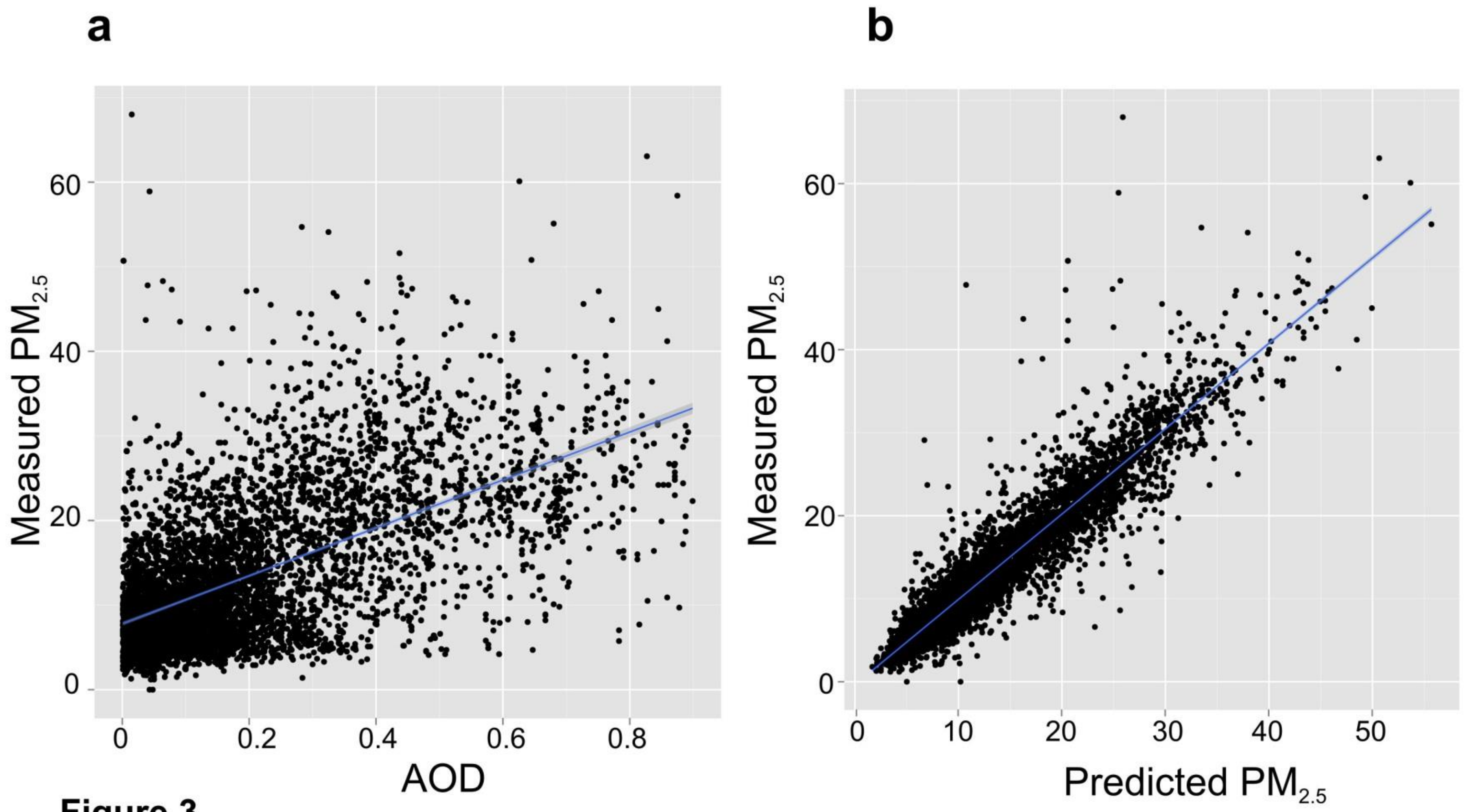


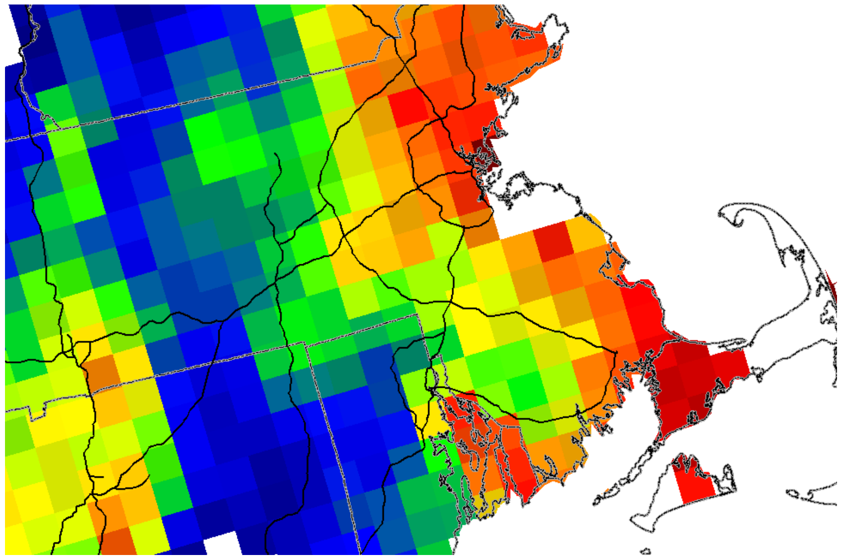
Figure 3

MODIS 1 km vs 10 km

MAIAC testing: A close collaboration with NASA group (Chudnovsky et al 2012)

