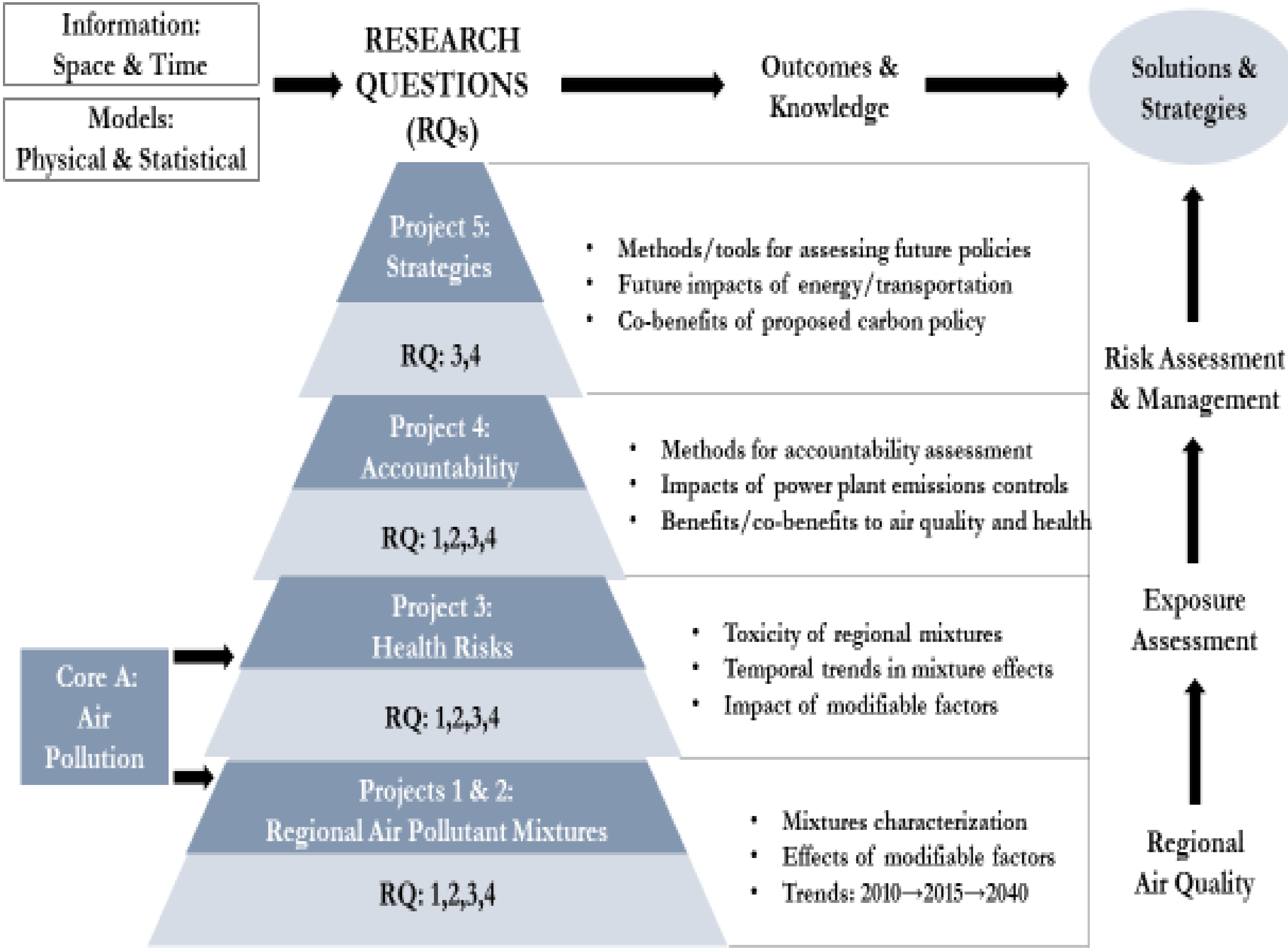
Center Title:

Regional Air Pollution Mixtures:
The past and future impacts of emissions controls and climate change on air quality and health

Institutions:
Harvard University
Massachusetts Institute of Technology

Name	Institution	Role	Background	Contribution
*Petros Koutrakis, Ph.D.	HSPH	PI Project 1	Env. Chemistry	Exposure assessment
**Brent Coull, Ph.D.	HSPH	PI Project 2	Biostatistics	Spatiotemporal models
Joel Schwartz, Ph.D.	HSPH	PI Project 3	Env. Epidemiology	Air pollution health effects
Francesca Dominici, Ph.D.	HSPH	PI Project 4	Biostatistics	Accountability assessment
Noelle E. Selin, Ph.D.	MIT	PI Project 5	Atm. Chemistry	Integrated assessment modeling
Loretta Mickley, Ph.D.	HSEAS	Co-PI, Project 1	Atm. Chem&Climate	Atm. chemistry modelling
Daniel Jacob, Ph.D.	HSEAS	Co-PI, Project 1	Atm. Chemistry	Atm. chemistry modelling
Antonella Zanobetti, Ph.D.	HSPH	Co-PI, Project 3	Biostatistics	Health effects analysis
Corwin Zigler, Ph.D.	HSPH	Co-PI, Project 4	Biostatistics	Policy assessment
Steven Barrett, Ph.D.	MIT	Co-PI, Project 5	Atm. Chemistry	Adjoint transport modelling
Susan Solomon, Ph.D.	MIT	Co-PI, Project 5	Atm. Chemistry	Climate and chemistry
John Reilly, Ph.D.	MIT	Co-PI, Project 5	Economics	Economic modelling
Kenneth Demerjian, Ph.D.	Retired	Consultant	Physical Chemistry	Source emissions
Joy Lawrence, Sc.D.	HSPH	Co-Investigator	Env. Health	Exposure assessment
Mike Wolfson, Ph.D.	HSPH	Co-Investigator	Chemistry	Air quality measurements
Christine Choirat, Ph.D.	HSPH	Co-Investigator	Computer Science	Data management
Choong-Min Kang, Ph.D.	HSPH	Co-Investigator	Chemistry	Air quality monitoring
Carey Friedman Ph.D.	MIT	Key Personnel	Env. Chemistry	Toxic air pollutants
Erwan Monier Ph.D.	MIT	Key Personnel	Climate Science	Climate change impacts

Center Framework



Project 1:

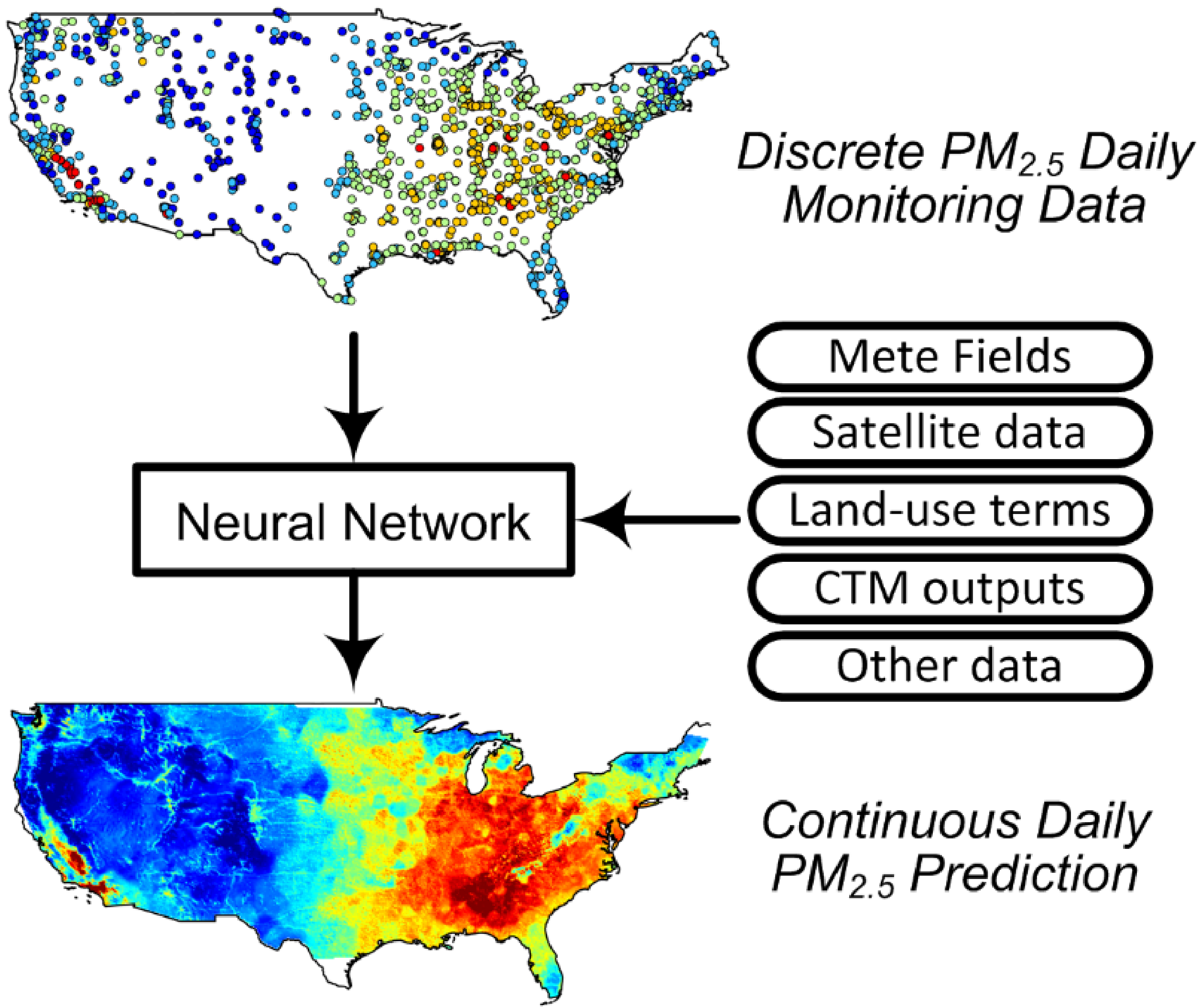
Regional Air Pollution:
Mixtures Characterization, Emission Inventories, Pollutant Trends, and Climate Impacts

Petros Koutrakis (lead PI);
Brent Coull; Daniel J. Jacob;
Loretta J. Mickley; and Joel Schwartz

Objective 1

- Compile comprehensive air pollution, weather, emissions, and GIS datasets for the entire continental US for the period 2000-2015.
  - Estimate gas and PM concentrations at a high spatial resolution by assimilating data from monitoring networks, satellite platforms, air pollution models, and spatiotemporal statistical models

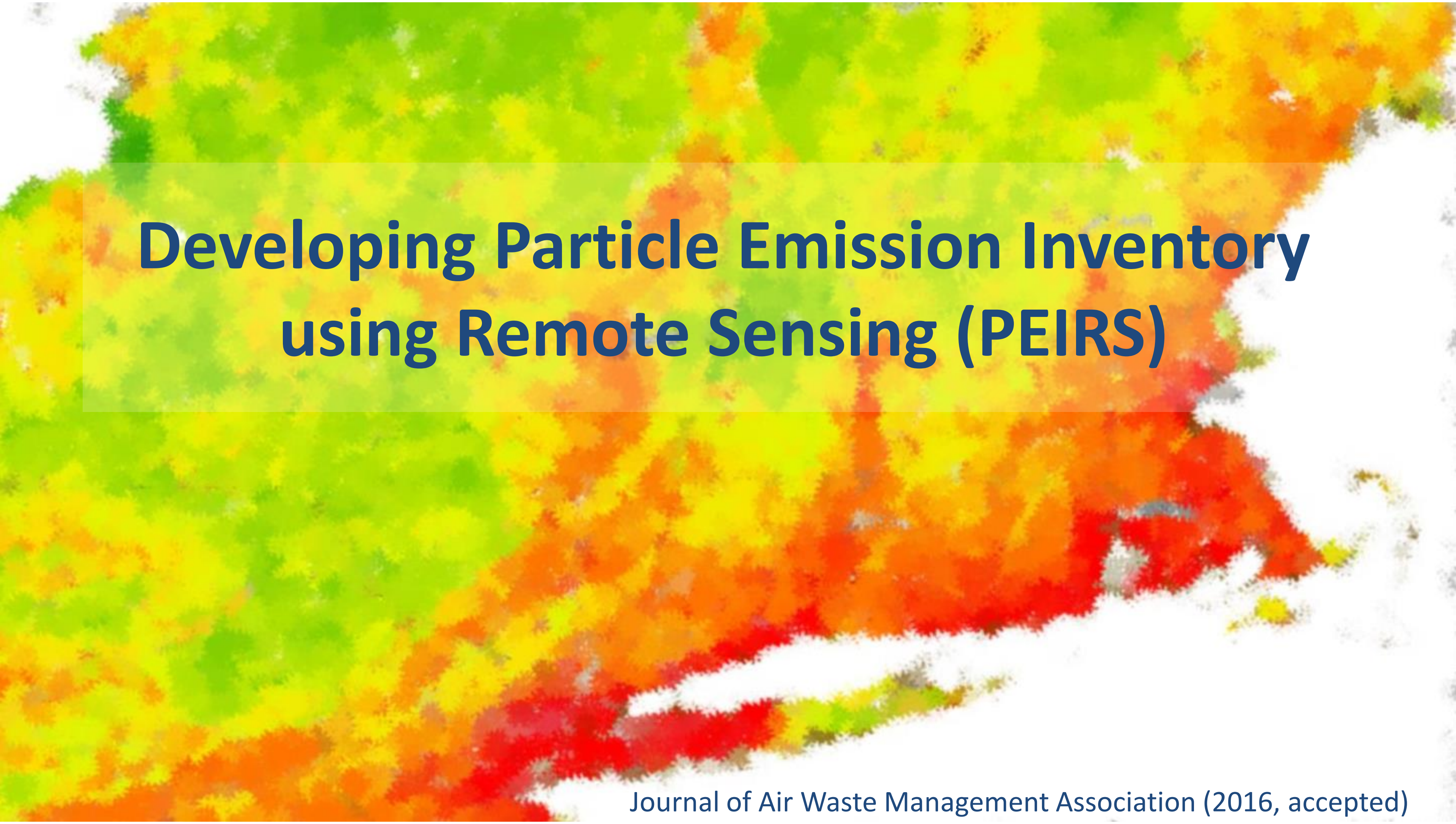
Model $PM_{2.5}$ mass and species
O_3 and Temperature



Objective 2

- Develop and make publically available a national $PM_{2.5}$ emission inventory database of high spatial resolution (1 km) for 2000-2015
  - This will be achieved through the application of a novel methodology we developed that predicts point and area source emissions using AOD measured by satellite remote sensors;

