Center for Air, Climate and Clean Energy Solutions (CACES)

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THE UNIVERSITY OF TEXAS AT AUSTIN
Middlebury College
BYU
Imperial College London
Health Canada
VirginiaTech
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CACES investigators

Carnegie Mellon University:
- ***Air***: **Peter Adams, Neil Donahue, Spyros Pandis, Albert Presto, Allen Robinson, R Subramanian**
- ***Energy***: **Ines Azevedo, Paulina Jaramillo, Scott Matthews, Jeremy Michalek**

Health Canada:
- **Rick Burnett: epidemiology**

Brigham Young University:
- **C Arden Pope: epidemiology**

Imperial College:
- **Majid Ezzati: epidemiology**

Middlebury College:
- **Nick Muller: economics**

University of Washington:
- **Julian Marshall, Chris Tessum: exposure, health, and impact assessment**

University of Minnesota:
- **Adam Boies, Jay Coggins, Jason Hill, Dylan Millet, Steve Polasky (economics, energy systems, transportation)**

University of Texas:
- **Josh Apte: exposure, health, and impact assessment**

Virginia Tech:
- **Steve Hankey: exposure, health, and impact assessment**

University of British Columbia:
- **Michael Brauer: exposure, health, and impact assessment**

Major Goals

Develop and improve a **suite of mechanistic and empirical models** that link emissions, concentrations, health, and economics for multiple pollutants at **high spatial resolution (100 m – 1 km)** over the entire continental U.S.

Challenge models with highly temporally-, spatially-, and chemically-resolved measurements in case-study locations.

Apply models and collect measurements to quantify the **near-source, intra-urban, inter-urban and regional differences in pollutant concentrations**, composition, and sources, and to further our mechanistic understanding of **processes driving those differences**.

Democratize state-of-the-art modeling and policy analysis tools to dramatically improve our collective ability to investigate air, climate, and energy solutions.

Major Goals

Improve our understanding of **air pollution's health impacts**, especially changes over **time and regional differences** influence population-wide mortality and life expectancy, and by developing **multi-pollutant concentration-response functions**.

Improve methods for **science-based policy assessments that integrate advanced emissions, air quality, health, and economic** models for multiple pollutants (including climate forcers) using a life cycle approach.

Investigate a range of **technology and policy scenarios for addressing our nation's air, climate, and energy challenges**, and test their effectiveness at meeting policy goals such as improved health outcomes, climate outcomes, and cost-effectiveness.

Cross cutting themes

Regional differences in exposure and impacts from near-source to neighborhood to different parts of the U.S. focusing on modifiable factors.

Multipollutant including $PM_{2.5}$ (speciated and source-resolved), NO_x, ozone, air toxics, and ultrafine particles.

Integrating air quality, climate, and energy policy for multipollutant assessment of traditional pollutants with CO_2 and other radiative forcers.

New and expanded set of tools for policy assessment, air quality measurement and modeling, exposure assessment, epidemiology, and cost-benefit analysis.

Democratization of tools to researchers, policy analysts and decision-makers, and individual citizens.

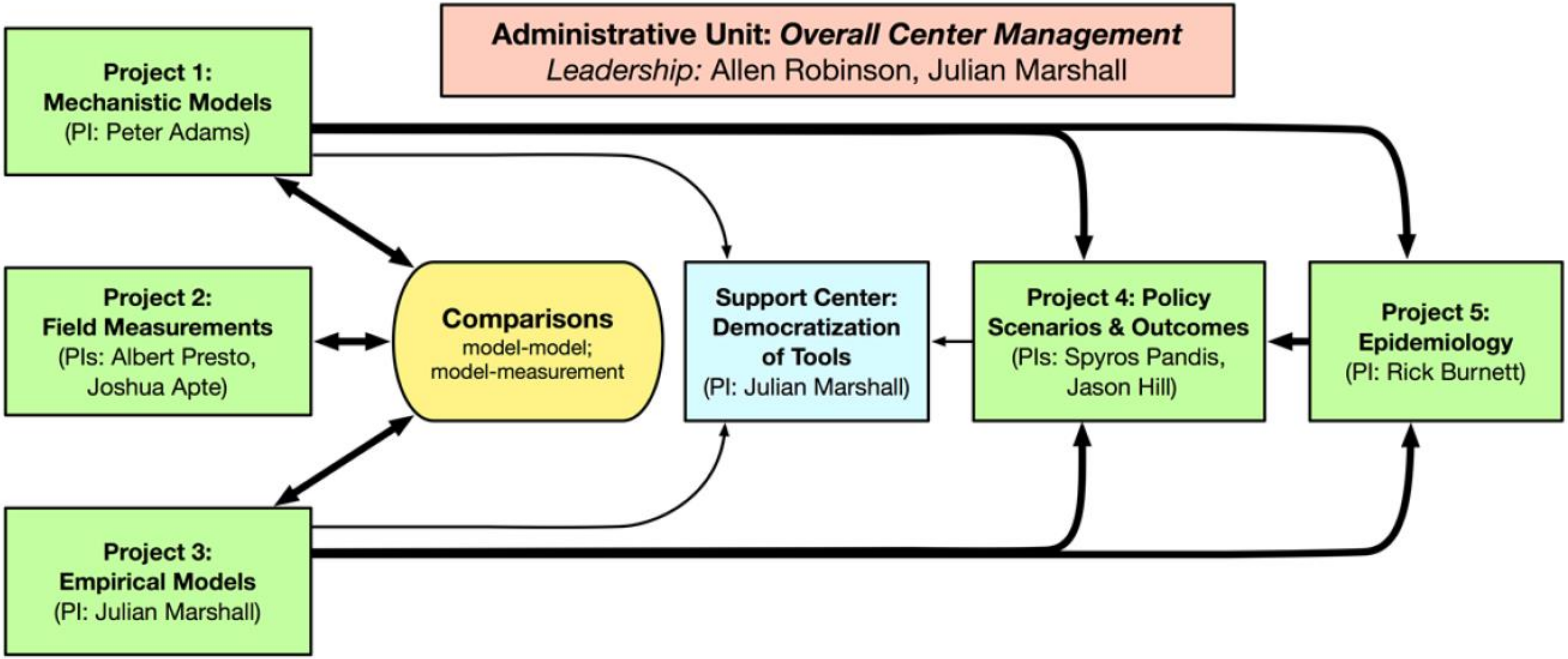
Environmental justice: quantifying how emission-changes would impact exposure gaps by race, income.

Organization: Five Projects

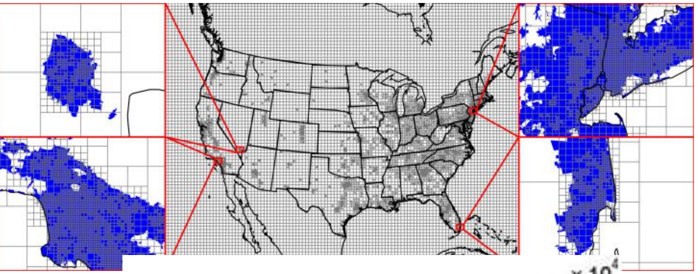
Overall directors: Allen Robinson, Julian Marshall

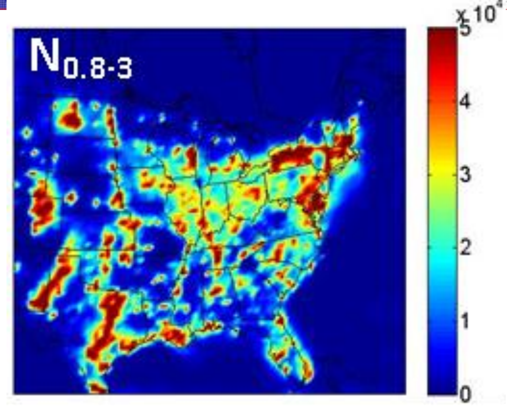
1. **Mechanistic models** (Peter Adams)
   - chemical transport models, reduced-complexity models, organics & UFs
2. **Field Measurements** (Albert Presto, Josh Apte)
   - 3 cities, high resolution distributed sensors, case studies (urban-rural, near roadway, etc)
3. **Empirical models** (Julian Marshall)
   - observation-based mapping, e.g. land-use regression
4. **Policy scenarios and outcomes** (Spyros Pandis, Jason Hill)
   - applications, proving that everything works, electricity and transportation decision-making
5. **Epidemiology** (Rick Burnett)
   - larger, unique epidemiological studies

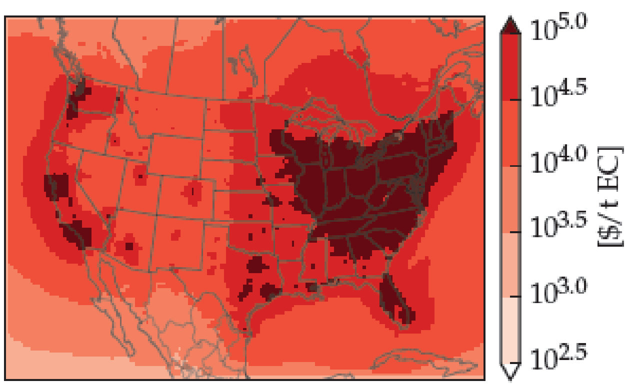
Organization: Five Projects



Project 1: Mechanistic air quality impact models







(a) EC: $170,000/t EC

<u>Reduced complexity models</u> for social costs, mortality, other health end points

- EASIUR, InMAP, APEEP, source-receptor matrices
- Assess limitations, best practices
- Widely disseminate

<u>Chemical transport models</u>

- Extend to higher spatial resolution (1 km)
- Advanced treatment of organics and ultrafine PM
- Near source physico-chemical transformation of organic PM

<u>Historical $PM_{2.5}$ levels</u> (for health study)

- Composition
- Source tagged

<u>Regional differences</u> of source apportionment ("tagging", PSAT)

Reduced Complexity Models

InMAP methodology

1 emissions
InMAP reads annual total emissions from an arbitrary shapefile and allocates them to the model grid.

2 concentrations
InMAP calculates annual average changes in $PM_{2.5}$ concentrations caused by the input emissions.

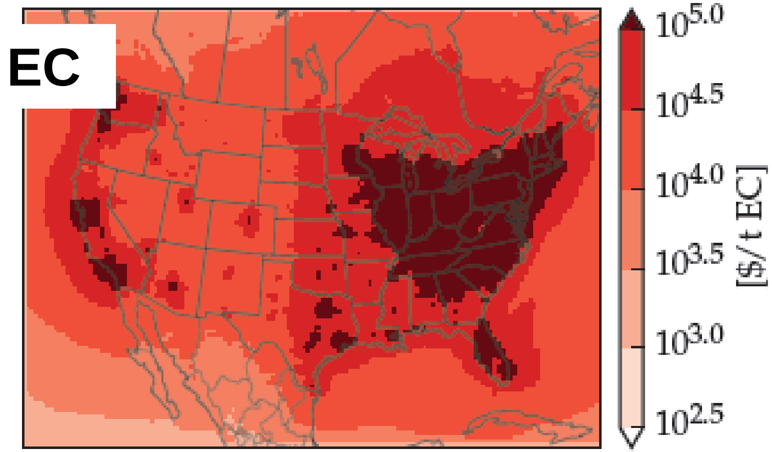
3 exposure
InMAP estimates changes in human $PM_{2.5}$ exposure caused by the input emissions using census data.

4 health impacts
Using epidemiological concentration-response functions, InMAP calculates the health impacts of the emissions.