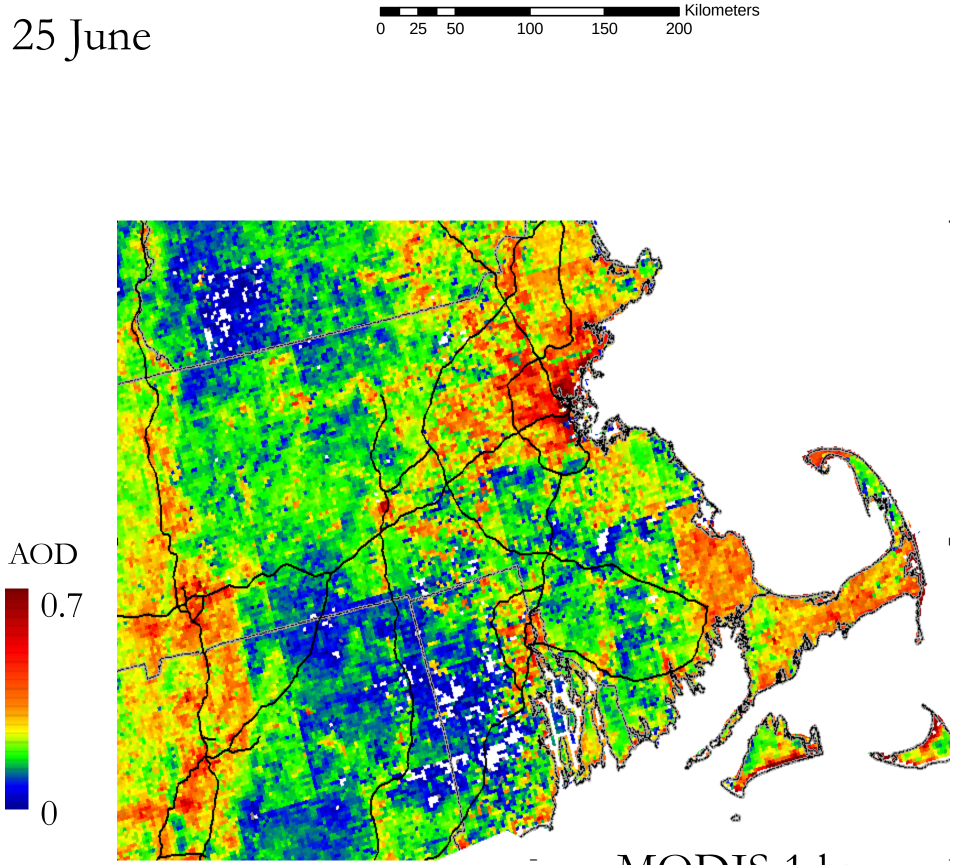
MAIAC data have less missing values

25 June



MODIS 10 km

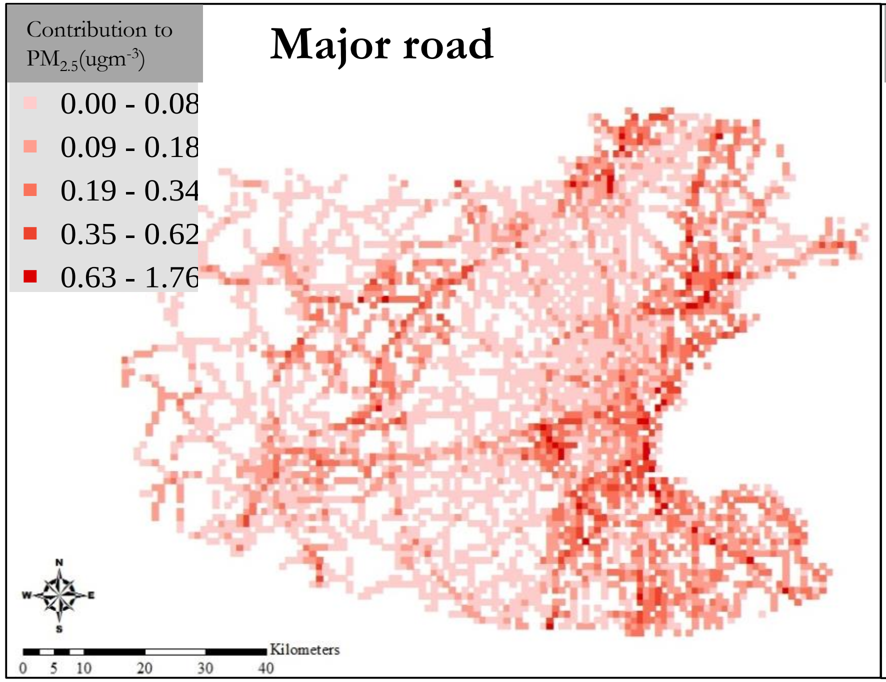
25 June

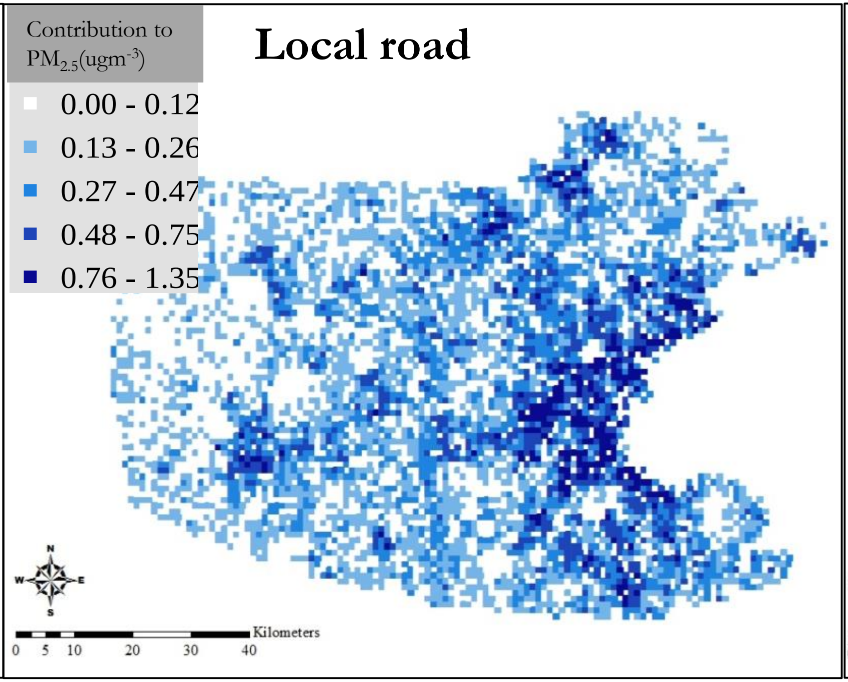


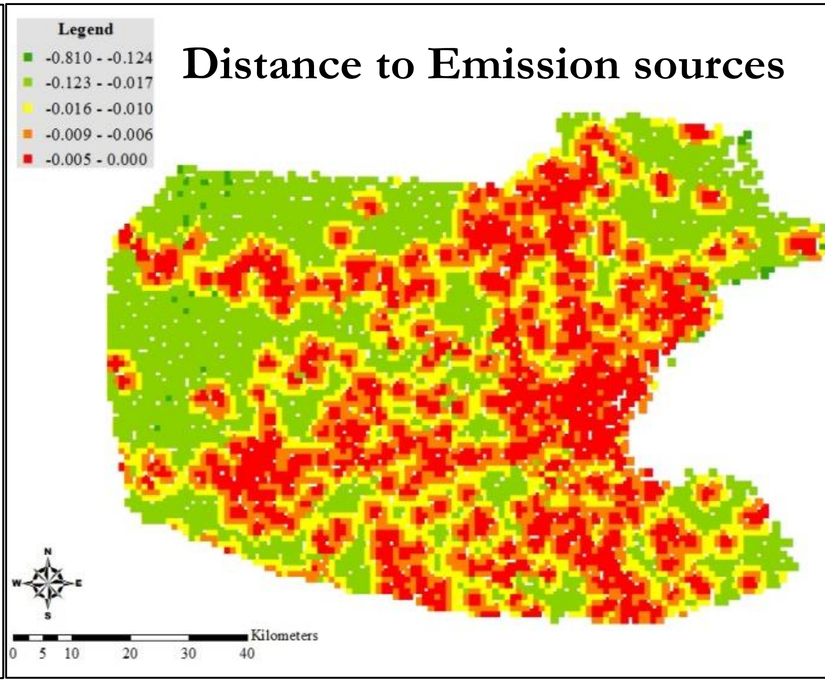
MODIS 1 km

Land Use Parameters

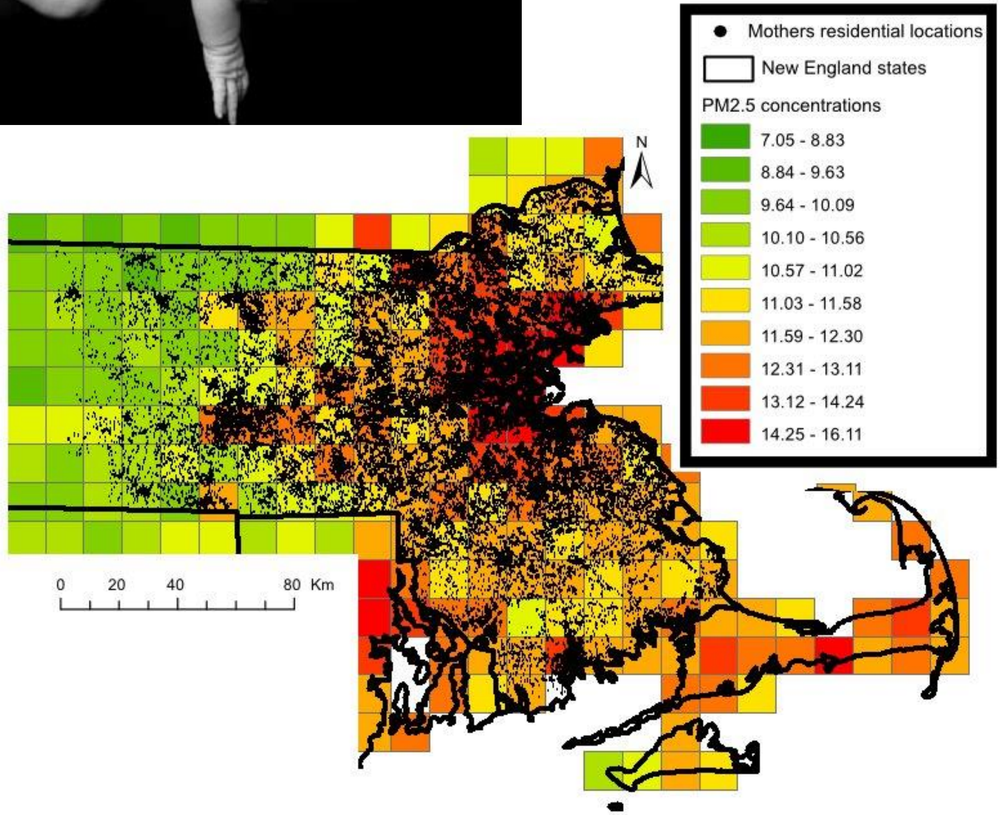
$$PMM_{ij} = aodij + Elevation_i + \%Urban\ spaces_i + \%Forest\ spaces_i + Major\ road\ length_i + Local\ Road\ length_i + Distance\ to\ emission\ sources_i$$







Using Satellite Based Exposure to Study the Effect of $PM_{2.5}$ on Birth Weight in Massachusetts



Exposure	Birth weight Change (in grams)(95% CI)
Last month	-8.80^{***} (-10.32 to -4.44)
Last trimester	-9.20^{***} (-15.00 to -3.30)
Entire birth period	-13.80^{***} (-21.10 to -6.05)

