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
<table>
<thead>
<tr>
<th>Name</th>
<th>Institution</th>
<th>Role</th>
<th>Background</th>
<th>Contribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>*Petros Koutrakis, Ph.D.</td>
<td>HSPH</td>
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<td>Exposure assessment</td>
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<tr>
<td>**Brent Coull, Ph.D.</td>
<td>HSPH</td>
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<td>Loretta Mickley, Ph.D.</td>
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<td>Corwin Zigler, Ph.D.</td>
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<td>Co-PI, Project 4</td>
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<td>Steven Barrett, Ph.D.</td>
<td>MIT</td>
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<td>Susan Solomon, Ph.D.</td>
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<td>John Reilly, Ph.D.</td>
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<tr>
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<td>Air quality measurements</td>
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<td>Christine Choirat, Ph.D.</td>
<td>HSPH</td>
<td>Co-Investigator</td>
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<td>Co-Investigator</td>
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<td>Env. Chemistry</td>
<td>Toxic air pollutants</td>
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<td>Erwan Monier Ph.D.</td>
<td>MIT</td>
<td>Key Personnel</td>
<td>Climate Science</td>
<td>Climate change impacts</td>
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</tbody>
</table>
**Research Framework**

- **Core A: Air Pollution**
  - RQ: 1, 2, 3, 4
  - Projects 1 & 2: Regional Air Pollutant Mixtures
    - Mixtures characterization
    - Effects of modifiable factors
    - Trends: 2010→2015→2040
  - Project 3: Health Risks
    - Toxicity of regional mixtures
    - Temporal trends in mixture effects
    - Impact of modifiable factors
    - RQ: 1, 2, 3, 4
  - Project 4: Accountability
    - Methods for accountability assessment
    - Impacts of power plant emissions controls
    - Benefits/co-benefits to air quality and health
    - RQ: 1, 2, 3, 4
  - Project 5: Strategies
    - Methods/tools for assessing future policies
    - Future impacts of energy/transportation
    - Co-benefits of proposed carbon policy

- **Information: Space & Time**
- **Models: Physical & Statistical**
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

Discrete PM$_{2.5}$ Daily Monitoring Data
- Mete Fields
- Satellite data
- Land-use terms
- CTM outputs
- Other data

Continuous Daily PM$_{2.5}$ Prediction
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

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

**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

\( \alpha \): Air exchange rate (Wind speed/Length)

\( \alpha \gg \) deposition rate

\( C(t) \): PM\(_{2.5}\) Concentration inside box
\( C_u \): PM\(_{2.5}\) Concentration upwind

1km

1km
PEIRS 12 Year Averaged PM$\textsubscript{2.5}$ 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**

Period 1
2002-2004

Period 4
2011-2013

<table>
<thead>
<tr>
<th>Emissions (Tons/yr/km²)</th>
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</thead>
<tbody>
<tr>
<td>0 - 21</td>
</tr>
<tr>
<td>22 - 25</td>
</tr>
<tr>
<td>26 - 29</td>
</tr>
<tr>
<td>30 - 32</td>
</tr>
<tr>
<td>33 - 37</td>
</tr>
<tr>
<td>38 - 43</td>
</tr>
<tr>
<td>44 - 54</td>
</tr>
<tr>
<td>&gt;55</td>
</tr>
</tbody>
</table>
Spatial trends **warm season**

Emissions (Tons/yr/km²)

- 0 - 4
- 5 - 6
- 7 - 8
- 9 - 10
- 11 - 11
- 12 - 13
- 14 - 15
- >15

**Period 1**
2002-2004

**Period 4**
2011-2013
State avg. trend (2002 – 2013)

Y axis: Emission Trend (Tons/yr/km²)

-2 -3.6 -3.4  
New York

-5.5 -9.3 -8
Vermont

-5.1 -5.6 -10.4
Massachusetts

-8.8 -3.5
Connecticut

-24.4
New Hampshire

-27.1
Rhode Island

ΔQ
\( \frac{\text{Tons}}{\text{Year} \cdot \text{km}^2} \)

-30 -25 -20 -15 -10 0

-5 -10

All seasons  Warm season  Cold season

- Non attainment states
- Home heating oil drop 40%
- Improved insulation, furnace
- Economic crisis late 2008-2010
Intra-urban variability

