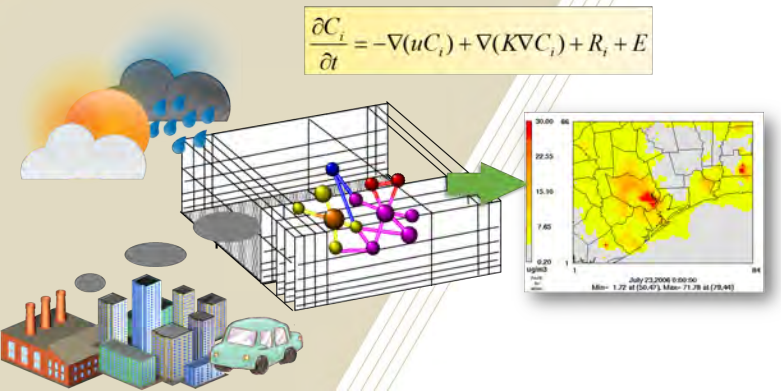
Air Pollution and CO2 Controls: Co-benefits of controls

Armistead (Ted) Russell, Petros Vasilakos, Amir Hakami, Yongtao Hu, Talat Odman, Charley Driscoll & Clean Energy Futures Team,, and Many More



ASME TEC Talk
September 10, 2025

Georgia Tech
CREATING THE NEXT

Acknowledgements

Lots of Organizations (and people) have directly or indirectly contributed to this presentation (these are a few):

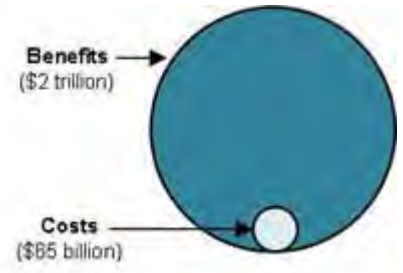
But the opinions are all mine, and the views expressed are those of the author and do not necessarily represent the views of any of the organizations that have help formulate those views.

Topics

- Air pollution and health
  - We spend about $65 billion/yr
  - Benefits are about $2 trillion
    - Primarily PM reduction on mortality



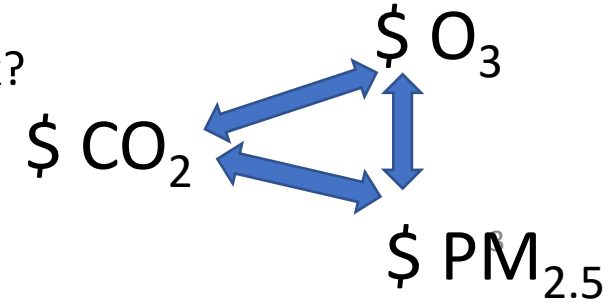
US EPA;



- Climate and Emissions Controls
  - What is, has and can be done
    - Some work on both, others not

- Air quality modeling
  - Chemical transport models
    - Combining atmospheric physics and chemistry modeling: Some basics

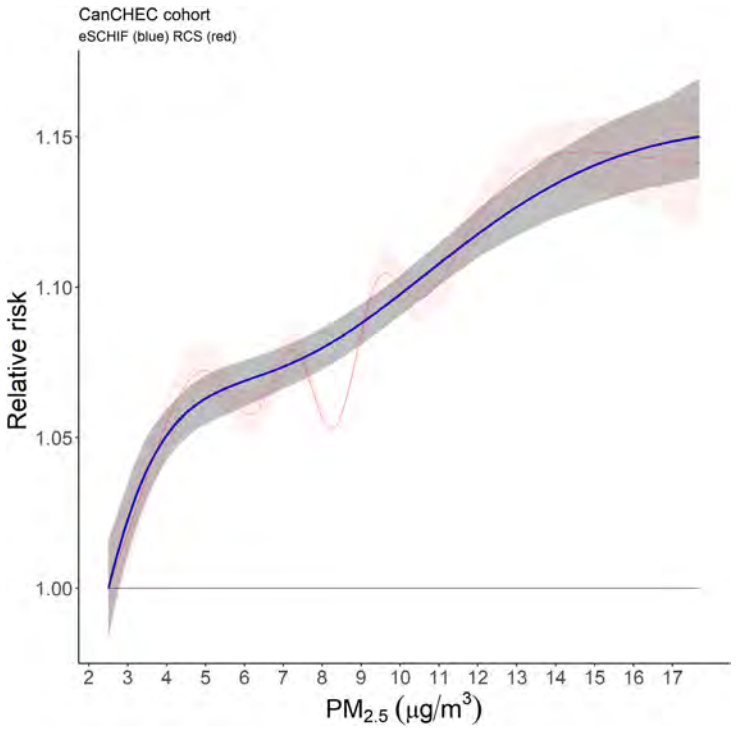
- Addressing air quality and climate together
  - Climate control costs will be large: how can we get more bang for our buck?



- Wrap up

Air Quality and Health

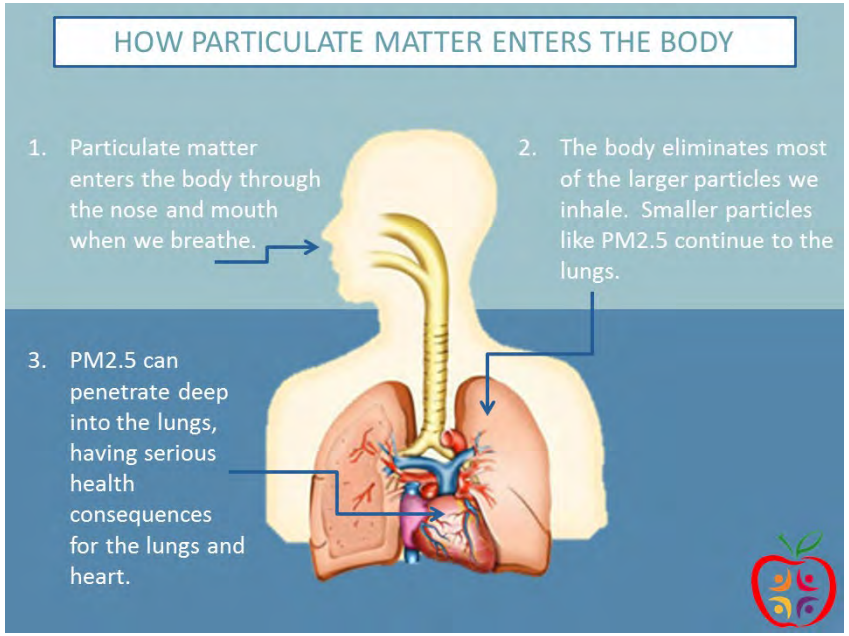
Weichenthal et al., (2022) Sci. Adv.



