Crash Course in Air Pollution for Policy Analysts

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Overview

- Goal
  - Include air pollution into climate/energy analyses in appropriate fashion
- Outline
  - Motivation: air pollution epidemiology, health impacts, social costs
  - Air pollution sources and behavior
  - Tools for impact estimates
  - Recent research

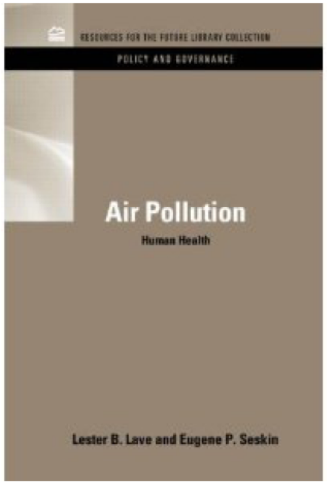
(Please hold substantive questions until end)

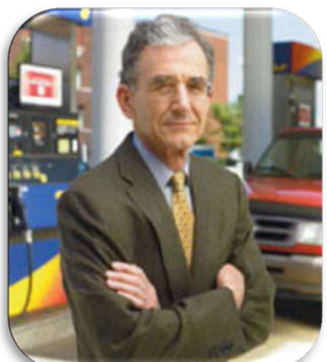
Types of Air Pollution

- Criteria Air Pollutants (NAAQS)
  - $PM_{2.5}$ and PM_{10}
  - Ozone
  - CO, NO_x, SO_2, Lead
- Hazardous Air Pollutants

- $PM_{2.5}$ = mass concentration ($\mu g\ m^{-3}$) of particles smaller than 2.5 μm diameter (usually 200-300 nm)

Mortality: Relative Risk





Prof. Lester Lave
(CMU)
1939-2011

21 August 1970, Volume 169, Number 3947 **SCIENCE**

Air Pollution and Human Health

The quantitative effect, with an estimate of the dollar benefit of pollution abatement, is considered.

Lester B. Lave and Eugene P. Seskin

"There is evidence that over 20 percent of cardiovascular morbidity and *<u>about 20 percent of cardiovascular mortality could be saved</u>* if air pollution were reduced by 50 percent." (Lave and Seskin, 1970)

Large Body of Evidence

Table 2. Comparison of percentage increase (and 95% CI) in relative risk of mortality associated with long-term particulate exposure.

Study	Primary Sources	Exposure Increment	Percent Increases in Relative Risk of Mortality (95% CI)		
			All Cause	Cardiopulmonary	Lung Cancer
Harvard Six Cities, original	Dockery et al. 1993[26]	10 µg/m^3 $PM_{2.5}$	13 (4.2, 23)	18 (6.0, 32)	18 (−11, 57)
Harvard Six Cities, HEI reanalysis	Krewski et al. 2000[177]	10 µg/m^3 $PM_{2.5}$	14 (5.4, 23)	19 (6.5, 33)	21 (−8.4, 60)
Harvard Six Cities, extended analysis	Laden et al. 2006[184]	10 µg/m^3 $PM_{2.5}$	16 (7, 26)	28 (13, 44)[a]	27 (−4, 69)
ACS, original	Pope et al. 1995[27]	10 µg/m^3 $PM_{2.5}$	6.6 (3.5, 9.8)	12 (6.7,17)	1.2 (−8.7, 12)
ACS, HEI reanalysis	Krewski et al. 2000[177]	10 µg/m^3 $PM_{2.5}$	7.0 (3.9, 10)	12 (7.4, 17)	0.8 (−8.7, 11)
ACS, extended analysis	Pope et al. 2002[179]	10 µg/m^3 $PM_{2.5}$	6.2 (1.6, 11)	9.3 (3.3, 16)	13.5 (4.4, 23)
	Pope et al. 2004[180]			12 (8, 15)[a]	
ACS adjusted using various education	Dockery et al. 1993[26]	10 µg/m^3 $PM_{2.5}$	8–11	12–14	3–24
Cystic fibrosis	Goss et al. 2004[200]	10 µg/m^3 $PM_{2.5}$	32 (−9, 93)	–	–

For a 10 µg m^{-3} increase in $PM_{2.5}$, mortality rates (all causes) go up by 6-13% (3-25%)

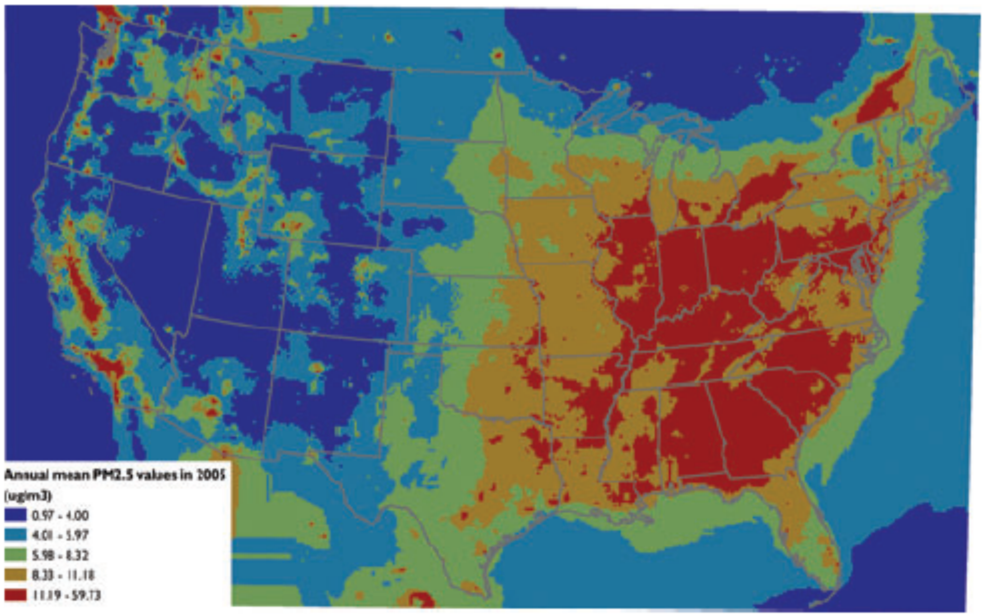
Causes: heart attacks, lung cancer, other respiratory

Table from Pope and Dockery (2006) “Health Effects of Fine Particulate Pollution: Lines that Connect”

A Simple Estimate

- US mortality rate: 2.5M deaths/yr (2011)
  - Center for Disease Control
- Typical $PM_{2.5}$ concentration ~10 $\mu g/m^3$
- Relative risk suggests ~10% increase in mortality
  - =250,000 deaths/yr due to $PM_{2.5}$
- Value of statistical life is ~$7M
- Result is $1.75 trillion/yr
- US GDP is ~$15 trillion/yr

More Detailed Estimates



Fann et al. (2011) "Estimating the National Public Health Burden Associated with Exposure to Ambient PM2.5 and Ozone"

Figure 2: Annual mean PM2.5 concentrations (merged monitoring and modeling data)
Red is > 11 μg/m3

- These concentrations used in similar calculation (with population density)
- Result is 130,000 deaths/year
- Global estimate is close to 4 million/yr (Anenberg et al. 2010)

Social Cost Metrics

$$\text{Social Cost} \simeq \begin{pmatrix} \Delta\text{Mortality Rate} \\ \text{by } \Delta\text{PM}_{2.5} \end{pmatrix} \times (\text{Exposed Population}) \times (\text{Value of a Statistical Life})$$

- Requires
  - AQ model (emissions → concentrations)
  - epidemiology “concentration-response” (mortality)
  - exposure (population density, spatial resolution)
  - value of a statistical life
- Frequently reported as $ per ton emissions
- “Marginal emissions” ($/ton)
  - assumes linear response; appropriate for small Δ

OMB Analysis

Costs and Benefits of Major Federal Rules (billions of $2001)

Agency	Number of Rules	Benefits	Costs
Department of Agriculture	6	0.9 to 1.3	1.0 to 1.34
Department of Energy	10	8.0 to 10.9	4.5 to 5.1
Department of Health and Human Services	18	18.0 to 40.5	3.7 to 5.2
Department of Homeland Security	1	< 0.1	< 0.1
Department of Housing and Urban Development	1	2.3	0.9
Department of Justice	4	1.8 to 4.0	0.8 to 1.0
Department of Labor	6	0.4 to 1.5	0.4 to 0.5
Department of Transportation (DOT)	26	14.6 to 25.5	7.5 to 14.3
Environmental Protection Agency (EPA)[16]	32	81.8 to 550.7	23.3 to 28.5

(air quality is 77 to 535)

Source: Office of Management and Budget (OMB); "2011 Report to Congress on the Benefits and Costs of Federal Regulations…"; http://www.whitehouse.gov/sites/default/files/omb/inforeg/2011_cb/2011_cba_report.pdf

Air Pollution Often Dominates

Simultaneously Mitigating Near-Term Climate Change and Improving Human Health and Food Security

Science (2012)

Drew Shindell,[1*] Johan C. I. Kuylenstierna,[2] Elisabetta Vignati,[3] Rita van Dingenen,[3]

Black carbon mitigation may have some benefits as a short-lived climate forcer

…but definitely has large benefits now for health (25x as big)

	CH_4	BC Tech
Valuation		
Climate, billions $US	331 ± 118	142 (+71/–106)
($US per metric ton CH_4)	(2381 ± 850)	
Crops, billions $US	4.2 ± 1.2	3.6 ± 2.6
($US per metric ton CH_4)	(29 ± 8)	
Health, billions $US	148 ± 99	3717 (+3236/–2563)
($US per metric ton CH_4)	(1080 ± 721)	

Motivation: Recap

It's all about the $PM_{2.5}$

(>90% of air pollution social cost)

Jargon (and implications)

- **Primary**: a pollutant species that is *directly emitted* by a source
- **Secondary**: a pollutant species that is *produced in atmosphere* via chemical reaction

- All ozone and most $PM_{2.5}$ is secondary
  - Tends to complicate the behavior/analysis

- Summer: atmospheric *photochemistry* more active (more secondary pollution)
- Winter: sometimes more *stagnant* air