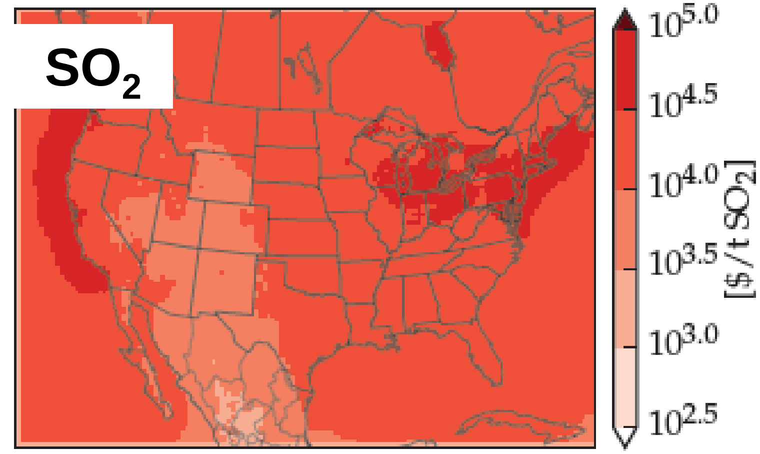
5 economic damage
Optionally, health damages can be converted to economic damages using a Value of Statistical Life metric.

6 environmental justice
InMAP calculates how different demographic groups are exposed to $PM_{2.5}$ even when the groups live in adjacent neighborhoods.

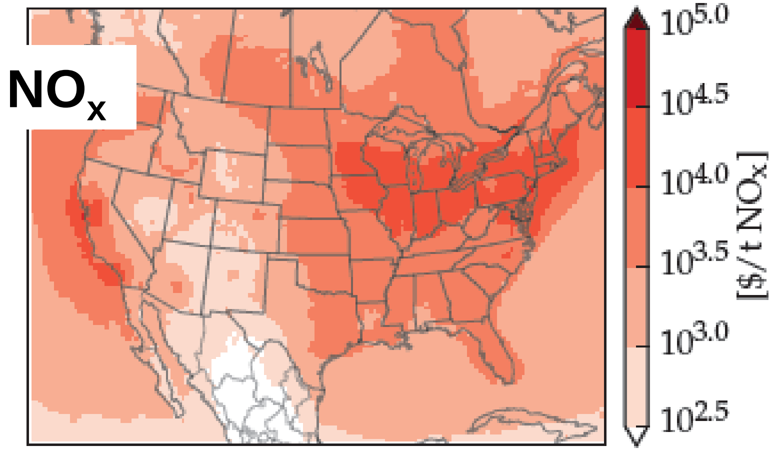
Predictions of Social Costs



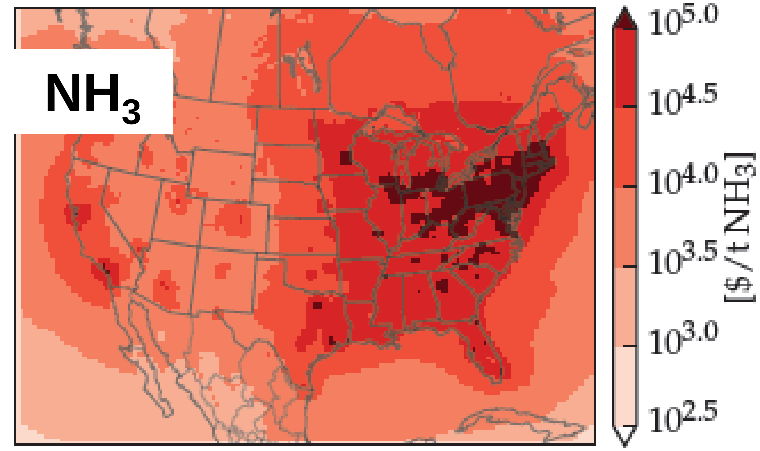
(a) EC: $170,000/t EC



(b) SO_2: $27,000/t SO_2



(c) NO_x: $9,700/t NO_x



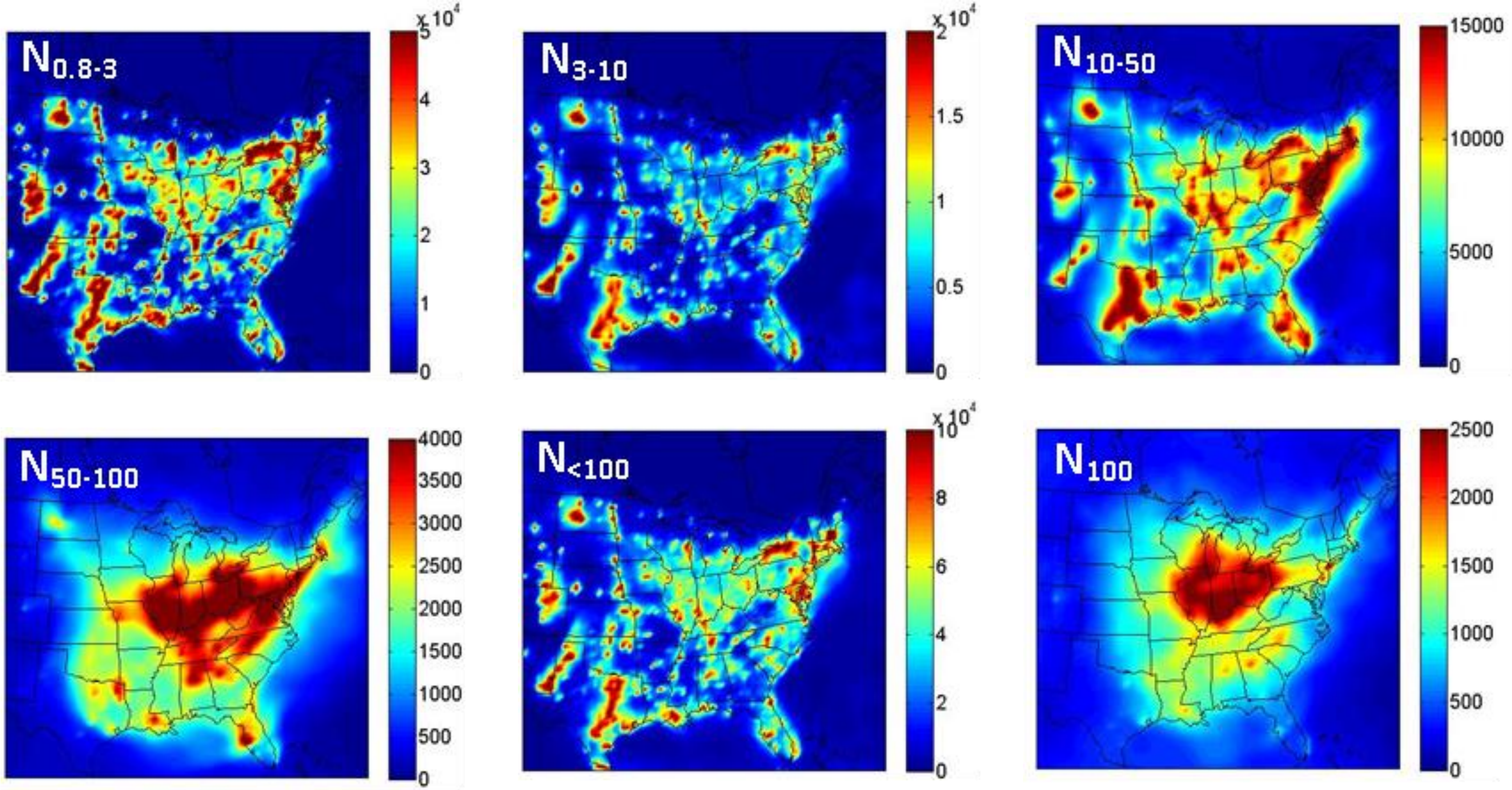
(d) NH_3: $46,000/t NH_3

Planned Extensions to Reduced-Form Models

- Species: organic PM2.5, ultrafine particles, ozone
- Resolution: 1 km
- Temporal: Seasonal resolution
- Impacts: multi-pollutant concentration-response functions

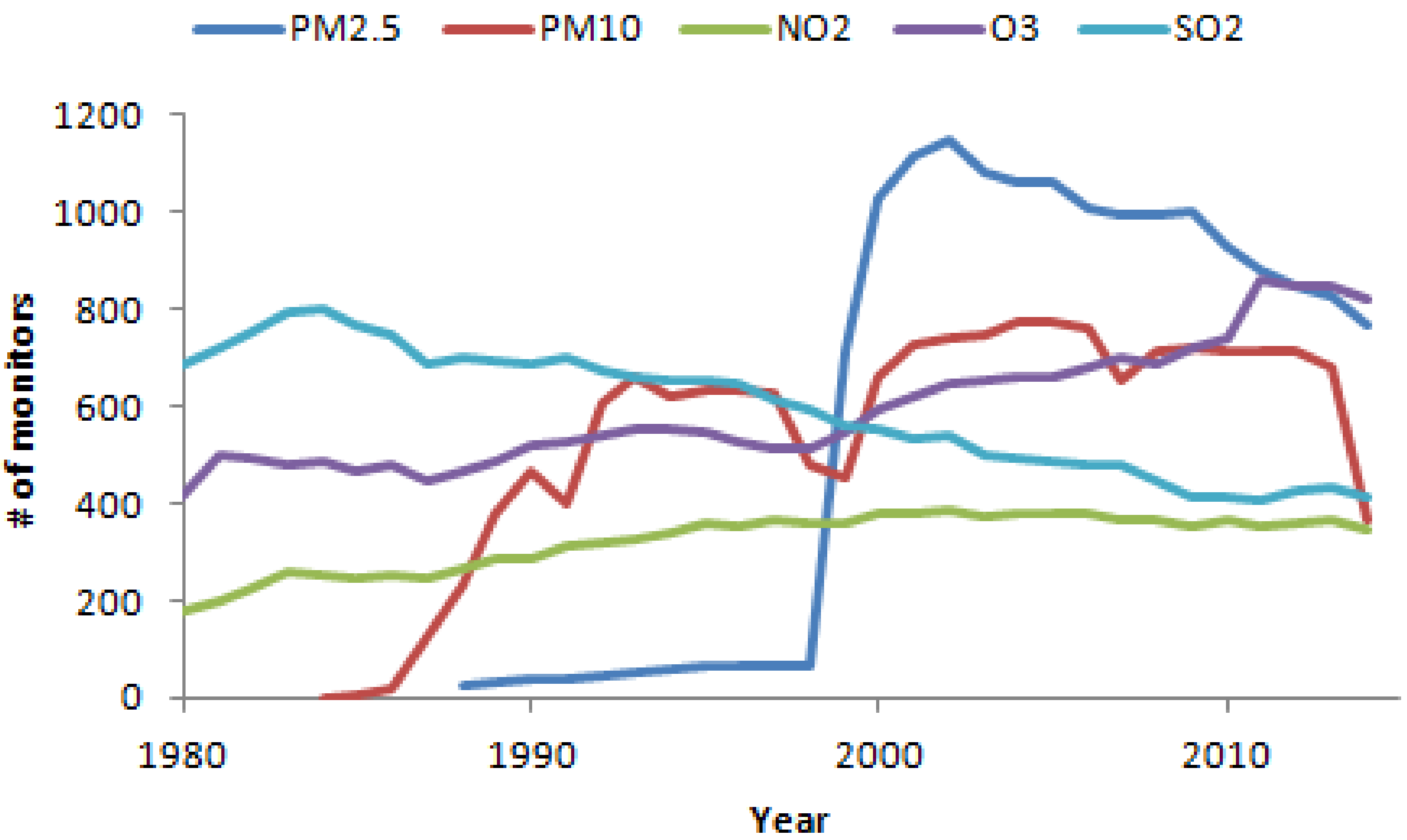
- Intercomparison: quantify strengths and weakness
- Develop best practice guidance

Ultrafine Particle Modeling



$N_{x\text{-}y}$ denotes the number of particles between x and y nm in diameter.