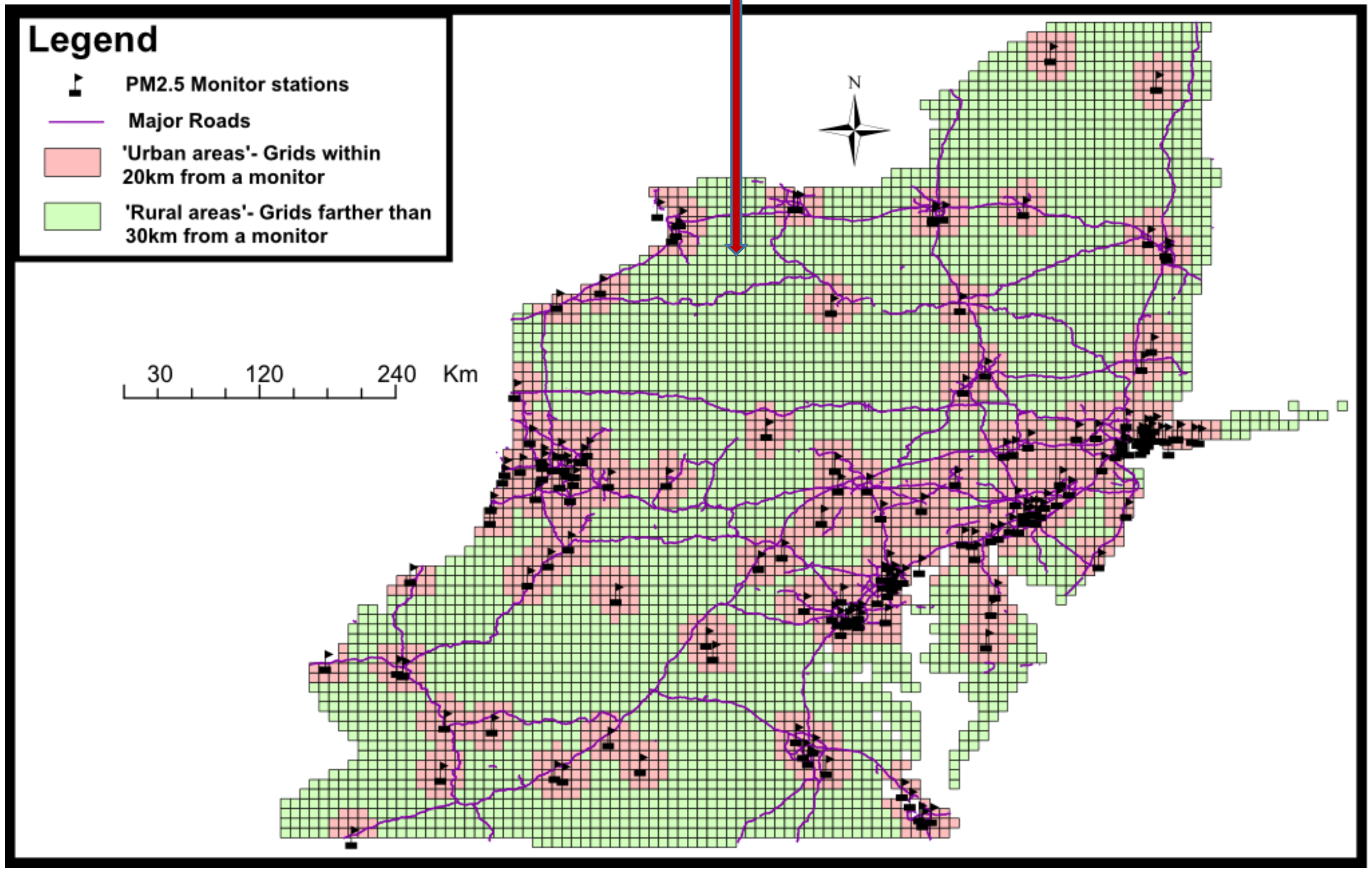
$PM_{2.5}$ Mortality in Middle Atlantic States

$PM_{2.5}$ exposure type	Percent increase [a]
Short term $PM_{2.5}$ exposure	1.19 (0.81 to1.57)
Long term $PM_{2.5}$ exposure	26.47 (3.28 to 54.90)
Number of obs. [b]	375,048

Percent increase and 95% confidence intervals for mortality associated with a 10-μg/m^3 increase for both long term and short term $PM_{2.5}$ exposures.

Higher Risks for Rural Populations

No health Studies



Map of the study area showing the MEDICARE population within and outside 20 km of a $PM_{2.5}$ monitor

Iraq and Afghanistan Wars: Soldier Health US VA Study

- Reports of returning soldiers
  - Wheezing, Asthma, COPD Sanders et al. 2005; Roop et al. 2007
  - Smoking. Perceptions

- PM Sources (IOM, 2011)
- Natural
  - Dust Storms
- Anthropogenic
  - Open-pit refuse burning
  - Aircraft engines
  - Diesel generators

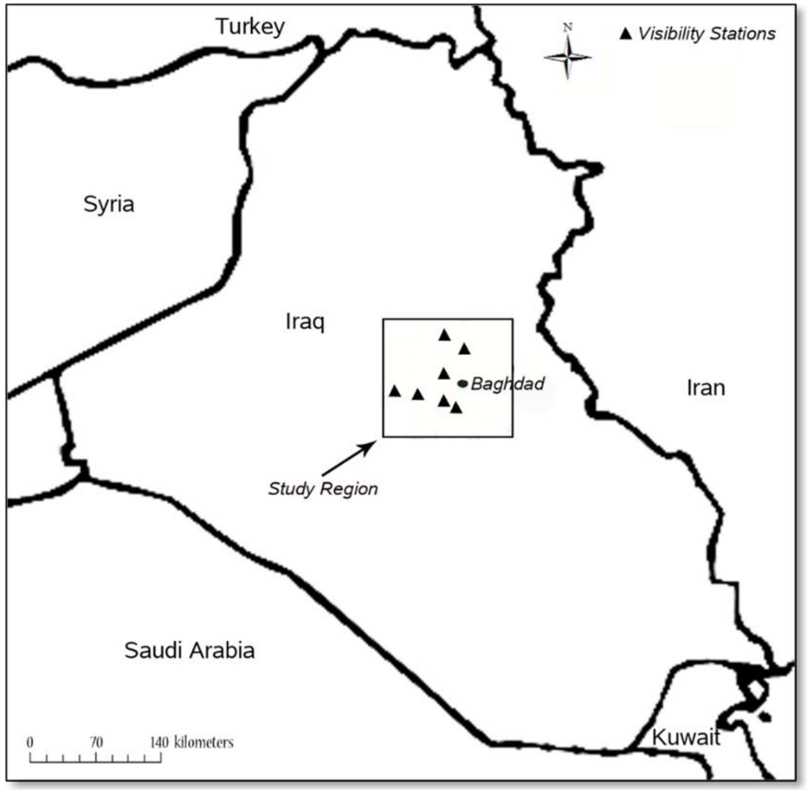
Exposure Assessment

- No Data!
- Use airport visibility to calibrate MODIS MAIAC
  - Over 100 Airforce Bases
  - 24-hour data
- Convert spatiotemporal visibility data to $PM_{2.5}$
- Estimate month average exposures