PM2.5 Composition

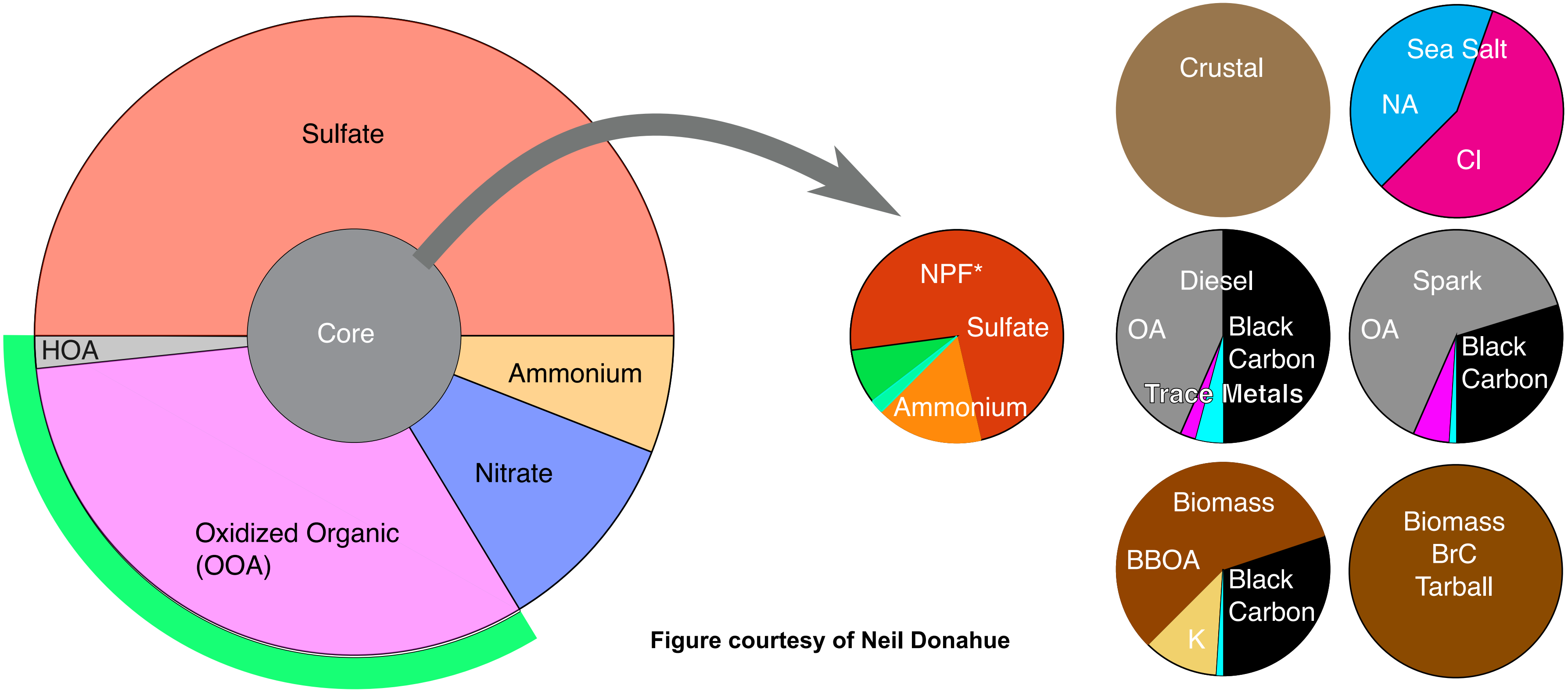
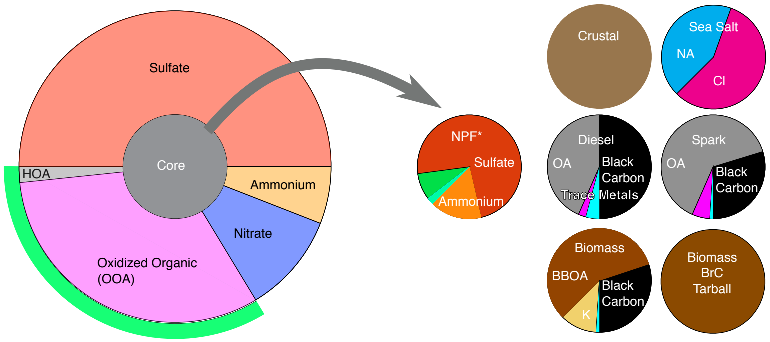


Figure courtesy of Neil Donahue

- Small, source-specific core of *primary* PM (<100 nm; ~10% of mass)
- Thick coating of *secondary* PM that condensed over several days (200-300 nm; ~90% mass)

PM2.5 Composition

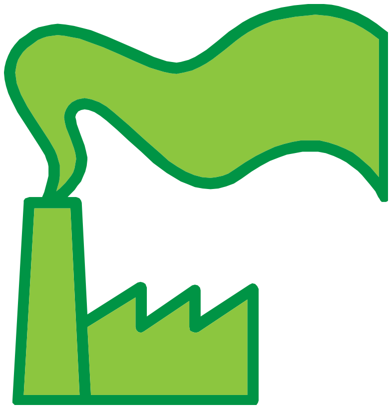


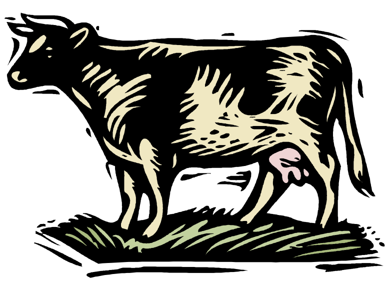
- Roughly equal parts ***inorganics*** (sulfate-nitrate-ammonium) and ***organics***
  - ~10% black (elemental) carbon and trace metals
- Standard concentration-response (C-R) functions from epidemiological studies ***treat all components the same***
- Atmosphere is busy, complicated place
  - not just emissions, float around, removal
- For the most part, there are no “sulfate particles”, “diesel particles”, etc

PM2.5: Basic Facts

- Removal is mostly by precipitation
    - $PM_{2.5}$ atmospheric lifetime is ~few days
    - Transport/impact distances are 100s-1000+ km

Inorganic PM2.5





$\longrightarrow$ SO_2 (g) $\xrightarrow{\text{oxidation}}$ sulfate PM

$\longrightarrow$ NO_x (g) $\xrightarrow{\text{oxidation}}$ HNO_3 (g)

$\downarrow$

$\longrightarrow$ NH_3 (g) $\longrightarrow$ nitrate PM? ammonium PM?

SO_4-NO_3-NH_3 ($iPM_{2.5}$) Thermodynamics

SO_4^{2-} (p)

HNO_3 (g)

> K_{eqm}(T,RH)?

Cold T favors nitrate formation

2 x SO_4^{2-}

NH_4^+ (p)

NH_3 (g)

NH_3 (free)

NH_4NO_3 (p)

<u>Sulfate-Nitrate "Substitution"</u>

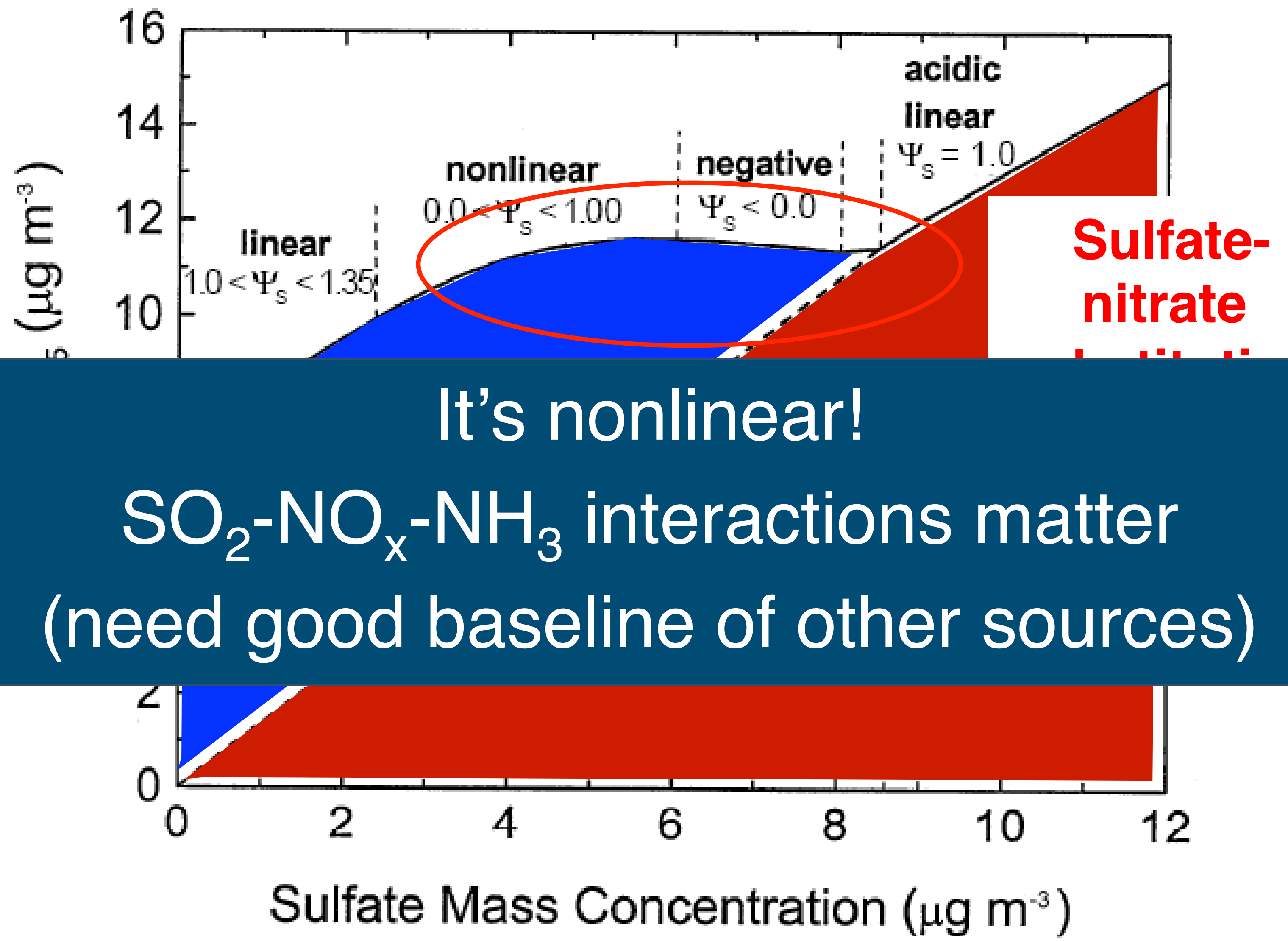
Sulfate aerosol ↓

Free ammonia ↑

Nitrate aerosol ↑

Net aerosol mass ~

NH_3 and Inorganic Particulate Matter ($iPM_{2.5}$)



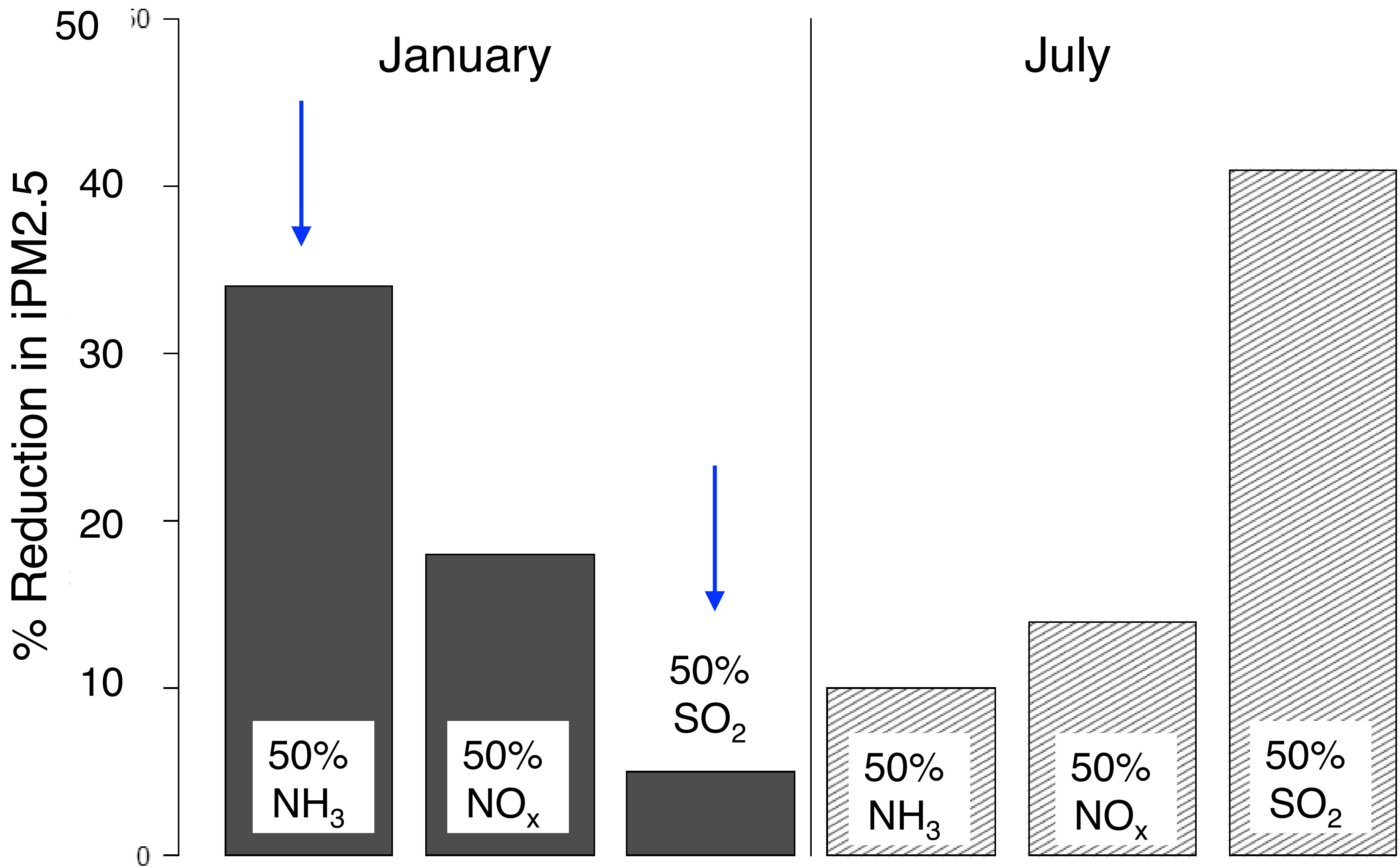
It's nonlinear!