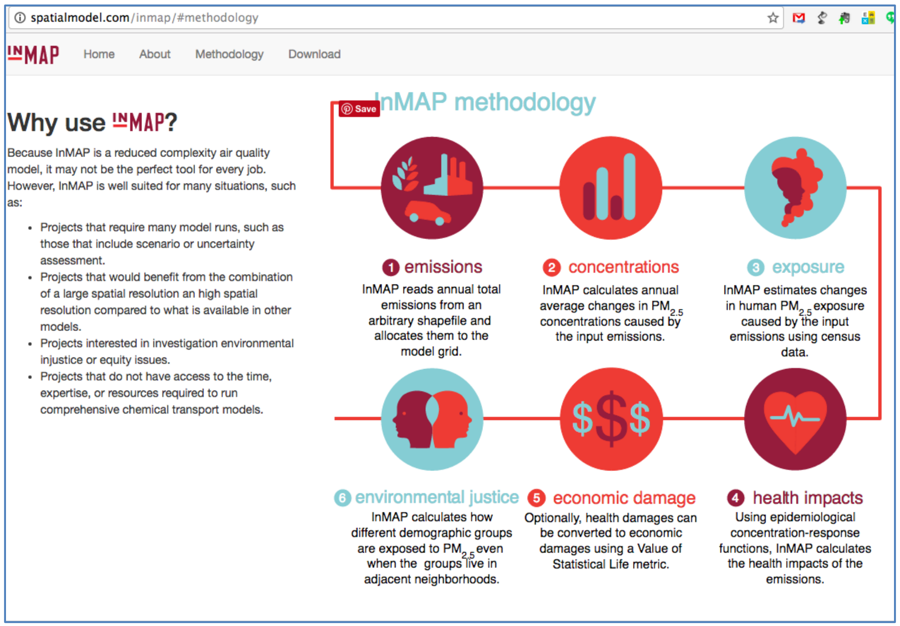
Historical Reconstruction of PM Levels



1980 - present

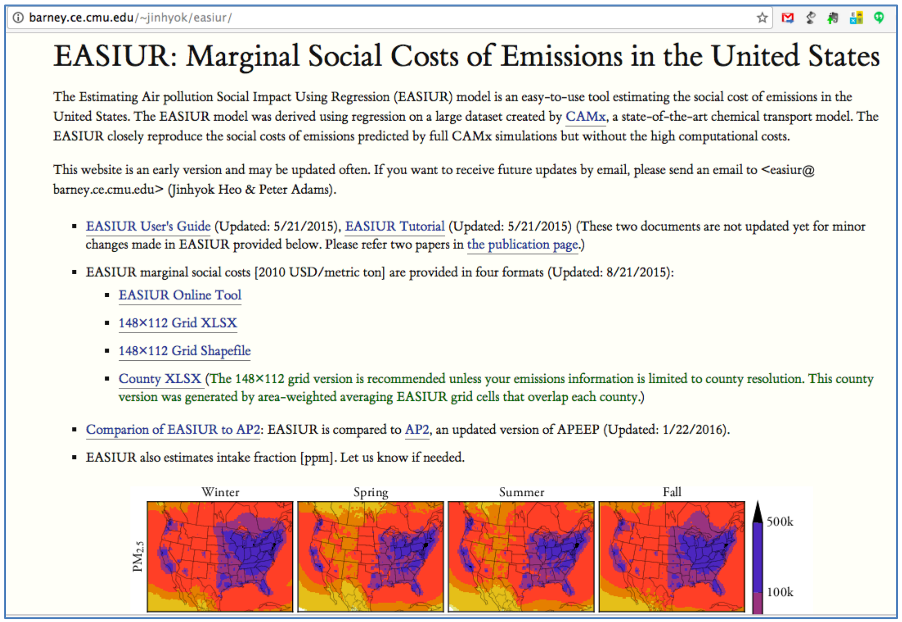
Wide Dissemination

InMAP



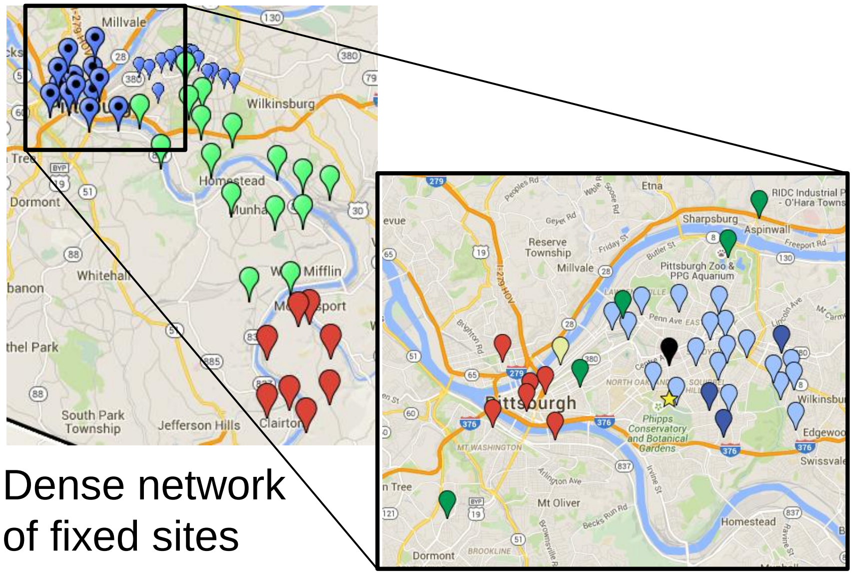
http://spatialmodel.com/inmap/

EASIUR



http://barney.ce.cmu.edu/~jinhyok/easiur/

Project 2: Air Quality Observatory

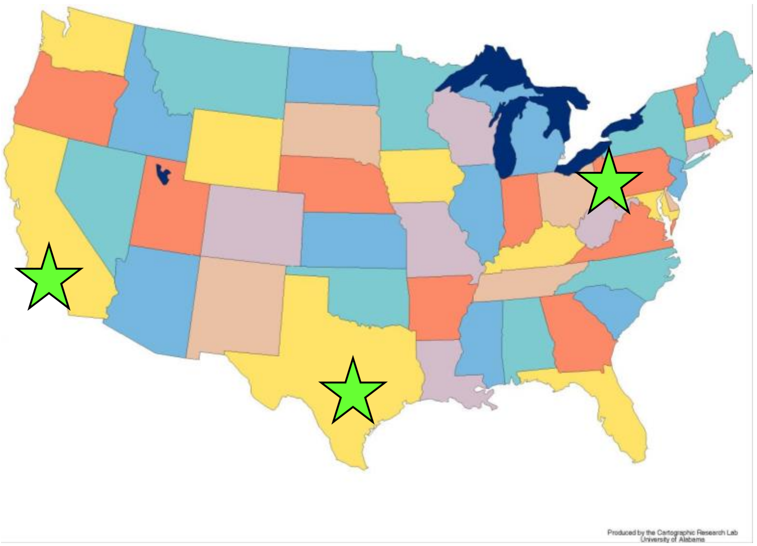


Dense network of fixed sites

- Quantify role of **modifiable factors** (emissions and land use) on spatial temporal patterns of pollutant concentrations
- **Evaluate models** at high spatial and temporal resolution
- Develop **mechanistic understanding** of physico-chemical processes near sources

Mobile sampling to quantify block by block exposure.

Target Cities



Los Angeles, Austin, Pittsburgh

Case Studies

Near Road

Goods Movement

Airports

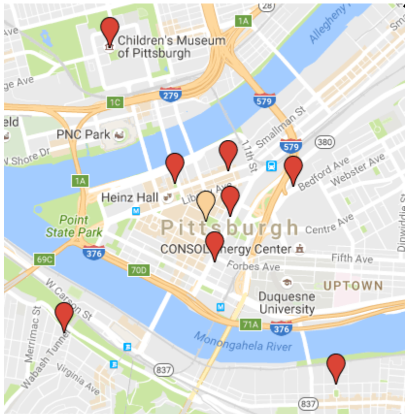
Industrial

Restaurants

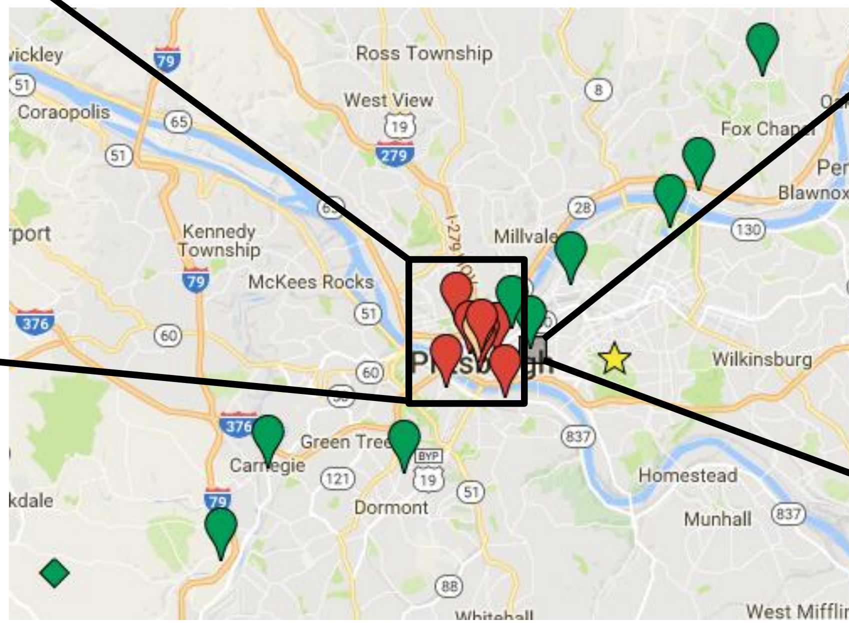
Urban Form

Multi-modal sampling

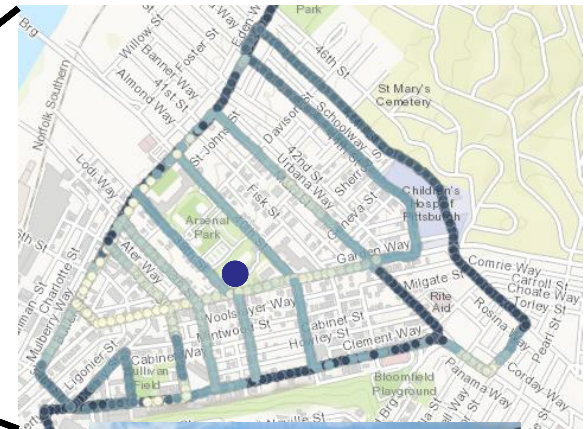
Fixed Sites



Transect Case Study



Mobile sampling



Project 2 – Observatory

CACES

Multi-modal sampling

Fixed Sites

Supersite

- Instruments: CO, NOx, SO_2, O_3 monitors, SMPS (particle size), water-based CPC, AMS (part time), MAAP (black carbon), RAMP with optical $PM_{2.5}$

Extended site

- Instruments: SMPS, water-based CPC, CO, NOx monitors, MAAP, RAMP with optical $PM_{2.5}$