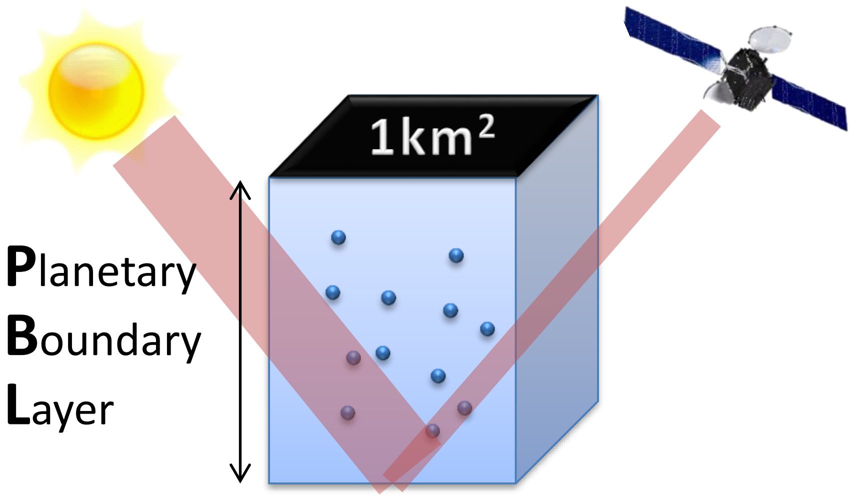
Developing Particle Emission Inventory using Remote Sensing (PEIRS)



Journal of Air Waste Management Association (2016, accepted)

AOD-$PM_{2.5}$ relationship

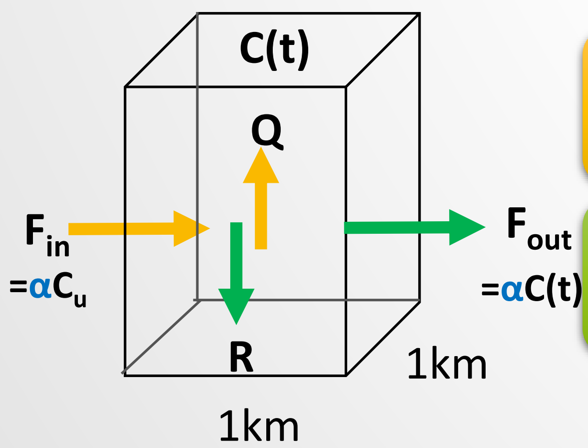
$$C_{PM2.5} \propto \frac{AOD}{PBL}$$



EMISSION MODEL

Mass Balance

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



$C(t)$: $PM_{2.5}$ Concentration inside box
C_u: $PM_{2.5}$ Concentration upwind

Source

- **F_{in}**: Inflow $PM_{2.5}$ transported from upwind
- **Q**: Local emission **(Primary + Secondary $PM_{2.5}$)**

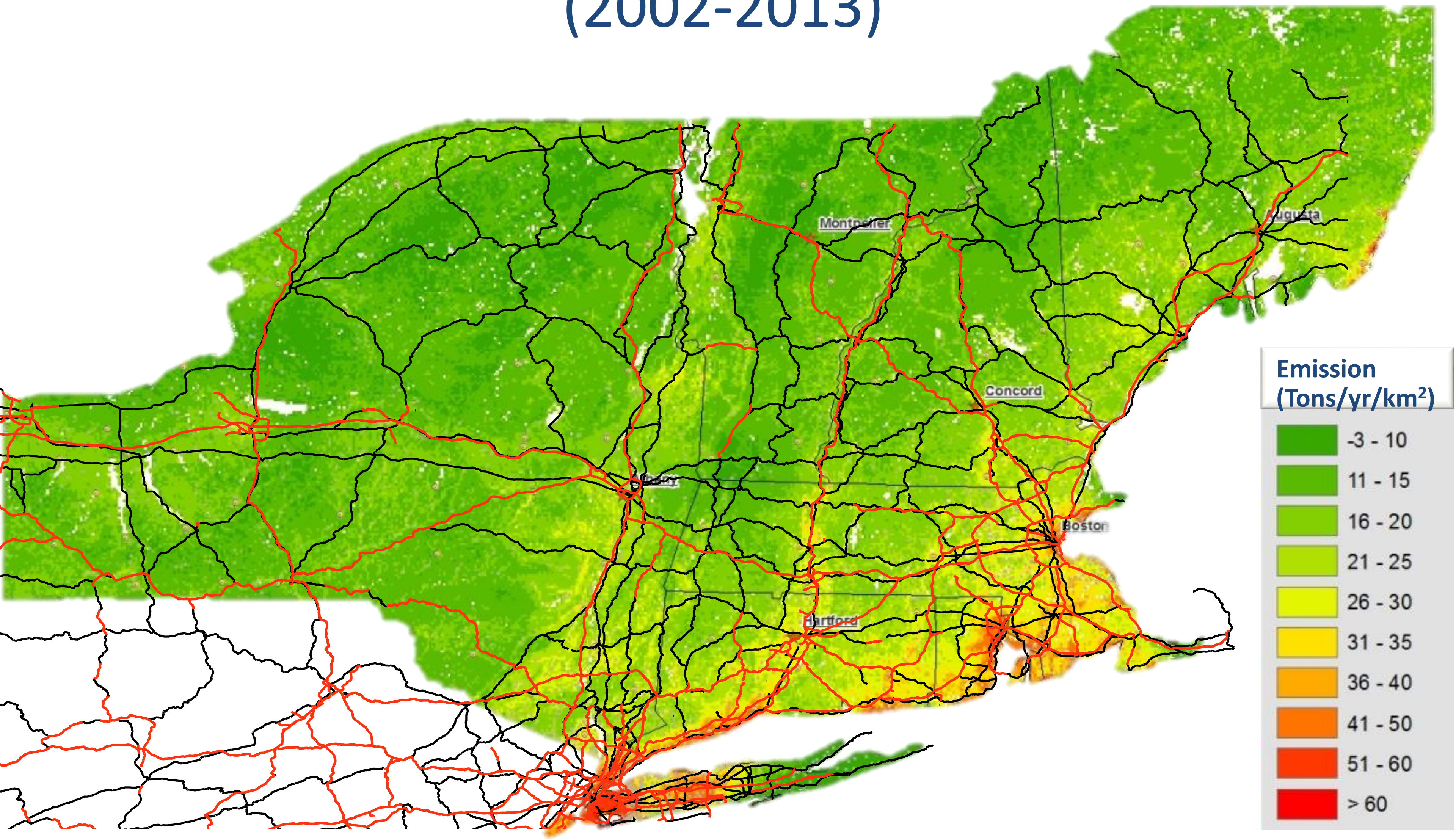
Sinks

- **F_{out}**: Outflow $PM_{2.5}$ to downwind
- **R**: Removal by deposition

α: Air exchange rate (Wind speed/Length)

α >> deposition rate

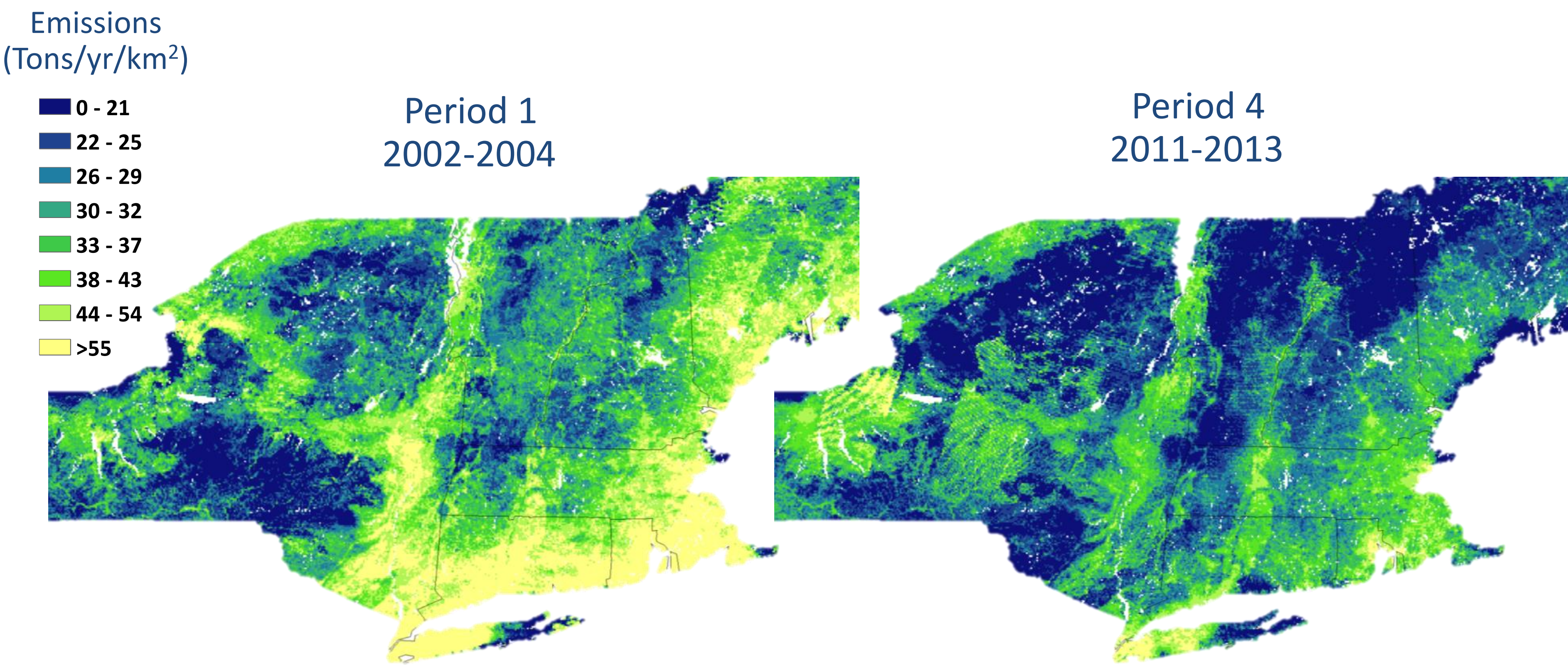
PEIRS 12 Year Averaged $PM_{2.5}$ Emission Estimates (2002-2013)



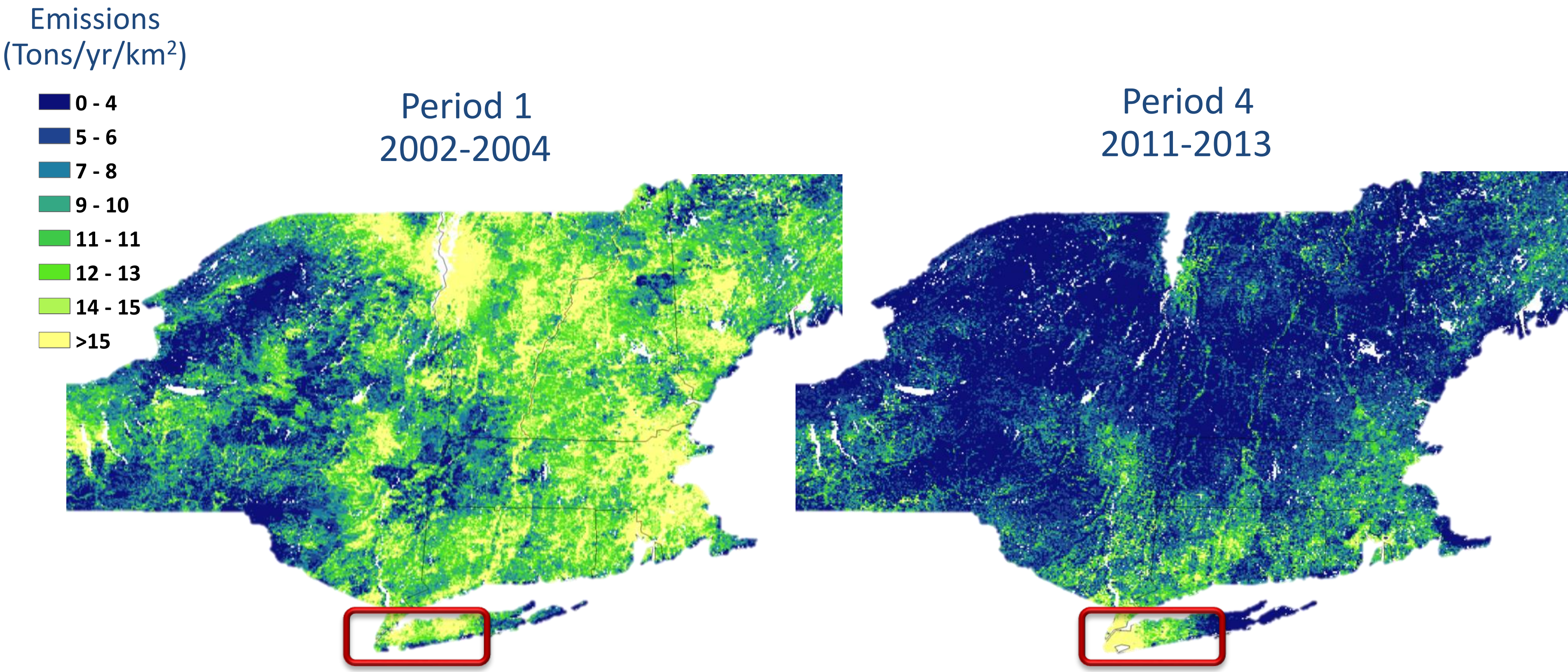
Objective 3

- Characterize spatial and temporal trends of pollutant mixtures.
  - Perform cluster analysis to group areas that exhibit distinct pollutant profiles or mixtures, referred to as "Air Pollution Regions,"
  - Analyze their spatial patterns and temporal trends to investigate the impact of regulations, climate change, and modifiable factors on regional mixtures; and