SO_2-NO_x-NH_3 interactions matter

(need good baseline of other sources)

Source: West et al. 1999 Marginal PM2.5: Nonlinear Aerosol Mass Response to Sulfate Reductions in the Eastern United States JAWMA 49

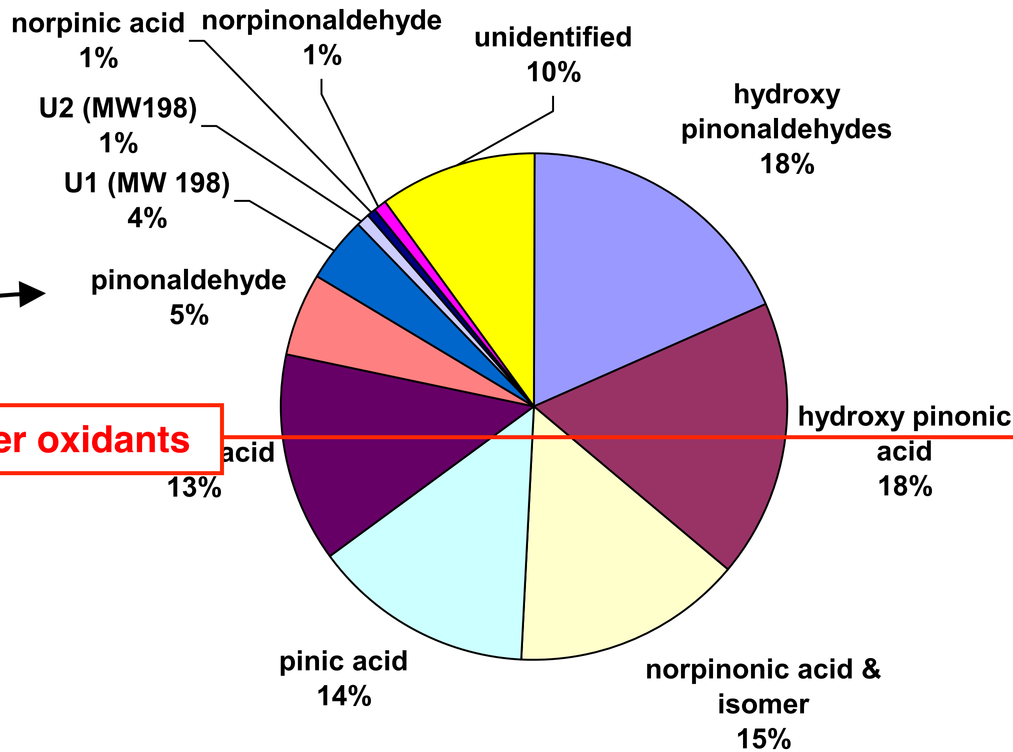
Effectiveness: $iPM_{2.5}$ Sensitivity



Pinder and Adams ES&T (2007)

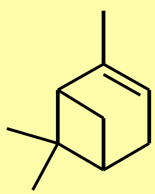
Organic Particle Composition

Slide adapted from Jianzhen Yu, HKUST; Yu et al. 1999



$+O_3$

+Other oxidants

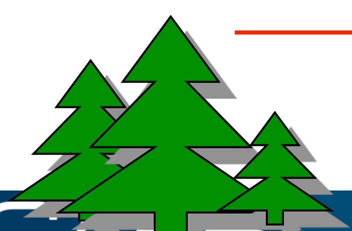


α-pinene

GC/MS with derivitization identifies 90% of product mass

1000s of organic species identified in ambient particles

…but typically only 5-15% of organic mass is speciated

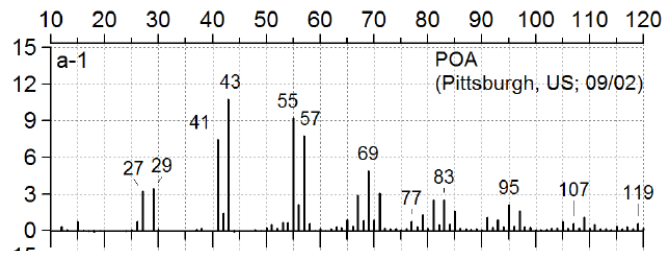


Other VOCs emitted

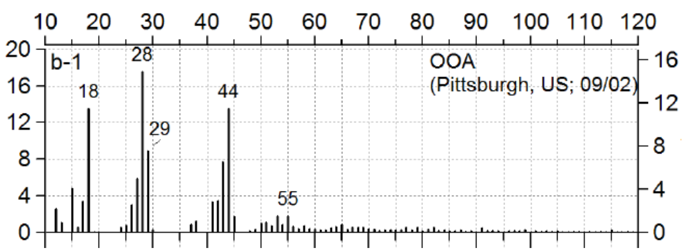
Other Sources

Particulate Organics are Highly Oxidized

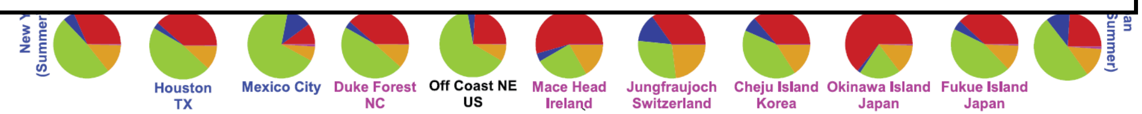
Hydrocarbon-like OA (HOA)



Oxygenated OA (OOA)

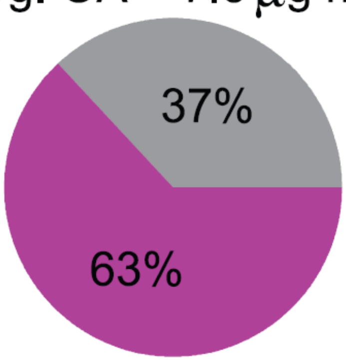


- •HOA ≈ fresh vehicle exhaust (~primary OA)
- •OOA: complex, but largely from atmospheric oxidation of VOCs (~secondary OA)
- •Conventional wisdom: fresh exhaust dominates
- •OOA fraction is high, even in urban areas
- •Chemical production of organic material more important than previously recognized



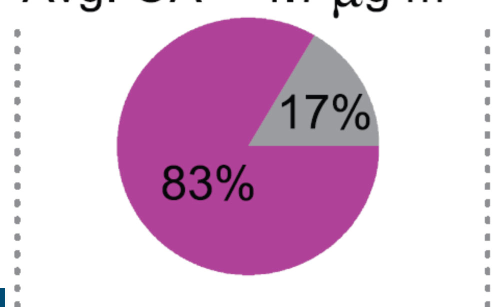
"Urban"

Avg. OA = 7.6 $\mu g\ m^{-3}$



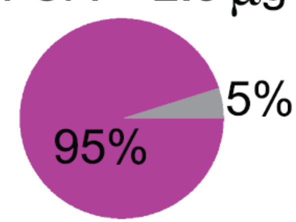
"Urban Downwind"

Avg. OA = 4.7 $\mu g\ m^{-3}$



"Rural Remote"

Avg. OA = 2.8 $\mu g\ m^{-3}$



Zhang et al., GRL 2007

Organic PM: Evolving Understanding

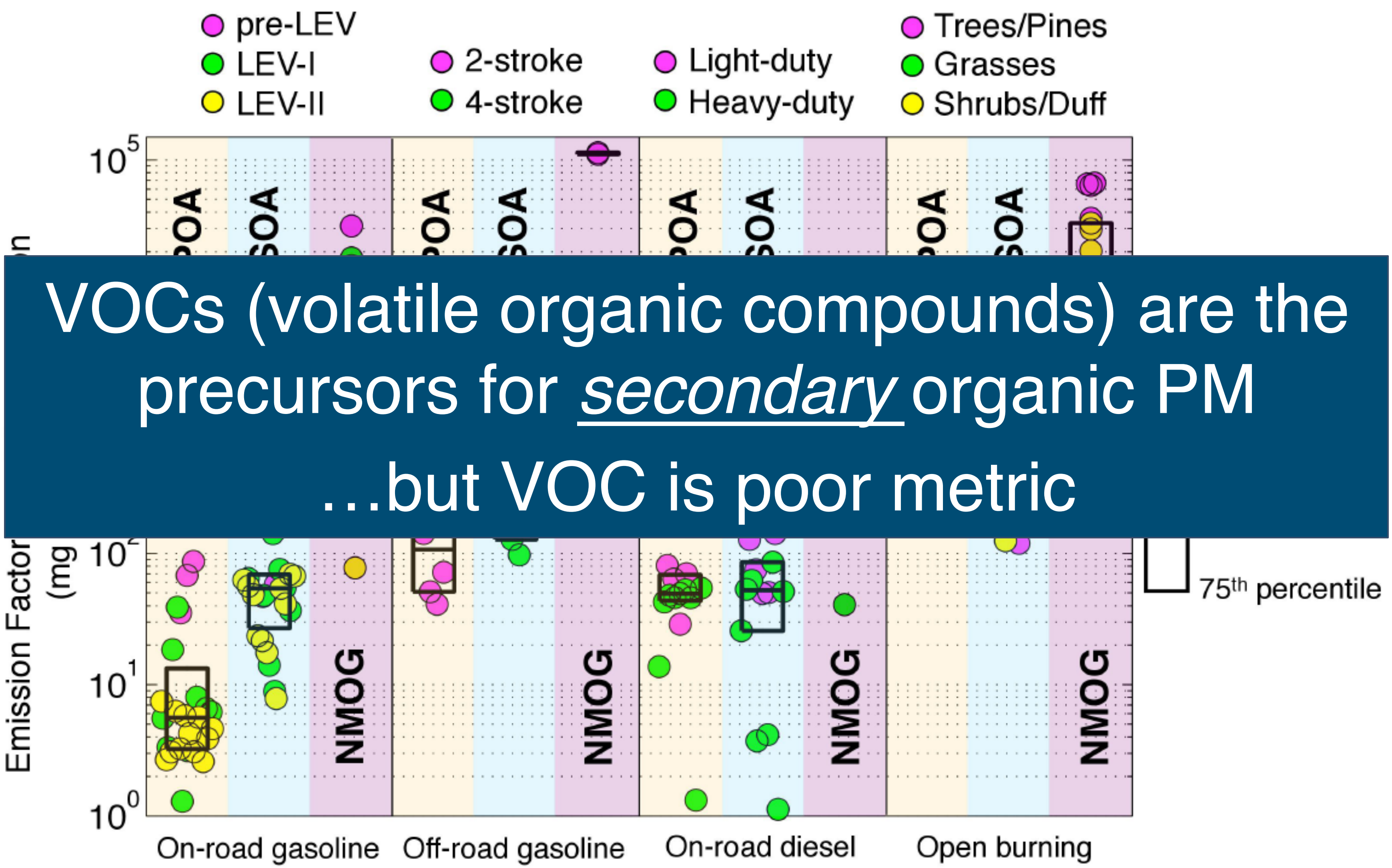
Rethinking Organic Aerosols: Semivolatile Emissions and Photochemical Aging

Allen L. Robinson,[1*] Neil M. Donahue,[1*] Manish K. Shrivastava,[1] Emily A. Weitkamp,[1] Amy M. Sage,[1] Andrew P. Grieshop,[1] Timothy E. Lane,[1] Jeffrey R. Pierce,[1] Spyros N. Pandis[1,2]

www.sciencemag.org SCIENCE VOL 315 2 MARCH 2007

- Explains secondary organic dominance
  - primary organics evaporate
  - overlooked organic PM precursors
  - greater oxidation
- paradigm shift … but still evolving

What Makes SOA?