Distributed sites

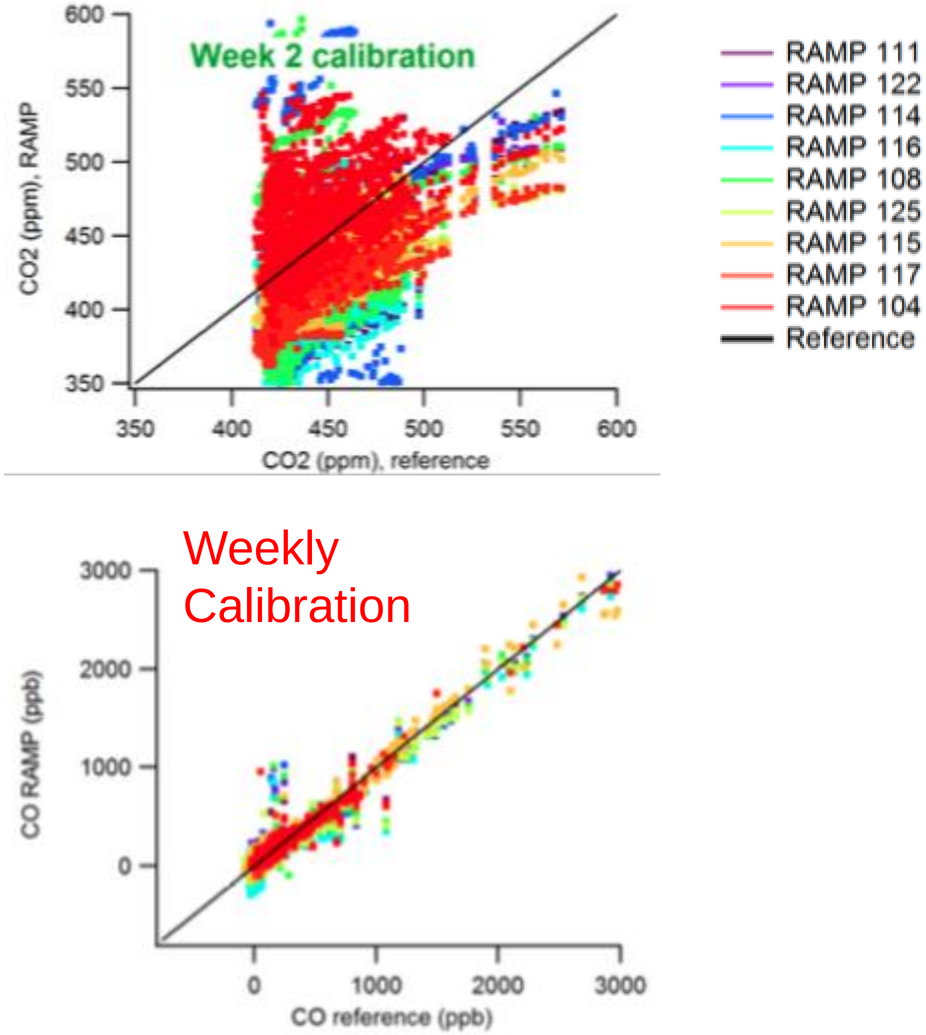
- Water-based CPC, RAMP with optical $PM_{2.5}$, some with BC measurements

Mobile

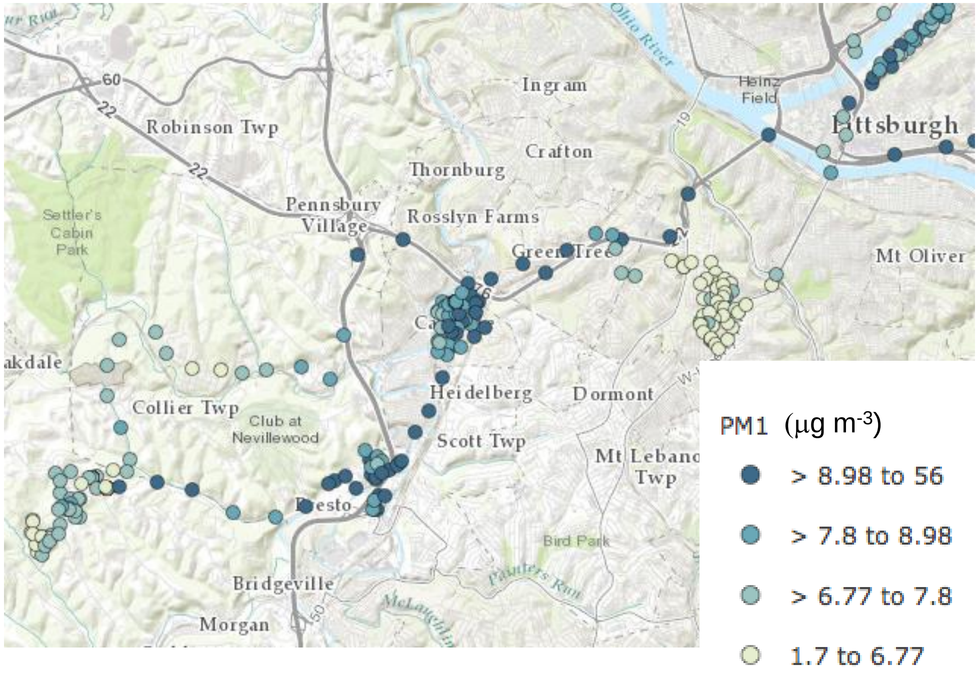
- Drive rasters in 1x1 km boxes in each case study
- Instruments: AMS, FMPS (particle size distribution), water-based CPC, CO, CO_2, NOx monitors, aethalometer (black carbon)

Low-cost sensors

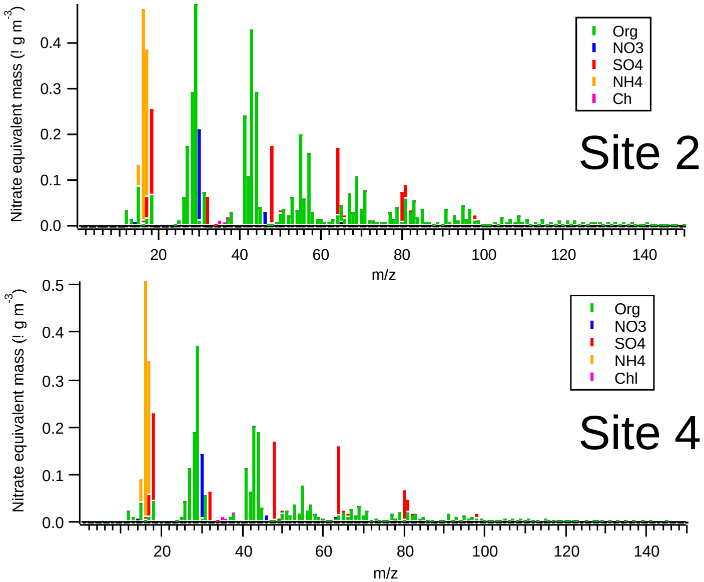
Co-location test at super site



Spatial distribution of organic aerosol

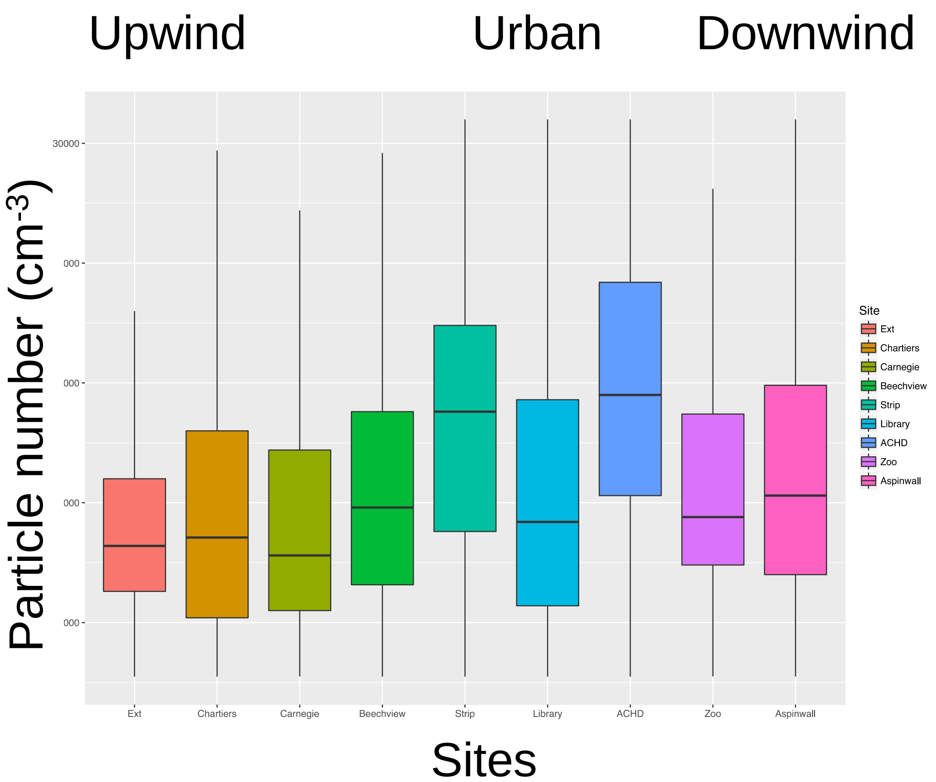


Spatial variation in PM_1 (OA + BC + SO_4 + NO_3 + NH_4) on a single morning

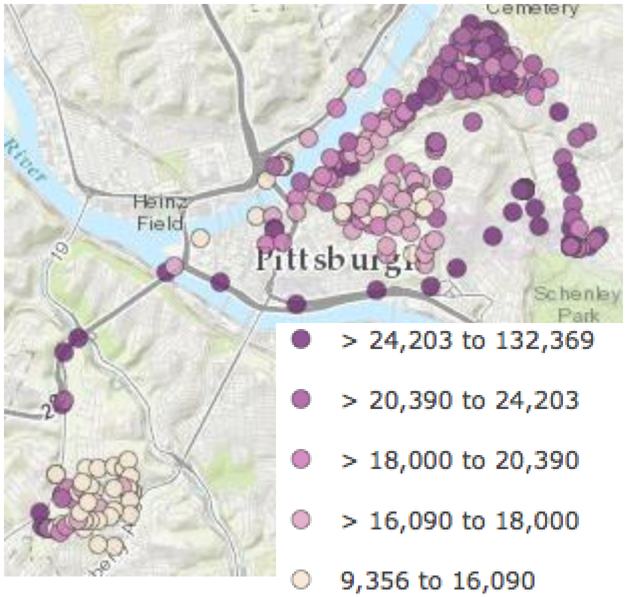


- Differences in mass spectra (43/44 ratio, m/z 57 abundance) suggest influence of different sources.
- Source impacts also evident in single particle AMS data