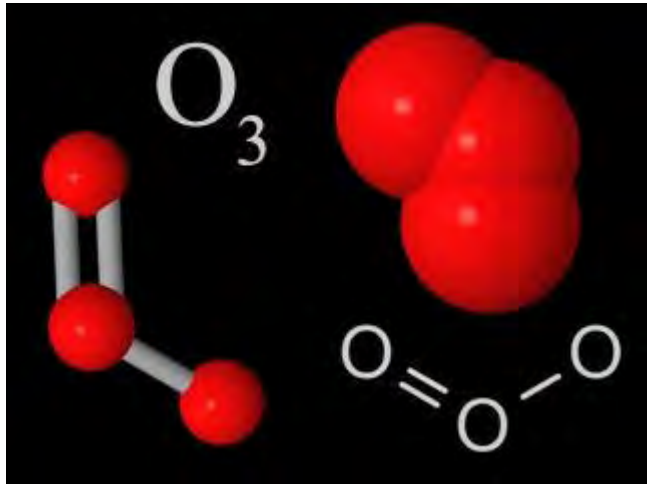
What about health and air quality

- Why a focus on air quality?
  - Air pollution is a killer (and leads to other diseases)!
  - Particulate matter
    - Very small particles in the air that get in to your lungs



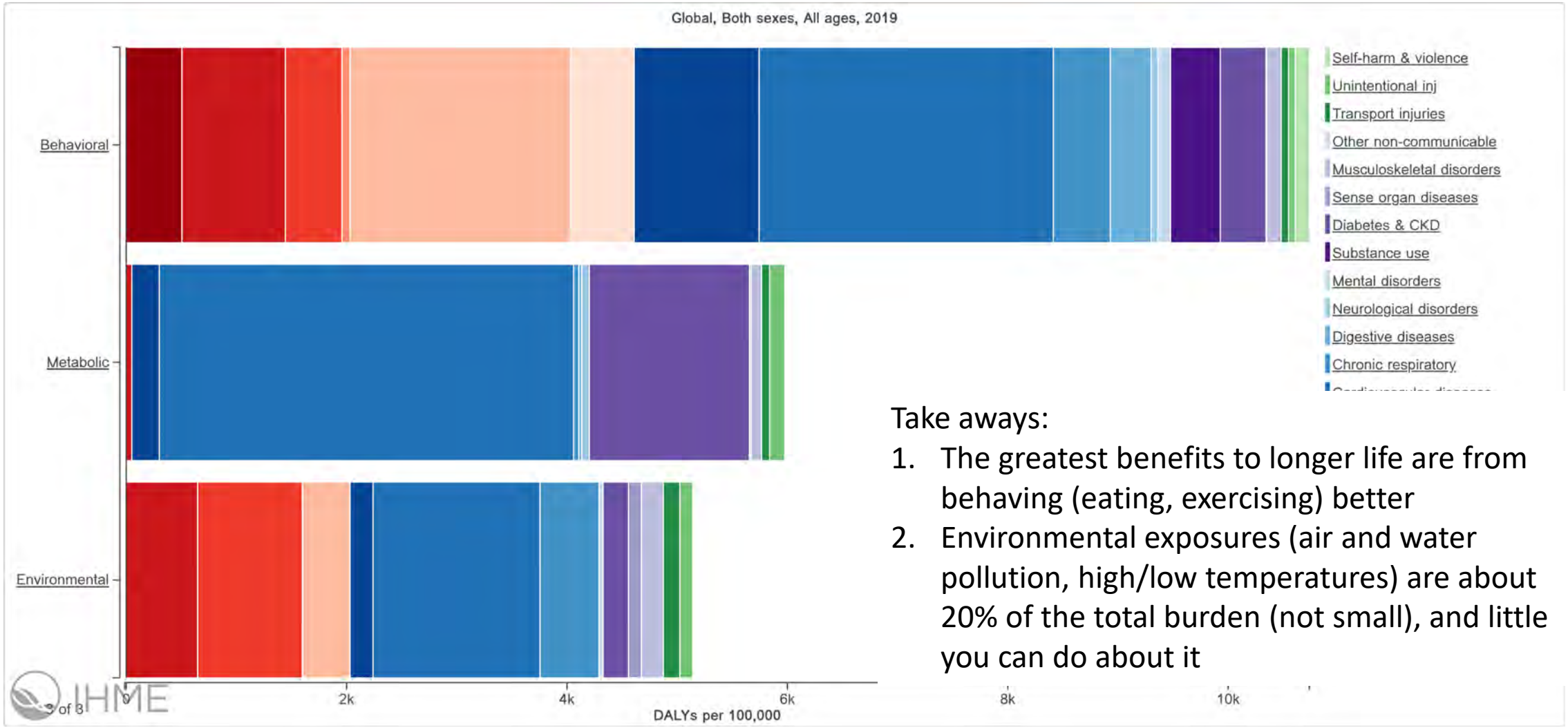


  - Ozone (O_3)
    - A reactive gas that triggers asthma and other diseases
    - An oxygen molecule (good) with an extra oxygen atom (bad)
    - Good in the stratosphere (about 15 km up), bad at ground level where people breathe



Sources: US EPA, UtahAir

Global Burden of Disease



Take aways:

1. The greatest benefits to longer life are from behaving (eating, exercising) better
2. Environmental exposures (air and water pollution, high/low temperatures) are about 20% of the total burden (not small), and little you can do about it

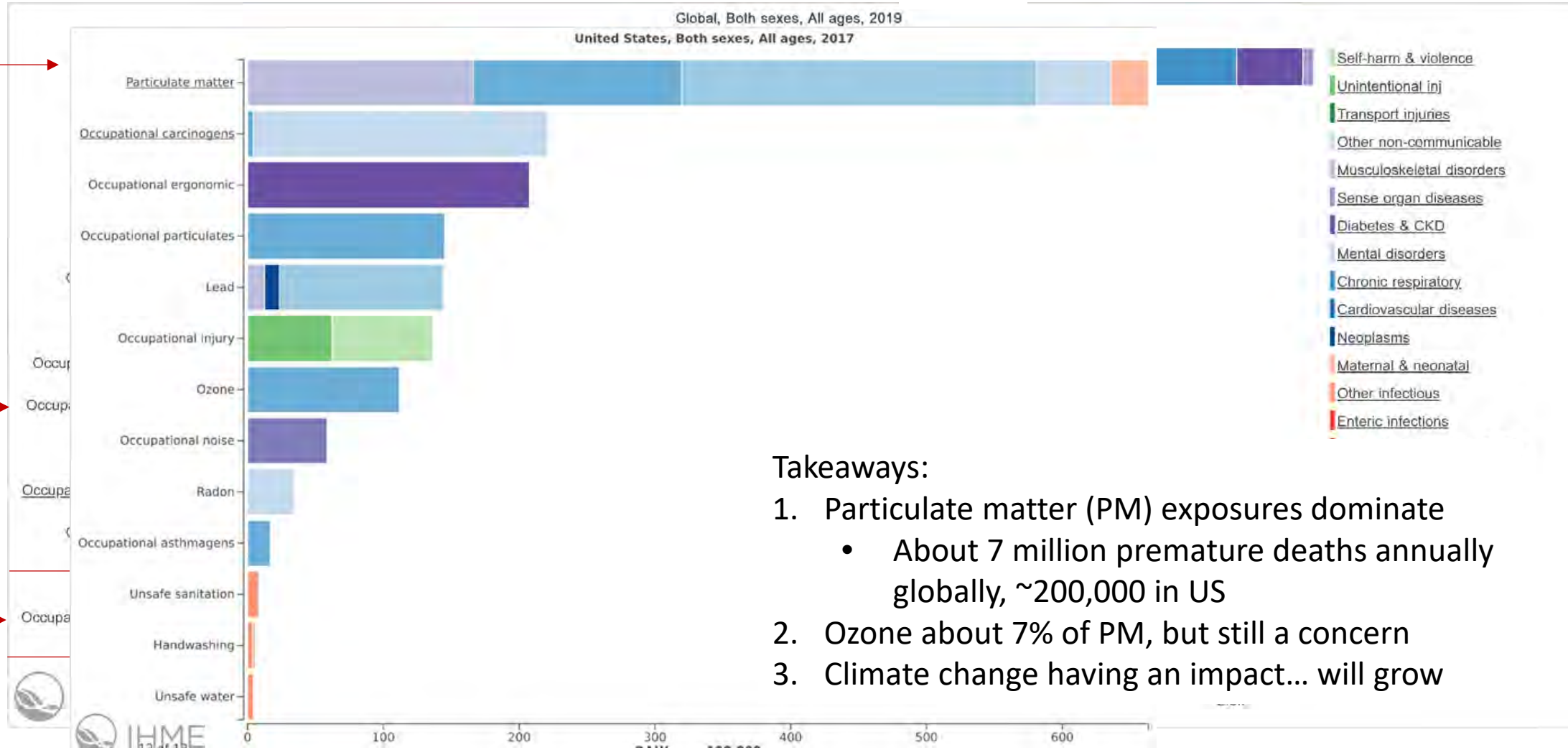
DALY: Disability-adjusted Life Year (lost), integrating premature death and how disabilities impact quality of life