Spatial trends **Cold season**

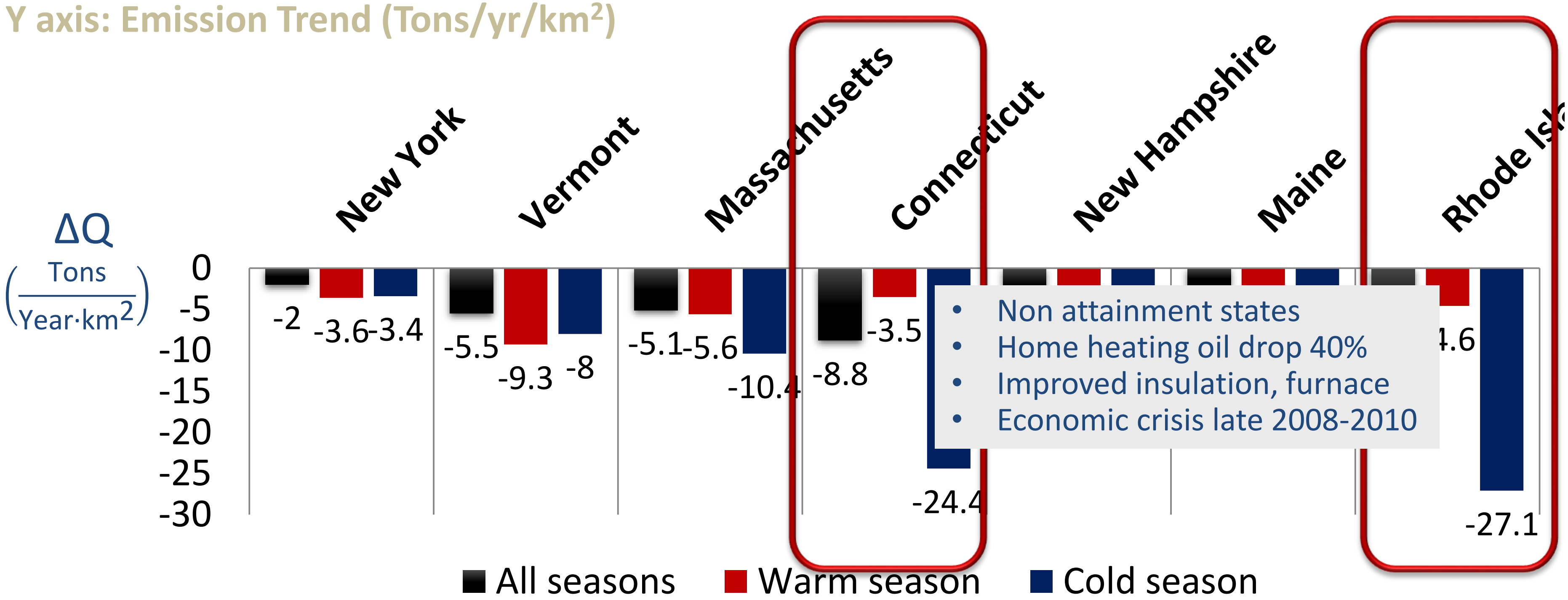


Spatial trends **warm season**



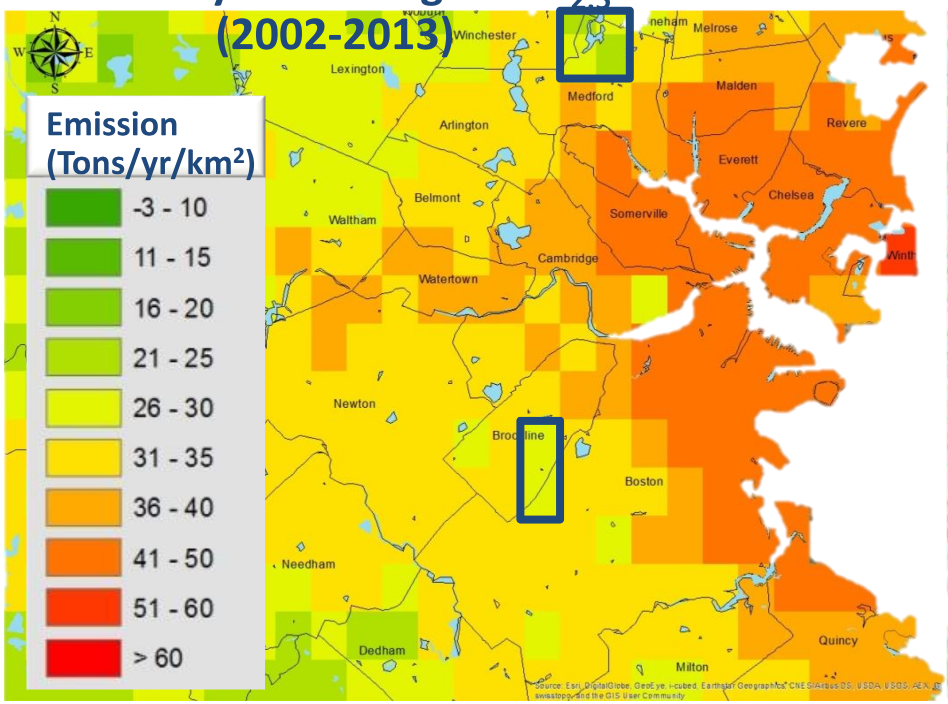
State avg. trend (2002 – 2013)

Y axis: Emission Trend (Tons/yr/km²)

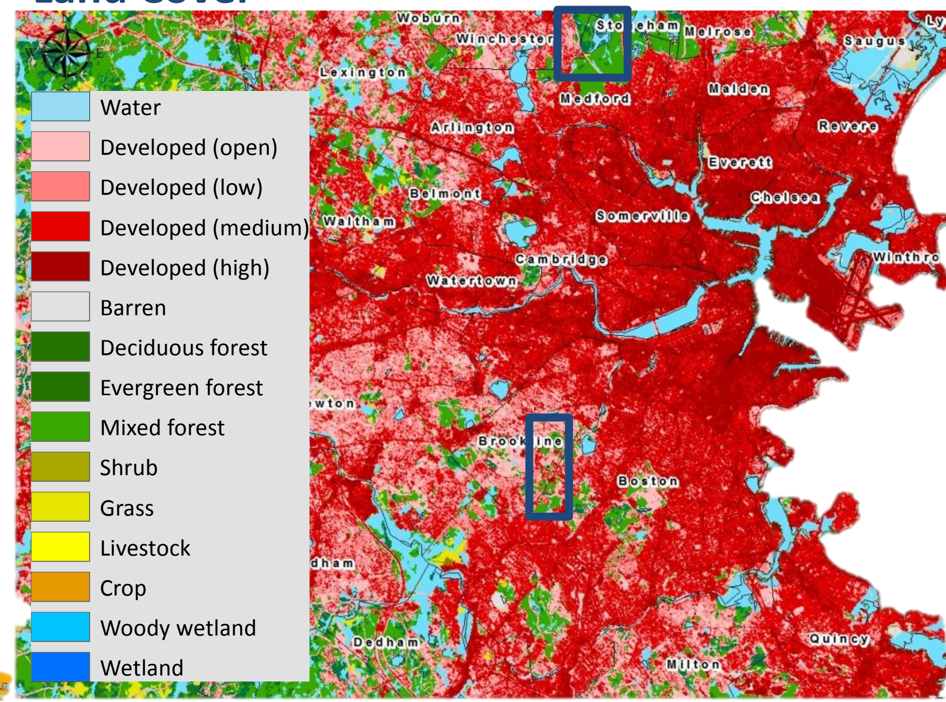


Intra-urban variability

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



Land Cover

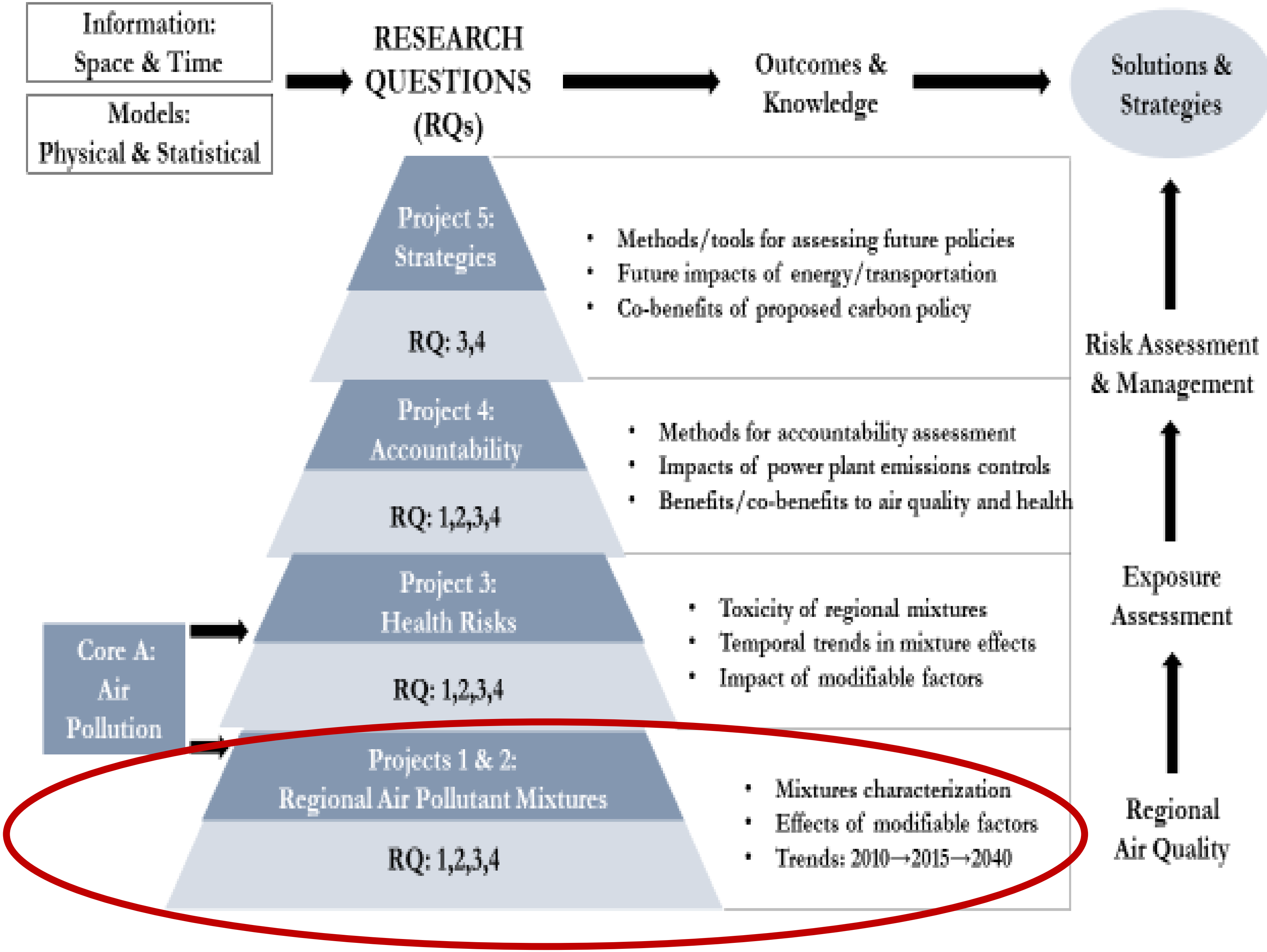


Objective 4

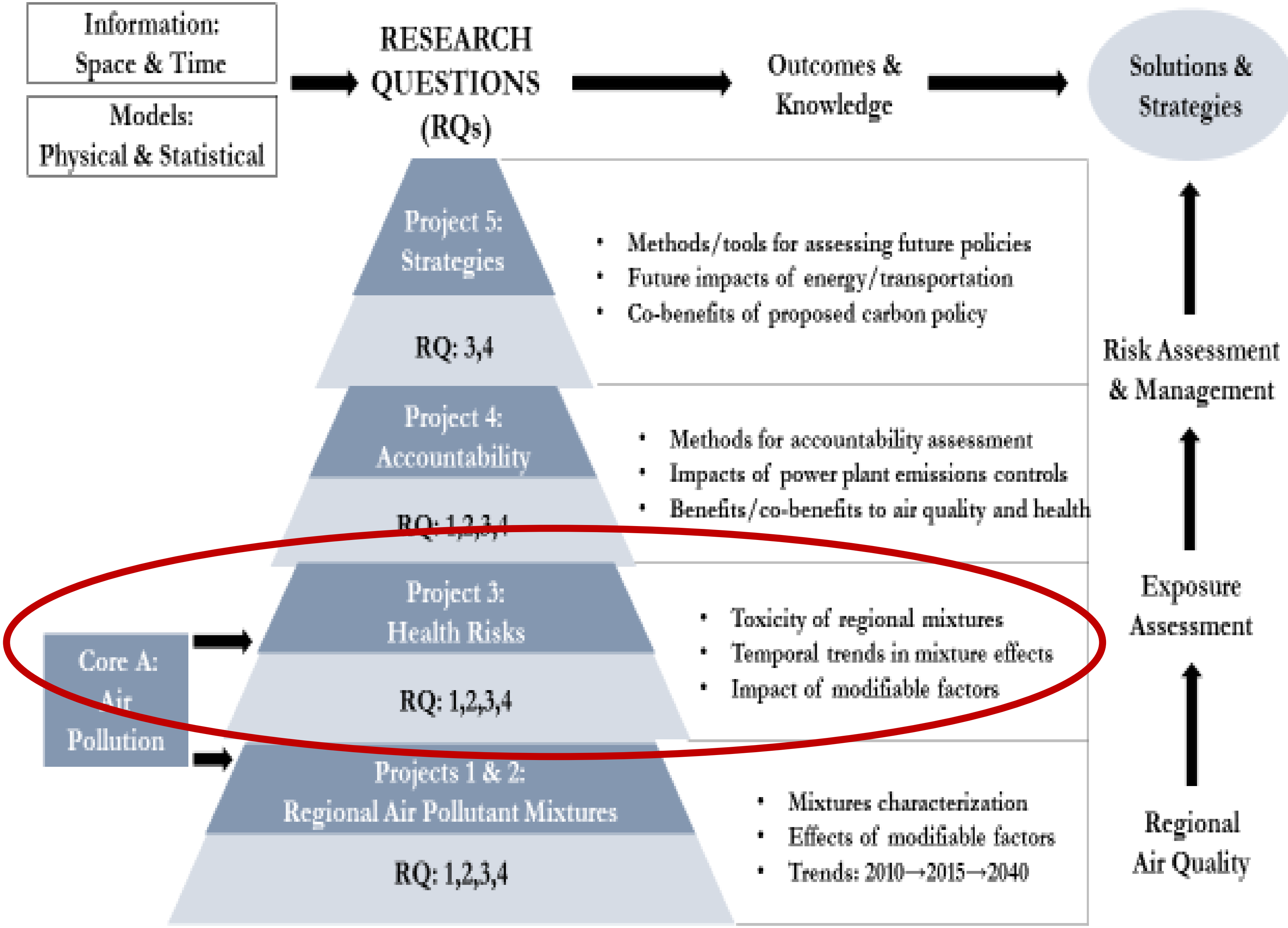
- Forecast the impact of regional climate change on air quality for 2016-2040 using an ensemble of climate models
  - Project the potential impact of climate change on regional pollutant mixtures and predict future regional air quality assuming no changes in anthropogenic emissions.