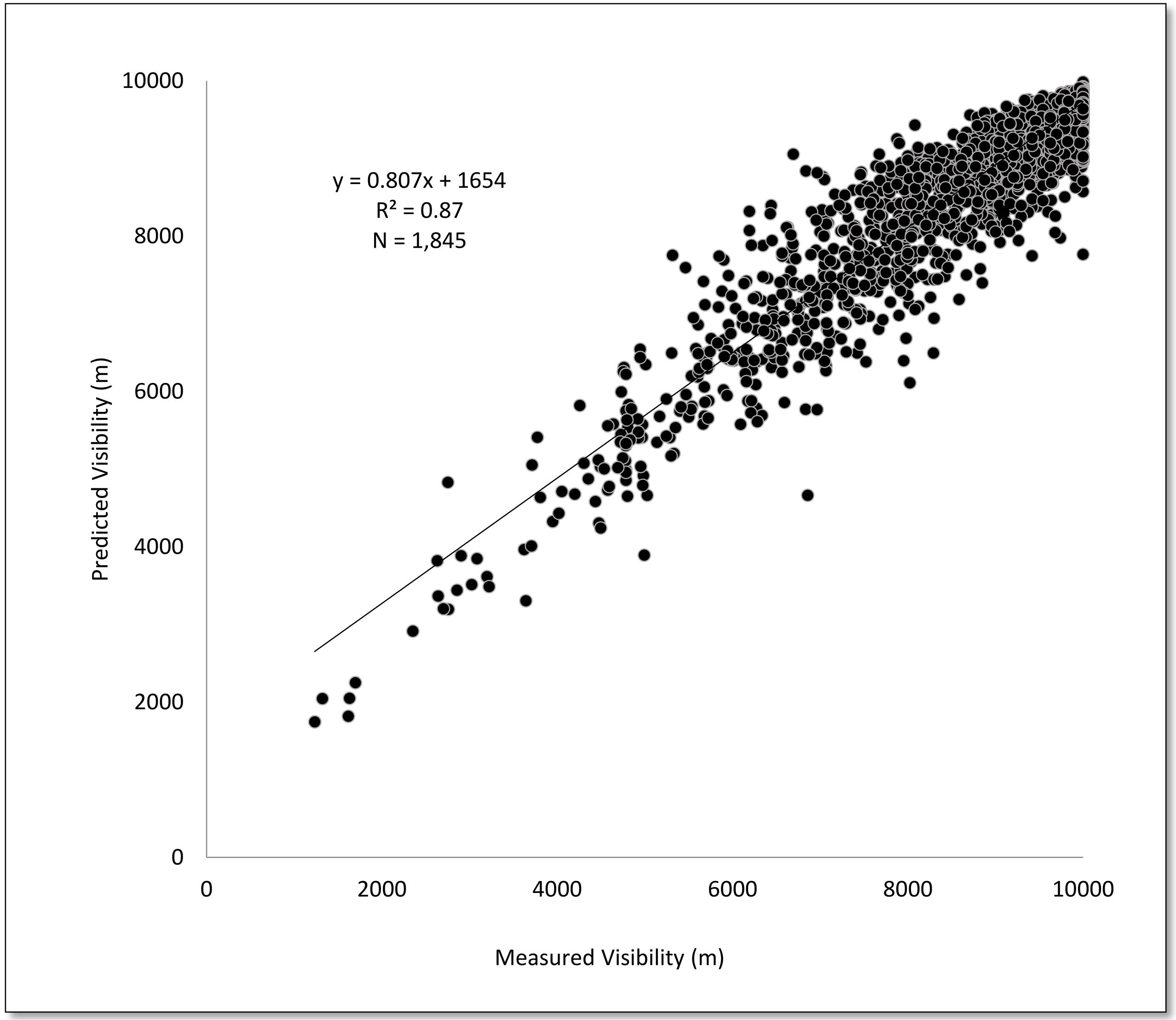
Calibrate AOD using Visibility

MAIAC, 1 x1 km

Iraq Jan: 2006 – Dec 2007
7 sites, 1,845 daily observations



Stage 1



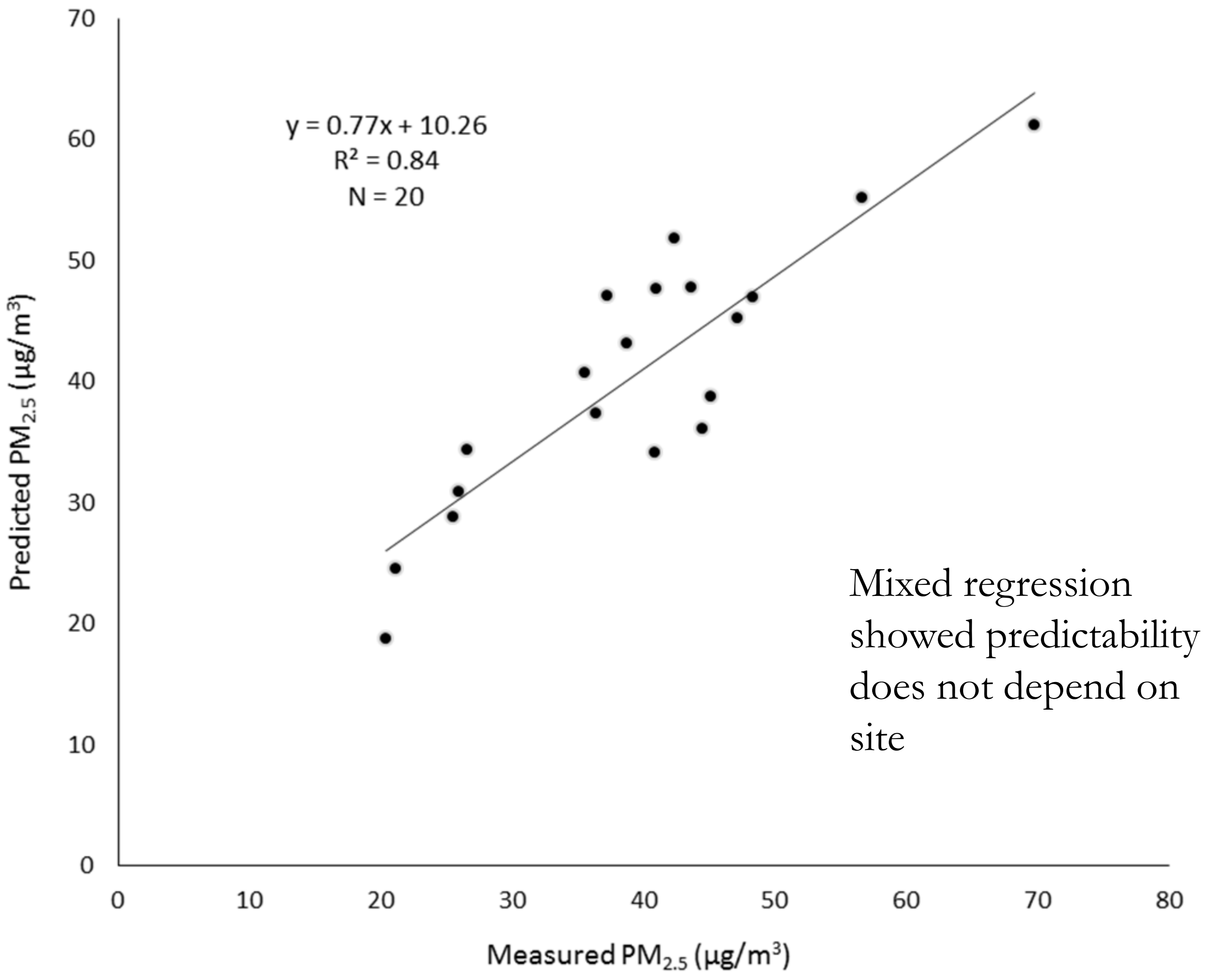
Relationship between daily predicted and measured visibility.

Matched Pairs

Site 1 (N = 532) → Trimester 1, Trimester 2, Trimester 3, Trimester 4

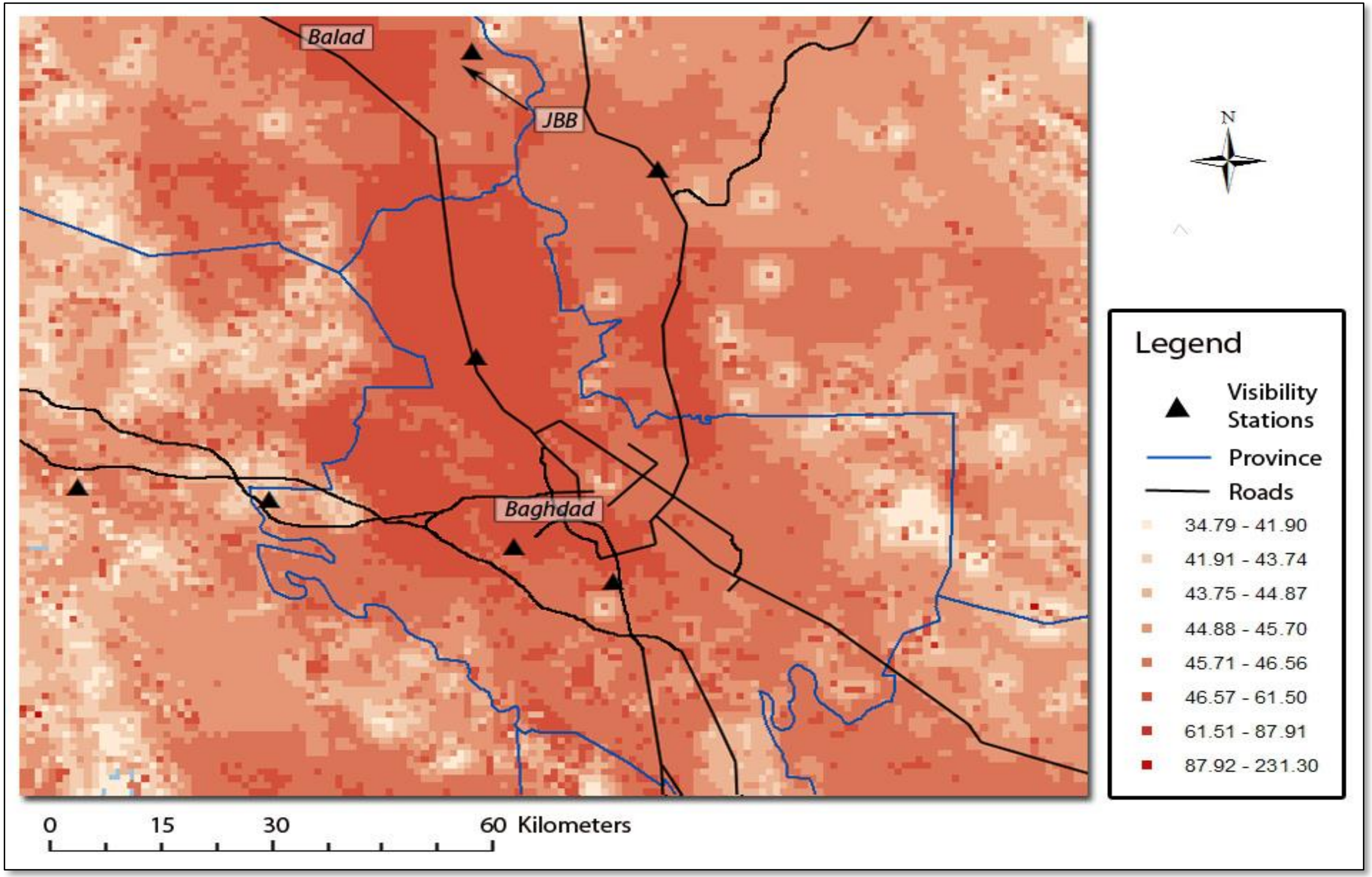
Site 2 (N = 48) → Trimester 1, Trimester 2, Trimester 3, Trimester 4