Ultrafine particles



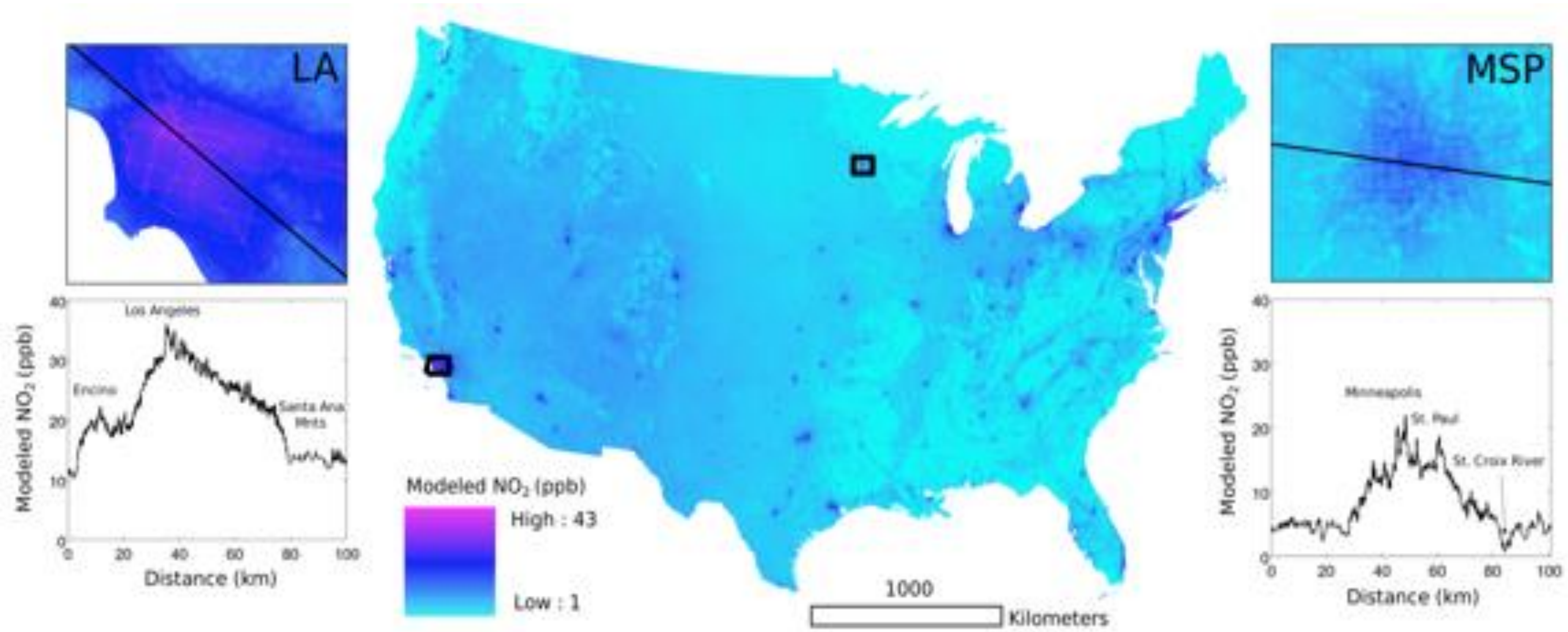
Particle number (cm^{-3})



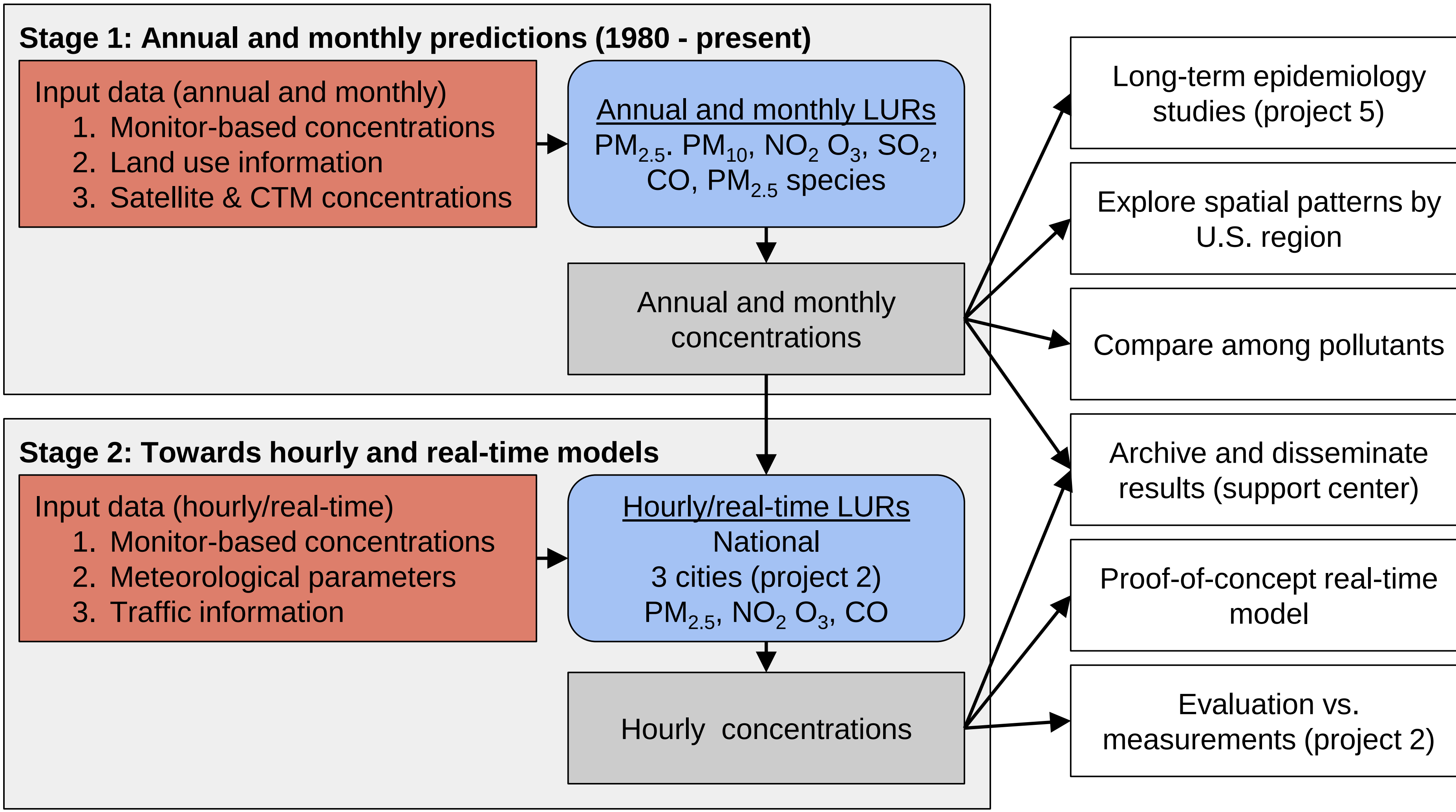
Neighborhood scale and smaller scale (episodic) variations in PN

Project 3. Empirical models

- National, multi-pollutant
- Satellite, land use, mechanistic models, EPA monitoring data
- 1980 – present
- Annual → monthly
- Daily

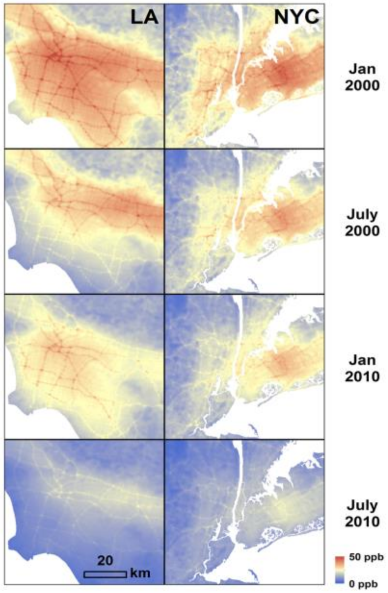


Project 3. Empirical models



Project 3. Empirical models – annual, monthly

Monthly NO_2



Source: Bechle et al., 2015

Challenges

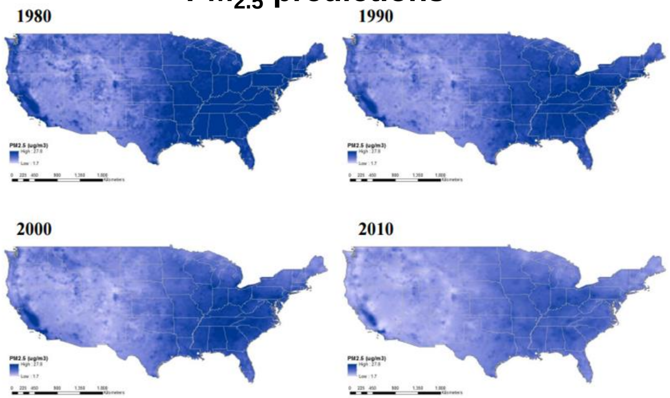
1. Number of models
   - **Annual:** 6+ pollutants ⨉ 36 y = 200+ models
   - **Monthly:** 6+ pollutants ⨉ 36 y ⨉ 12 months = 2,500+ models
2. Availability of monitoring data (see next slide)
3. Change in land-use over time; availability of data
4. Making predictions at many locations

Approach

- PLS + reduced dimensionality; Spatiotemporal model / scaling approach; Spatiotemporally varying covariates
- PostgreSQL, PostGIS
- Satellite & CTM estimates. Historical land use/cover

Sampson et al., 2011; Kim et al., *in press*; Keller et al., 2015; Bechle et al., 2015, Di et al., 2016

$PM_{2.5}$ predictions



Source: Kim et al., *In press*

Project 3. Empirical models – annual monitoring data

	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997
$PM_{2.5}$	0	0	0	0	0	0	0	0	28	35	36	39	47	49	59	66	65	65
PM_{10}	0	0	0	0	1	8	18	125	234	379	465	402	609	663	624	631	634	627
NO_2	179	202	223	257	250	245	253	249	264	285	289	310	321	328	341	362	350	367
O_3	418	499	495	482	484	468	479	444	465	489	522	526	542	552	551	544	529	517
SO_2	689	718	755	792	802	765	746	685	698	696	689	698	677	660	651	653	647	615

	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014
$PM_{2.5}$	69	714	1027	1115	1150	1084	1065	1063	1006	997	996	1001	928	885	849	825	767
PM_{10}	482	456	662	730	743	745	776	778	763	651	716	722	713	716	714	680	369
NO_2	360	363	380	381	386	373	382	381	379	367	365	350	364	356	360	369	348
O_3	515	545	593	621	647	657	660	658	680	701	689	719	740	861	849	846	819
SO_2	594	560	554	534	538	502	494	485	479	478	445	413	413	409	426	435	411

Also: CO, PM species

Data notes:

Most data from EPA

AQS http://aqsdr1.epa.gov/aqsweb/aqstmp/airdata/download_files.html

- $PM_{2.5}$: 1999 - present
- PM_{10}: 1983 - present
- NO_2, O_3, SO_2: 1980 - present

Additonal PM data from IMPROVE network

http://views.cira.colostate.edu/fed/DataWizard/Default.aspx

- $PM_{2.5}$: 1988 - present
- PM_{10}: 1999 - present

Data completeness rules
Maximum gap: 45 days
Minimum daily observations:
244 (daily measurements)
61 (1-in-3 measurements)
41 (1-in-6 day measurements)

Annual modeling suitability*
- < 100 monitors
- 200 monitors
- > 500 monitors

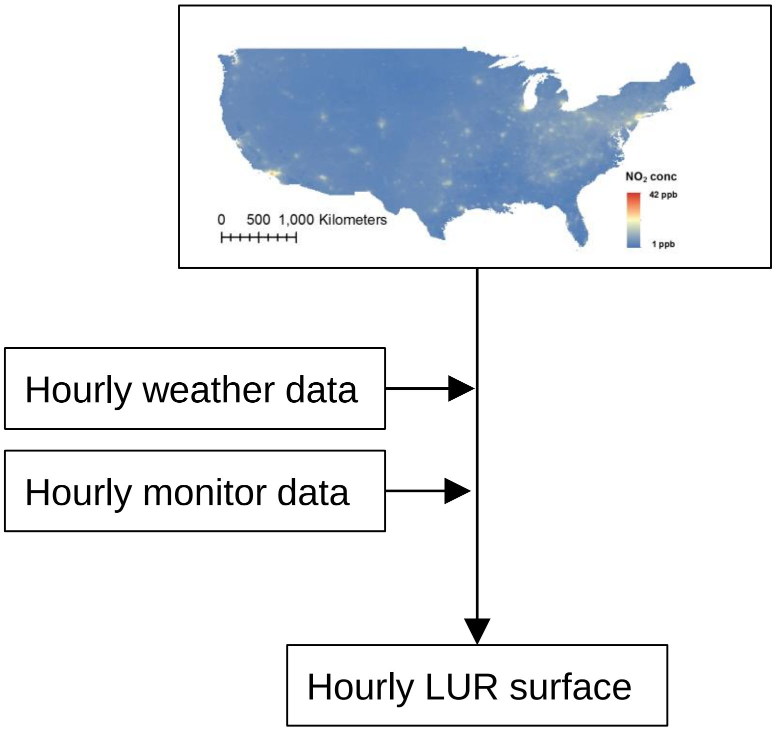
* based on Monte-Carlo simulations by Bechle et al., 2015