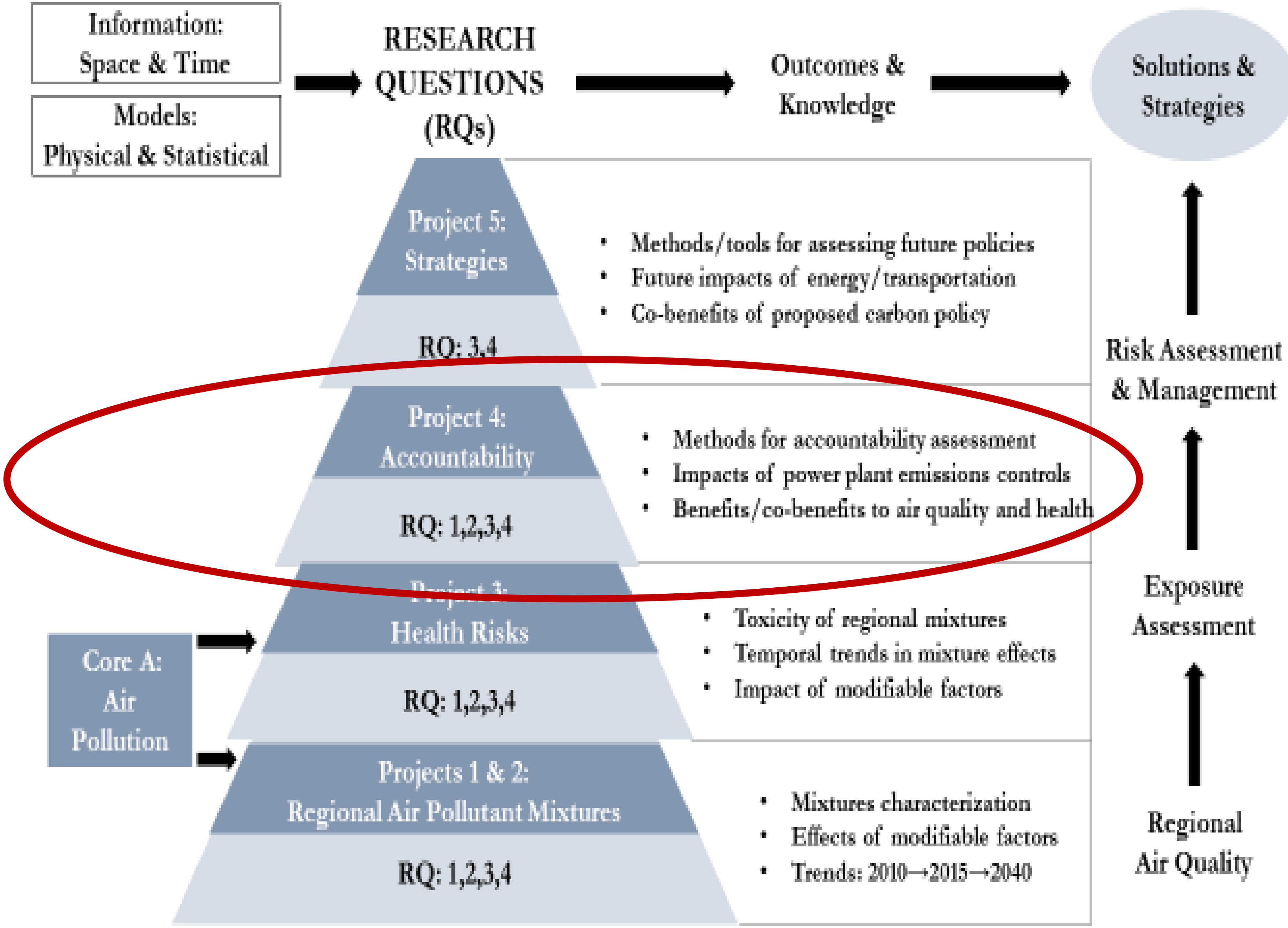
Thanks

Center Framework



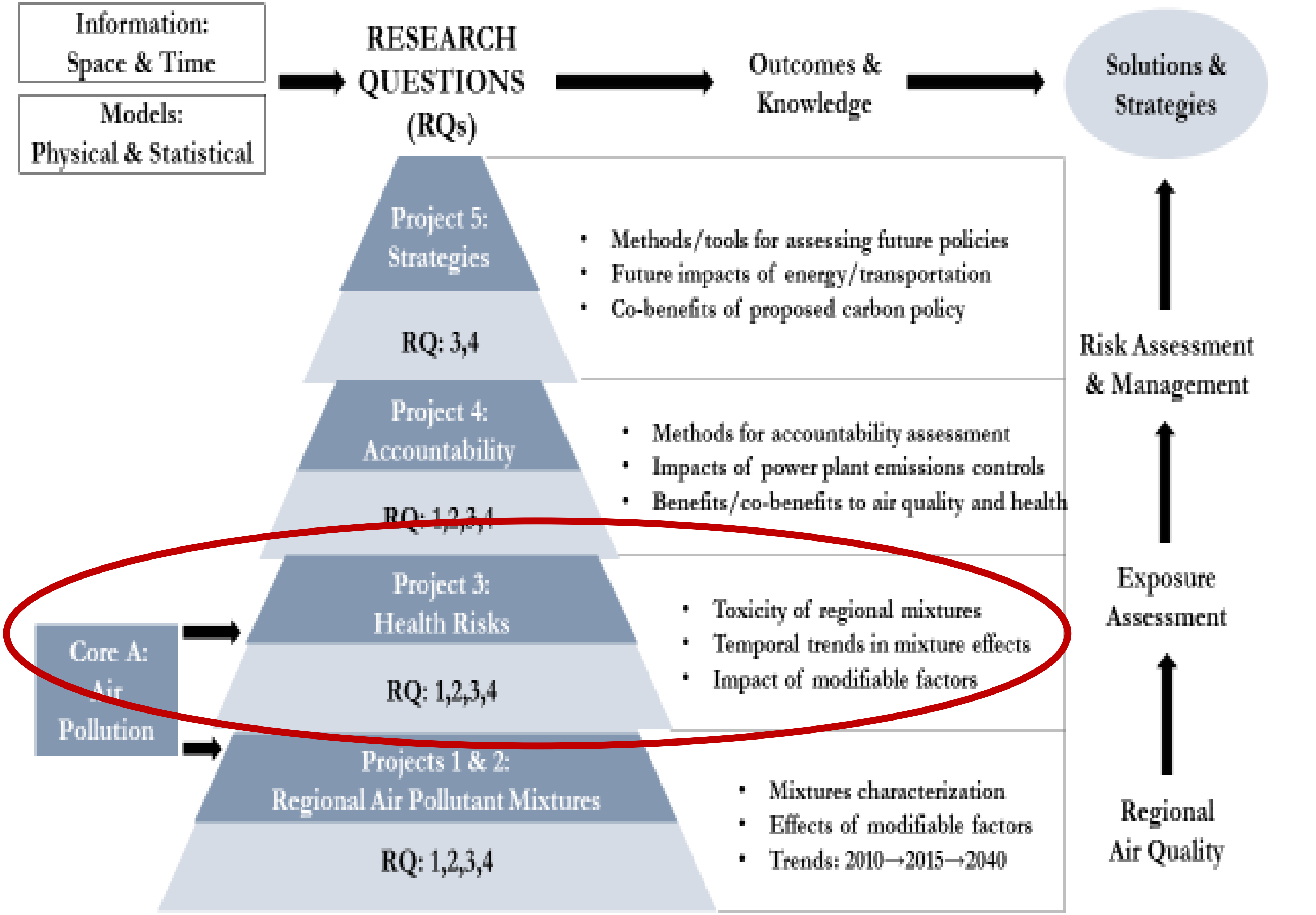
Center Framework

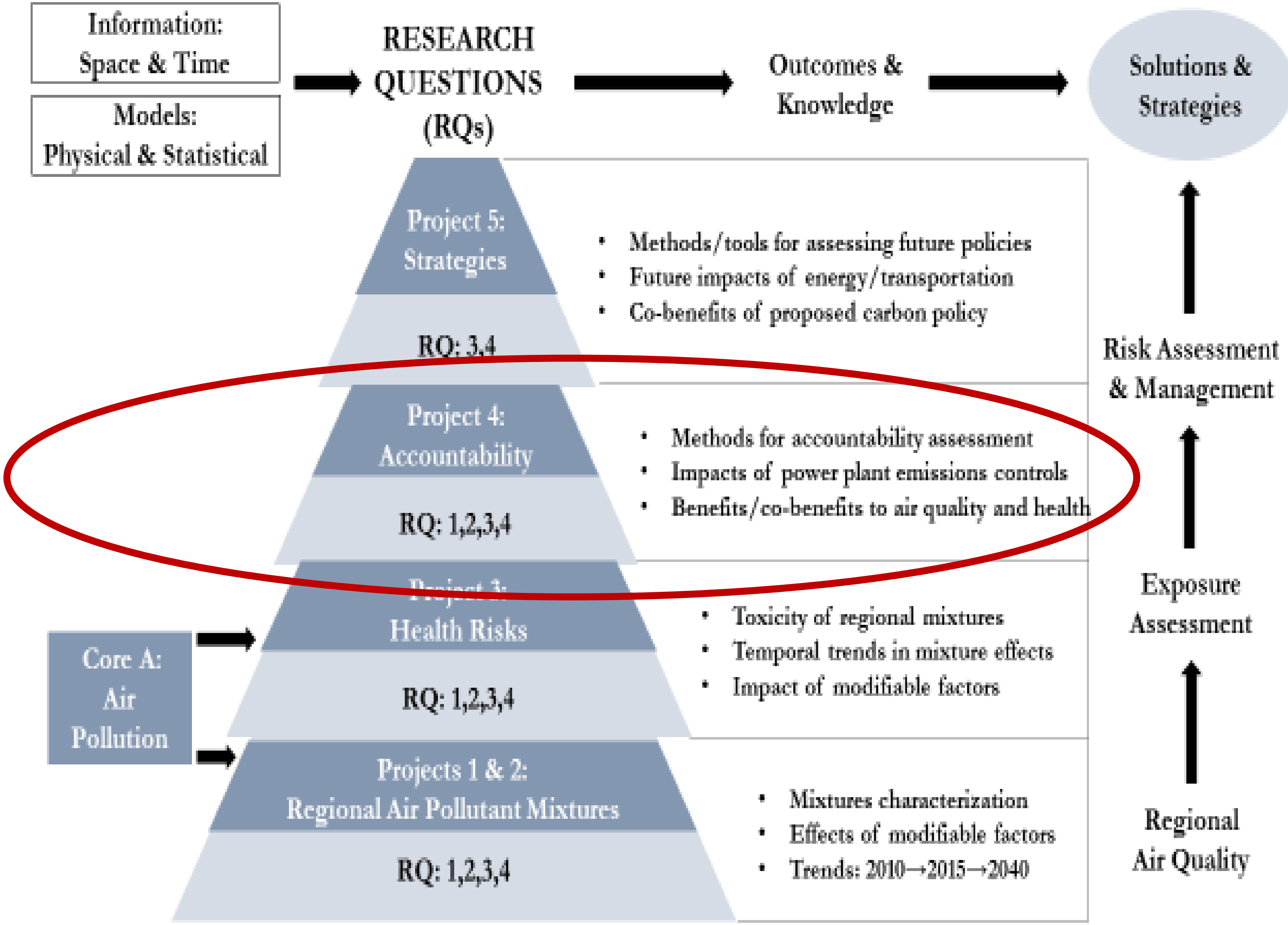




Information: Space & Time
Models: Physical & Statistical
RESEARCH QUESTIONS (RQs)
Outcomes & Knowledge
Solutions & Strategies
Project 5: Strategies
RQ: 3,4
Methods/tools for assessing future policies
Future impacts of energy/transportation
Co-benefits of proposed carbon policy
Project 4: Accountability
RQ: 1,2,3,4
Methods for accountability assessment
Impacts of power plant emissions controls
Benefits/co-benefits to air quality and health
Project 3: Health Risks
RQ: 1,2,3,4
Toxicity of regional mixtures
Temporal trends in mixture effects
Impact of modifiable factors
Core A: Air Pollution
Projects 1 & 2: Regional Air Pollutant Mixtures
RQ: 1,2,3,4
Mixtures characterization
Effects of modifiable factors
Trends: 2010→2015→2040
Risk Assessment & Management
Exposure Assessment
Regional Air Quality

Center Framework

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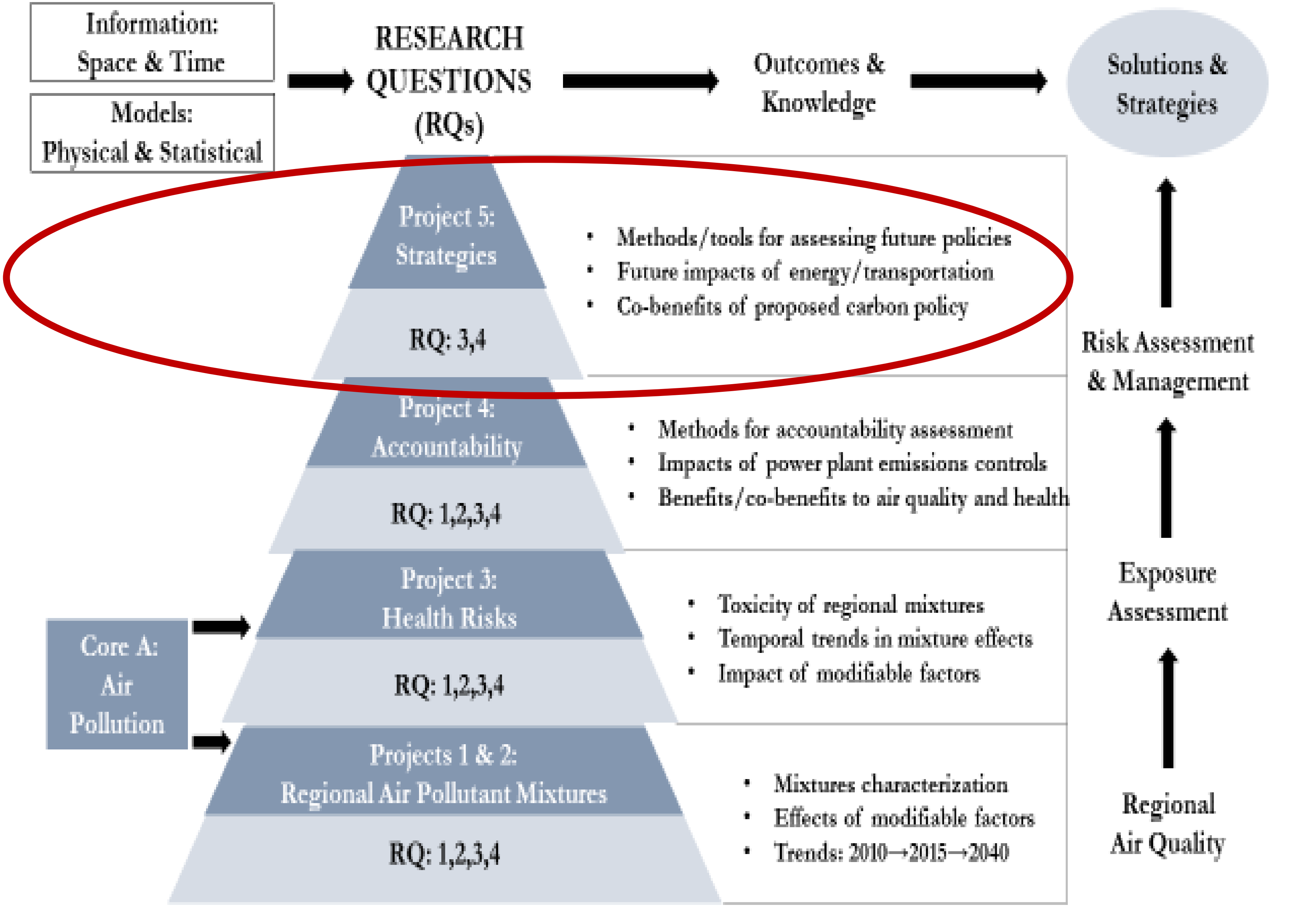
Center Framework