Site 3 (N = 69) → Trimester 1, Trimester 2, Trimester 3, Trimester 4



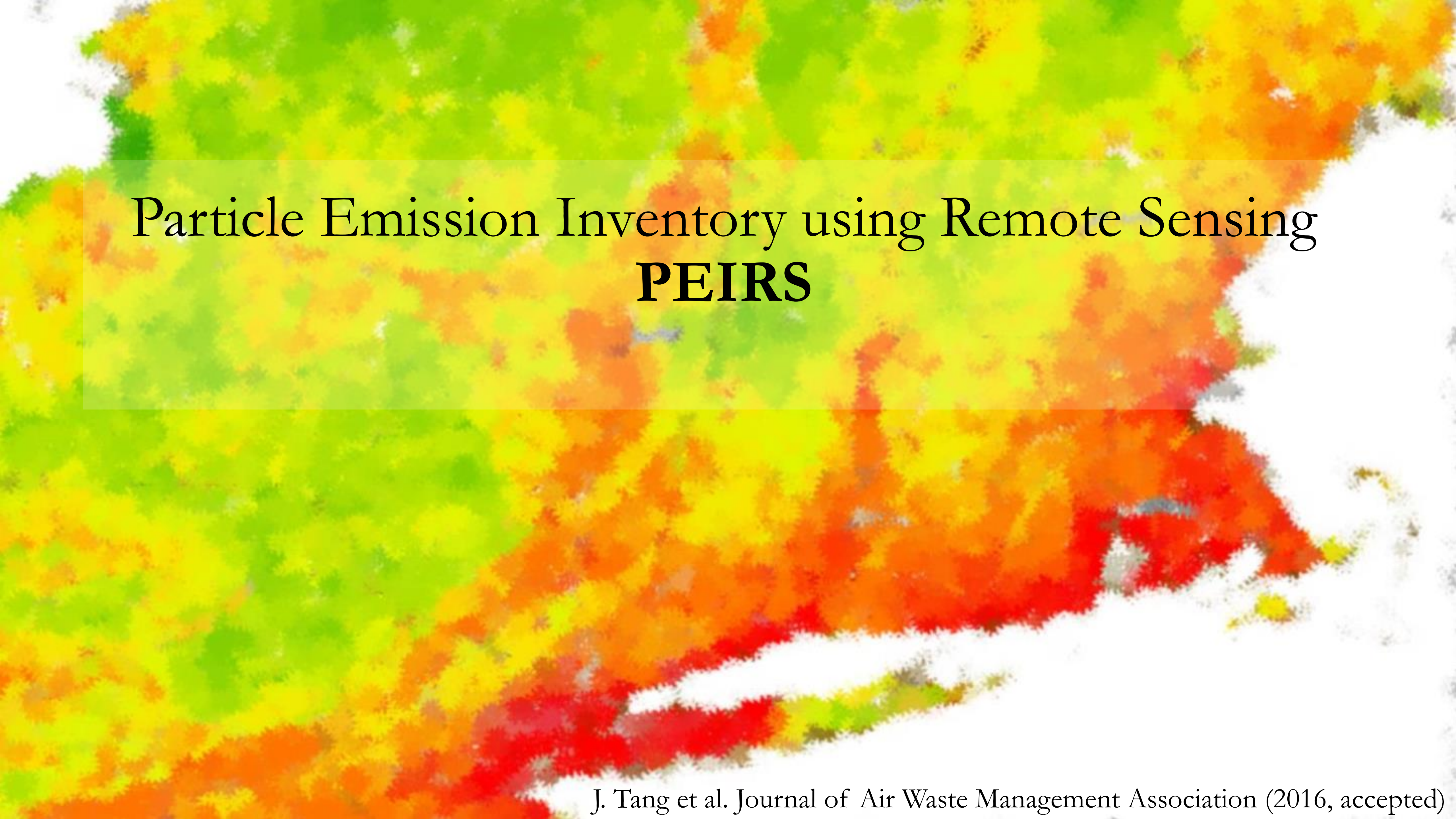
Mixed regression showed predictability does not depend on site

$$PM_{2.5} = \alpha + \beta_1 (1/\text{visibility}) + \beta_2 (\text{relative humidity})^2$$



Spatial pattern of 1x1 km $PM_{2.5}$ predictions averaged over two years (2006 and 2007)

Particle Emission Inventory using Remote Sensing
PEIRS

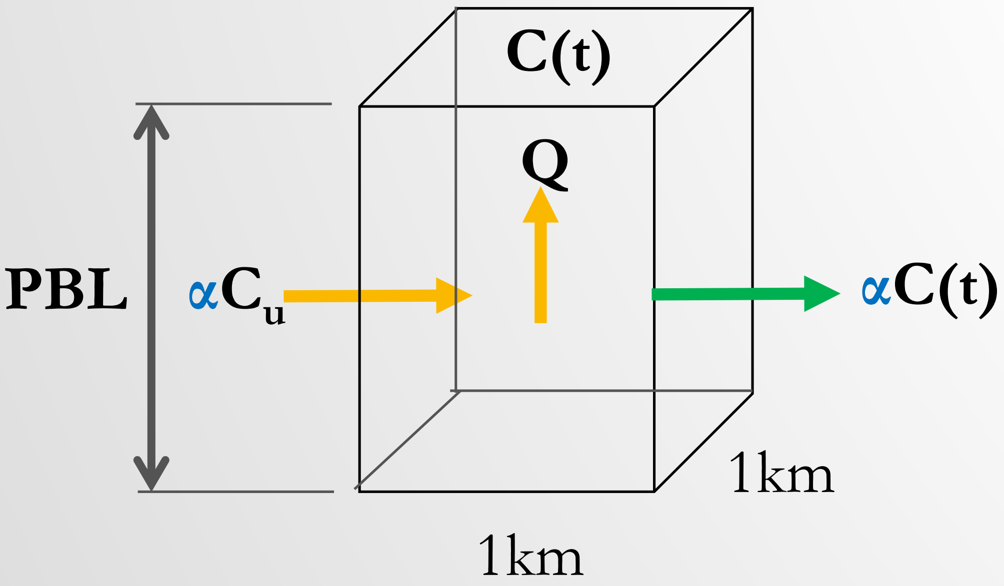


J. Tang et al. Journal of Air Waste Management Association (2016, accepted)

STAGE 2: EMISSION MODEL

Mass Balance

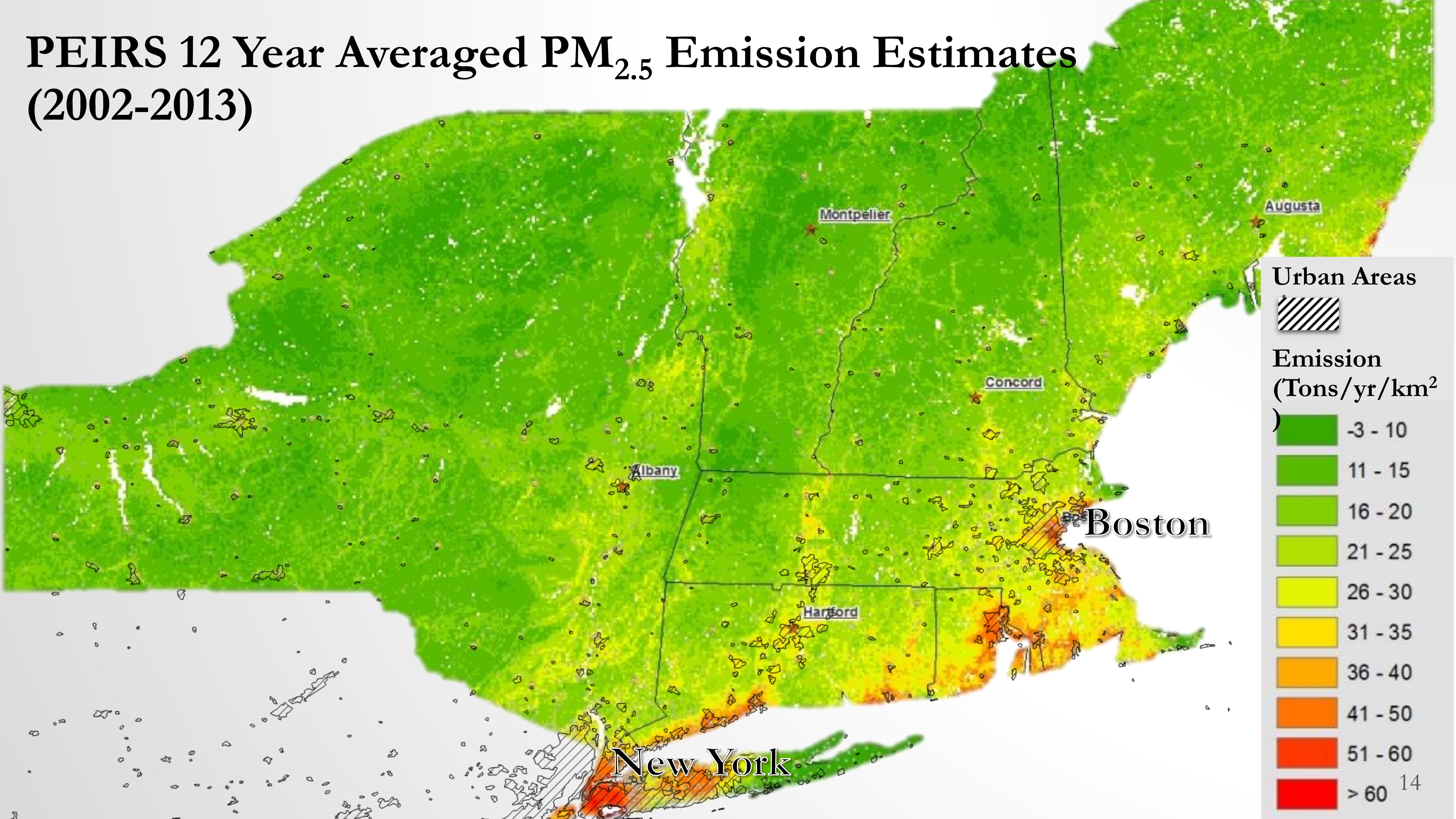
$$\frac{dC(t)}{dt} = \sum \text{Sources} - \sum \text{Sinks}$$