(source: GBD Vishub: https://vizhub.healthdata.org/gbd-compare/#0)

Global Burden of Disease: Environmental Causes

(a great resource: https://vizhub.healthdata.org/gbd-compare/)

World

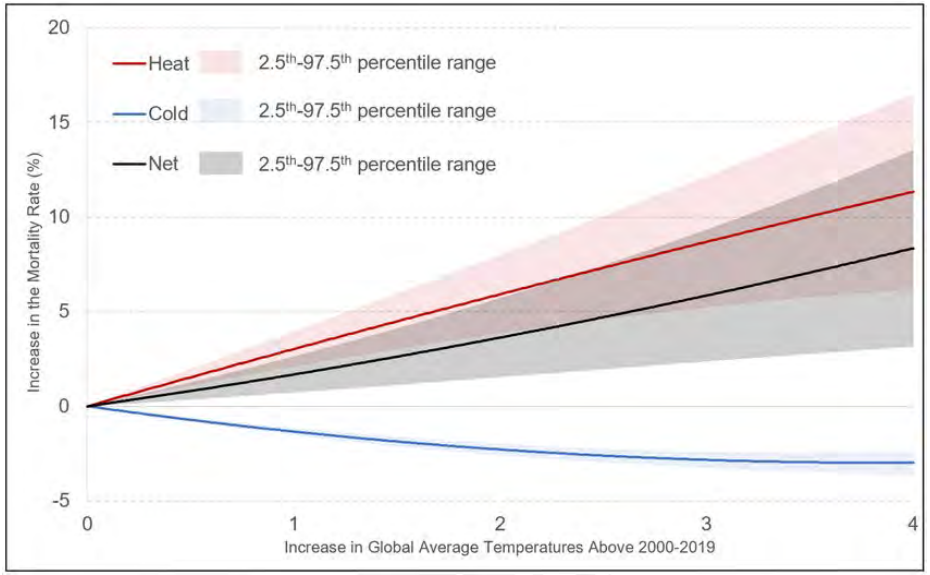


Takeaways:

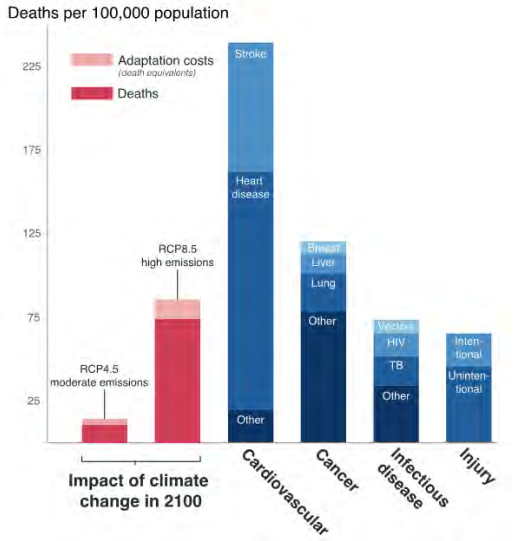
1. Particulate matter (PM) exposures dominate
   - About 7 million premature deaths annually globally, ~200,000 in US
2. Ozone about 7% of PM, but still a concern
3. Climate change having an impact… will grow

Climate and health

- Increased mortality with temperature increase
  - Fewer deaths from cold exposure, but increases from higher temperatures is larger
- Air pollution larger



Bressler, R.D. The mortality cost of carbon. *Nat Commun* **12**, 4467



Carleton et al., Q. J. of Economics, 2022

Question: Can we "use" air quality benefits to help pay for climate controls?

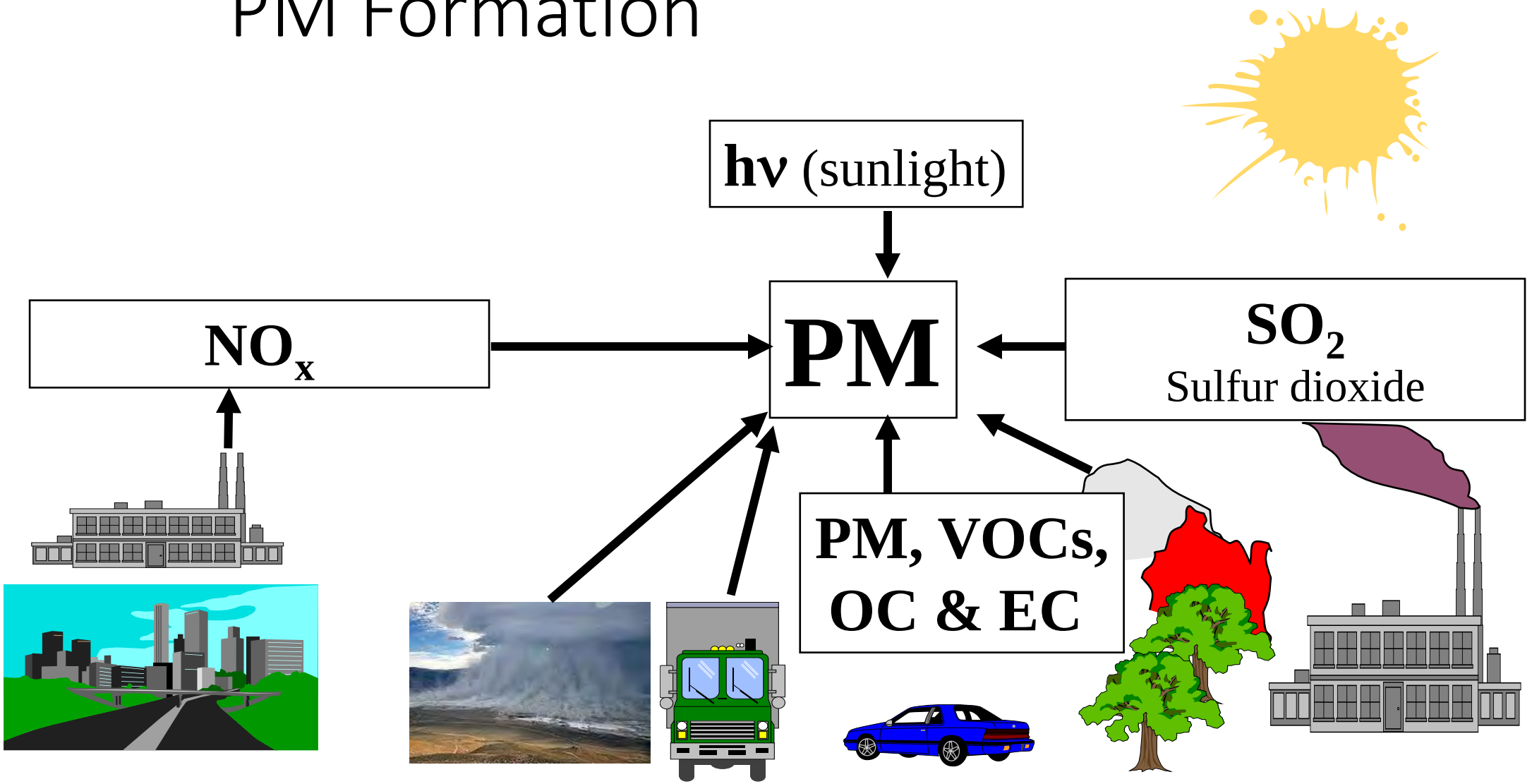
Env. Defense Fund



Air Pollution Formation

And its link to climate forcing

PM Formation

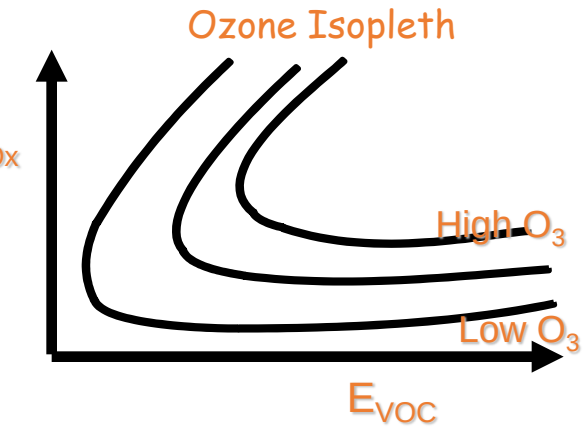


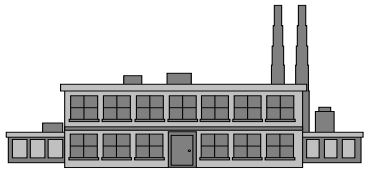
Ozone Formation

hν (sunlight)