Project 1

Petros Koutrakis (lead PI); Brent Coull; Daniel J. Jacob; Loretta J. Mickley; and Joel Schwartz

- Investigate pollutant mixtures across the US using historic (2000-2015) and projected (2016-2040) data
  - Compile data from networks, satellites, and the GEOS-Chem model
- Examine the impacts of modifiable factors, and changes in emissions and climate on mixtures by region

Project 2

Brent Coull (lead PI); Petros Koutrakis; Joel Schwartz

- Investigate pollutant mixtures in Massachusetts
- Use spatiotemporal models to
  - Identify modifiable factors related to transportation, energy, urbanization etc.
  - Evaluate several community control programs

Project 3

Joel Schwartz (lead PI); Brent Coull; Petros Koutrakis; Antonella Zanobetti

- Use unique datasets and novel causal inference methods to examine the causal impact of pollution and climate change on acute and chronic mortality:
  - **by region**
  - **by mixture and**
  - **by modifiable factors**

Project 4

Corwin Zigler (lead PI); Corwin Zigler;
Francesca Dominici Joel Schwartz;
Loretta J. Mickley; Steve Barrett

- Analyze data on emissions control technologies for 4,164 US power plants units for the 1995-2012
- Investigate the **causal impacts of specific control strategies** on emissions and population exposure and health

Project 5

Noelle E. Selin (lead PI); Steven Barrett; Susan Solomon; and John Reilly

- Project/Quantify future changes in socioeconomic drivers of air pollution and related health impacts
- Quantify the implications of technology improvements
  - **Energy and transportation sectors**
- Characterize **Carbon** policies
  - **Health co-benefits**

Harvard ACE Center Project 2:

Air Pollutant Mixtures in Eastern Massachusetts: Spatial Multi-resolution Analysis of Trends, Effects of Modifiable Factors, Climate, and Particle-induced Mortality

Brent Coull (PI), Petros Koutrakis, Joel Schwartz
Harvard T. H. Chan School of Public Heath

Objectives

1) Decompose high-resolution $PM_{2.5}$ mass and ground air temperature data into regional, sub-regional, and local spatial scales.
2) Conduct a spatiotemporal analysis of sub-regional and local variation in $PM_{2.5}$ mass and ground air temperature, and local $PM_{2.5}$ emissions.
   a) quantify the impact of modifiable factors
   b) identify locations of greatest impact
   c) identify lag times between implementation of a given control strategy and decreases in $PM_{2.5}$ mass and emissions

Objectives (continued)

3) Conduct spatial multi–resolution analysis of $PM_{2.5}$ mixtures.
   a) identify $PM_{2.5}$ elemental profiles that vary at regional, sub–regional, and local scales in Eastern Massachusetts
   b) identify modifiable factors driving urban background and local variability in $PM_{2.5}$ composition
4) Conduct an air pollution mortality study in Eastern Massachusetts using multi–resolution $PM_{2.5}$ mass and species data.

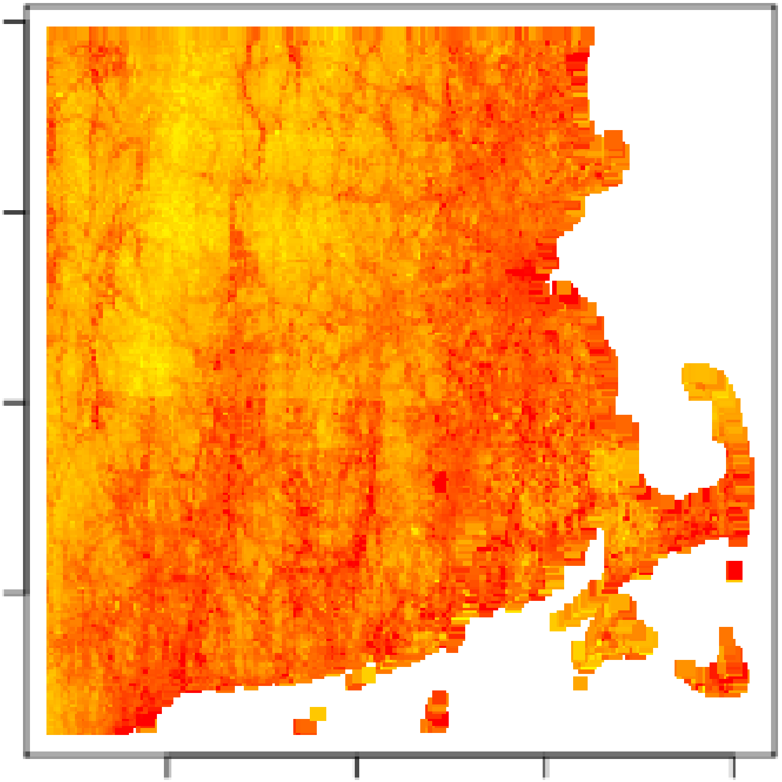
Exposure Data Sources (2000–2016)

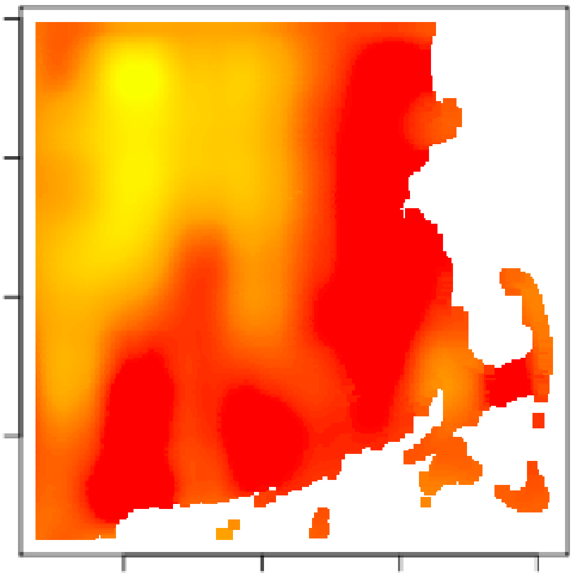
1) Ambient monitoring networks (AQS, Improve)
2) HCSPH Boston Supersite
3) Indoor $PM_{2.5}$ Samples
4) HEI–Funded Near Roadway Study
5) Satellite Remote Sensing Data on $PM_{2.5}$ Mass
6) Particle Emission Inventories
7) Ground Air Temperature Predictions
8) $PM_{2.5}$ Species

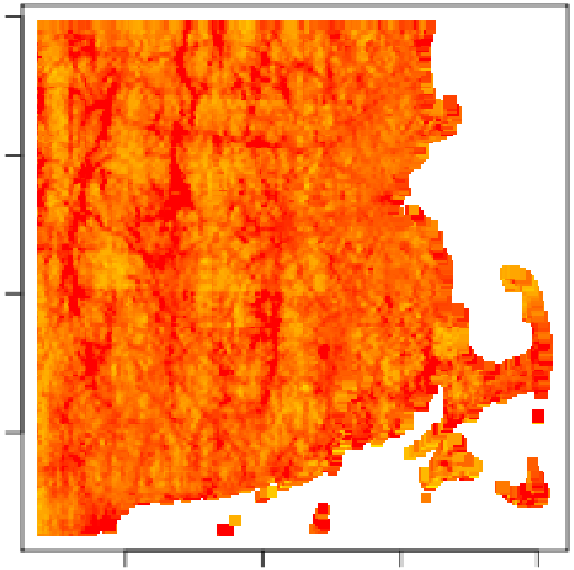
Data Sources on Modifiable Factors

1) U.S Energy Information Administration (EIA)
2) National Transit Database
3) American Community Survey (ACS)
4) National Emissions Inventory
5) US Census Bureau
6) Climate
7) PEIRS $PM_{2.5}$ emission estimates
8) Pollution Control Programs

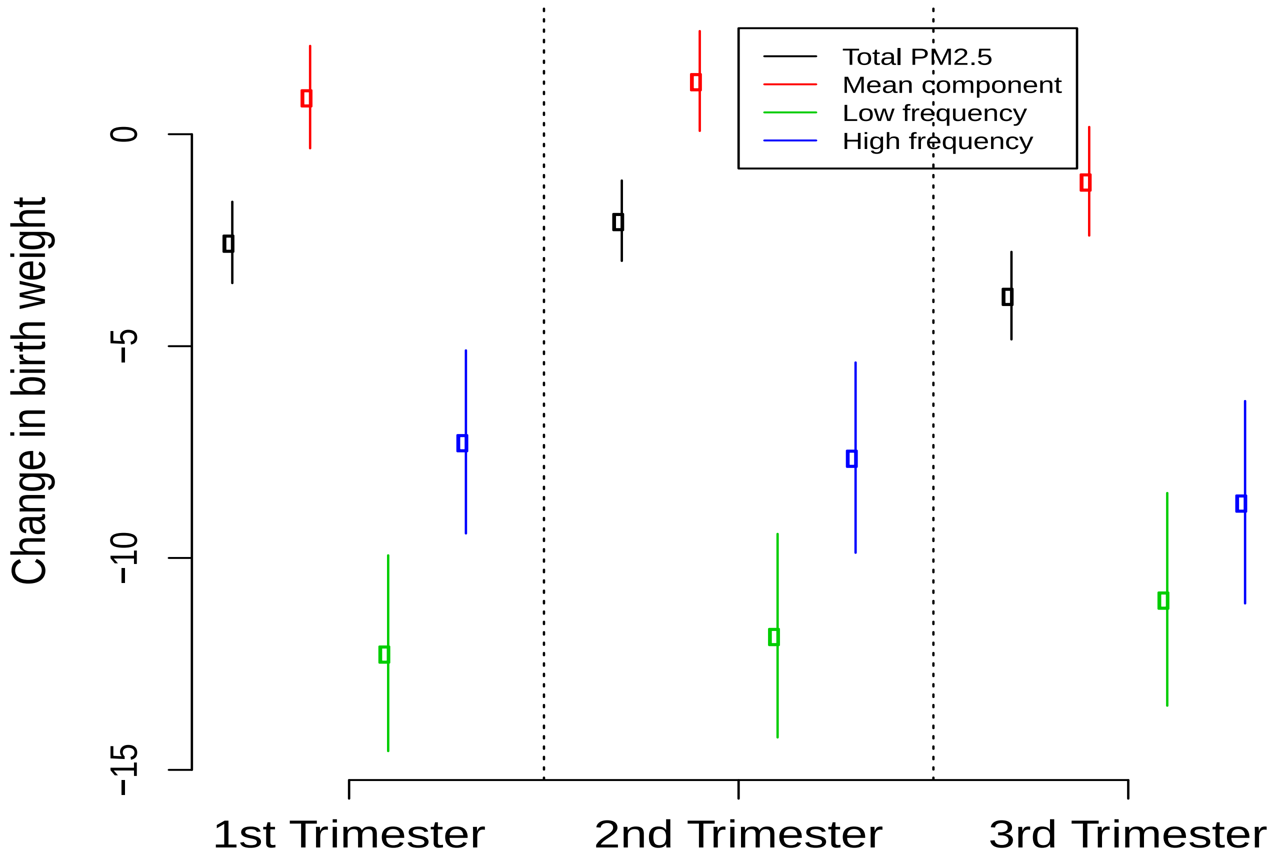
Multi-resolution Spatial Analysis: Pollution Source Impacts







Scale-specific associations with birthweight, MA 2003-2008



Harvard ACE Project 3:

Causal Estimates of Effects of Regional and National Pollution Mixtures on Health: Providing Tools for Policy Makers

Joel Schwartz (PI), Brent Coull, Petros Koutrakis
Harvard T. H. Chan School of Public Heath

Objectives

1) Identify and estimate the causal effects of annual air pollution and mixtures on human health
2) Analyze relative acute toxicity of pollution mixtures
3) Estimate the excess deaths resulting from air pollutant concentration changes due to weather changes in the last 20 years
4) Estimate the causal health effects of low-level air pollution exposure
5) Investigate air pollution-related health effects at high and low temperatures

Causal Effects of Annual Exposures on Mortality

1) Regional and national annual air pollution concentration and temperature *fluctuations* during the last 16 years
2) Regional and national air pollution *trends* during the last 16 years
3) Pollution mixtures, sources, and emissions
4) Differences in these effects by *modifiable factors*
5) National risk assessment on the *causal impact* of past pollution on mortality
6) Investigate the causal impact of AQI thresholds for $PM_{2.5}$ and O_3 due to behavioral adaptation

CT Mortality, $PM_{2.5}$, and temperature in New Jersey, 2004–2009

- 1938 Census Tracts in New Jersey
- 365,000 deaths from 2004–2009
- Mean 31.4 deaths per census tract and year
- 1x1km satellite-based daily estimates of
  - Temperature
  - $PM_{2.5}$
- Causal inference: Difference-in-differences approach

Wang et al. Estimating causal effects of long-term $PM_{2.5}$ exposure on mortality in New Jersey. Environmental Health Perspectives 2016; 124(8): 1182–8.

CT Mortality, $PM_{2.5}$, and temperature in New Jersey, 2004–2009

- Estimated 3.0% (0.2%, 5.9%) increase in mortality per 2 μg/m^3 increase in $PM_{2.5}$

Table 3. Percent change (95% confidence interval) in mortality per interquartile range increase (2 μg/m^3) increase in $PM_{2.5}$ at given summer and winter temperatures.

Mean summer temperature (°C)	Mean winter temperature (°C)	Percent change (95% CI) in mortality per IQR increase in $PM_{2.5}$
18.6[a] (Average)	5.9[b] (Average)	1.8% (–1.6, 5.2%)
17.6 (Average – 1)	5.9 (Average)	–1.6% (–4.2, 1.1%)
19.6 (Average + 1)	5.9 (Average)	1.6% (–0.6, 3.8%)
18.6 (Average)	4.9 (Average – 1)	1.6% (–0.6, 3.9%)
18.6 (Average)	6.9 (Average + 1)	5.3% (2.9, 7.8%)

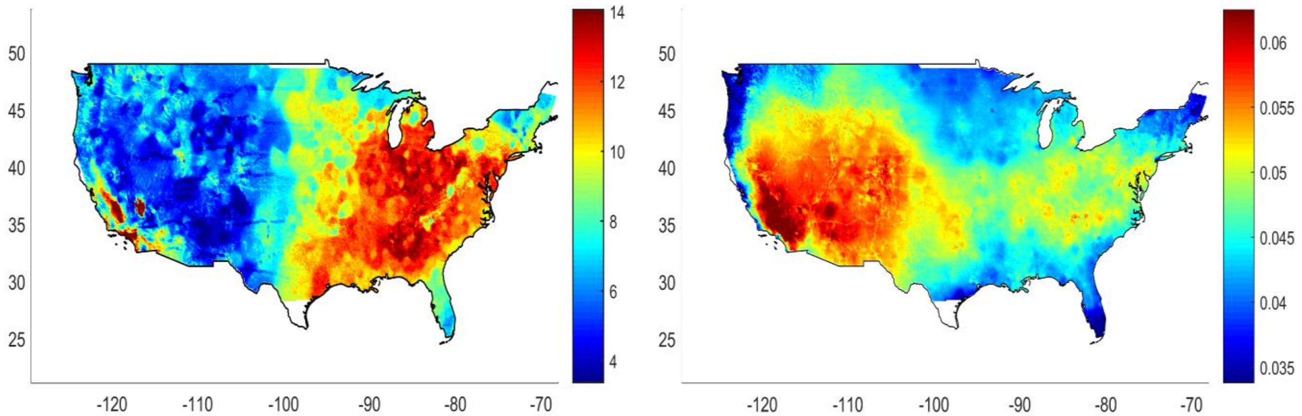
Abbreviations: CI, confidence interval; IQR, interquartile range
[a]Average of the census tract–specific mean summer temperature across 1,938 census tracts during 2004–2009.
[b]Average of the census tract–specific mean winter temperature across 1,938 census tracts during 2004–2009.