Project 3. Empirical models – hourly

Case-study cities: Real-time LUR in cities w/ measurements (project 2)

Assess feasibility of employing spatiotemporal traffic patterns in model-building

Use of dense measurements in project 2 for model-building or validation



Project 3. Empirical models: dissemination

Empirical Model Database   Home   About NO_2 PM   Other Pollutants

NO_2 (ppb)	2000-2010	Annual; Monthly	Block Centers*; Block Group; Tract	Contiguous U.S.	LUR with RS	Bechle et al.,2015 DOI, PubMed	J.D. Marshall	Download
NO_2 (ppb)	2006-2011	Annual; Monthly	Mesh Block Centers*	Australia	LUR with RS	Knibbs et al.,2014 DOI, PubMed	L.D. Knibbs	Available by request
NO_2 (ppb)	2005-2010	Daily	1-km grid	New England	LUR with RS	Lee & Koutrakis, 2014 DOI, PubMed	H.J. Lee	
NO_2 ($\mu g/m^3$)	2005-2007	Annual	100-m grid	Western Europe	LUR with RS	Vienneau et al.,2013 DOI, PubMed	D. Vienneau	Link

BME = Bayesian maximum entropy; LUR = land use regression; RS = remote sensing; UK = universal kriging; Models noted with * provide point-specific concentration estimates

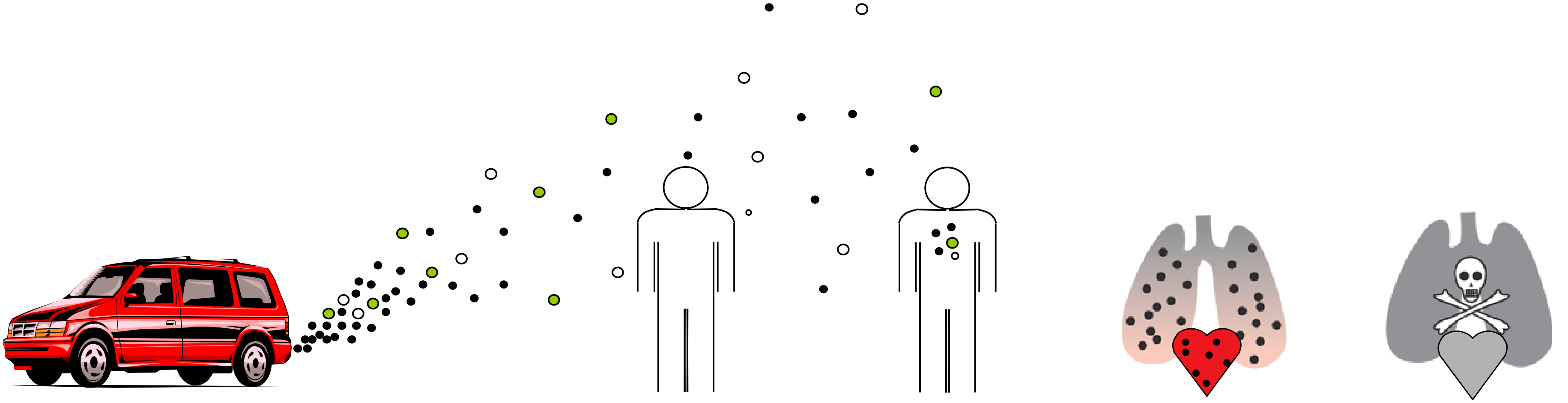
Particulate Matter (PM) Concentration Estimates

Pollutant	Years	Temporal Unit	Location Type	Geographic Coverage	Model Type	Citation	Contact	Data
$PM_{2.5}$ ($\mu g/m^3$)	1998-2014	Annual	0.01°×0.01°	Global	RS-derived estimates	van Donkelaar et al., 2016 DOI, PubMed	A. van Donkelaar	Link
$PM_{2.5}$ ($\mu g/m^3$)	1990; 1995; 2000; 2005; 2010; 2013	Annual	0.1°×0.1°	Global	Fused model with RS	Brauer et al., 2016 DOI, PubMed	M. Brauer	Link
$PM_{2.5}$ ($\mu g/m^3$)	2003-2011	Daily	1-km grid	Southeast U.S.	LUR with RS	Lee et al., 2015 DOI, PubMed		
$PM_{2.5}$ ($\mu g/m^3$)	2003-2011	Daily	1-km grid	Northeast U.S.	LUR with RS	Kloog et al., 2014 DOI	I. Kloog	
$PM_{2.5}$ ($\mu g/m^3$)	1999-2009	Annual	1.404°×0.784°*	Contiguous U.S.	LUR/BME	Reyes & Serre,2014 DOI, PubMed	M.L. Serre	Maps

www.spatialmodel.com/concentrations

Project 4. Air Pollutant Control Strategies in a Changing World

Project 4. Air Pollutant Control Strategies in a Changing World



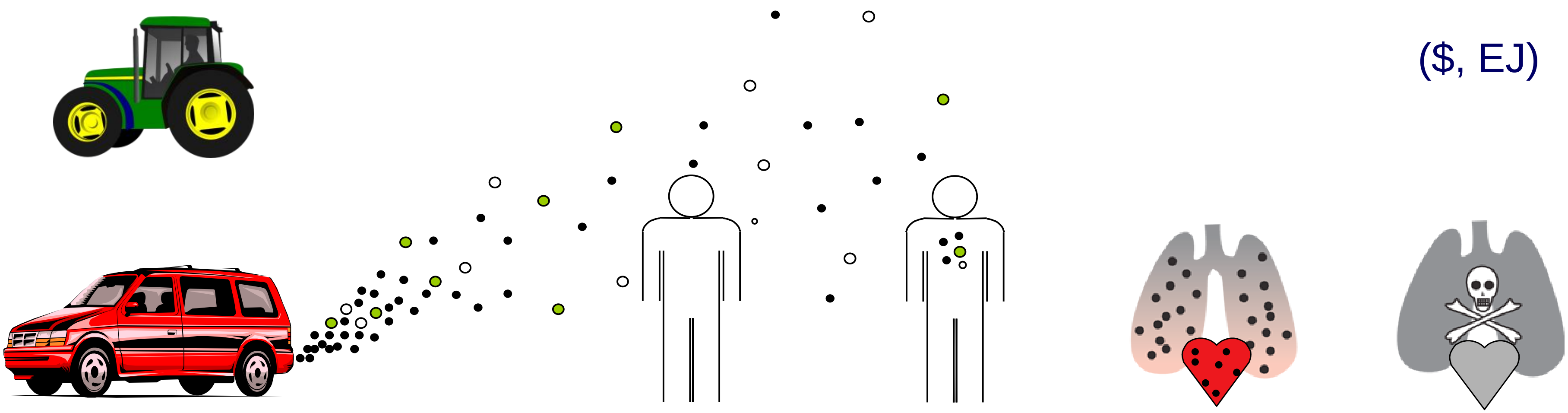
emissions → concentration → exposure → intake → dose → health effects

Project 4. Air Pollutant Control Strategies in a Changing World

(life-cycle)

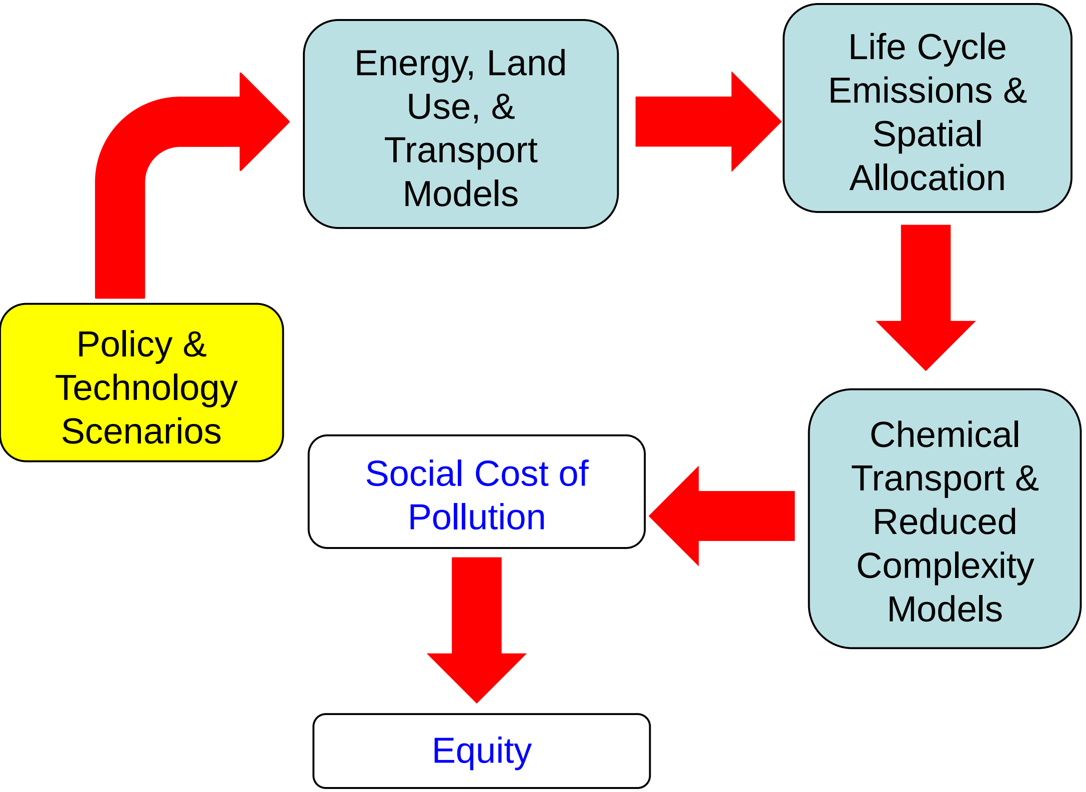
(reduced form models)

($, EJ)



emissions → concentration → exposure → intake → dose → health effects

Project 4. Scenarios – overview



Objective: Investigate technology and policy scenarios aimed at identifying actions that improve air quality while limiting climate change.