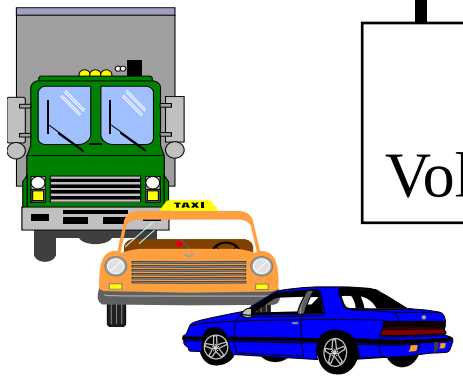
NO_x
oxides of nitrogen
($NO + NO_2$)

O_3

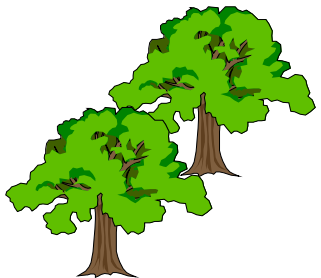








VOCs
Volatile organic compounds

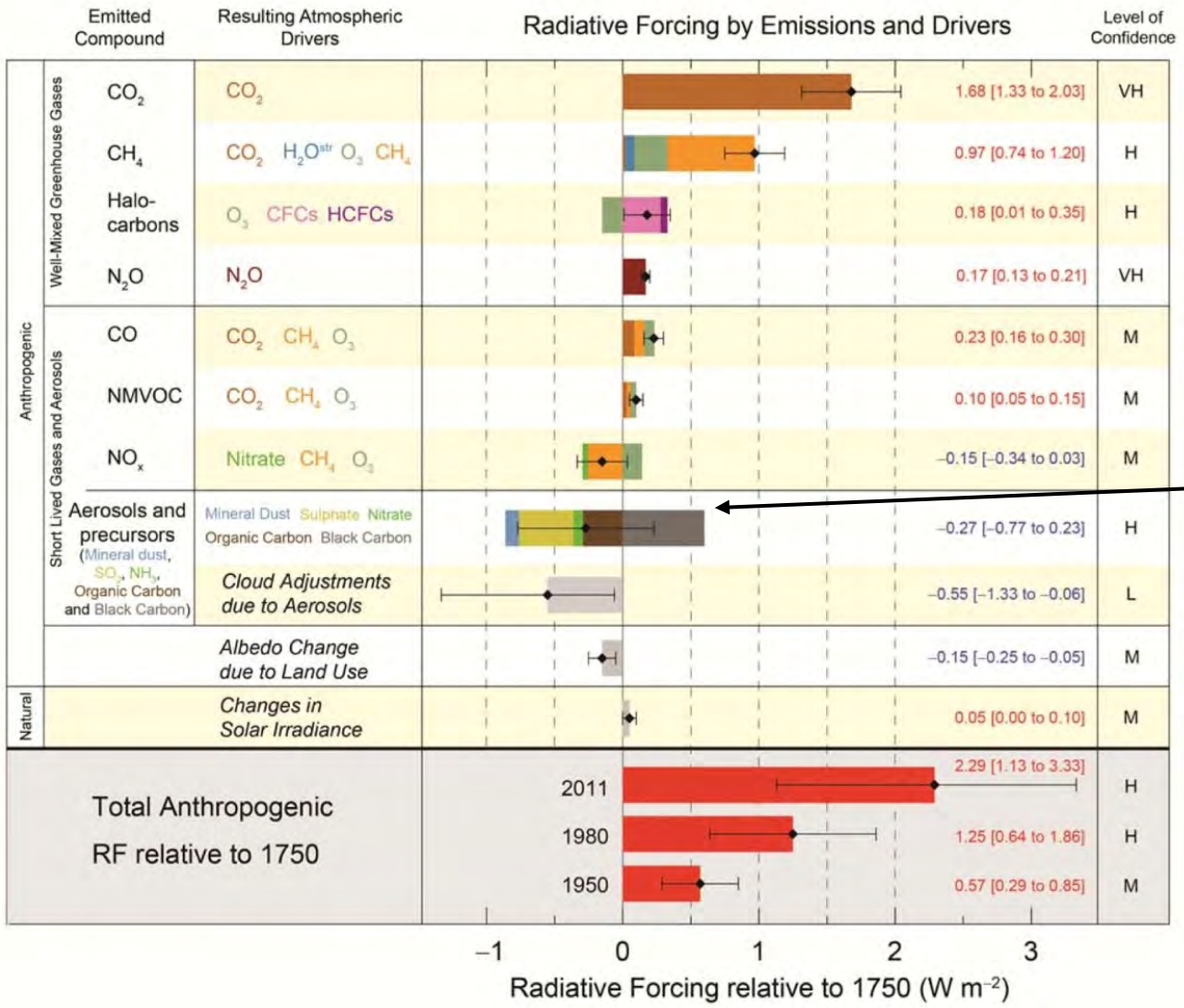


Air Pollution Impacts Climate Warming (and vice versa)

1. Many of the air pollutants of concern directly impact climate (methane, ozone, particulate matter) or contribute to greenhouse gases (CO, NOx, organic gases)

2. Climate warming will make air pollution worse: the "climate penalty"

3. **Controlling air pollution and GHGs can benefit each other (co-benefits)**

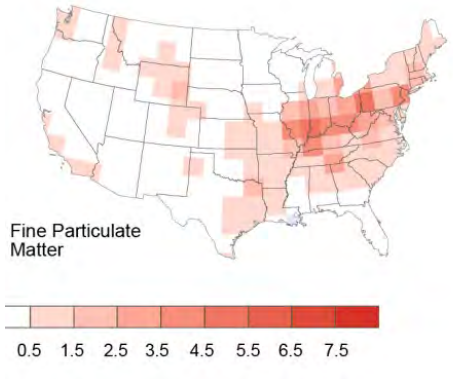


Black carbon is radiatively active (absorbs)

https://muchadoaboutclimate.wordpress.com/2014/01/09/key-figures-from-the-ipccs-ar5-report/