$$C = C_u + \frac{Q}{\alpha \times PBL}$$

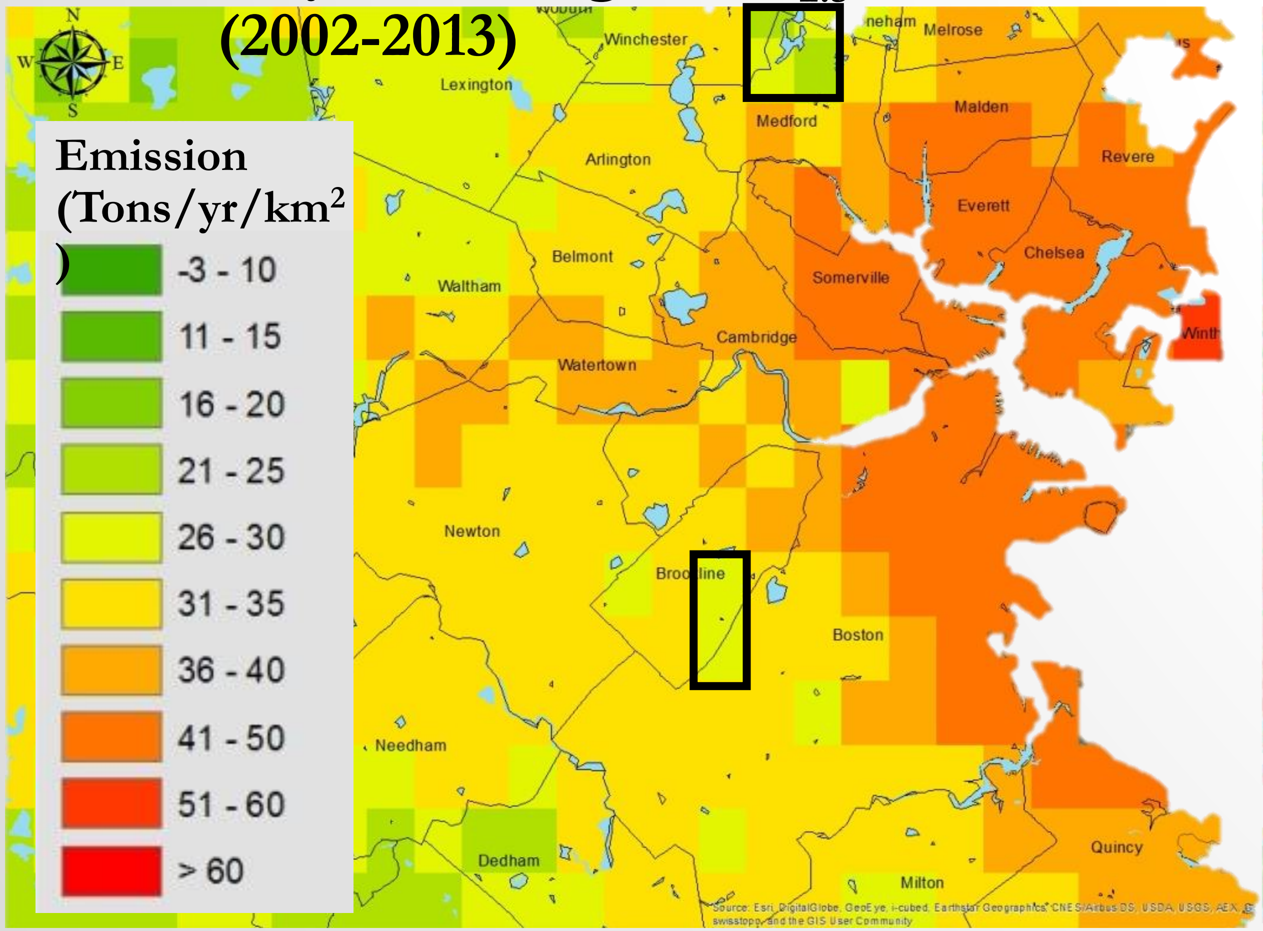
C: $PM_{2.5}$ Concentration inside box
C_u: $PM_{2.5}$ Concentration upwind
α: Air exchange rate (wind speed/Length)
Q: Emission inside box
PBL: Planetary Boundary Layer height

PEIRS 12 Year Averaged $PM_{2.5}$ Emission Estimates (2002-2013)

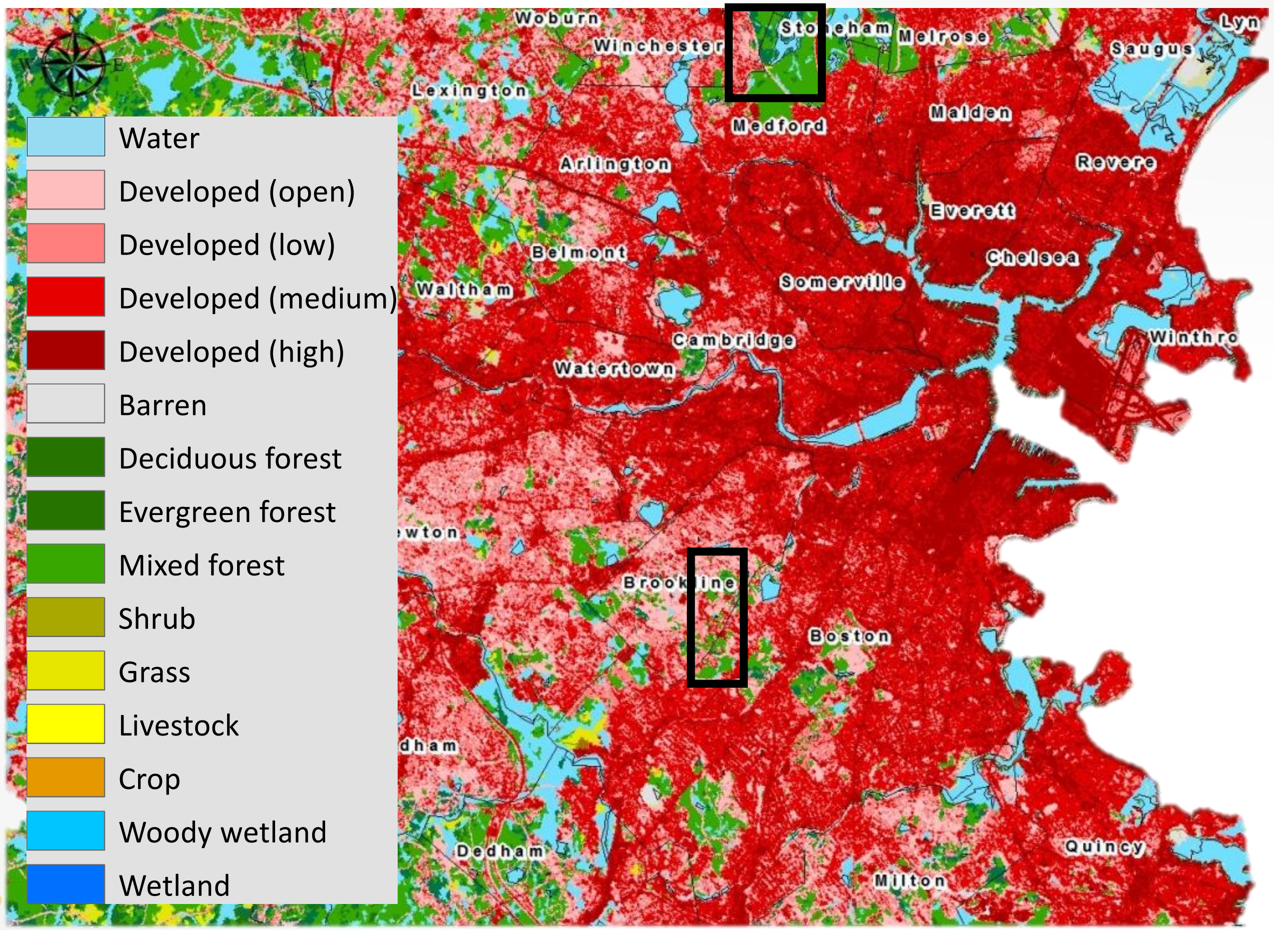


INTRA-URBAN VARIABILITY

PEIRS 12-year Averaged $PM_{2.5}$ Emission (2002-2013)