National Cohort Study of Effects of $PM_{2.5}$ and Ozone at Low Concentrations on Mortality

- All Medicare beneficiaries (n=67,682,479) in the continental United States from 2000 to 2012;
- Outcome: all-cause mortality
- Individual level Covariates: date of death (if died by December 31, 2012), age of entry, year of entry, sex, race, whether eligible for Medicaid (proxy for SES), and ZIP code of residence

National Exposure Assessment

- A neural network to incorporate satellite-based measurements, simulation outputs from a chemical transport model (CTM), land-use terms and other ancillary data to model monitored $PM_{2.5}$ and ozone.



Cross-validated R^2=0.84 for $PM_{2.5}$; R^2=0.76 for ozone on held out monitors

Di, Q., Kloog, I., Koutrakis, P., Lyapustin, A., Wang, Y. and Schwartz, J., 2016. Assessing PM2. 5 Exposures with High Spatiotemporal Resolution across the Continental United States. *Environmental science & technology*,*50*(9), pp.4712-4721.
Di, Q., Rowland, S., Koutrakis, P. and Schwartz, J., 2016. A Hybrid Model for Spatially and Temporally Resolved Ozone Exposures in the Continental United States. *Journal of the Air & Waste Management Association*, (just-accepted).

ZIP code and county-level covariates

- U.S. censuses
  - % of Hispanic people, % of black, median household income, median value of owner occupied housing, % of population above age 65 living below the poverty level, % with less than high school education (above age of 65), % of owner occupied housing units, and population density.
- Behavioral Risk Factor Surveillance System (BRFSS) of the Centers for Disease Control and Prevention (CDC)
  - Ever smoking rate, BMI
- The Dartmouth atlas of health care
  - % of Medicare enrollees having a blood lipid (LDL-C) test, a hemoglobin A1c test, and at least one ambulatory visit to a primary care clinician

Statistical Analysis

- Cox proportional hazards model
  - Stratified by sex, race, SES, and 5-year categories of age at entry; the remaining covariates described above were directly entered into the model
- Two-Pollutant Analysis
- Random intercepts for each ZIP

Results

	Two-Pollutant Analysis (prediction model)	Low Exposure Analysis (prediction model)	Two-Pollutant Analysis (monitoring data)
$PM_{2.5}$	1.136 (1.133,1.138)	1.214 (1.209, 1.220)	1.128 (1.125, 1.131)
Ozone	1.015 (1.014, 1.016)	1.012 (1.011, 1.013)	1.003 (1.002, 1.004)

A Causal Inference Framework to Support Policy Decisions by Evaluating the Effectiveness of Past Air Pollution Control Strategies for the Entire United States

Project 4 of the Harvard/MIT ACE Center

Corwin M. Zigler

Department of Biostatistics, Harvard T.H. Chan School of Public Health

September 15, 2016

Project 4 Team

- Corwin Zigler (PI, Harvard Biostatistics)
- Francesca Dominici (co-PI, Harvard Biostatistics)
- Joel Schwartz (Harvard Env. Health)
- Loretta Mickley (Harvard Engineering and Applied Sciences)
- Steve Barrett (MIT, Aeronautics and Astronautics)

Overall Project Goal

To develop a new **methodological framework** to investigate the effectiveness of specific control strategies for impacting the largest power-generating units in the United States.

Example: Evaluate the effectiveness of installing scrubbers on coal plants

Overall Project Goal

To develop a new **methodological framework** to investigate the effectiveness of specific control strategies for impacting the largest power-generating units in the United States.

Example: Evaluate the effectiveness of installing scrubbers on coal plants

- Data with unprecedented accuracy, reproducibility, and coverage
- Rooted in principles of causal inference
- Statistics + Atmospheric Science
- Extensions to other air quality interventions
- Refine/complement existing frameworks for regulatory impact assessment

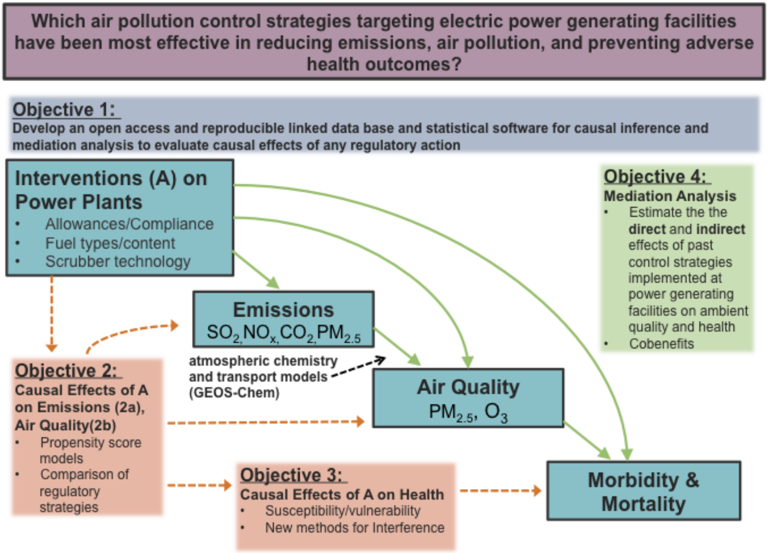
Specific Objectives

1. **Develop national and linked data base** on emissions, control technologies, ambient air quality, weather, population dempgrpahics, and Medicare hospitalization and mortality outcomes.

Estimate causal effects of past control strategies implemented at power plants on:

2. Emissions and ambient pollution.
3. Mortality and morbidity in the entire US Medicare population.

4. **Estimate the relative importance of direct vs. indirect pathways** through which past control strategies improve air quality and health.



Which air pollution control strategies targeting electric power generating facilities have been most effective in reducing emissions, air pollution, and preventing adverse health outcomes?
Objective 1:
Develop an open access and reproducible linked data base and statistical software for causal inference and mediation analysis to evaluate causal effects of any regulatory action
Interventions (A) on Power Plants
• Allowances/Compliance
• Fuel types/content
• Scrubber technology
Emissions
SO_2, NO_x, CO_2, $PM_{2.5}$
atmospheric chemistry and transport models (GEOS-Chem)
Air Quality
$PM_{2.5}$, O_3
Morbidity & Mortality
Objective 2:
Causal Effects of A on Emissions (2a), Air Quality(2b)
• Propensity score models
• Comparison of regulatory strategies
Objective 3:
Causal Effects of A on Health
• Susceptibility/vulnerability
• New methods for Interference
Objective 4:
Mediation Analysis
• Estimate the the direct and indirect effects of past control strategies implemented at power generating facilities on ambient quality and health
• Cobenefits

Objective 1: National Data Base

Data Sources: Air Markets Program Data, Air Quality System, Center for Medicare and Medicaid Services, National Climactic Data Center, CDC, US Census, satellite data/fusion (Project 1)

- Some commonly used, but not in a uniform way
- Some underused
- Linking/aligning in time and space
- Data access and replicability
  - Tools for data sharing (Harvard Dataverse)
  - Tools for data linkage (R, open GIS)
- Unprecedented accuracy and granularity
  - Individual-level health outcomes, CEMs, 1x1km resolution pollution

“Causal Inference” $\Rightarrow$ Comparison Between:

(1) What *actually* happened after an intervention

(2) What *would have happened* without the intervention

"Causal Inference" $\Rightarrow$ Comparison Between:

(1) What *actually* happened after an intervention

- Observed changes in:
  - Emissions
  - Air quality
  - Health indicators

(2) What *would have happened* without the intervention

- "Counterfactual scenario"

$\Rightarrow$ Effect of the specified intervention *isolated* from changes due to concurrent programs/actions/trends

Estimating the “Counterfactual Scenario”

Defining causal effects as comparisons with counterfactual scenarios is familiar

The **key question** is how to characterize the what *would have happened* without the intervention:

- Emissions
- Ambient air quality
- Health outcomes

Project 4 will leverage both **statistical methods for causal inference** and **state of the art atmospheric modeling**.

Objective 2: Causal Effects on...

Emissions

- Statistical methods for causal inference
- Observed data on power plant characteristics, CEMs, etc.
- The “counterfactual” for each individual power plant

⇒ “Counterfactual” emissions scenario

Objective 2: Causal Effects on...

Emissions

- Statistical methods for causal inference
- Observed data on power plant characteristics, CEMs, etc.
- The “counterfactual” for each individual power plant

$\Rightarrow$ “Counterfactual” emissions scenario

Air Quality

- Input emissions scenarios into GEOS-Chem chemical transport model
- Predicted air quality under two scenarios:
  1. “observed scenario”
  2. “‘counterfactual” or “world avoided”

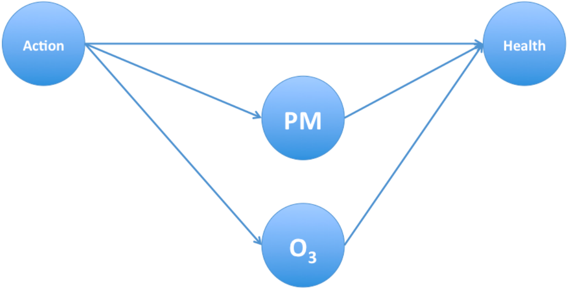
$\Rightarrow$ Causal effect on air quality

Objective 3: Causal Effects on Health Outcomes

- Directly quantify effects of intervention on health
  - Without reliance on historical C-R functions
  - Without limiting to effects due to a *single* pollutant
- Use observed individual-level health data from CMS
- Must account for **pollution transport**
  - GEOS-Chem, HYSPLIT
  - Causal inference with “interference”
- Investigate regional/equitable distribution of benefits across populations

Objective 4: Mediation Analysis

- Quantify the extent to which regulatory impacts can be attributed to:
  1. Changes in targeted modifiable factors
  2. Co-benefits/costs to other factors
- "Causal Pathways"
- Relative importance of targeted factors
- Identify most influential pathways



“Evidence-Based Practice” for Air Quality Interventions

Refine/complement existing frameworks with detailed retrospective evaluation of *specific* actions

- Observed population-level data, tools for curation/distribution
- Statistical Methods for Causal Inference + Atmospheric Science
- Compare effectiveness of interventions
- What works best, is most efficient, etc.
- Co-benefits/costs
- Relative importance of pathways

Thank You.

Project 5: Projecting and Quantifying Future Changes in Socioeconomic Drivers of Air Pollution and its Health-Related Impacts

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EPA ACE Centers Kickoff Meeting
15 September 2015

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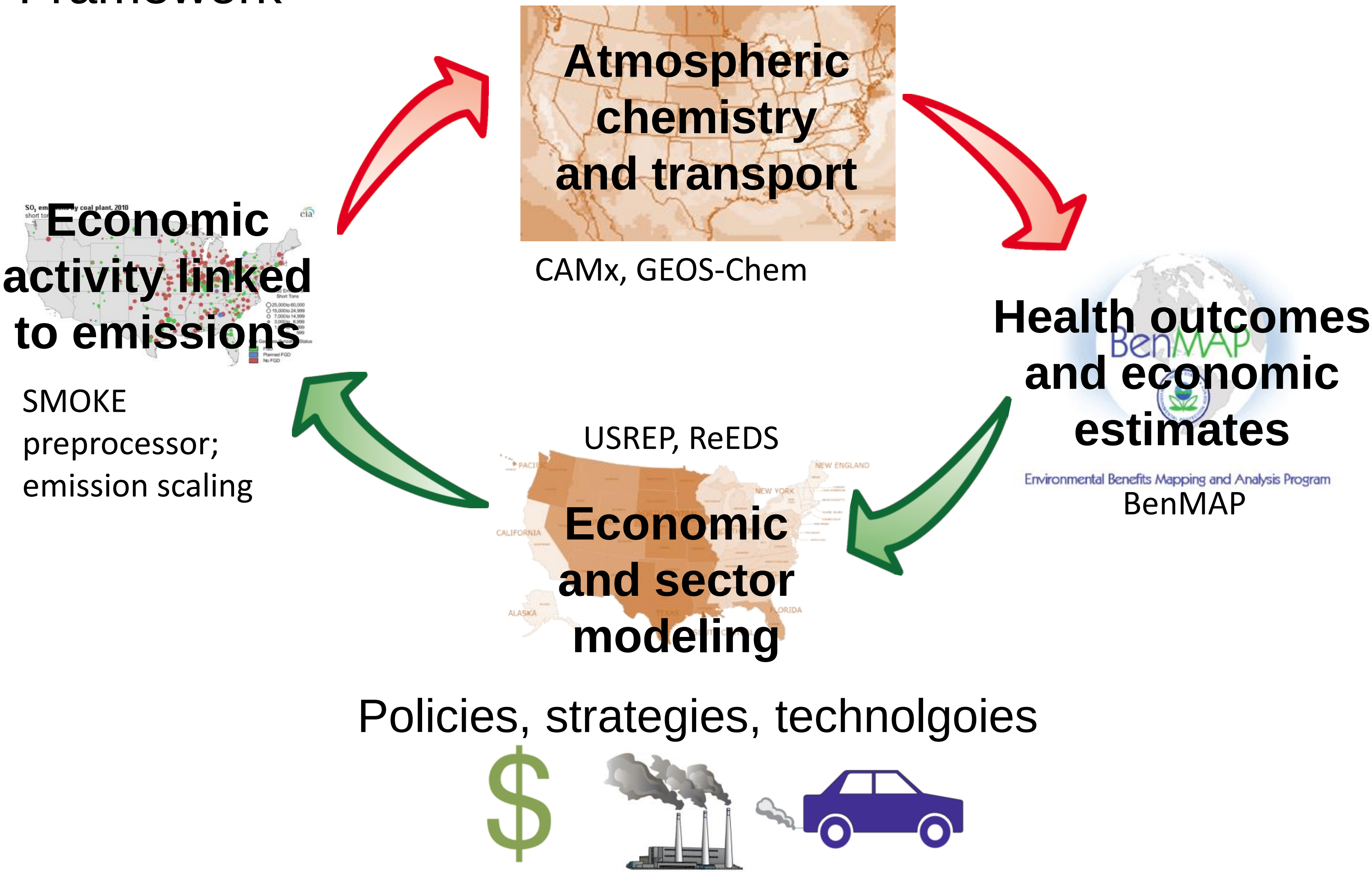
Objectives

- **Objective 1. Improving methods and tools**
  - Further develop and enhance methods and tools for understanding and assessing the relative importance of global change, technologies, and policies to air quality, relative to other uncertainties.
- **Objectives 2 and 3: Air pollution and health implications of policies and technologies**
  - Quantify the future implications of modifiable factors such as technologies and efficiency improvements in the energy and transportation sectors on regional differences in air pollution impacts.
  - Characterize state- and regional-level carbon policy implementation measures with respect to their air pollution health co-benefits.
- **Objective 4. Air toxics**
  - Assess how human exposure and impacts from different pollutants and mixtures may shift over time, and identify potential strategies for regions to shift to less toxic mixtures.
- **Objective 5. Influence of Climate**
  - Identify the importance of climate (e.g., temperature, meteorological) change to the formulation of robust strategies for mitigating health and environmental impacts.