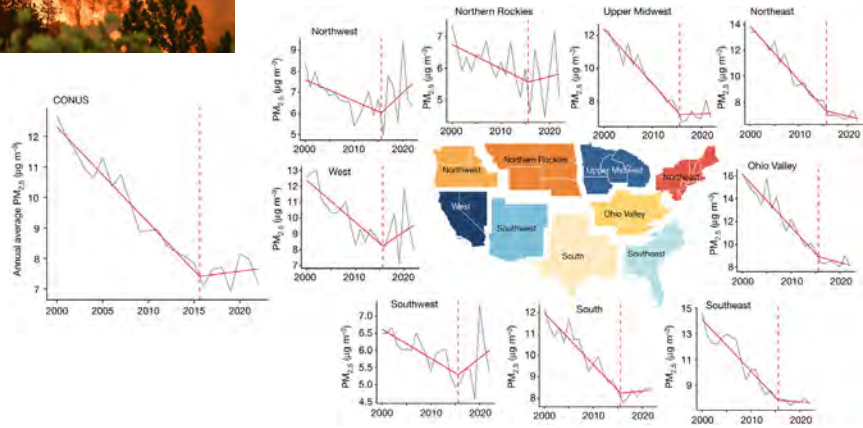
The “Climate Penalty” & Fires

US EPA

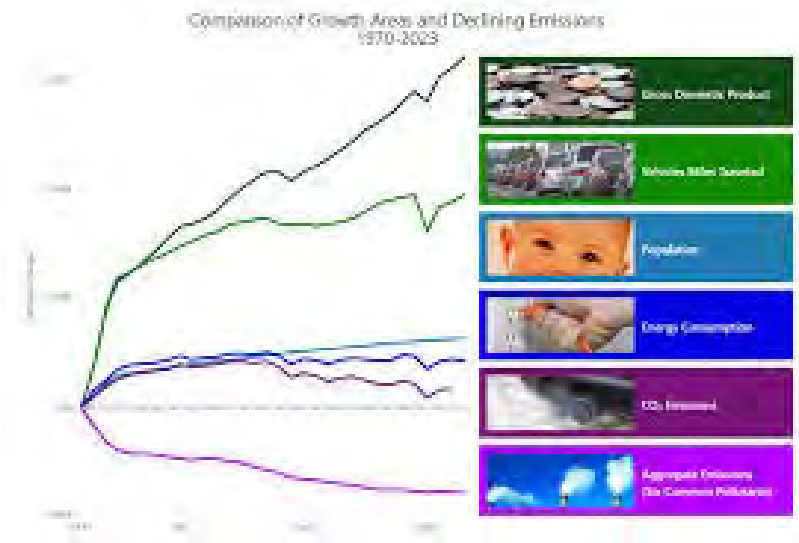


- Goes both ways: Climate change can worsen air pollution
  - Particulate matter
    - Increased emissions
      - Fires!!!!
    - More rapid chemistry
  - Ozone
    - Increased emissions
      - Fires!!!!
    - More rapid chemistry
    - Increased stagnation
  - Could add $100,000,000s in increased control costs to reach air quality goals





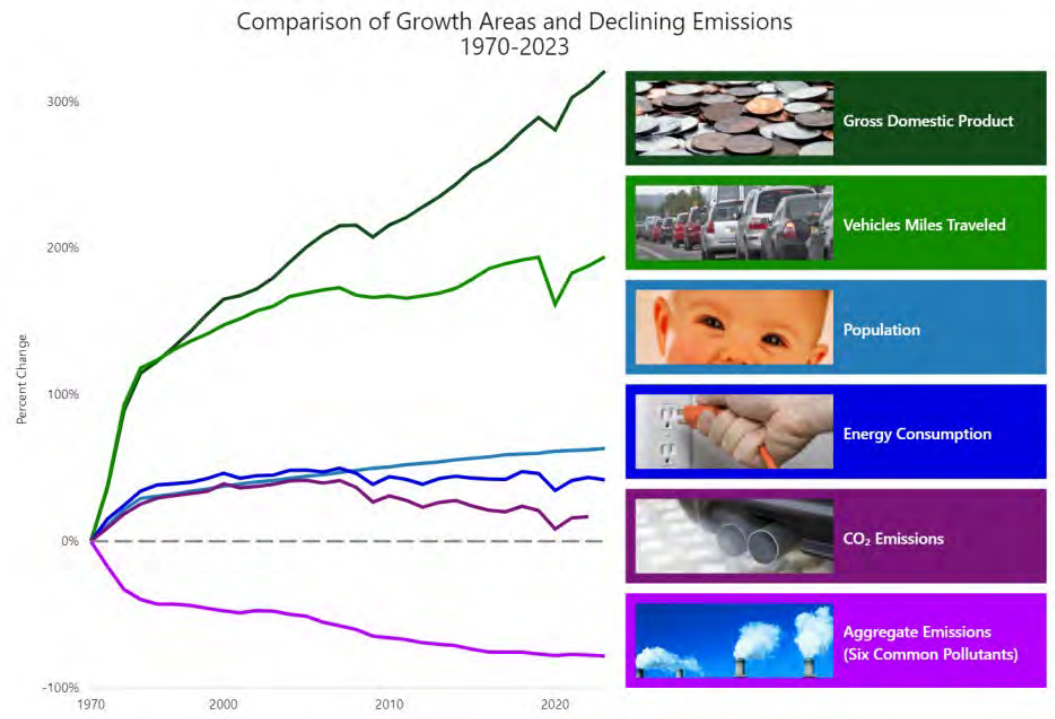
Burke, M., Childs, M.L., de la Cuesta, B. et al. The contribution of wildfire to PM2.5 trends in the USA. Nature 622, 761–766 (2023). https://doi.org/10.1038/s41586-023-06522-6



Air Pollution and Greenhouse gas Controls

US is doing a great job at reducing “traditional” air pollutants: CO2 not so much

US Emissions, VMT, GDP, Energy trends

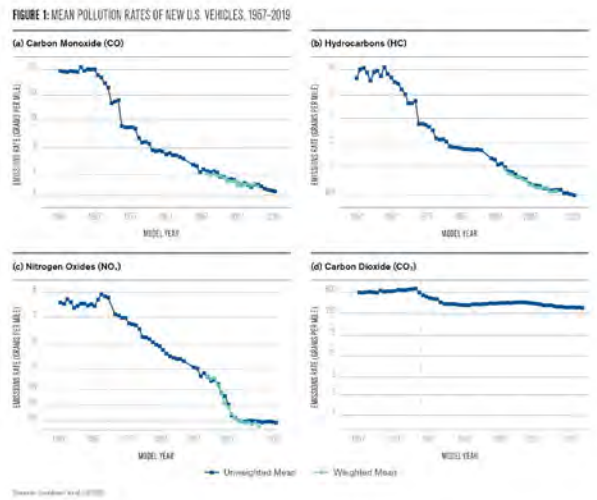


- Trends analyses show decreases in emissions of traditional pollutants (CO, VOCs, NOx, PM, SO2, lead) despite increases in GDP, VMT, population and energy
  - Improved air with increased economic activity
- CO2 was going up, now decreasing
  - CO2/energy going down

US EPA

Air quality controls: Long history, big impact Already

van Benthem et al "How Effective Are Vehicle Exhaust Standards?", Kleinman Center (2022)



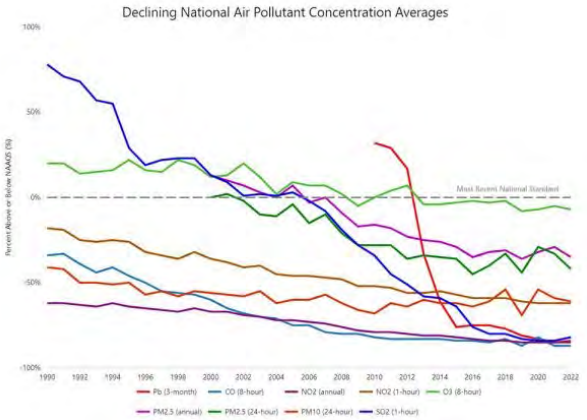
Stationary (power plants, industry)

- Power plants historically large sources of ozone and PM precursors (NOx, SO2)
- Fuel switching
  - Coal ➔ natural gas
    - Very little SO2, reduced NOx
    - Driven by economics and regulations
  - Renewables
    - Solar, wind
- Flue gas controls
  - SO_2 Scrubbers (90+% control)
  - Filters, electrostatic precursors (90+% control)
  - NOx Catalysts (SCRs) (90+% control)
- Vapor controls (refineries, surface coatings and such)