VOCs (volatile organic compounds) are the precursors for *secondary* organic PM

…but VOC is poor metric

Jathar et al. PNAS (2014) Unspeciated organic emissions from combustion sources…

NMOG ≈ VOCs

PM2.5 Recap and Implications

- Most $PM_{2.5}$ mass is the result of ***atmospheric processing*** rather than direct emission
- Bad news: $PM_{2.5}$ mass is either
  - Nonlinear (inorganic)
    - need good understanding of nearby sources of SO_2, NO_x, NH_3
  - Poorly understood (organic)
    - don't trust VOCs as indicator
    - assume large uncertainties
- Good news: CAPS is in the next building

Tools Overview

- Need to relate emissions → concentrations → health impacts → monetization

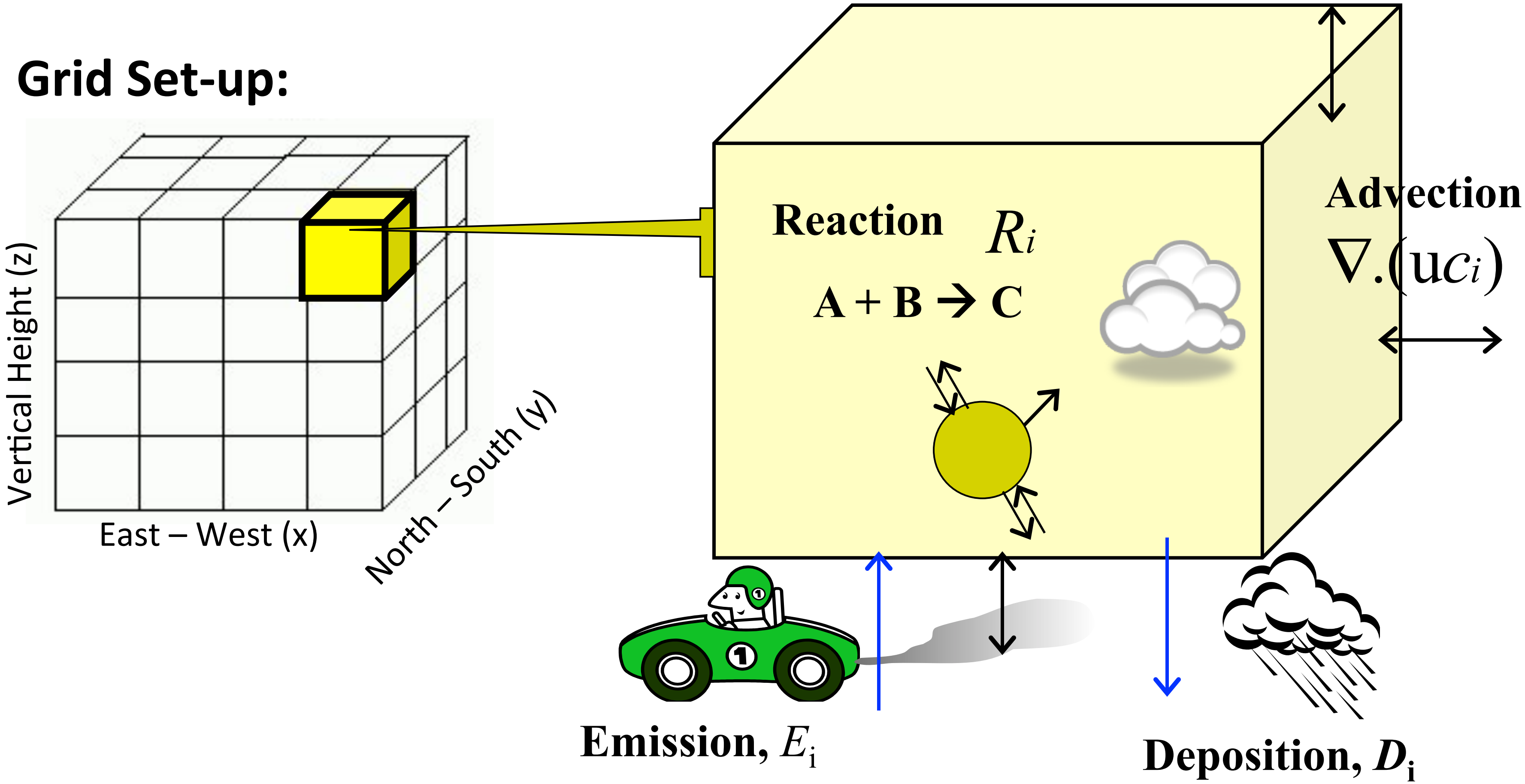
1. Chemical transport models (CTMs)
   - PMCAMx, CMAQ, WRF-Chem, others
2. Dispersion models
   - AIRMOD, CALPUFF, CRDM (derivation), others
3. Reduced-form models
   - CRDM (source-receptor), APEEP

- Note: BenMAP is not an AQ tool (takes conc as input)

CTMs: Overview

- Divide atmosphere into 3D grid of locations
- Each grid box has a mass balance ("continuity" equation)
- Use rate of change (dc_i/dt) to step forward in time

Grid Set-up:



CTMs: Continuity Equation

$$\underbrace{\frac{\partial c_i}{\partial t}}_{} + \underbrace{\frac{\partial}{\partial x}\left(\overline{u}c_i\right) + \frac{\partial}{\partial y}\left(\overline{v}c_i\right) + \frac{\partial}{\partial z}\left(\overline{w}c_i\right)}_{} = \underbrace{\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial c_i}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_{yy}\frac{\partial c_i}{\partial y}\right) + \frac{\partial}{\partial z}\left(K_{zz}\frac{\partial c_i}{\partial z}\right)}_{} + \underbrace{R_i + E_i - D_i}_{}$$

advective transport
by mean wind

transport by turbulent eddies

(local) rate of change of species i
in current grid cell

reaction
emissions
deposition

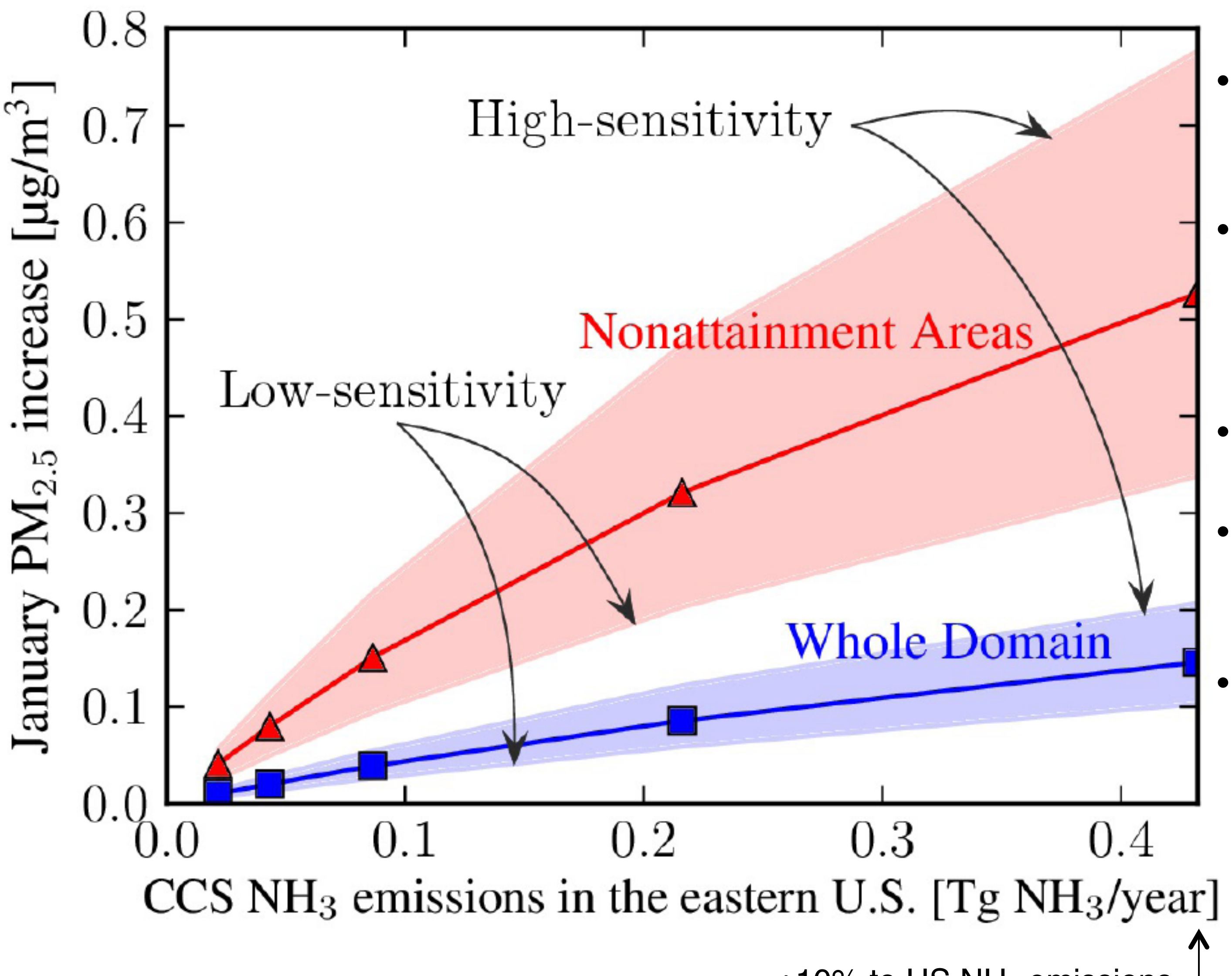
→Solve for $c_i(x,y,z,t)$

- c_i: concentration of species i
- D_i: rate of change due dry and wet deposition
- E_i: rate of change due to emissions
- $K_{xx,yy,zz}$: eddy diffusivities in x,y,z directions
- R_i: production/loss by reaction (defined broadly)
- t: time
- u,v,w: mean wind speed in x,y,z directions
- x,y,z: spatial coordinates

CTMs

- State-of-the-art
  - include all relevant processes … as best we understand them
- Challenging
  - simulations can take days or weeks, even on high-end computers
  - FORTRAN (!)
  - not bad to run once overhead is paid
- Used for *real* regulatory analyses
  - new EPA rules: CAIR, CSAPR, etc.
  - SIP planning
- Everything else is screening tool (simplified)