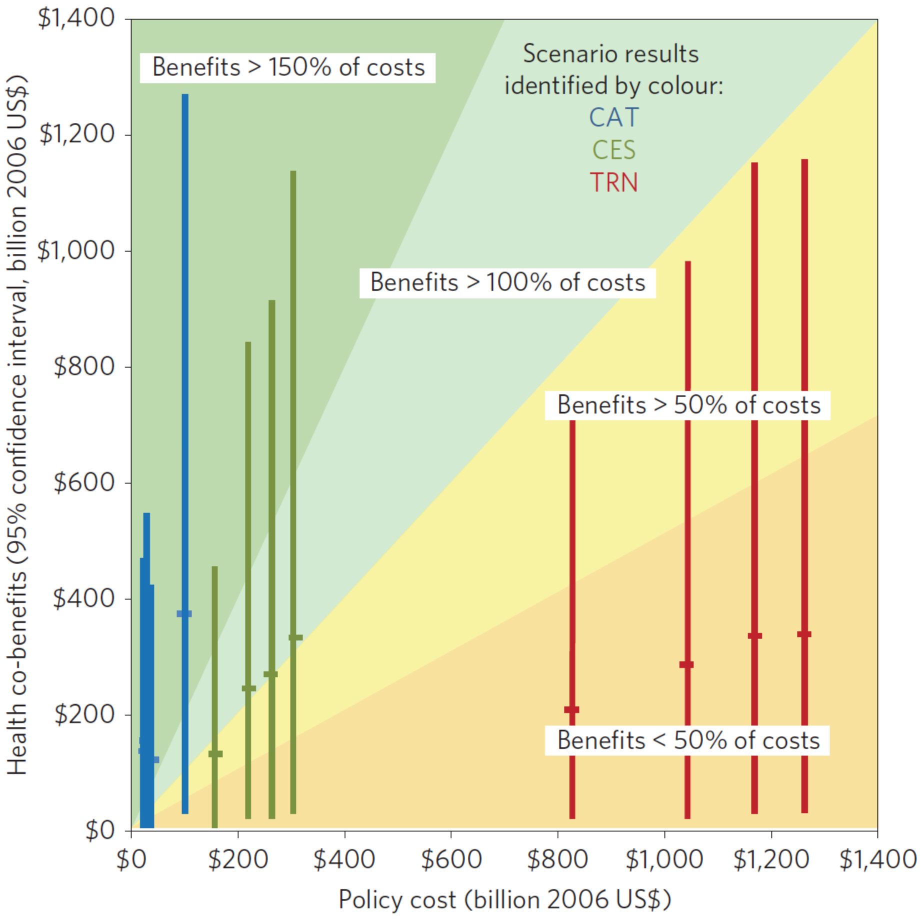
Objective 1: Improving methods and tools

MIT Integrated Economy-Air Quality-Health Assessment Framework



Objective 2/3: Air pollution and health implications of policies and technologies

Potential for co-benefits from CO_2 policy at national scale



Co-benefits exceed costs for cap-and-trade, clean energy policies at national scale

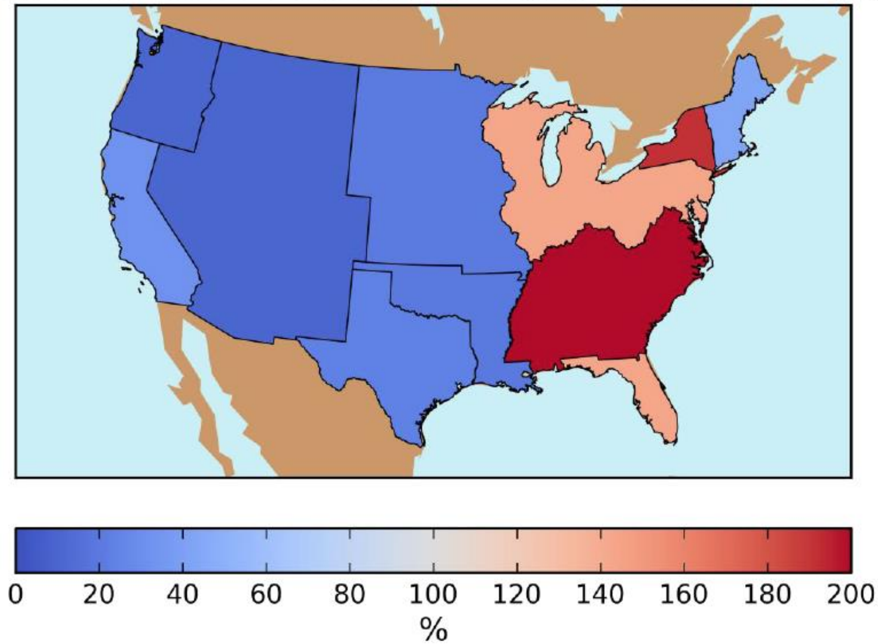
- Each line: a different economic assumption
- Vertical error bars: 95% CI for benefits

For more information: Thompson, T.M., S. Rausch, R. K. Saari, and N. E. Selin. 2014. "A Systems Approach to Evaluating the Air Quality Co-Benefits of U.S. Carbon Policies." Nature Climate Change 4, 917-923.

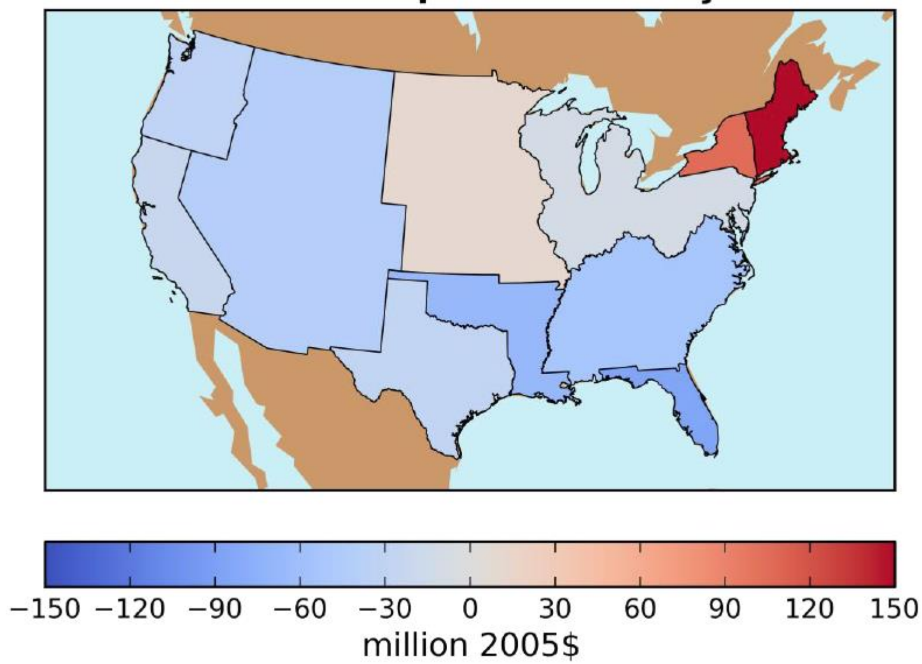
Objective 2/3: Air pollution and health implications of policies and technologies

Coupled approach shows feedbacks and dynamics of air pollution health impacts

CAT Ratio of Co-Benefits to Magnitude of Costs (%)



CAT Residuals from Fitting Welfare Impact of Mortality



For more information: R.K. Saari, N.E. Selin, S. Rausch and T.M. Thompson. 2015. "A self-consistent method to assess air quality co-benefits from US climate policies." Journal of the Air and Waste Management Association, 65(1):74-89.

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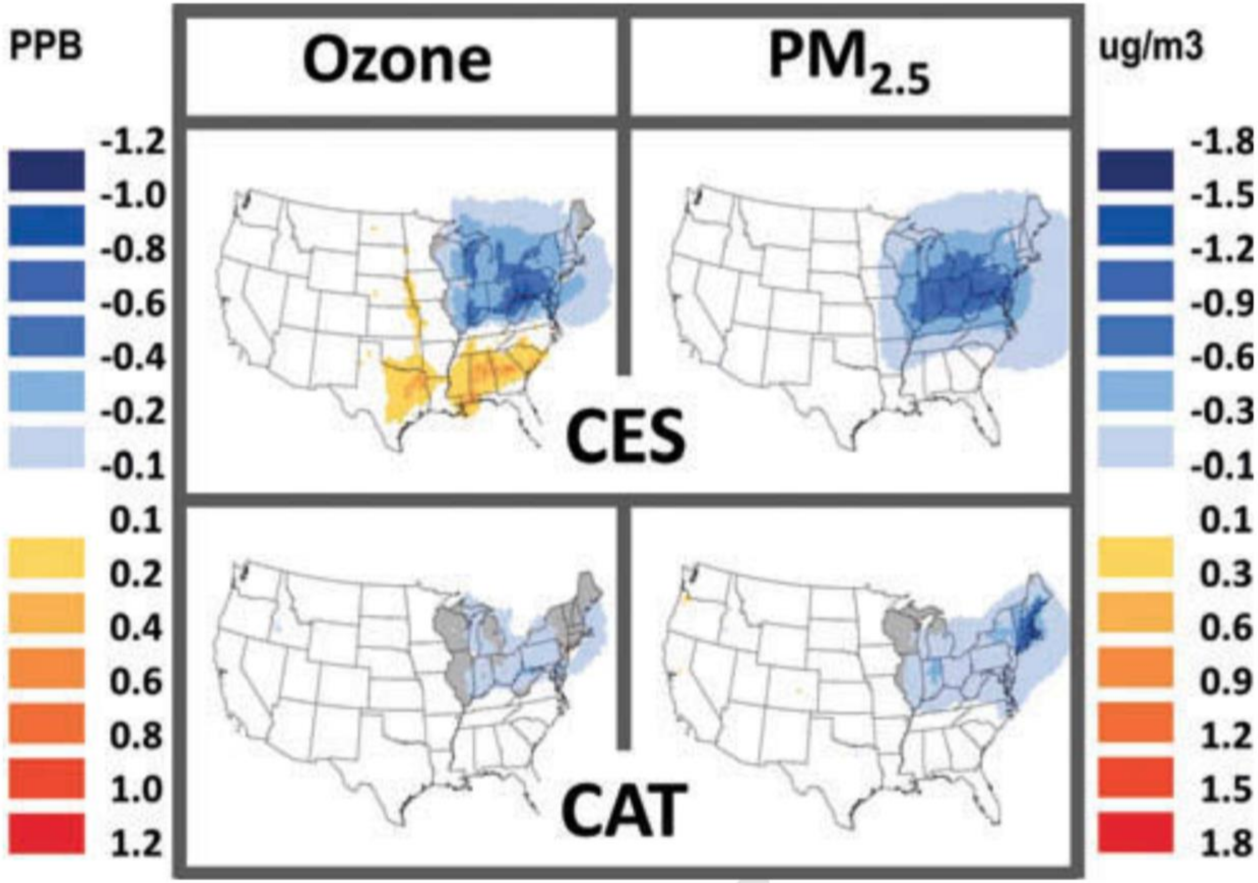
Objective 2/3: Air pollution and health implications of policies and technologies

Regional policies can have nation-wide impacts



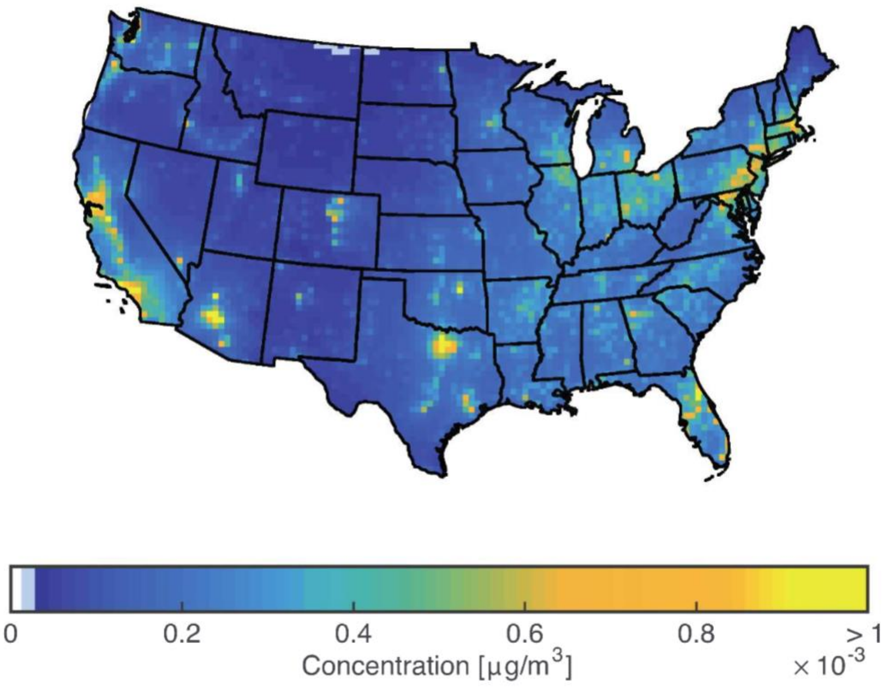
Co-benefits for Northeast clean energy, cap-and-trade policies

- Regional benefits exceed costs
- Some areas of potential disbenefit

For more information: Thompson, T.M., S. Rausch, R. K. Saari, and N. E. Selin. 2016. "Air Quality Co-Benefits of Subnational Climate Policies." Journal of the Air and Waste Management Association