Mobile

- Catalysts (90+% control)
  - Gasoline (historically)
  - Diesel (more recent)
  - New gas/diesel cars and trucks (and trains) are remarkably clean
    - Limited reductions on CO_2
- Combustion controls
  - Also important for catalyst efficiency
- Going electric
  - Does not make them totally clean
    - Tire wear
    - Dust
    - Brake wear

Controls are working ➔



US EPA

Benefits and Costs of the Clean Air Act from 1990 to 2020

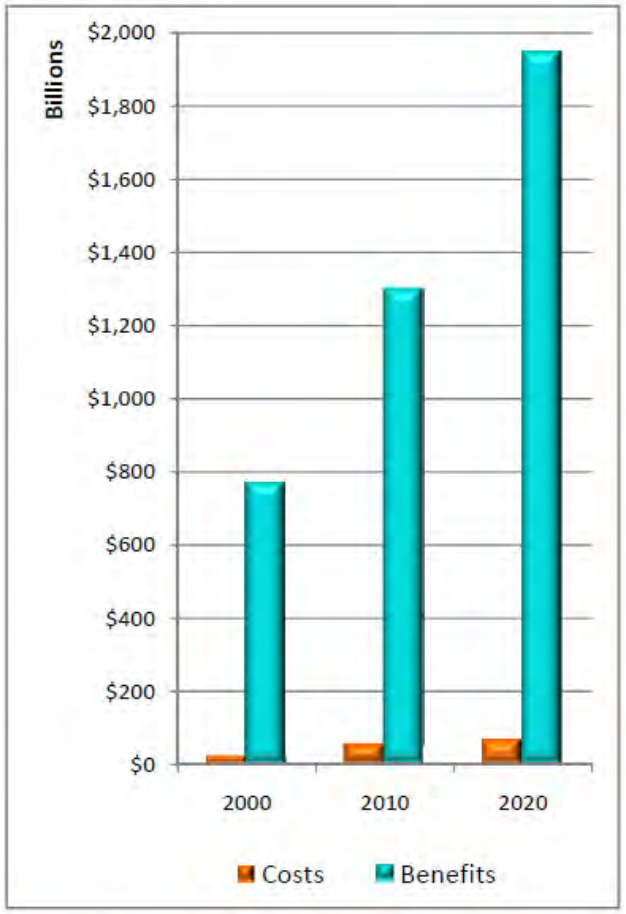


Exhibit 1. Primary Central Estimates of direct benefits and direct costs for the 2000, 2010, and 2020 study target years. (In billions of 2006 dollars). The graph shows the extent to which benefits exceed costs throughout the study period.

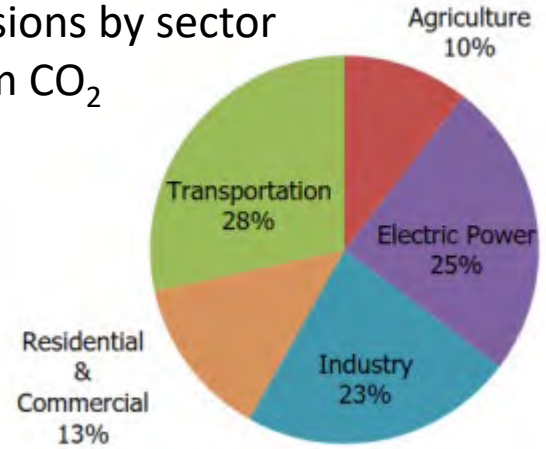
Health Effect Reductions (PM2.5 & Ozone Only)	Pollutant(s)	Year 2010	Year 2020
PM2.5 Adult Mortality	PM	160,000	230,000
PM2.5 Infant Mortality	PM	230	280
Ozone Mortality	Ozone	4,300	7,100
Chronic Bronchitis	PM	54,000	75,000
Acute Bronchitis	PM	130,000	180,000
Acute Myocardial Infarction	PM	130,000	200,000
Asthma Exacerbation	PM	1,700,000	2,400,000
Hospital Admissions	PM, Ozone	86,000	135,000
Emergency Room Visits	PM, Ozone	86,000	120,000
Restricted Activity Days	PM, Ozone	84,000,000	110,000,000
School Loss Days	Ozone	3,200,000	5,400,000
Lost Work Days	PM	13,000,000	17,000,000

Exhibit 8. Differences in key health effects outcomes associated with fine particles (PM2.5) and ozone between the *With-CAAA* and *Without-CAAA* scenarios for the 2010 and 2020 study target years. (In number of cases avoided, rounded to 2 significant digits). The table shows the reductions in risk of various air pollution-related health effects achieved by 1990 Clean Air Act Amendment programs, with each risk change expressed as the equivalent number of incidences avoided across the exposed population.

U.S. EPA Office of Air and Radiation. The Benefits and Costs of the Clean Air Act from 1990 to 2020: Summary Report. March 2011 (http://www.epa.gov/air/sect812/feb11/summaryreport.pdf)

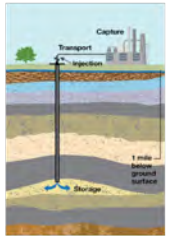
CO_2 (GHG) Controls

GHG emissions by sector
~ 80% from CO_2



Stationary (EP, Ind, R&C)

- Power plants
  - Fuel switching in combustion
    - Coal ➔ natural gas➔hydrogen/ammonia/biomass
      - Less CO2 per C & better efficiency (combined cycle plants)
  - Renewables
    - Solar, wind (on top of hydro)
- Carbon capture and sequestration/storage (CCS)
  - Limited application to date
    - Recent research suggests that the total available sequestration may not be as large as previously thought
  - Link together with fuel switching (coal to gas) for a bigger bang
    - Technologies to capture CO2 may also lead to reduced NOx, …
- All sources
  - Efficiency improvements



From the atmosphere

- Direct air capture
- "Natural" (trees, ocean fertilization

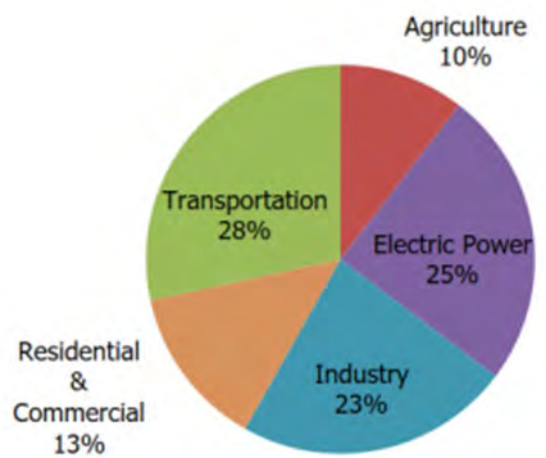


Mobile

- Improved fuel mileage
  - Some improvements there but there are limitations
    - Hybrids
    - Combustion controls
    - …
- Renewable fuels
  - Ethanol (&methanol)
  - Hydrogen (comes in different "colors")
  - Benefits dependent on fuel and how they fuels are produced (producing requires energy)
  - Alternative fuels can lead to traditional emissions
- Going electric
  - But it depends on how the electricity is produced