CTMs: Treating Uncertainty



- Full-fledged Monte Carlo impossible
- Bounding cases possible (with intuition)

- Example: CCS ammonia
- some observed nonlinearity in PM response
- did "high/low sensitivity" bounds (different SO_2, NO_x, NH_3 from non-CCS sources)

Heo et al. submitted to ES&T (2014)

Social Costs from CTMs

The influence of location, source, and emission type in estimates of the human health benefits of reducing a ton of air pollution

Neal Fann · Charles M. Fulcher · Bryan J. Hubbell

	Area source carbon	Mobile source carbon	EGU & Non-EGU carbon	Area source SOx	EGU SOx	Non-EGU SOx	VOC	Area source NH3	Mobile source NH3	EGU NOx	Non-EGU NOx	Mobile source NOx
National	$720,000	$550,000	$460,000	$40,000	$							
Atlanta	$670,000	$590,000	$620,000	$48,000	$							
Chicago	$510,000	$580,000	$600,000	$29,000	$							
Dallas	$1,100,000	$790,000	$1,100,000	$140,000		$29,000	$600	$16,000	$36,000	$34,000	$920	$370
Denver	$280,000	$450,000	$220,000	$75,000	$6,400	$19,000	$1,400	$10,000	$58,000	$3,200	$3,800	$2,700
NY/Phi	$570,000	$710,000	$780,000	$14,000	$74,000	$50,000	$4,300	$53,000	$140,000	$1,500	-$2,600	-$8,200
Phoenix	$2,500,000	$1,700,000	$980,000	$73,000		$550,000	$2,000	$15,000	$43,000	$11,000	-$2,100	-$680
Salt Lake	$140,000	$150,000	$65,000	$15,000		$9,100	$2,600	$29,000	$43,000		$4,200	$1,500
San Joaquin	$910,000	$560,000	$720,000	$140,000	$350,000	$46,000	$5,700	$36,000	$140,000	$28,000	$28,000	$43,000
Seattle	$500,000	$570,000	$720,000	$54,000	$6,300	$52,000	$560	$18,000	$49,000	$120,000	-$2,300	-$8,100

Computational limitations → limited resolution

- 9 urban areas + national average
- sources: EGUs, mobile sources, area sources

Geographic Definition of Nine Urban Areas Modeled in Response Surface Model

Fann et al. 2009

Social Cost: Interpretation

- Reflects efficiency of precursor to $PM_{2.5}$ mass

Emissions	Social Cost ($/ton)	Notes
Primary, inert $PM_{2.5}$	$500-750k	It's already PM2.5!
SO_2	$40-80k	Sizeable fraction will react to form sulfate
NH_3	$40k	Requires reactions, conditional based on T etc
NO_x	$10-15k	
VOCs	$2k	Most VOCs don't form organic PM

- Spatial variation due to population density
- Seasonal variation per known $PM_{2.5}$ chemistry

Values from Fann et al. 2009

EPA RSM (Response Surface Model)

- Good
  - Reduced-form model tuned to CMAQ CTM
  - captures nonlinearities over wide range of emissions
- Limitations
  - limited spatial resolution on sources (national or 9 cities)
  - outdated organic PM chemistry
- Uses
  - good for large, national changes in inorganic $PM_{2.5}$ (e.g. EGU regs)

Geographic Definition of Nine Urban Areas Modeled in Response Surface Model

Gaussian Dispersion Models

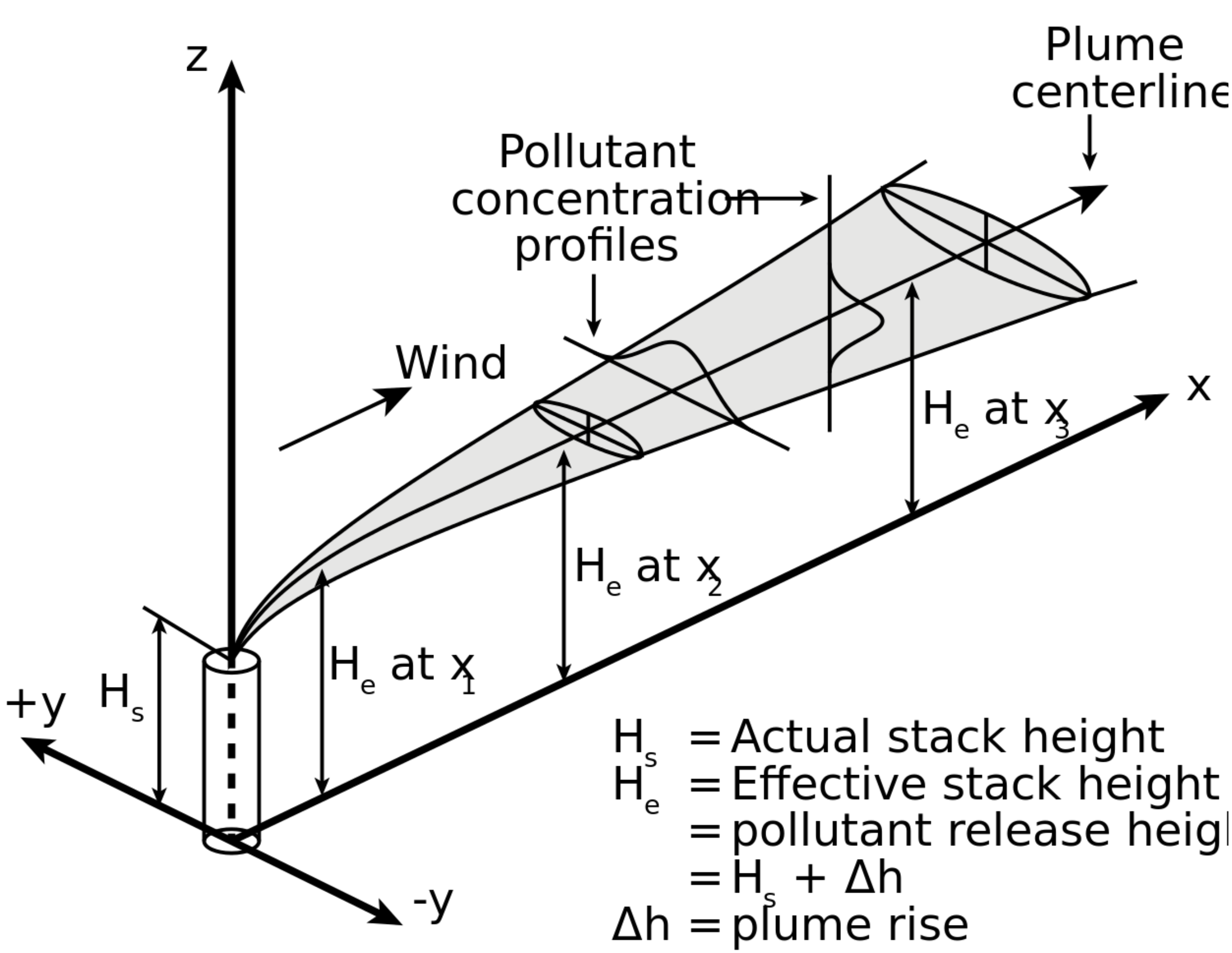


Image from Wikipedia Commons

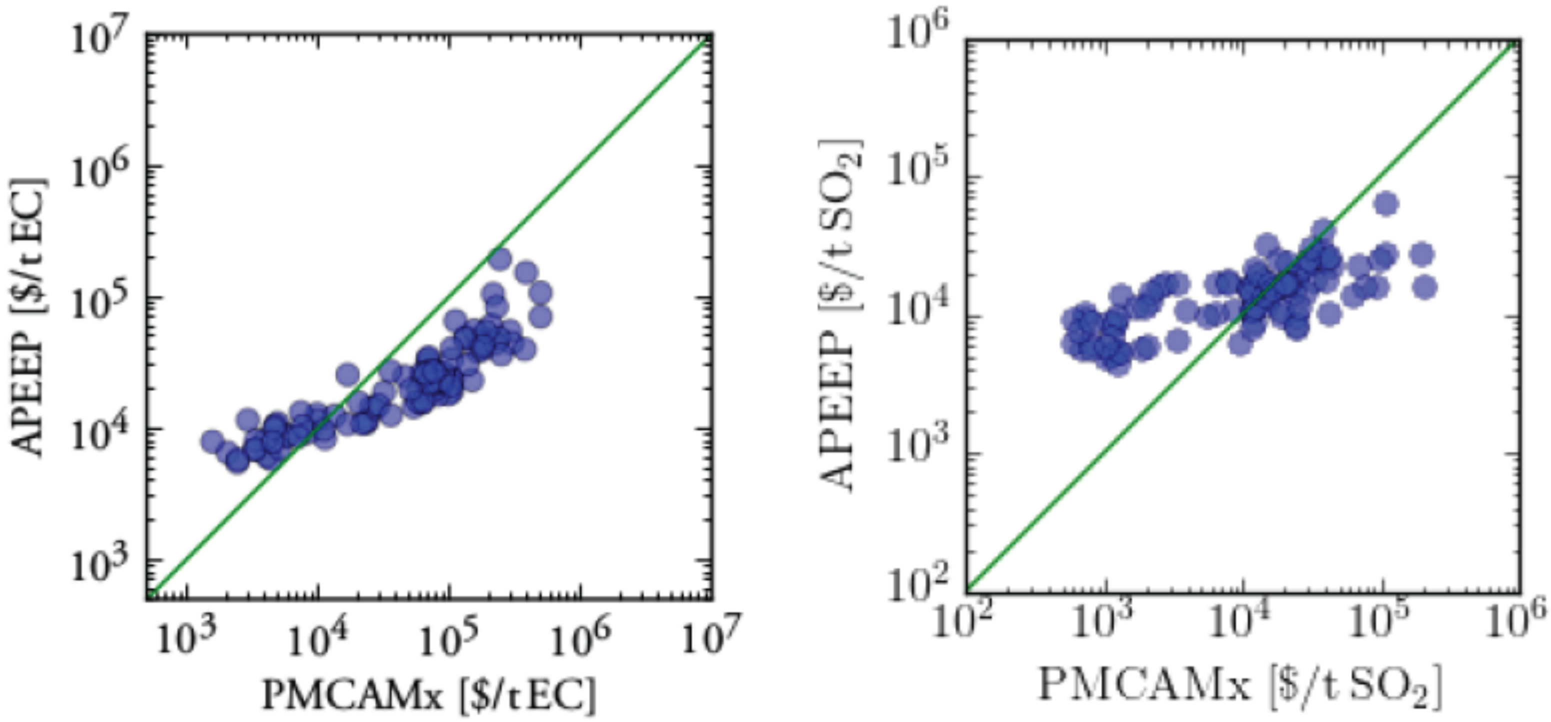
Gaussian Dispersion Models

- Plume (steady-state) or puff (non-steady state)
- Examples: AIRMOD, CALPUFF
- **Pros**: pretty simple, computationally efficient
- **Cautions**: need to average over enough meteorological conditions
- **Cons**:
  - Limited (first-order losses) or no atmospheric processing
  - Recommended only for near source (<100 km)
- **Uses**: single-source, nearby impacts for non-reactive species

CRDM + APEEP

- EPA Climatological Regional Dispersion Model (1996 plus 2004 update)
- Source-receptor matrix
  - relates county-level emissions to county-level conc.
- Core is dispersion model but applied to *<u>all sources nationally</u>*
- Some variation in meteorological fields
- Fixed NO_x oxid. rate; RH-dependent for SO_2
- Highly simplified inorganic $PM_{2.5}$ interactions
  - nitrate PM will form given enough NH_3, then divide by 4 for seasonal effects
- Obsolete organic PM
- APEEP is CRDM plus conc-response, VSL
- COBRA is basically a user interface for CRDM plus calculation of impacts

CRDM/APEEP vs CTMs



- Simplest (EC) and next simplest (SO_2) species
- National-average values are quite similar
- Spatial distributions different; CTM has more variability
- Hypothesis: dispersion model smooths out too much at long distances?