- Policy, technology, and sector interactions.
- Multi-pollutant
- Life cycle approach for *economy-wide* emissions.
- Models to translate emissions to concentrations to public health to monetary impacts

Project 4. Scenarios – focus areas




Electricity Production
Transportation
Land Use
Climate Change


Example scenarios/interactions/ "modifiable factors"

Policies in Place	Policy Scenarios
• CSAPR • MATS • CAA – NAAQs • Carbon STDs • CAFE • ZEV • AFV Subsidies • LCFS • Gasoline tax	• Carbon Tax/C-A-T • Carbon STD – existing EGUs • Biofuel RPS • Modified gas tax. • $PM_{2.5}$, VOC, NH_3

Policy Interactions	Compliance Strategy
• CSAPR – Carbon STDs • ZEV/Transport – NAAQs • Gas tax/Carbon tax • Existing CAA/ $PM_{2.5}$, VOC, NH_3 • ZEV/CAFE/AFV Incentives	• CCS • Renewables • Nuclear • International (Offsets) • Criteria abatement tech. • Alt. fuel vehicles • Vehicle efficiency improvement

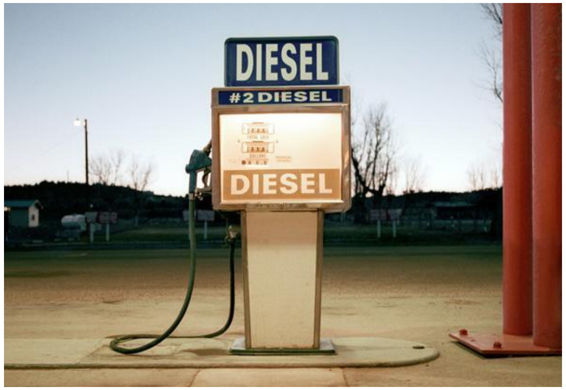
Transportation alternatives

Grid-independent gasoline-electric **hybrid** vehicles

Compressed natural gas **(CNG)** vehicles

Electric vehicles (**EV**s) with electricity from:

- U.S. grid average (varies by region)
- Coal
- Natural gas
- Corn stover
- Wind, wave, or solar power (WWS)

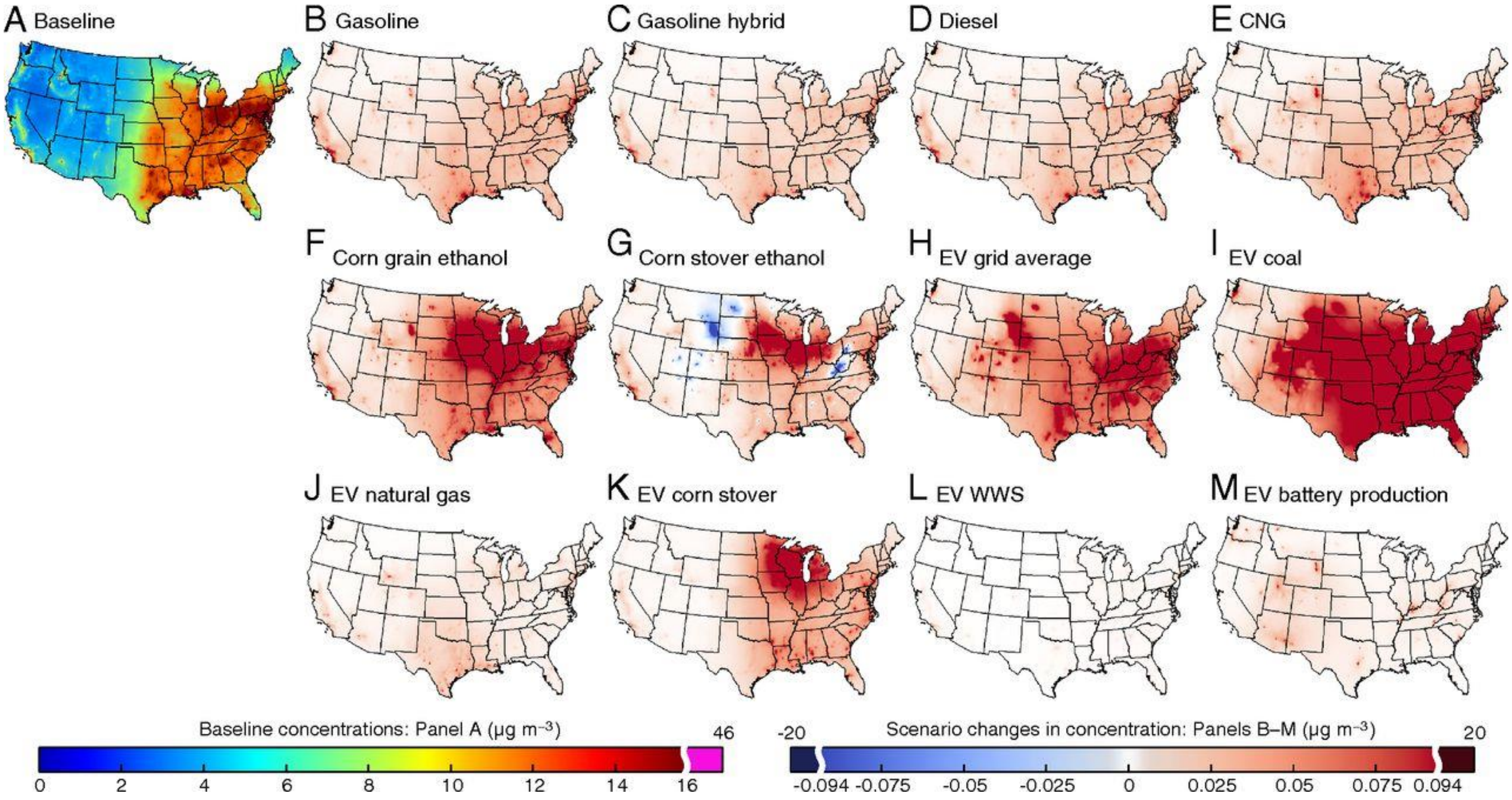


Diesel vehicles

Ethanol vehicles using **corn grain** or **corn stover**

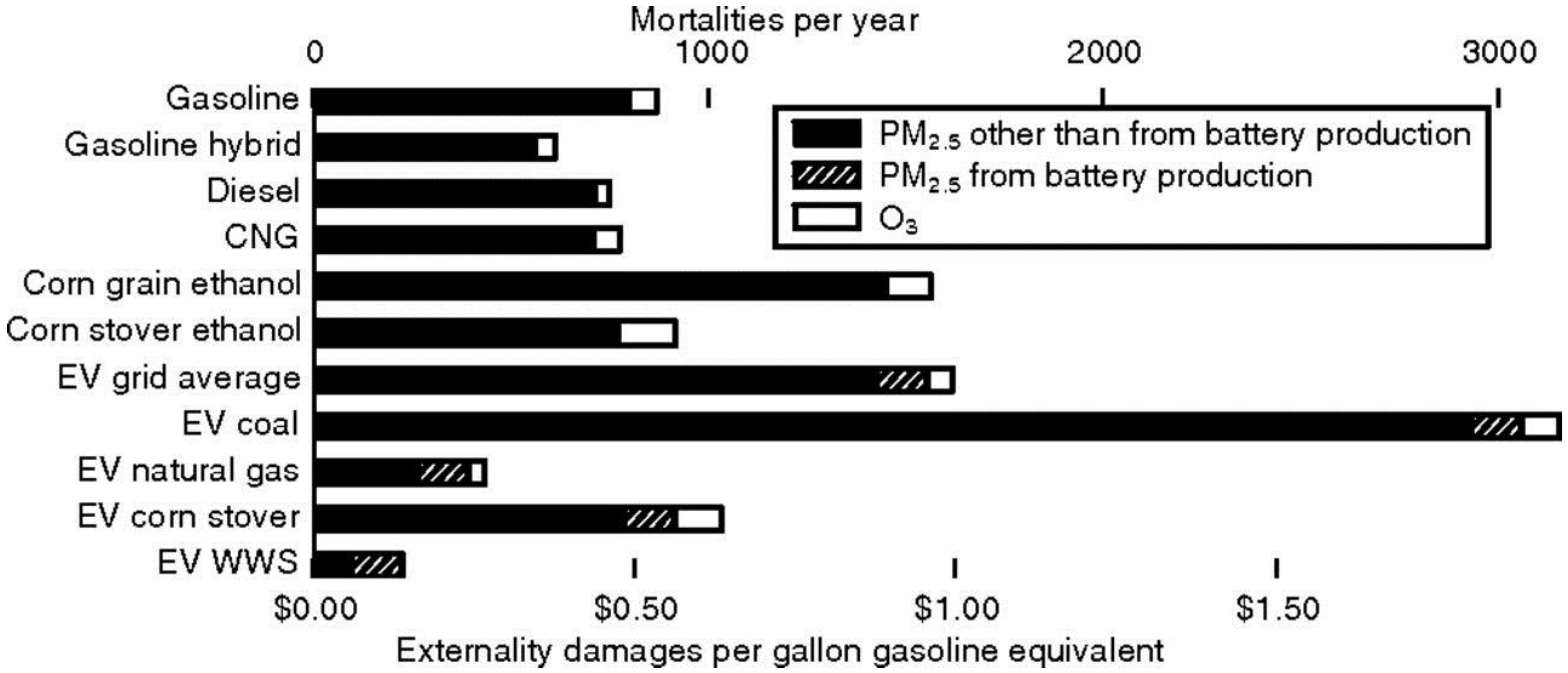
Transportation alternatives

Annual average $PM_{2.5}$ concentrations and their changes



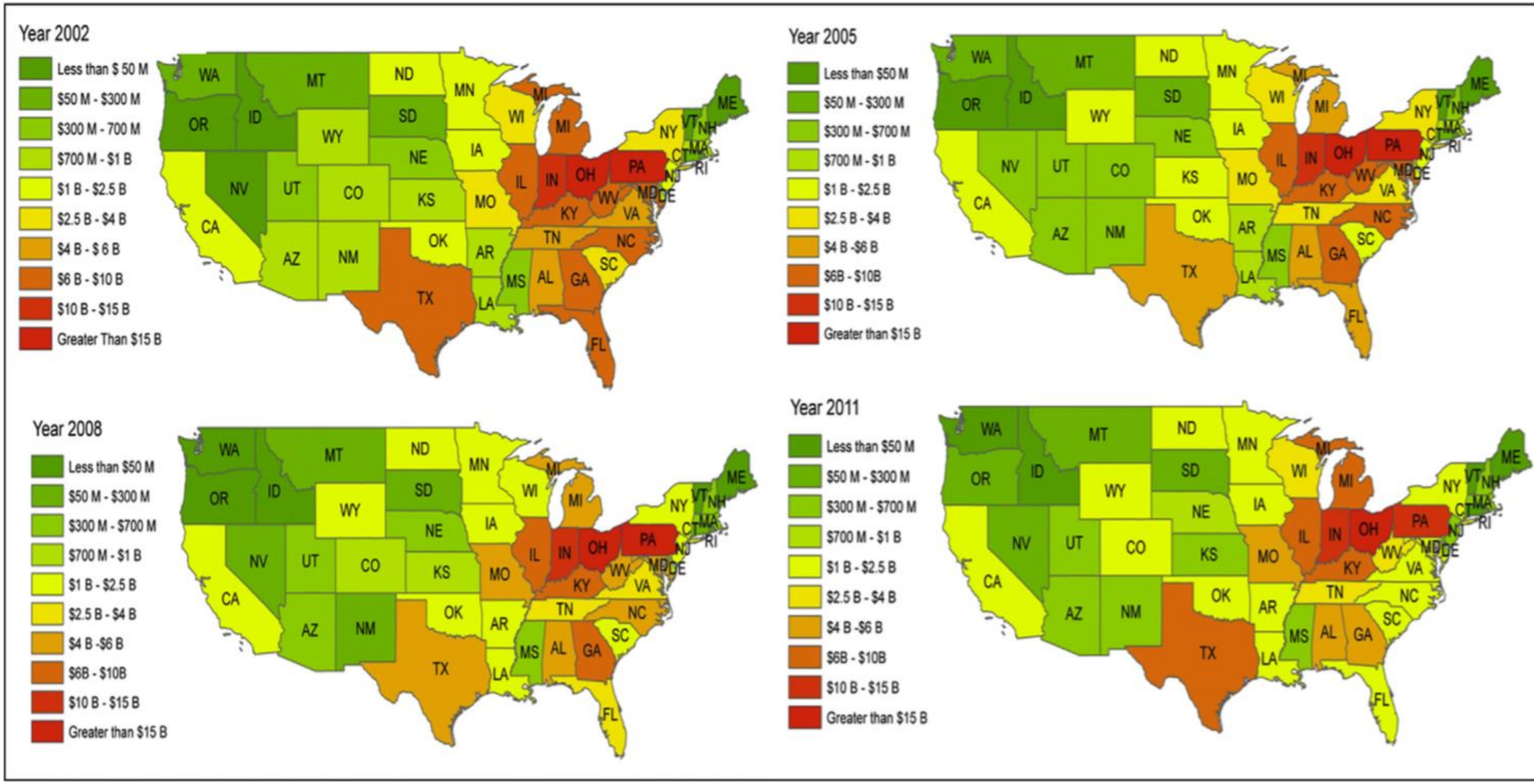
Tessum et al. PNAS 2014;111:18490-18495

Transportation alternatives



Tessum et al. PNAS 2014;111:18490-18495

Energy production: externalities



Jaramillo and Muller, Energy Policy 2016;90:202-211

Project 5. Health effects of air pollution

- Quantify relationship between mortality & ambient concentrations (NO2, CO, O3, PM2.5, PM2.5 components (sulfate, nitrate, ammonium, BC, OC) and sources),
- Quantify **benefits of lower ambient concentrations** of these pollutants on lowering death rates and increasing life expectancy of the entire U.S. population,
- Describe the **spatial and temporal variation in these relationships over the contiguous U.S.**

Mortality Data

1. Death rates from 1982 to 2011 for all counties in the U.S. from the U.S. National Center for Health Statistics (NCHS); and,
2. The 1986-2004 annual National Health Interview Surveys (NHIS), linked to mortality through 2011.