Land Cover

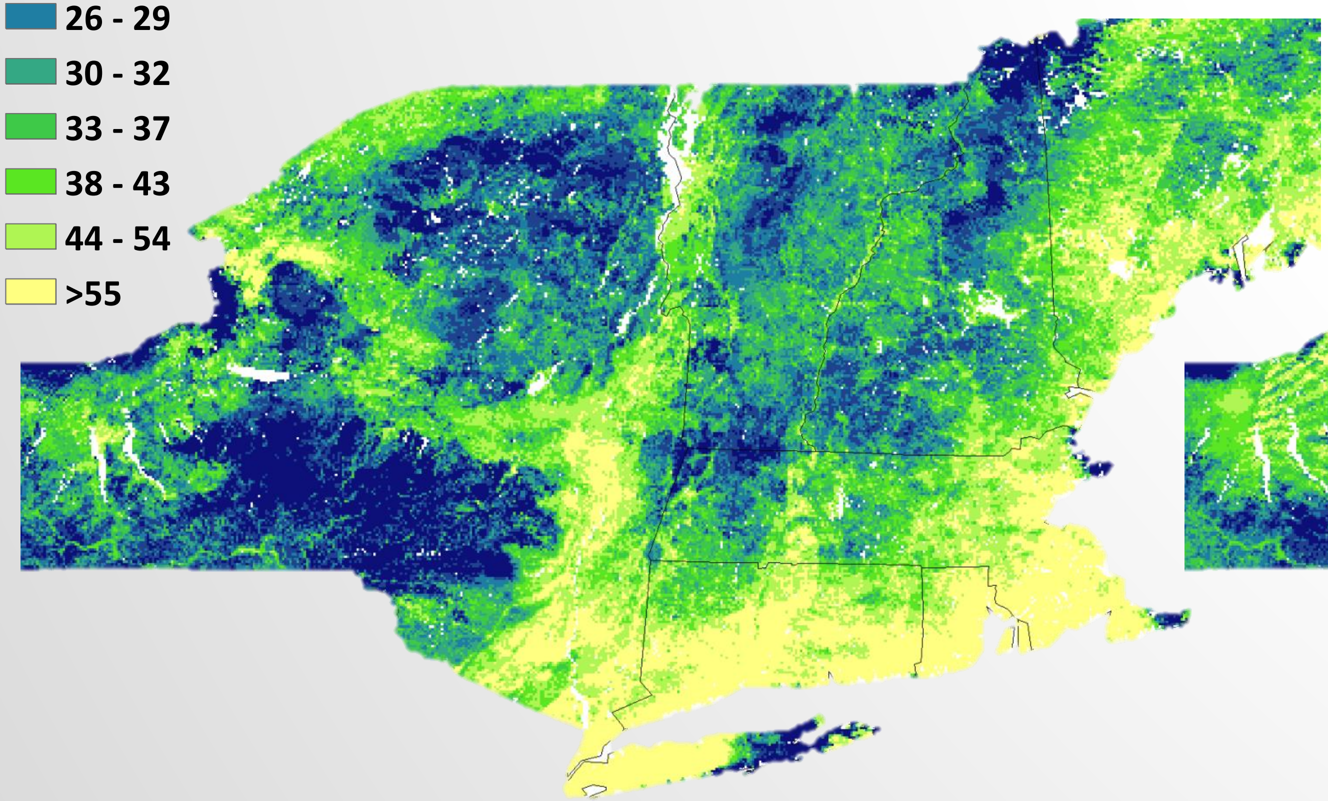


SPATIAL TRENDS **COLD SEASON**

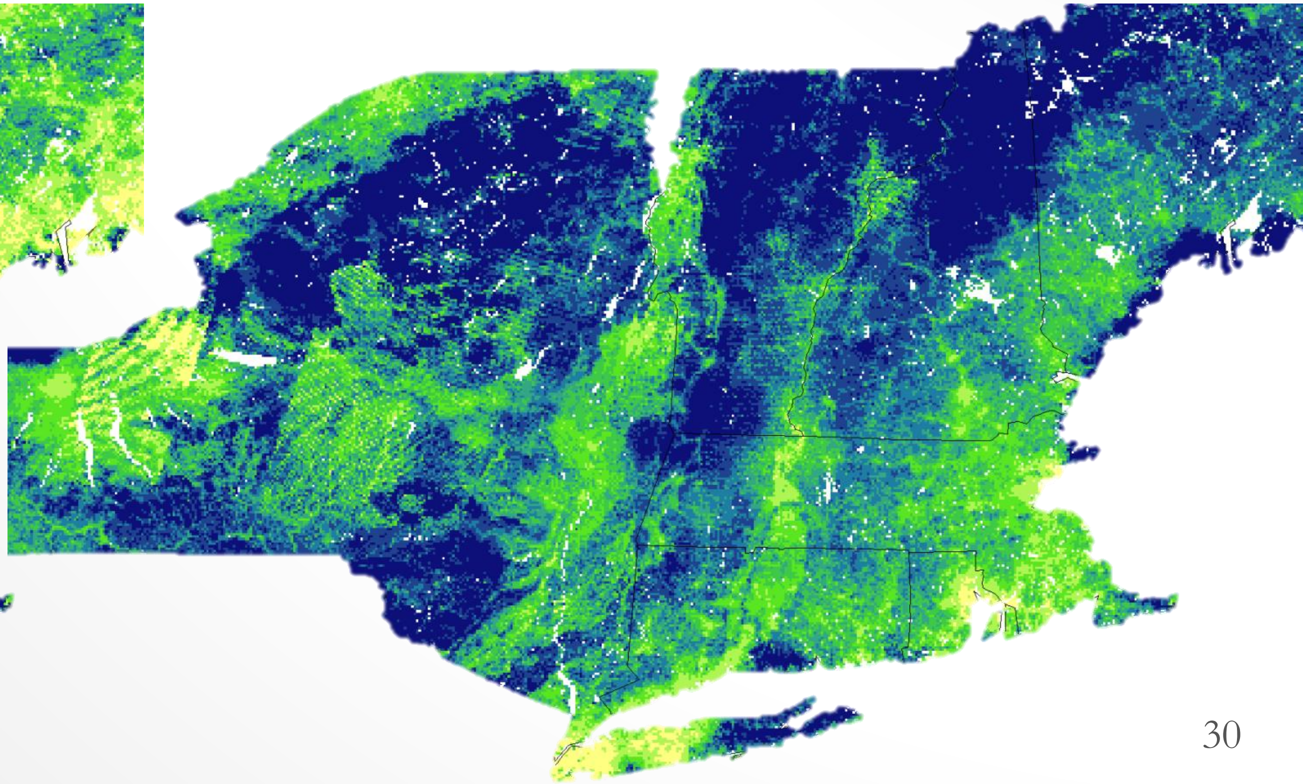
Emissions
(Tons/yr/km^2)

- **0 - 21**
- **22 - 25**
- **26 - 29**
- **30 - 32**
- **33 - 37**
- **38 - 43**
- **44 - 54**
- **>55**

Period 1
2002-2004



Period 4
2011-2013



LAND USE REGRESSION

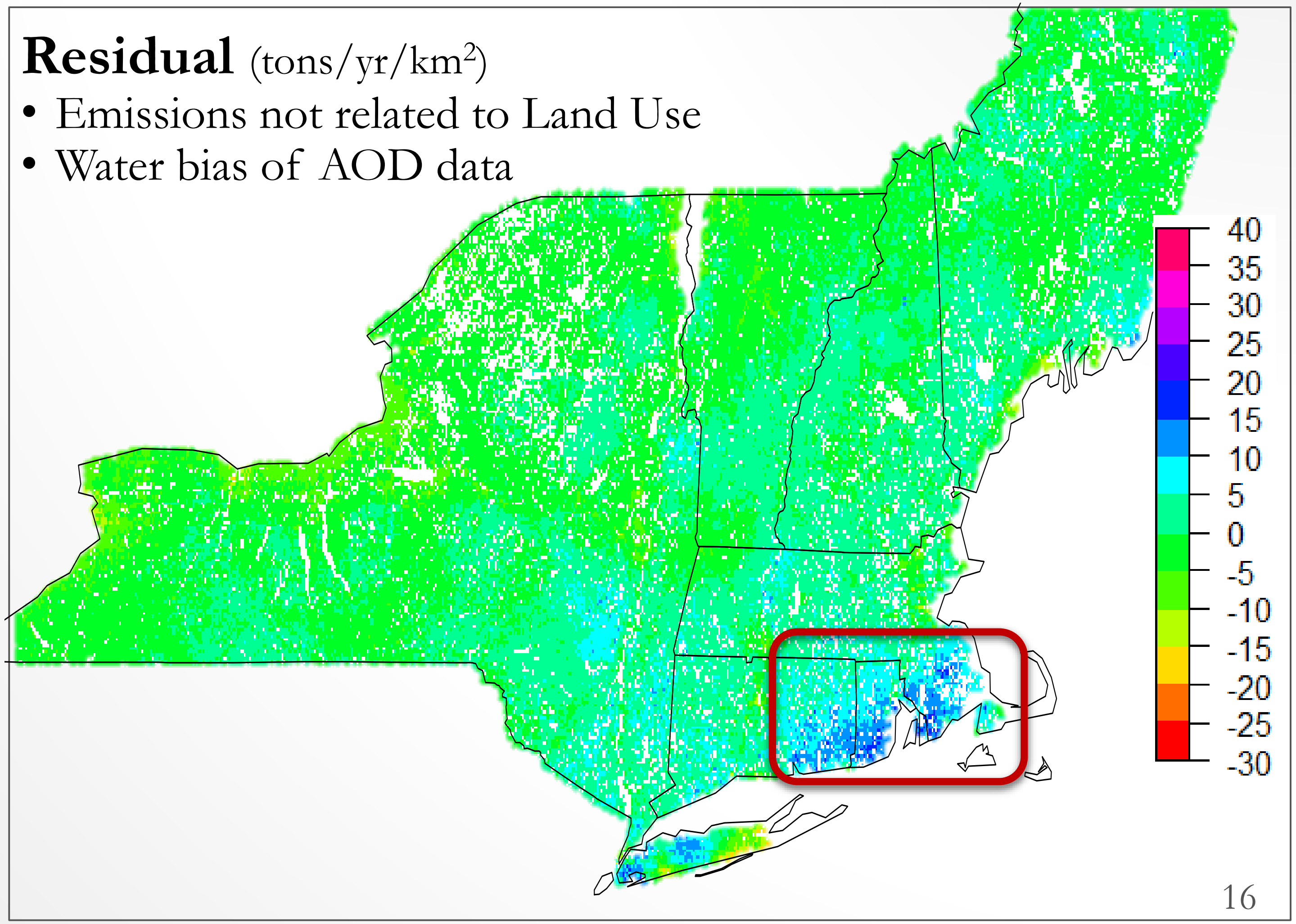
$$\text{PEIRS} = \sum \beta_i \text{LU}_i + \varepsilon$$