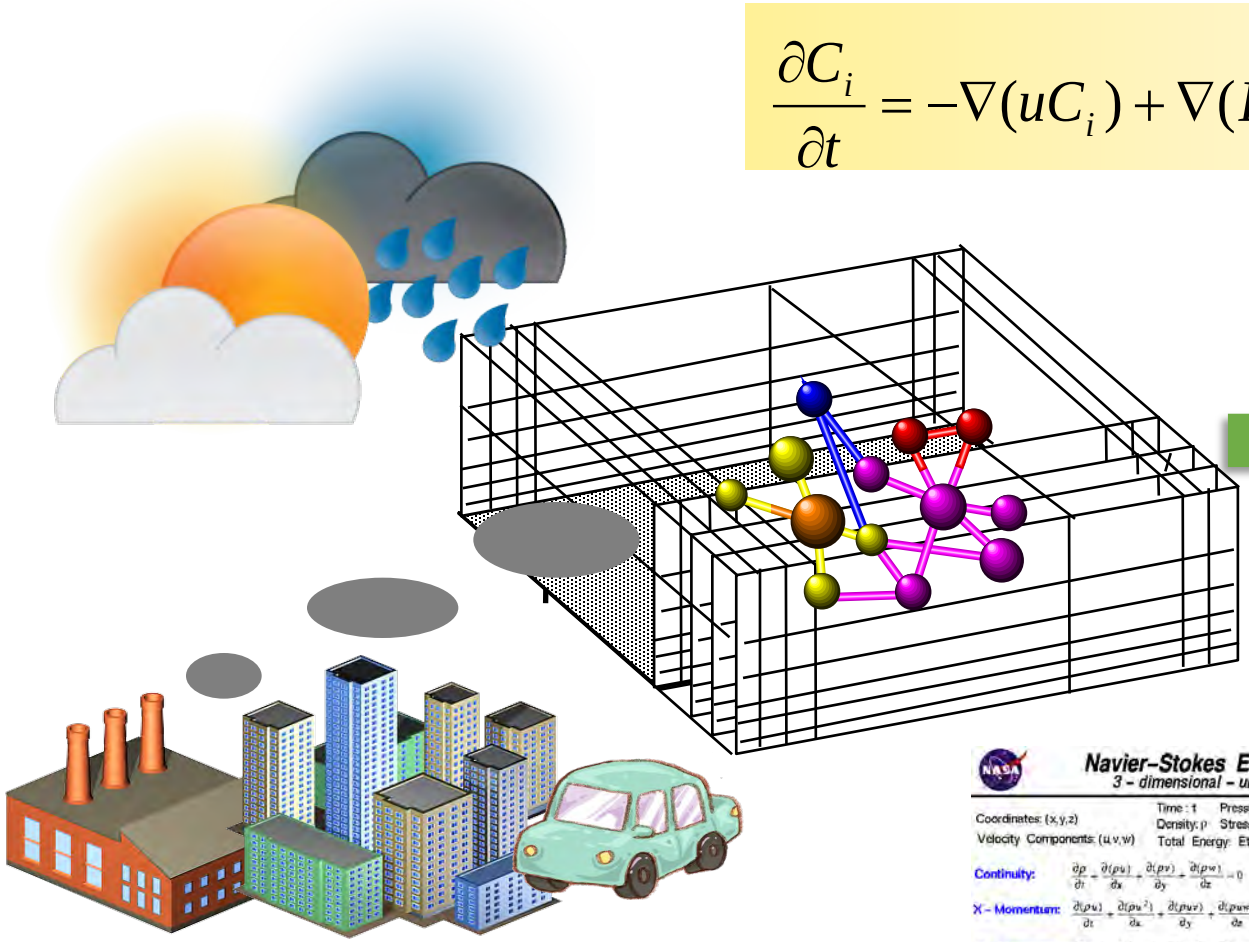
GHG and Traditional Air Pollution Controls: How they can work together

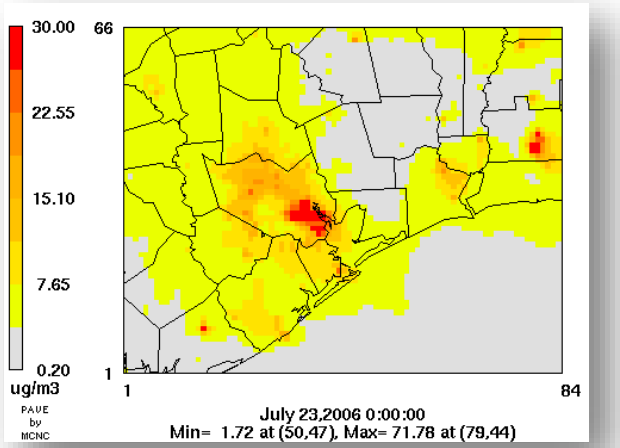
- Some technologies may reduce both traditional air pollutants and CO2
  - Can get a bigger apparent bang for your buck than thinking about either alone.
- Stationary
  - Fuel switching coal➔ natural gas
    - With/without CCS
  - Renewables
- Mobile
  - Going electric, particularly in tandem with stationary controls that reduce CO_2.

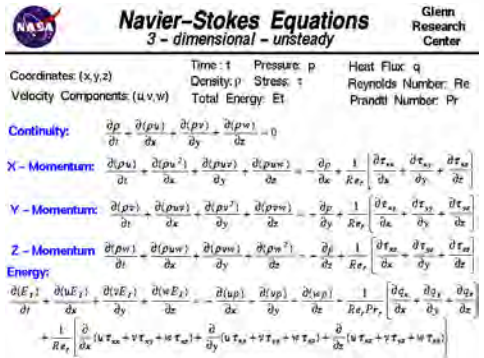


Atmospheric Modeling

$$\frac{\partial C_i}{\partial t} = -\nabla(uC_i) + \nabla(K\nabla C_i) + R_i + E$$

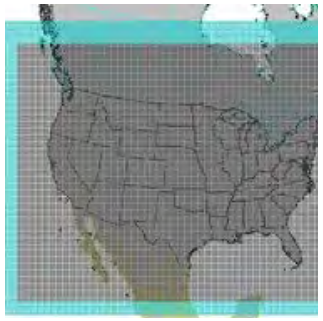


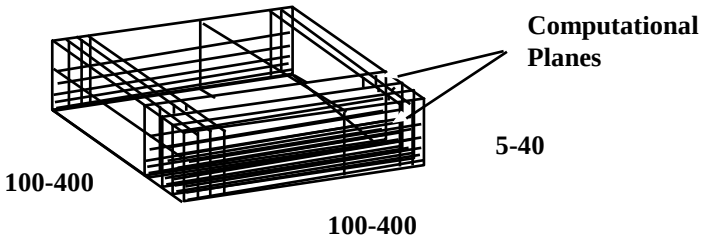




Air Quality Model: Links emissions to air quality

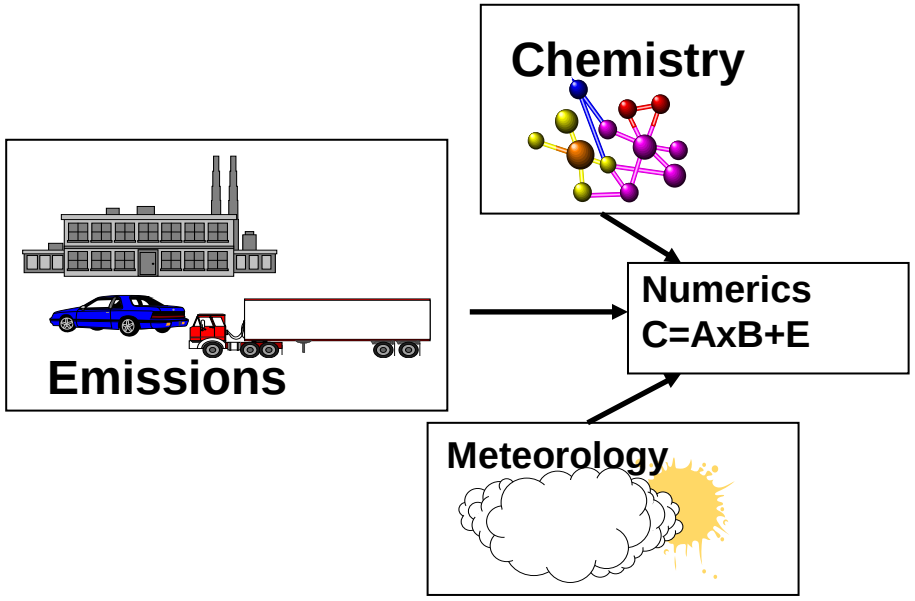
- Representation of physical and chemical processes
  - Numerical integration routines
    - CFD-like codes with chemical kinetics
      - LES, k-ε, K-theory, depending on resolution and application
- Scientifically most sound method to link future emissions changes to air quality