Exposure data

- Empirical models (satellite, EPA monitoring data, CTMs, land use)

Project 5 – Epidemiology

Characterise Spatial-Temporal Changes in Mortality Risk Associated with Changes in Complex Mixtures of Atmospheric Pollutants

Rick Burnett
Arden Pope
Mike Brauer
Majid Ezzati

Space-Time Resolved National Exposure Surfaces 1980-2011 NO2, CO, O3, PM2.5, sulfate, nitrate, ammonium, BC and OC and source contributions to PM2.5
Projects 1 & 3

National Health Interview Survey (1985-2009) Linked to Mortality (2011)

Transition from Subject to County Level Exposure & Risk Factor Adjustment

Age-sex county level mortality counts 1980-2011

Age-Sex Space-Time Resolved Multiple Pollutant Non-Linear Concentration-Mortality Functions

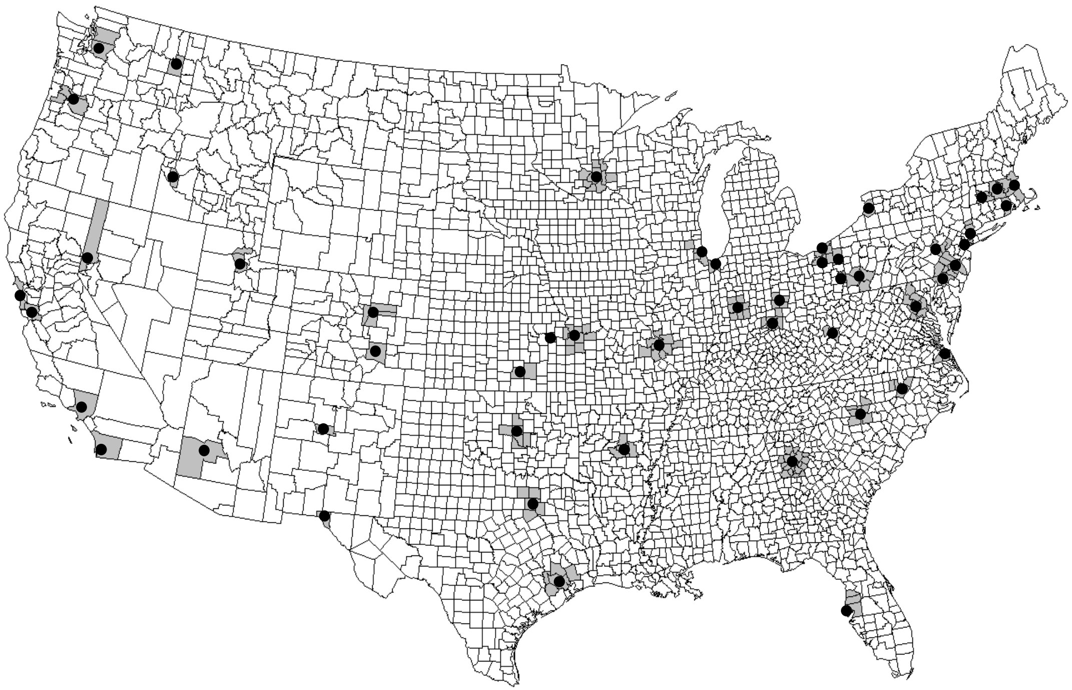
Quantify benefits of future changes in ambient concentrations due to specific mitigation strategies on future changes in death rates and life expectancy of the entire U.S. population and regions
Project 4

The NEW ENGLAND JOURNAL of MEDICINE

Fine-Particulate Air Pollution and Life Expectancy in the United States

C. Arden Pope, III, Ph.D., Majid Ezzati, Ph.D., and Douglas W. Dockery, Sc.D.

January 22, 2009



Matching $PM_{2.5}$ data:1979-1983, 1999-2000, 51 Metro Areas

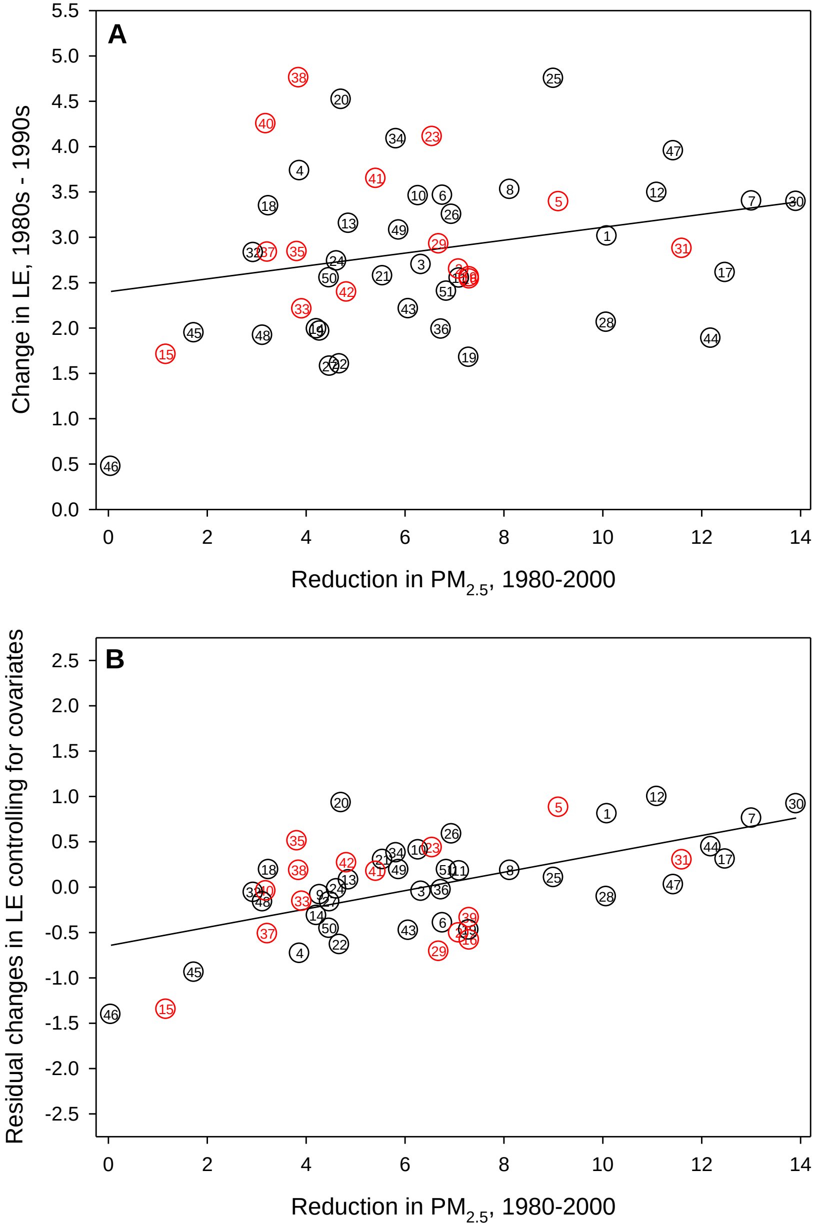
Life Expectancy data for 1978-1982, 1997-2001 in 211 counties in 51 Metro areas

Evaluate changes in life expectancy with changes in $PM_{2.5}$ for the 2-decade period of approximately 1980-2000.

CACES extends analysis to all US counties, w/ time-resolved exposures

No covariate control

County-level covariate control



CACES will

Extend data to all US counties & monthly 1980-2011 temporal exposure resolution

Extend analysis within Bayesian time-space framework

National Centre for Health Statistics "National Health Interview Survey Mortality Cohort" (NHIS)

- Annual population representative survey on lifestyle & health
- 1985-2009 panels linked to mortality up to 2011
- Mortality risk factor information – age, sex, race, education, marital status, income, BMI, smoking (sub-sample up to 1996, complete after)
- Restricted-use file contains geographic identifiers (i.e. census block)
- Analysis conducted at NCHS Research Data Centre
- Purpose of cohort
  - Compare risk estimates of CACES generated exposures based on standard cohort design to other cohort studies
  - Examine sensitivity of risk estimates using exposure and covariate control at subject level and county level averages to inform county-mortality study – exposure error & ecological bias !
- ***NHIS is largest (subjects/deaths) of all US cohorts!***

Preliminary results using public-use files

- Publicly available data for 1985-2001 panels linked to 2011 mortality, 2002-2009 panels not publically available – need to analyze at RDC
- MSA smallest geographic identifier – Census block available at RDC
- Linked census tract $PM_{2.5}$ estimates for 1998-2004 time period population averaged up to MSA using hybrid LU-space-time model (Berkerman et al., ES&T 2013)
- 1.2 million adult subjects linked to mortality file for 1986-2001 panels with 240,000 deaths
    - 0.4 million living in a MSA with 78,000 deaths
- Hazard ratio for $10\mu/m^3$ increase in $PM_{2.5}$ after risk factor adjustment including smoking: Results generally consistent with other US based cohort studies

Summary: CACES' Five Projects

Directors: Allen Robinson (CMU), Julian Marshall (UW)

1. Mechanistic models
2. Measurements
3. Empirical models
4. Policy scenarios
5. Epidemiology

Themes:

- Regional differences; multi-pollutant; "modifiable factors".
- Integrating air quality, climate, and energy policy.
- New and expanded set of tools.
- Democratization of tools.
- Environmental justice

Areas for collaboration?

1. Setting scenarios (e.g., “low-coal”, “high-coal”, region-specific policies,…)
2. Reduced-form models
3. Empirical model estimates
4. Common metrics: EJ, VSL
5. Approaches for increasing “policy relevant”
6. …other?

Center for Air, Climate and Clean Energy Solutions (CACES)

Allen L Robinson
Carnegie Mellon University

Julian D Marshall
University of Washington

Thank you!

Carnegie Mellon University
W UNIVERSITY of WASHINGTON
THE UNIVERSITY OF TEXAS AT AUSTIN
Middlebury College
BYU
Imperial College London
Health Canada
VirginiaTech
UNIVERSITY OF MINNESOTA
THE UNIVERSITY OF BRITISH COLUMBIA