Recap: Current Tools

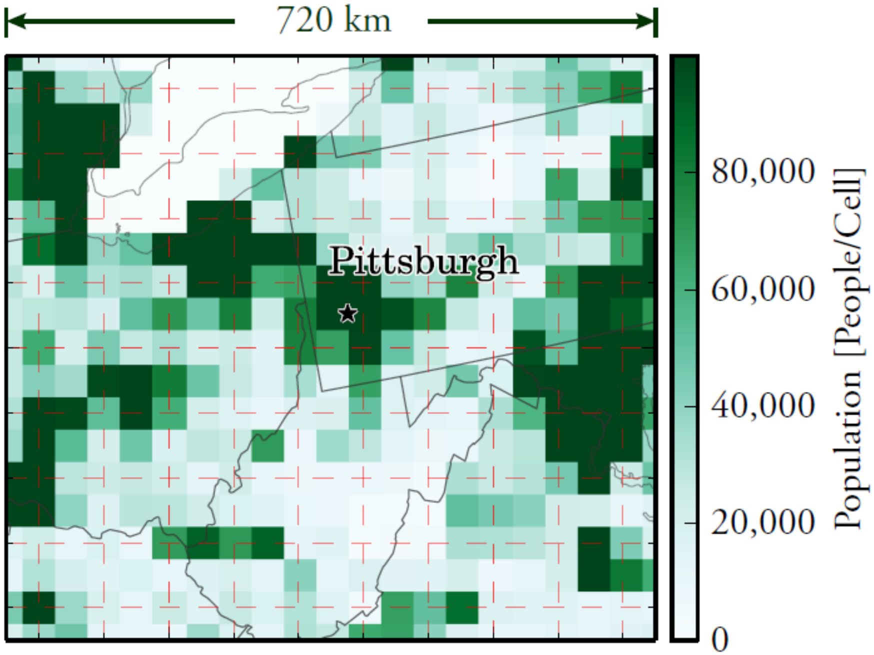
- CTMs: slow, for experts (and collaborators)
- Dispersion: not generally applicable
- Reduced-form are either:
  - Derived from dispersion models (CRDM, APEEP)
  - Have old understanding of organic PM (all)
  - Limited spatial resolution (RSM)

- Want reduced-form tools that are
  - Computationally efficient; high spatial resolution
  - Derived from modern CTMs; easy-to-update

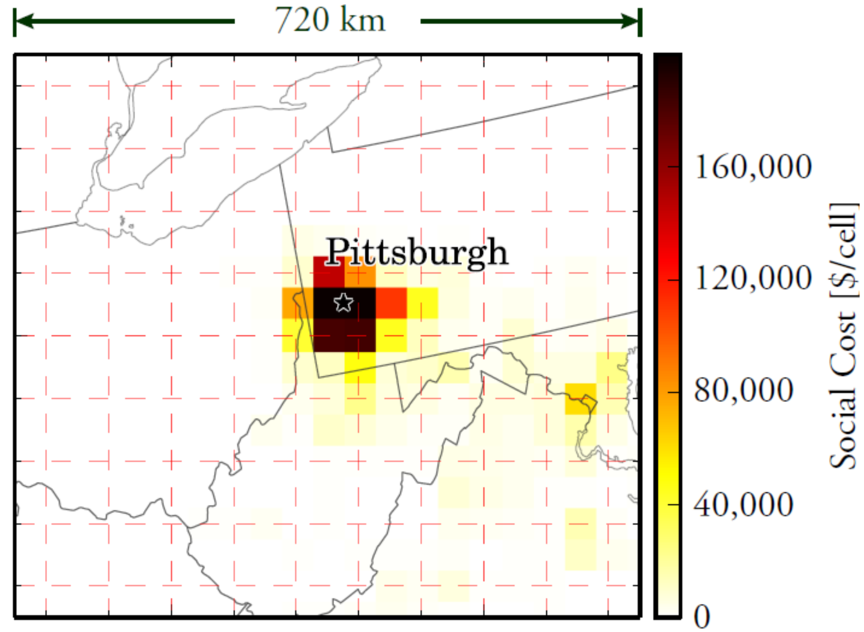
EASIUR

<ins>E</ins>stimating <ins>A</ins>ir pollution <ins>S</ins>ocial <ins>I</ins>mpacts <ins>U</ins>sing <ins>R</ins>egression (EASIUR)

$$\text{Social Cost} \simeq \begin{pmatrix}\Delta\text{Mortality Rate} \\ \text{by } \Delta PM_{2.5}\end{pmatrix} \times \boxed{(\text{Exposed Population})} \times (\text{VSL})$$



Population around Pittsburgh



Social Cost of Pittsburgh Elemental Carbon

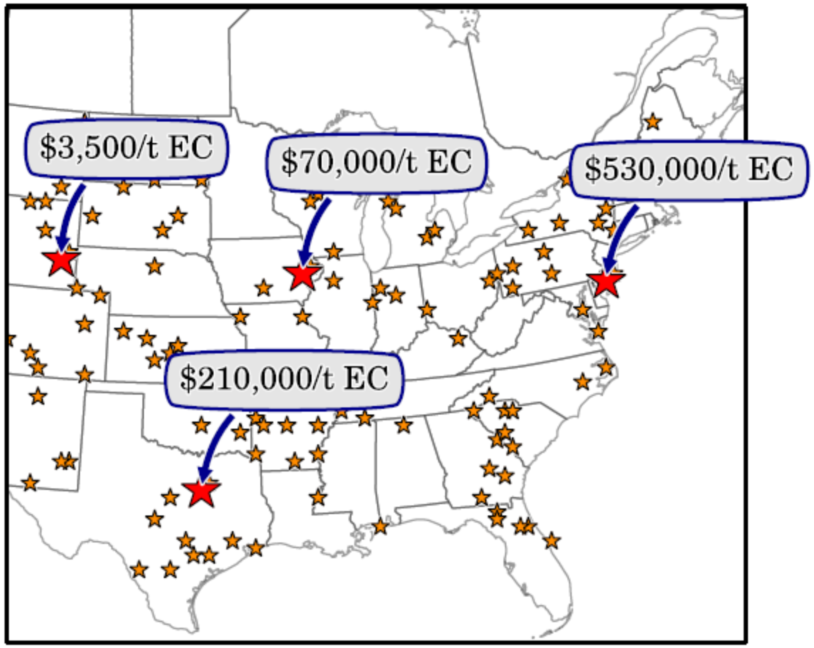
3 t EC/day emitted in Pittsburgh

Research Design

Our goal is to derive:

Per-tonne Social Cost [$/t]	= *f* (Population, Atmospheric Variables)
Intake Fraction [ppm]	= *g* (Population, Atmospheric Variables)

3. Calculate per-tonne social costs and intake fractions for the 100 locations.



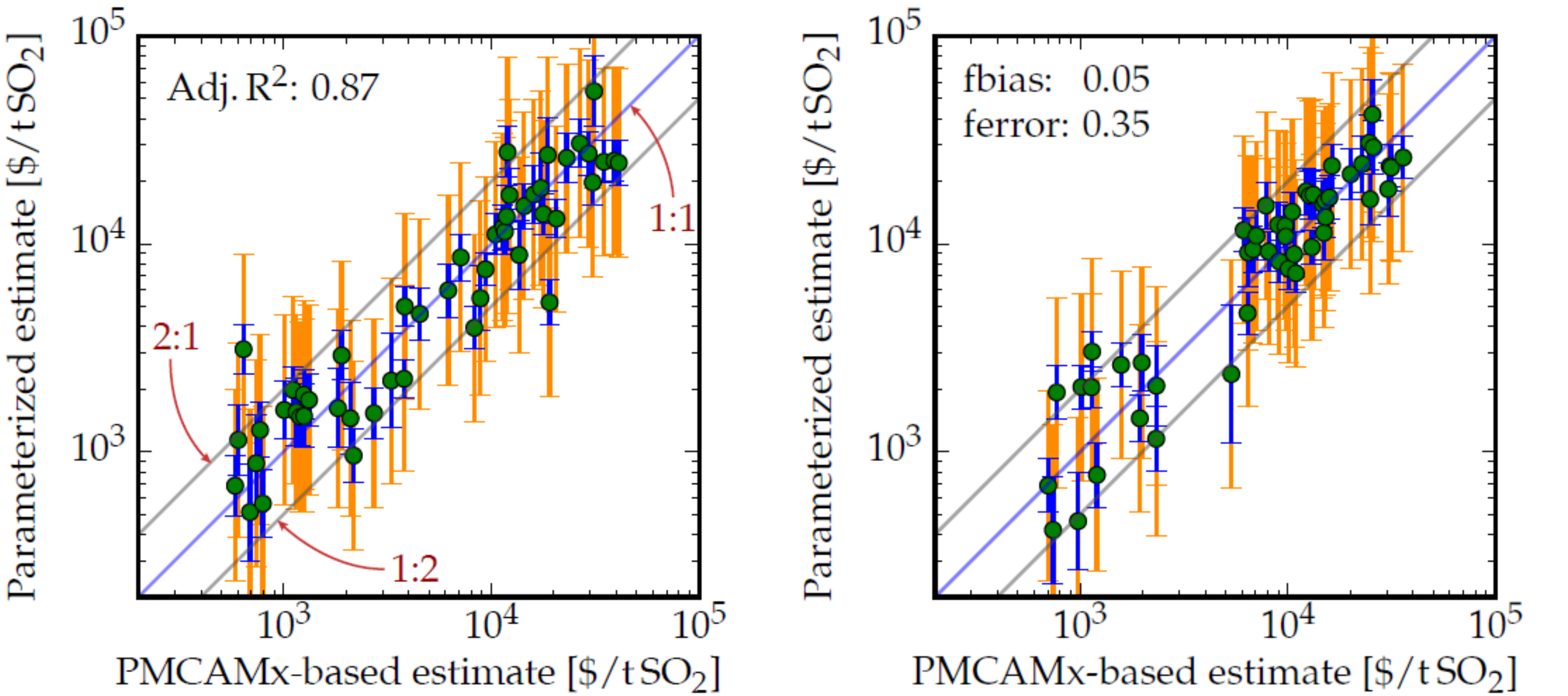
- Concentration-Response Function: Pope et al (2002), one of the most widely used epidemiological studies.
- VSL: $6.3M in 2000 USD from U.S. EPA.