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

<table>
<thead>
<tr>
<th>Emission (Tons/yr/km$^2$)</th>
<th>-3 - 10</th>
<th>11 - 15</th>
<th>16 - 20</th>
<th>21 - 25</th>
<th>26 - 30</th>
<th>31 - 35</th>
<th>36 - 40</th>
<th>41 - 50</th>
<th>51 - 60</th>
<th>&gt; 60</th>
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Land Cover
- Water
- Developed (open)
- Developed (low)
- Developed (medium)
- Developed (high)
- Barren
- Deciduous forest
- Evergreen forest
- Mixed forest
- Shrub
- Grass
- Livestock
- Crop
- Woody wetland
- Wetland
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

RESEARCH QUESTIONS (RQs)

Outcomes & Knowledge

Solutions & Strategies

Risk Assessment & Management

Exposure Assessment

Regional Air Quality

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Research Questions (RQs)

Outcomes & Knowledge

Solutions & Strategies

Risk Assessment & Management
- Exposure Assessment
- Regional Air Quality
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 Health
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 birth weight, MA 2003-2008

![Graph showing changes in birth weight by trimester and PM2.5 components](image)
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 Health
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

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.

<table>
<thead>
<tr>
<th>Mean summer temperature (°C)</th>
<th>Mean winter temperature (°C)</th>
<th>Percent change (95% CI) in mortality per IQR increase in PM$_{2.5}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>18.6$^a$ (Average)</td>
<td>5.9$^b$ (Average)</td>
<td>1.8% (−1.6, 5.2%)</td>
</tr>
<tr>
<td>17.6 (Average – 1)</td>
<td>5.9 (Average)</td>
<td>−1.6% (−4.2, 1.1%)</td>
</tr>
<tr>
<td>19.6 (Average + 1)</td>
<td>5.9 (Average)</td>
<td>1.6% (−0.6, 3.8%)</td>
</tr>
<tr>
<td>18.6 (Average)</td>
<td>4.9 (Average – 1)</td>
<td>1.6% (−0.6, 3.9%)</td>
</tr>
<tr>
<td>18.6 (Average)</td>
<td>6.9 (Average + 1)</td>
<td>5.3% (2.9, 7.8%)</td>
</tr>
</tbody>
</table>

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


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
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

<table>
<thead>
<tr>
<th></th>
<th>Two–Pollutant Analysis (prediction model)</th>
<th>Low Exposure Analysis (prediction model)</th>
<th>Two–Pollutant Analysis (monitoring data)</th>
</tr>
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<tbody>
<tr>
<td><strong>PM$_{2.5}$</strong></td>
<td>1.136 (1.133, 1.138)</td>
<td>1.214 (1.209, 1.220)</td>
<td>1.128 (1.125, 1.131)</td>
</tr>
<tr>
<td><strong>Ozone</strong></td>
<td>1.015 (1.014, 1.016)</td>
<td>1.012 (1.011, 1.013)</td>
<td>1.003 (1.002, 1.004)</td>
</tr>
</tbody>
</table>
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 demographics, and Medicare hospitalization and mortality outcomes.

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

2. Emissions and ambient pollution.


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 database 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

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 direct and indirect effects of past control strategies implemented at power generating facilities on ambient quality and health
- Cobenefits

Emissions: SO₂, NOₓ, CO₂, PM₂.₅
Air Quality: PM₂.₅, O₃
Morbidity & Mortality

atmospheric chemistry and transport models (GEOS-Chem)
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” ⇒ Comparison Between:

(1) What *actually* happened after an intervention

(2) What *would have happened* without the intervention
“Causal Inference” ⇒ 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”

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

⇒ “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”

⇒ 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
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
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

- Economic activity linked to emissions
  - SMOKE preprocessor; emission scaling

- Atmospheric chemistry and transport
  - CAMx, GEOS-Chem

- Economic and sector modeling
  - USREP, ReEDS

- Health outcomes and economic estimates
  - BenMAP

- Policies, strategies, technologies

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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

Objective 2/3: Air pollution and health implications of policies and technologies
Coupled approach shows feedbacks and dynamics of air pollution health impacts

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

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.

Objective 4: Air toxics

CO$_2$ controls can also have benefits for mercury emissions

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

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

**US-average population-weighted annual concentrations:**

Objective 5: Climate
Natural variability can affect estimates of the “climate penalty”

2100 Reference scenario U.S.-average O₃ “climate penalty” estimated using 5 model initializations:

F. Garcia-Menendez et al., under review
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- **Publication links and more info at:** [http://mit.edu/selingroup](http://mit.edu/selingroup)