$R^2 = 65\%$

Land Use	Emission (Tons/yr/km^2)
Traffic	0.4 ~ 28
Developed area	5.6 ~ 13
Population	0.1 ~ 2.7
Pasture	0.34
Industrial Points	0.58

Residual (tons/yr/km^2)

- Emissions not related to Land Use
- Water bias of AOD data



Thank you!

Policy Implications [REMOTE SENSING vs SENSORS]

- Better exposure assessment => higher effect estimates
- Study in places with no monitoring (not possible before)
- Rural populations are at higher risk
- Dissect acute and chronic effects
- Study simultaneously climate and air pollution effects

But all these effects are based on exposure predictions, which are not necessarily equivalent with the FRM or equivalent methods

Inter-Site

Means by site

- 22.4 - 79.7 μg/m^3

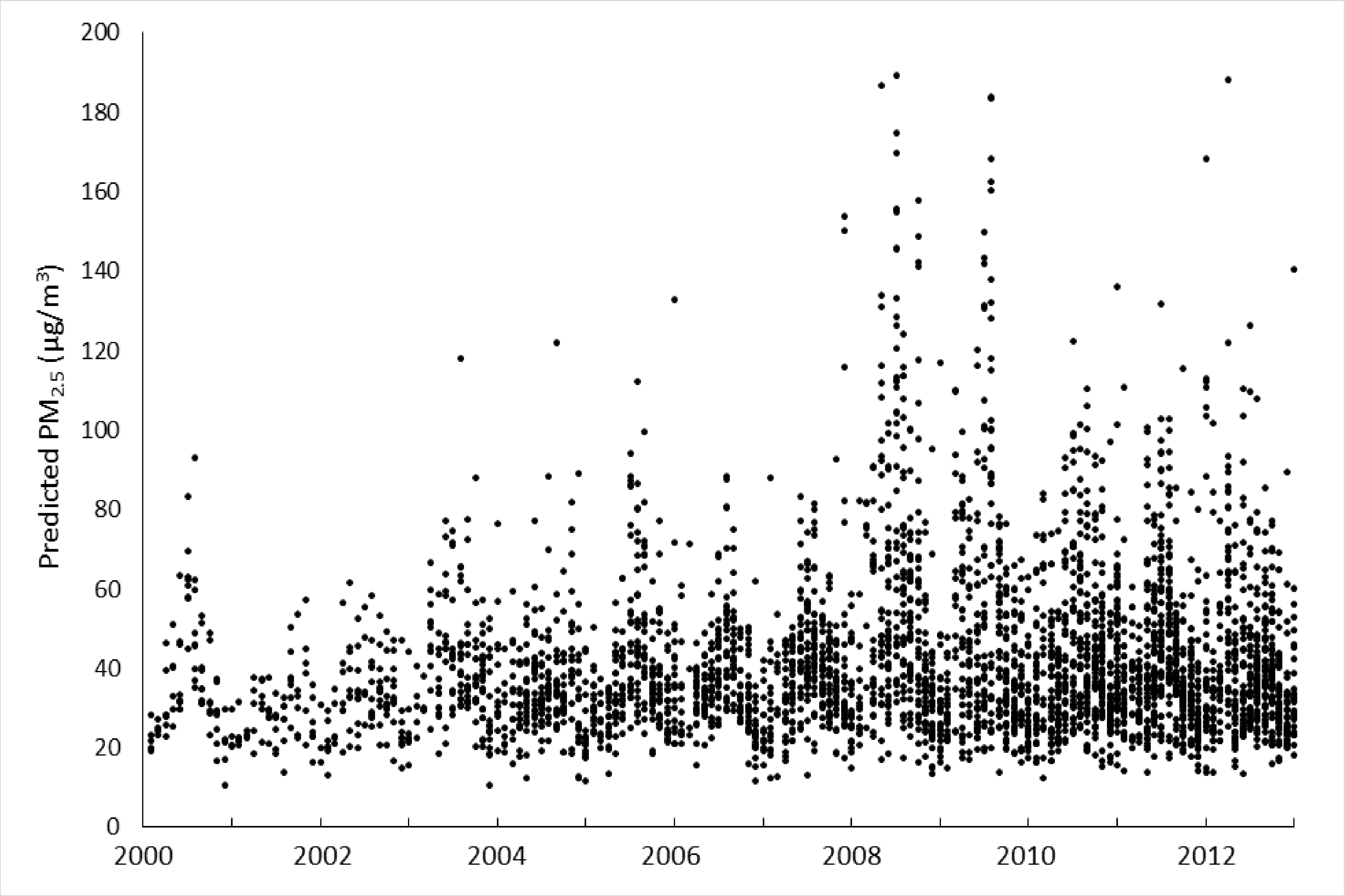
Intra-Site

50% sites

- $\Delta > 73$ μg/m^3

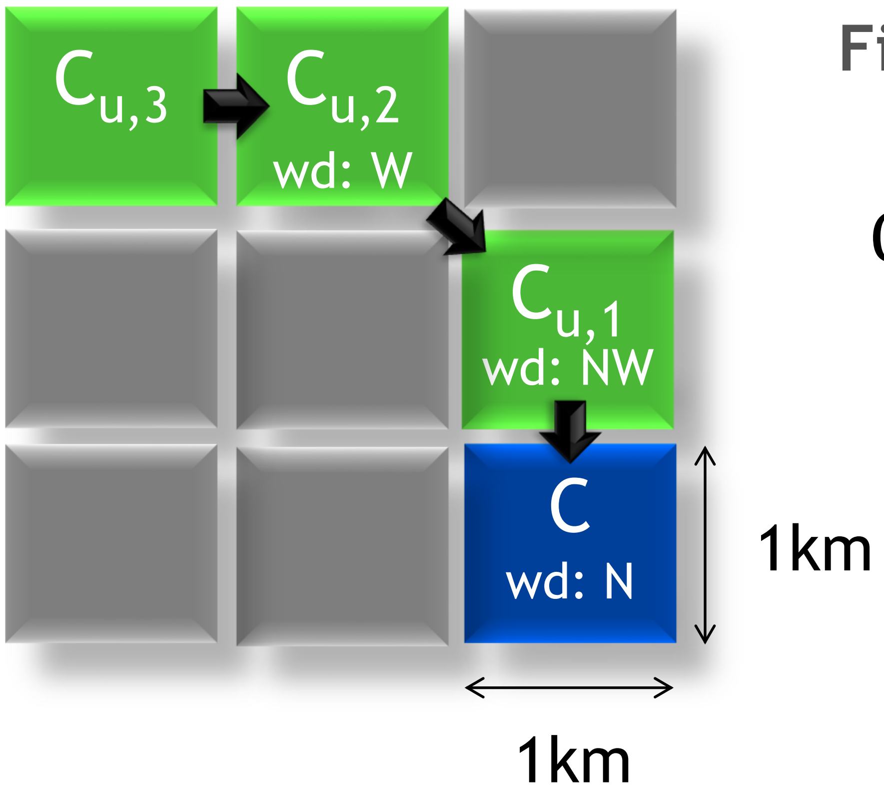
20% sites

- $\Delta > 120$ μg/m^3



Monthly PM$_{2.5}$ predictions for 104 military sites In Southwest Asia and Afghanistan from 2000-2012

Stage 2: Emission model



Final model

$$C = \sum_{i=1}^{3} C_{u,i} \times \text{Temperature} + \frac{Q}{\alpha \times PBL}$$

C : $PM_{2.5}$ Concentration inside box
C_u : $PM_{2.5}$ Concentration upwind
α : Air exchange rate
Q : Emission inside box
PBL : Planetary Boundary Layer height
wd : Wind direction

Study Area: North East US

Study Period: 2002 - 2013

Data	Source	Temporal scale	Spatial scale
Aerosol Optical Depth	MODIS Aqua	Daily	1km x 1km
Ground level $PM_{2.5}$	EPA monitors	Daily	Point
Weather	NOAA NARR	Daily	1km x 1km
Land use vars.	USGS/ESRI®	Cross-sectional	1km x 1km
NEI Primary $PM_{2.5}$	EPA	Annual (2008,2011)	County