PSAT "source tagging" algorithm lets us get 100 location-specific emissions perturbations in ~5 simulations

EASIUR: SO_2 Results

$$\text{Social Cost }[\$/\text{t } SO_2] = 1.1 \cdot 10^{48} \cdot Pop_w^{0.97} \cdot Wind^{-0.47} \cdot Temp^{-22} \cdot WVap^{1.4}$$

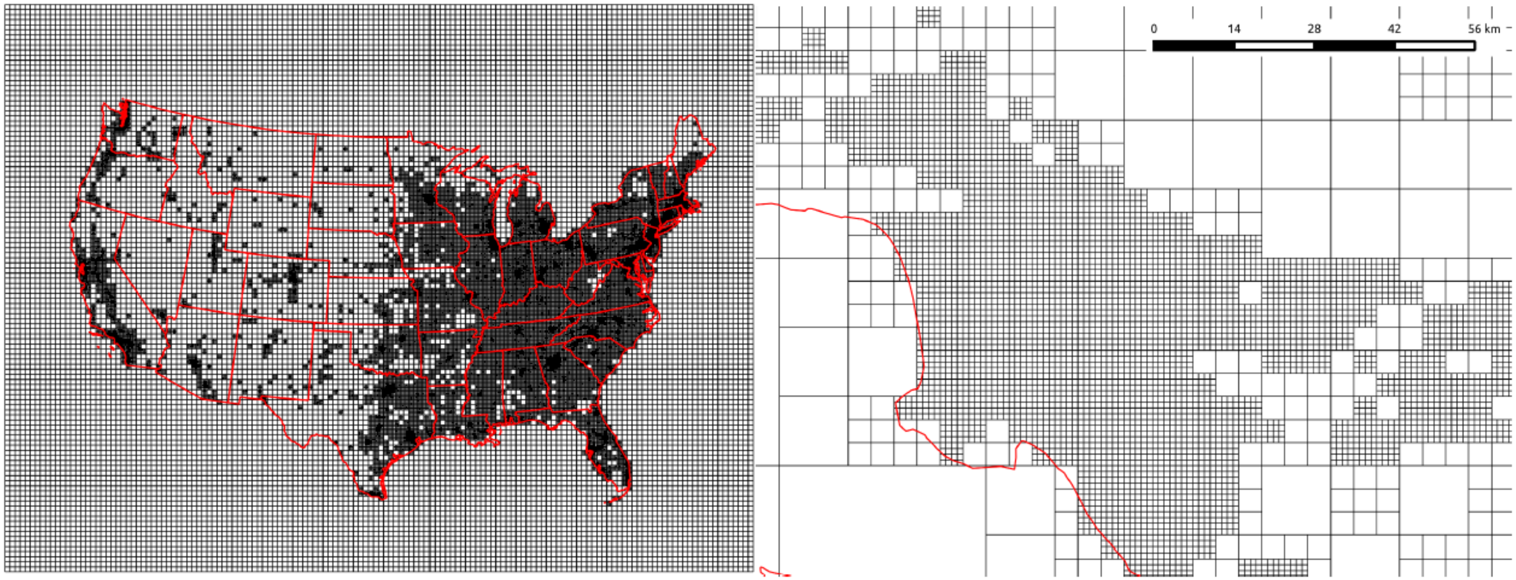
Pop_w: w. pop, *Wind*: wind speed, *Temp*: temperature [K], *WVap*: water vapor [ppm]



(a) Fitted values (b) Out-of-sample evaluation

Similar performance for NO_x and NH_3, even highly nonlinear wintertime cases

InMAP

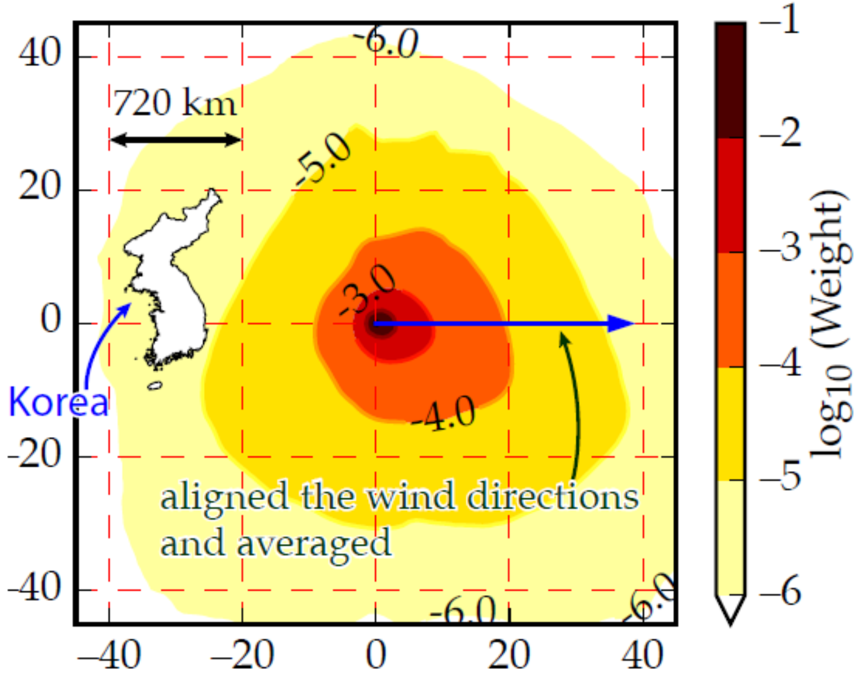


- Chris Tessum and Julian Marshall (UMN)
- InMAP: Intervention Model for Air Pollution
- Structured like CTM except
  - Annual-average conditions → computationally efficient
  - Rate parameters taken from a CTM
  - Variable horizontal resolution

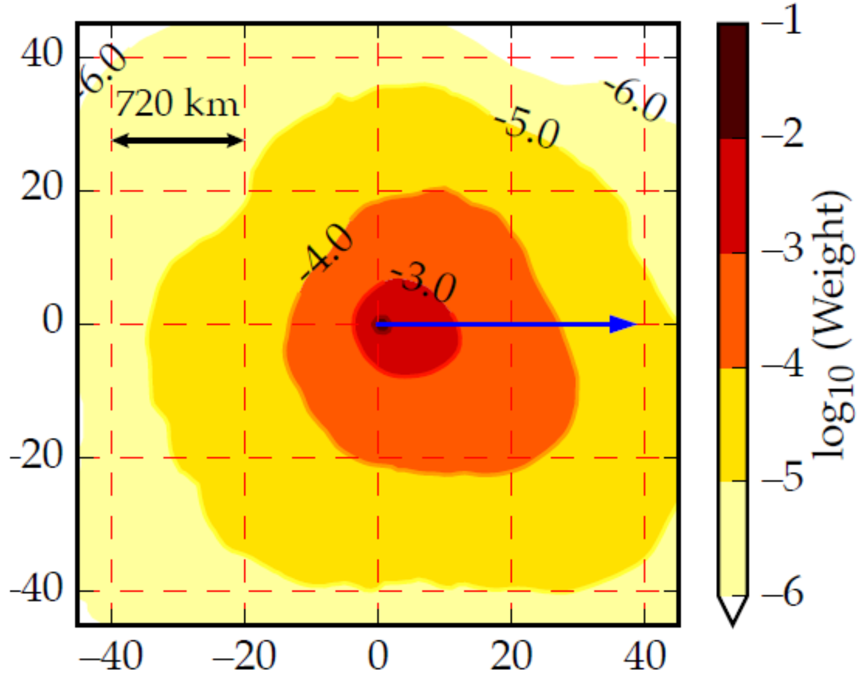
Summary

- $PM_{2.5}$ shows up big in cost-benefit analyses
- Airborne PM is fairly complex
  - Inorganics: nonlinear
  - Organics: poorly understood
- Current tools vary in complexity
  - all have limitations
  - may be suitable for some analyses when chosen with care
- Better tools (EASIUR, InMAP) nearing publication
- CAPS is nearby (Doherty Hall 2110)