Objective 4: Air toxics

Small sources (Pb from general aviation) can have large impacts

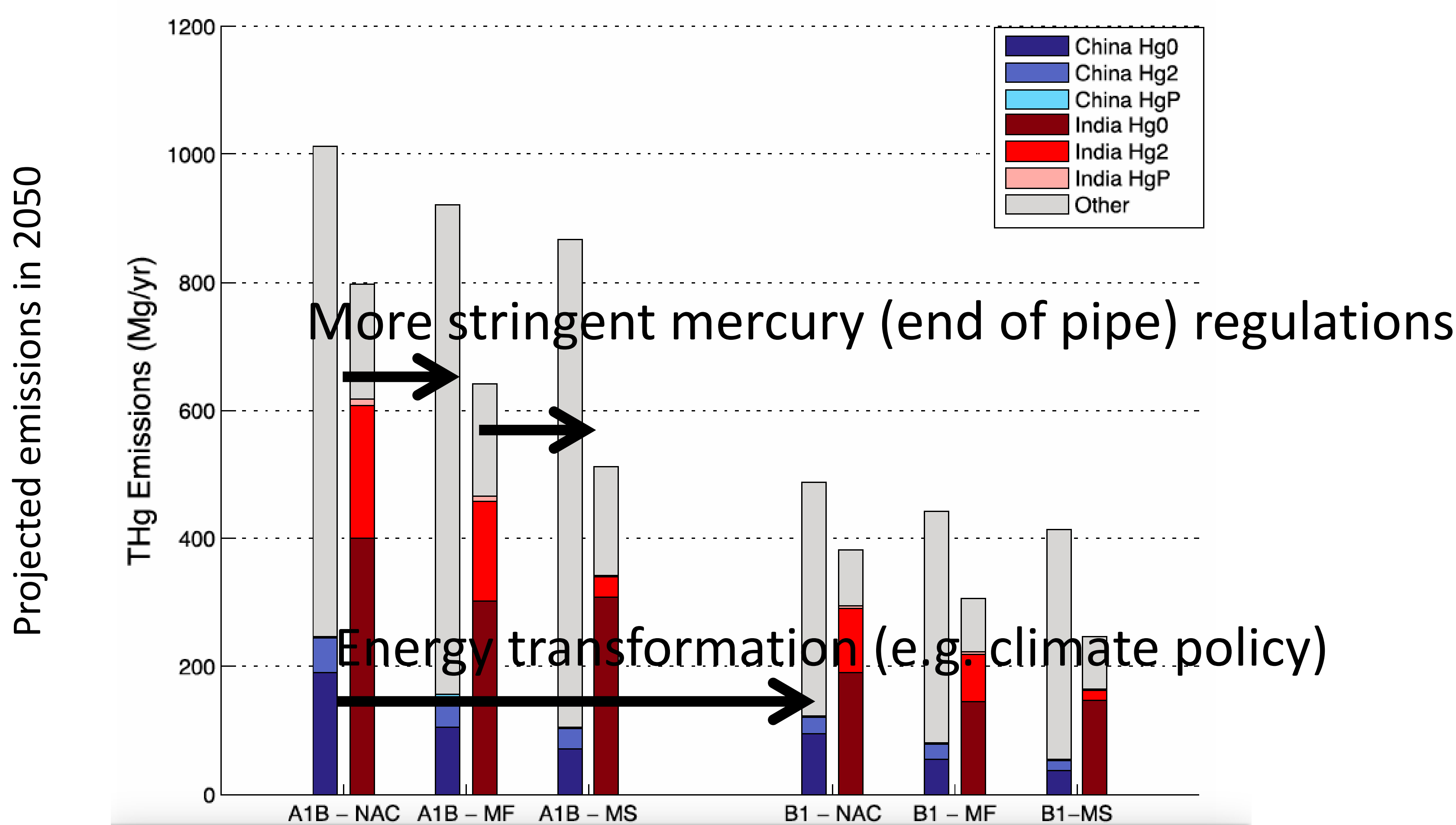


Lead emissions from general aviation aircraft over the U.S. can lead to $1 billion in damages from lifetime earnings reductions (due to IQ loss), plus an additional $0.5 billion due to lost productivity

For more information: P. J. Wolfe, A. Giang, A. Ashok, N. E. Selin and S. R. H. Barrett. 2016. "Costs of IQ Loss from Leaded Aviation Gasoline Emissions." Environmental Science and Technology, 50 (17):9026–9033

Objective 4: Air toxics

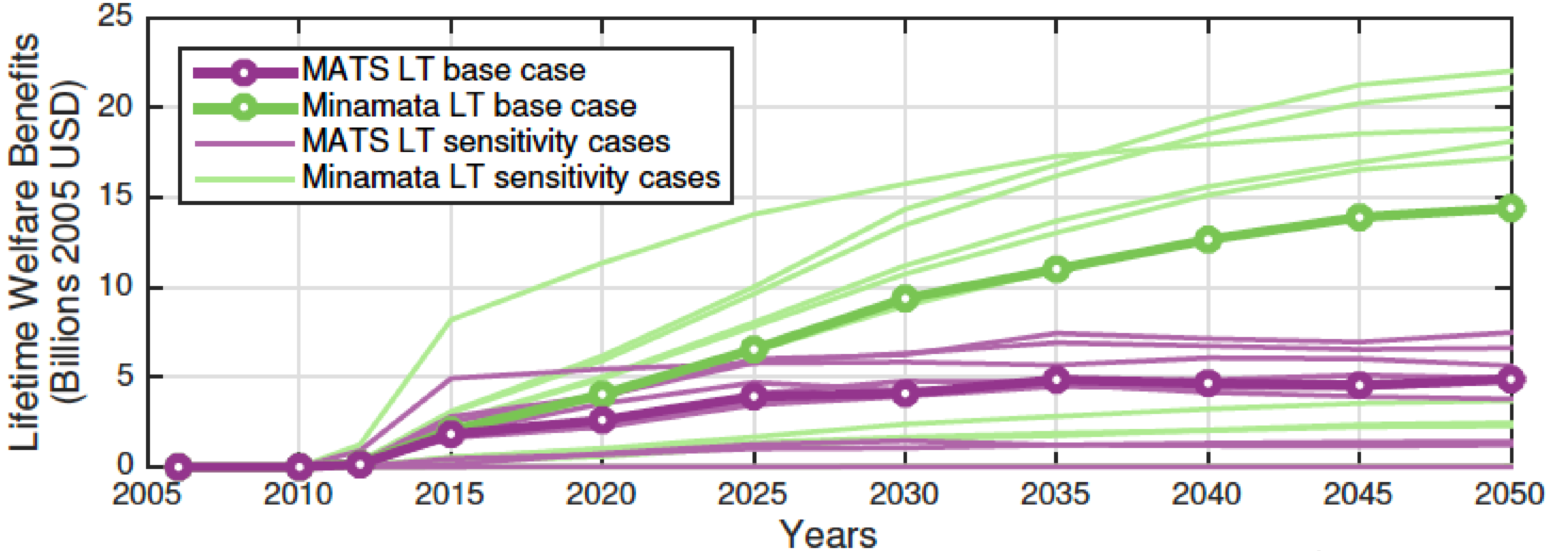
CO_2 controls can also have benefits for mercury emissions



For more information: A. Giang, L. C. Stokes, D. G. Streets, E. S. Corbitt, and N. E. Selin. 2015. "Impacts of the Minamata Convention on mercury emissions and global deposition from coal-fired power generation in Asia." Environmental Science and Technology 49, 5326-5335.

Objective 4: Air toxics

Mercury impacts can be assessed using similar approaches



Cumulative lifetime benefits by 2050 estimated at **$147 billion**

Plus uncertainty analysis and alternative economic methods

For more information: A. Giang and N.E. Selin, 2016, "Benefits of Mercury Controls for the United States," Proceedings of the National Academy of Sciences 113(2):286-291.

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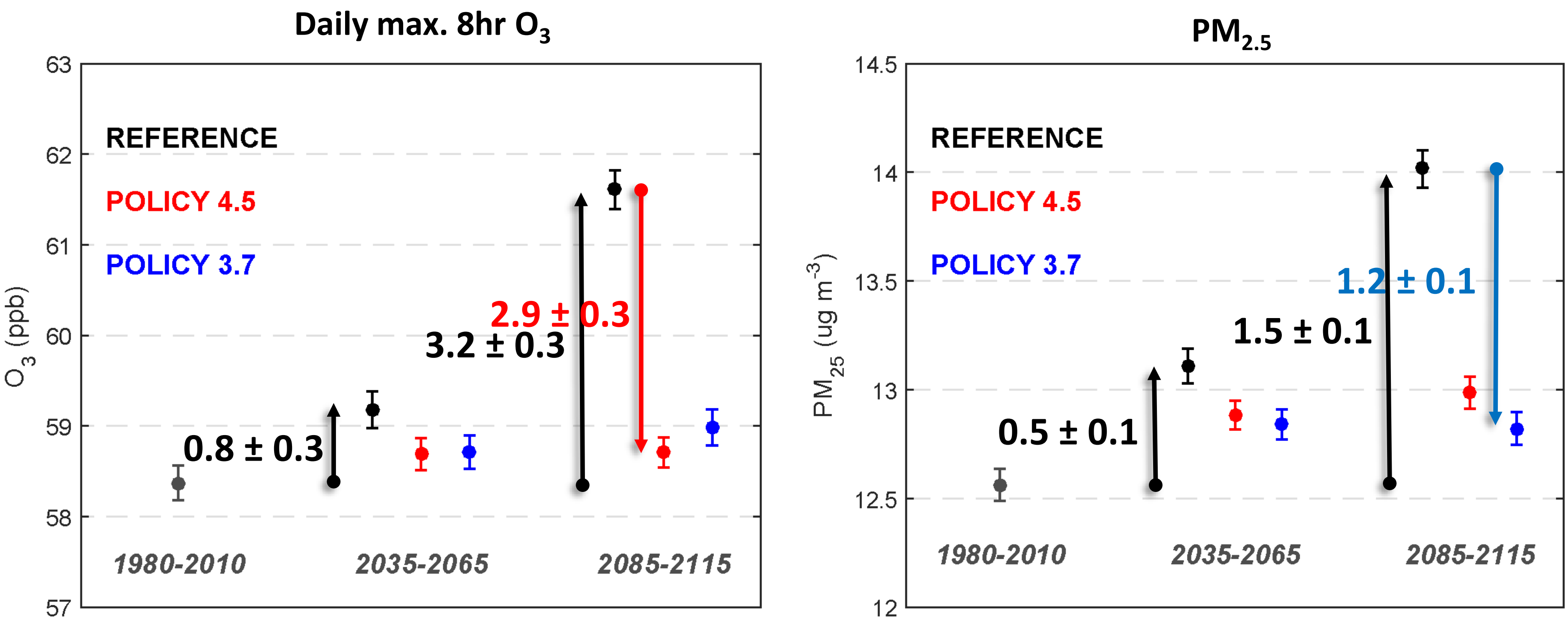
Objective 5: Climate
Carbon policy can have direct benefit to U.S. air pollution

US-average population-weighted annual concentrations:

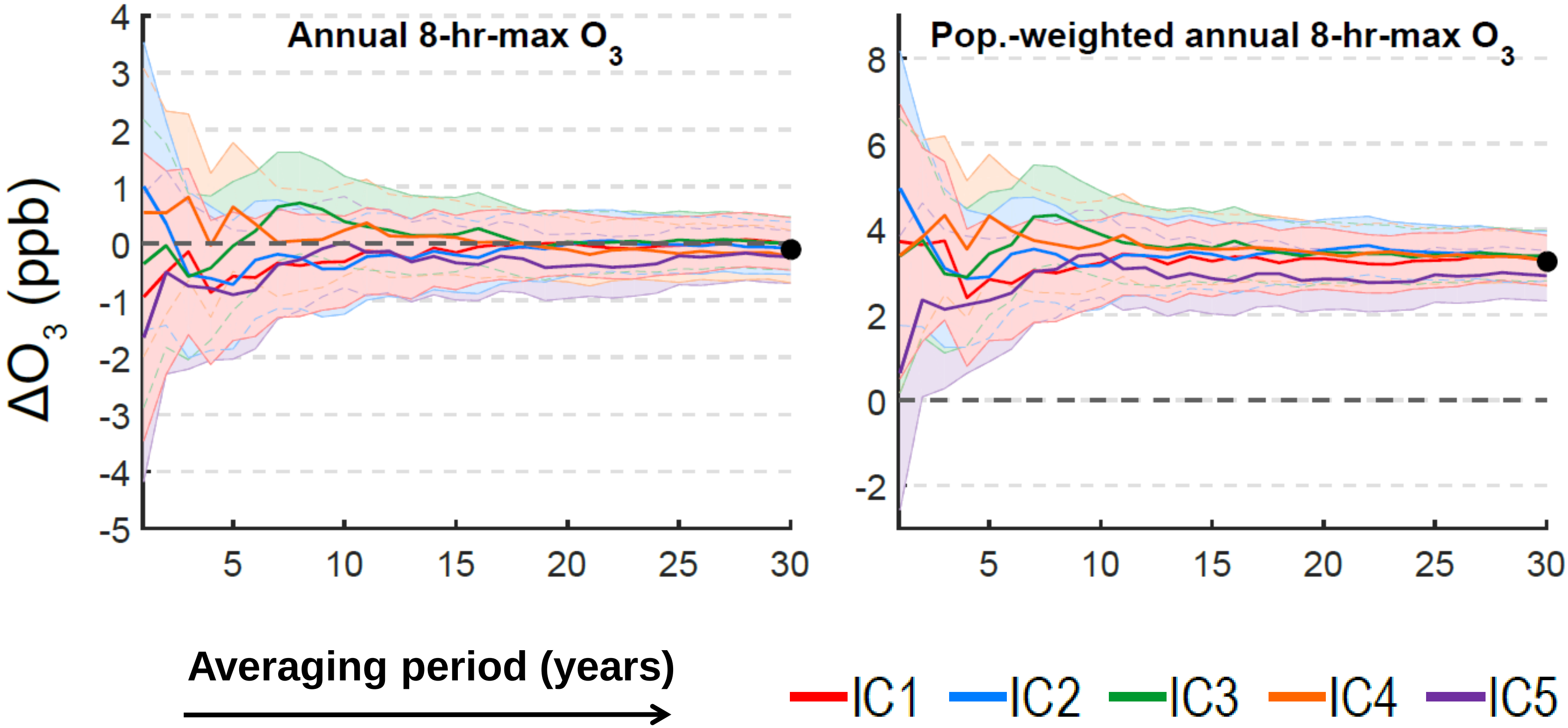


For more information: F. Garcia-Menendez, R. K. Saari, E. Monier, and N. E. Selin. 2015. "U.S. air quality and health benefits from avoided climate change under greenhouse gas mitigation." *Environmental Science and Technology, 49*, 7580–7588.

Objective 5: Climate

Natural variability can affect estimates of the "climate penalty"

2100 Reference scenario U.S.-average O_3 "climate penalty" estimated using
<u>5 model initializations</u>:



F. Garcia-Menendez et al., under review

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Selin Group
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- ***Publication links and more info at: http://mit.edu/selingroup***

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