Exposed Population

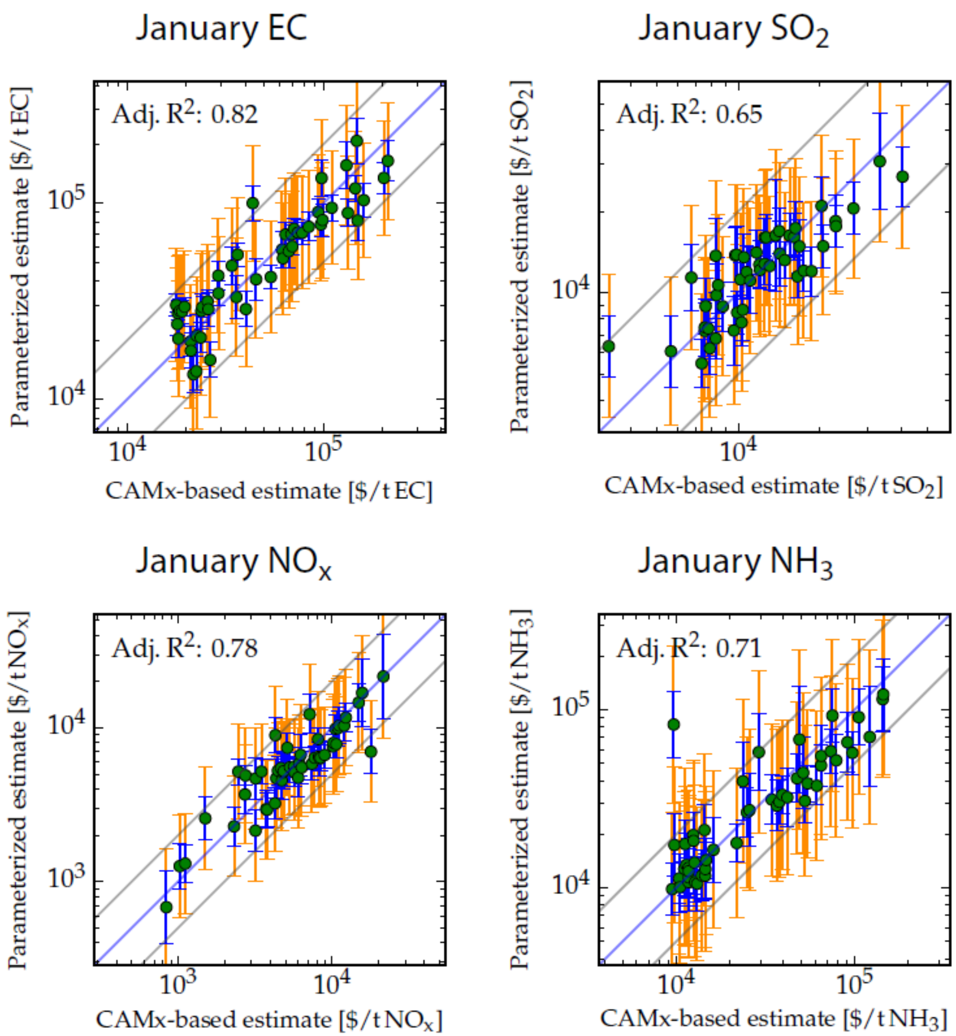


(a) EC Average Plume Weight



(b) SO_2 Average Plume Weight

Now, Expanding to Build a Fully Working Set of Models

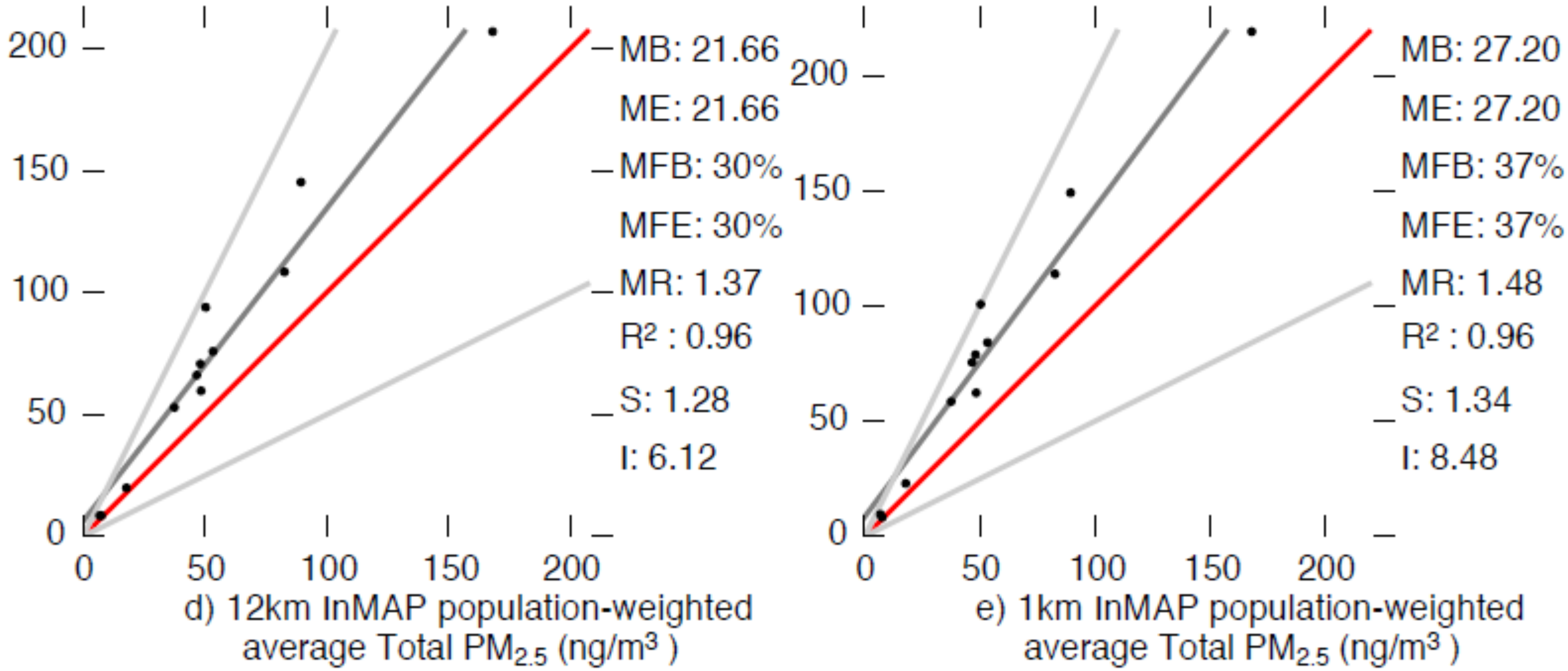


We are currently expanding our parameterization:

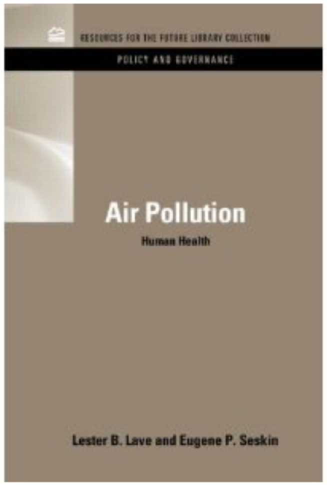
- More species: EC, SO_2, NO_x, NH_3 (for both area and point sources)
- Four seasons
- Contiguous United States

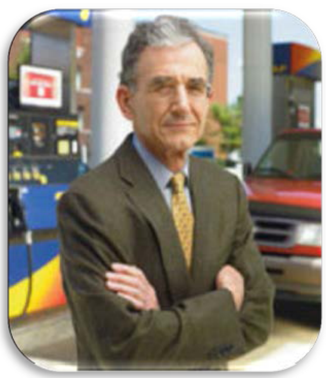
Winter is the most challenging due to the non-linear thermodynamics of inorganic species, but we have good results for Winter, as shown on the left, and better results for other seasons.

InMAP Evaluation



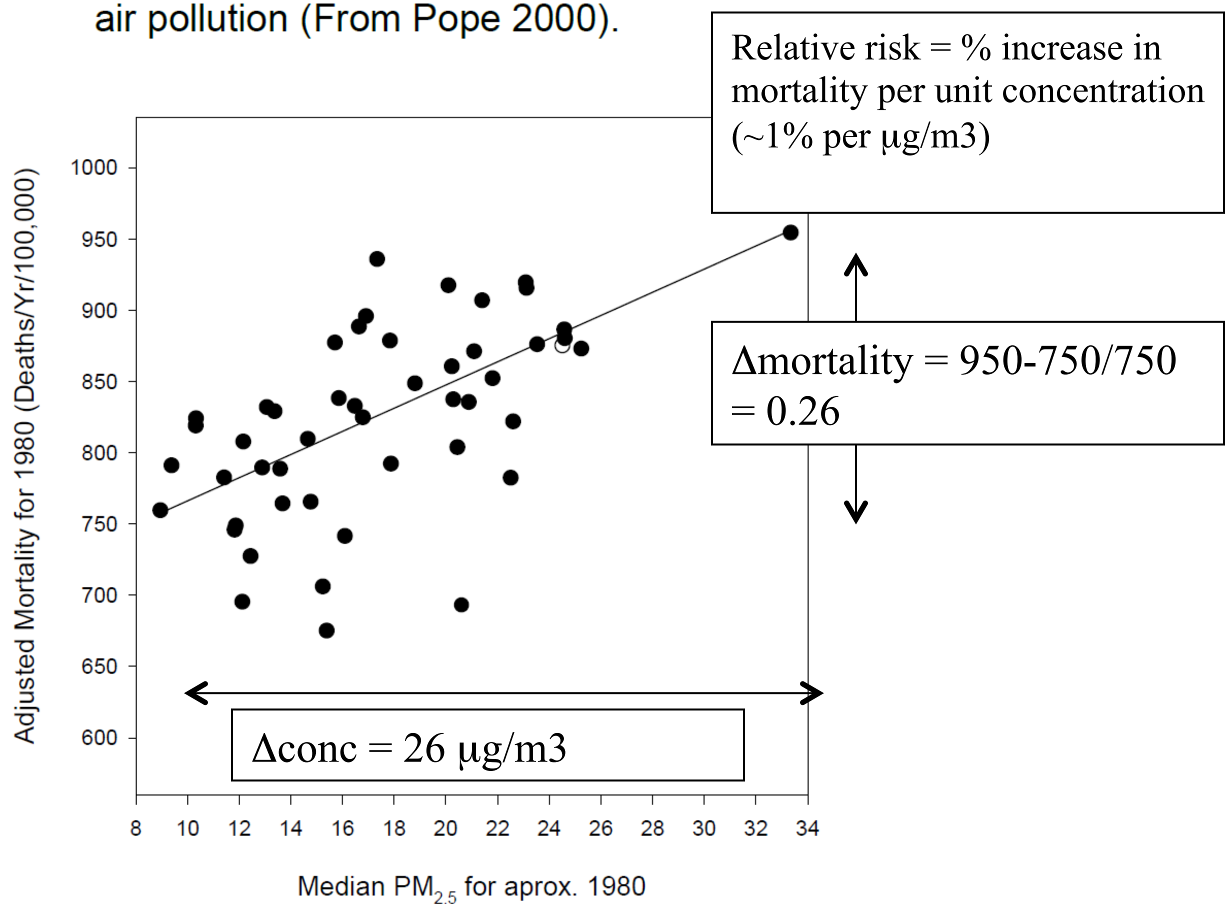
Mortality: Relative Risk





Prof. Lester Lave
(CMU)
1939-2011

Age-, sex-, and race- adjusted population-based mortality rates in U.S. cities for 1980 plotted over various indices of particulate air pollution (From Pope 2000).



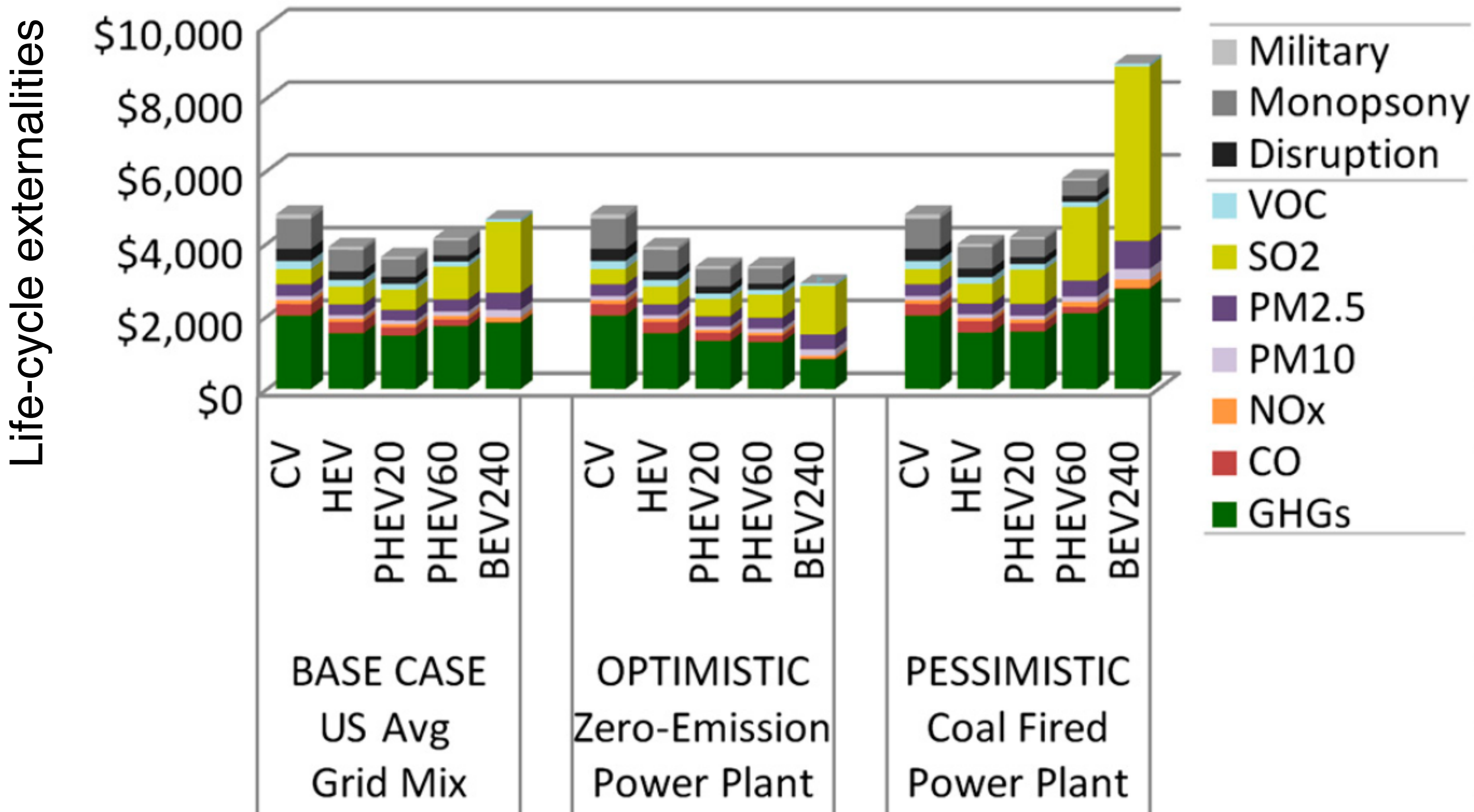
Slide used with permission from C. Arden Pope III (Particulate Air Pollution and Human Health: Science, Controversy, and Public Policy)

Costs and Benefits

- Cross-State Air Pollution Rule (CSAPR)
  - most recent EPA rule targeting $PM_{2.5}$
- Emissions reductions (2014 vs 1990)
  - SO2: ~80%
  - NOx (annual): ~70%
- Estimated to prevent 13,000-34,000 premature deaths/year
- Cost-benefit analysis
  - Costs: $2.4 billion/year
  - Benefits: $120 to $280 billion/yr

http://www.epa.gov/airtransport/pdfs/CSAPRPresentation.pdf

Air Pollution Needs Consideration



Air pollution ($PM_{2.5}$) damages were comparable to climate ones

Michalek et al. PNAS (2011)