Air Quality Model





Transport chem. emissions

$$\frac{\partial c_i}{\partial t} = -\nabla(\mathbf{u}c_i) + \nabla(\mathbf{K}\nabla c_i) + R_i + S_i$$

$c_i(x,y,z,t)$ = conc. of species i

Atmospheric Diffusion Equation

Discretize

$$\frac{\partial c}{\partial t} + L(\mathbf{x},t)c = f(\mathbf{x},t)$$

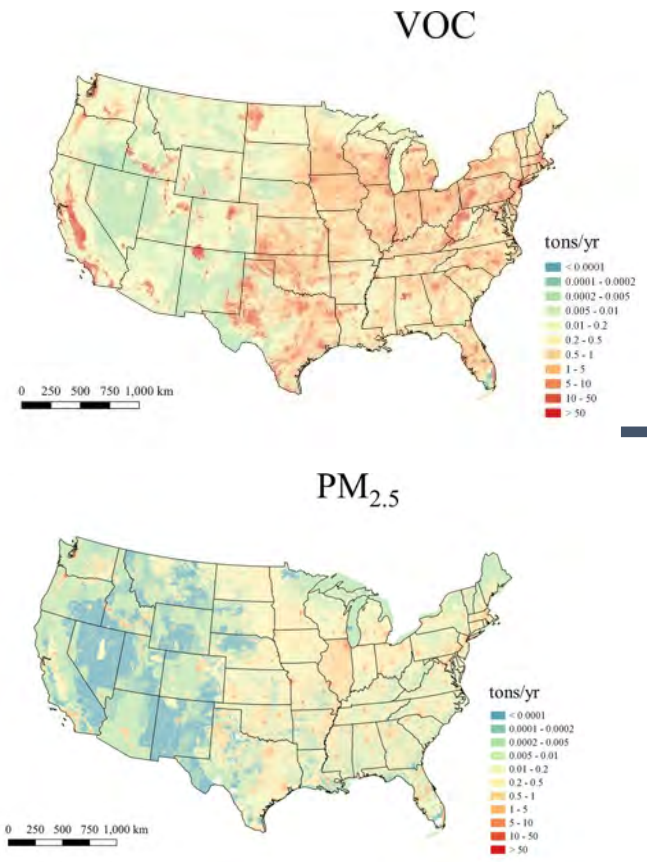
Operator splitting

$$c(t+2\Delta t) = L_x(\Delta t)\, L_y(\Delta t)\, L_{cz}(2\Delta t)\, L_y(\Delta t)\, L_x(\Delta t)\, c(t)$$

Note: **u** and **K** come from meteorological modeling, solving the Navier-Stokes equations run before or in tandem with chemical model

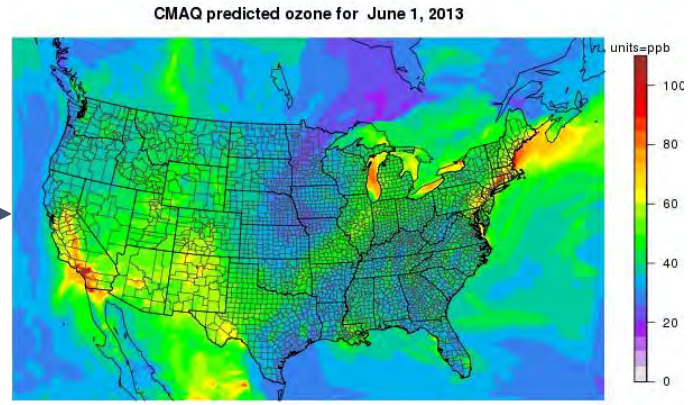
~200 species x ~40000 hor. grids x ~35 layers= ~280 million coupled, stiff non-linear differential equations

Air quality model



Air Quality Model

$$\frac{\partial c_i}{\partial t} = -\nabla(\mathrm{u}c_i) + \nabla(\mathrm{K}\nabla c_i) + R_i + S_i$$



US EPA

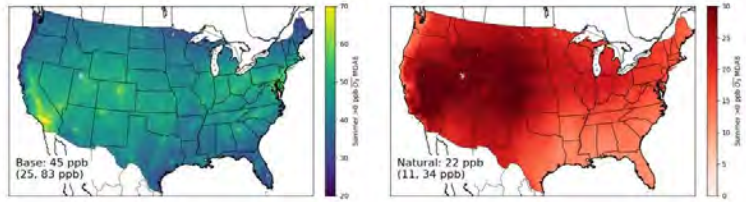
Ma, S., Tong, D.Q. Neighborhood Emission Mapping Operation (NEMO): A 1-km anthropogenic emission dataset in the United States. *Sci Data* **9**, 680 (2022). https://doi.org/10.1038/s41597-022-01790-9

Air quality model and policy analysis

- AQMs used to address policy questions, e.g.
  - Where does our ozone come from (remember, it is not emitted: it is formed in the atmosphere from rather non-linear chemistry):
    - Policy question: how much of our ozone is natural, comes from other countries, or is from US human emissions
  - What would happen if we reduce emissions, e.g., how much would ozone go down if we reduce NOx emissions in Atlanta:

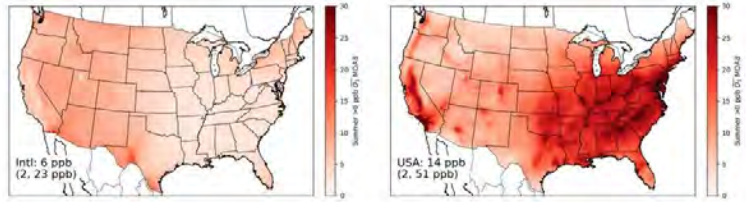
US EPA

Base

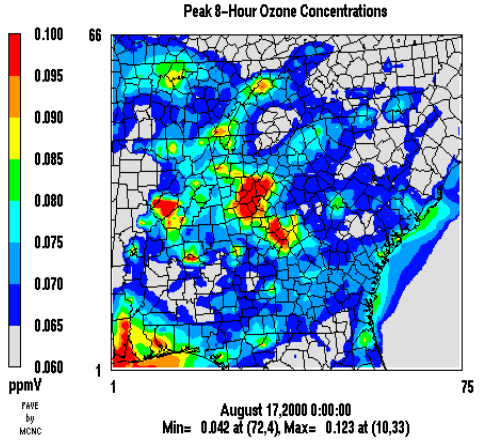


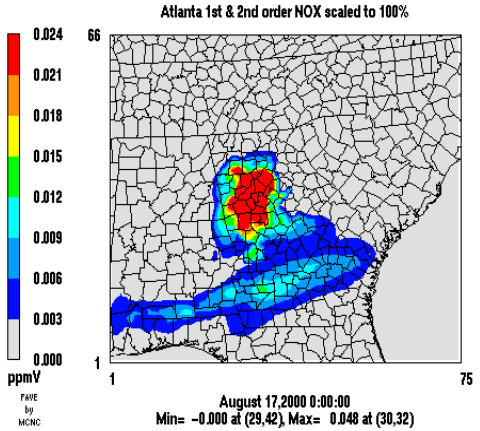
Natural

International



US Anthropogenic





Georgia Tech

Neat Applications of Air Quality Models to Address both Air Quality and Climate

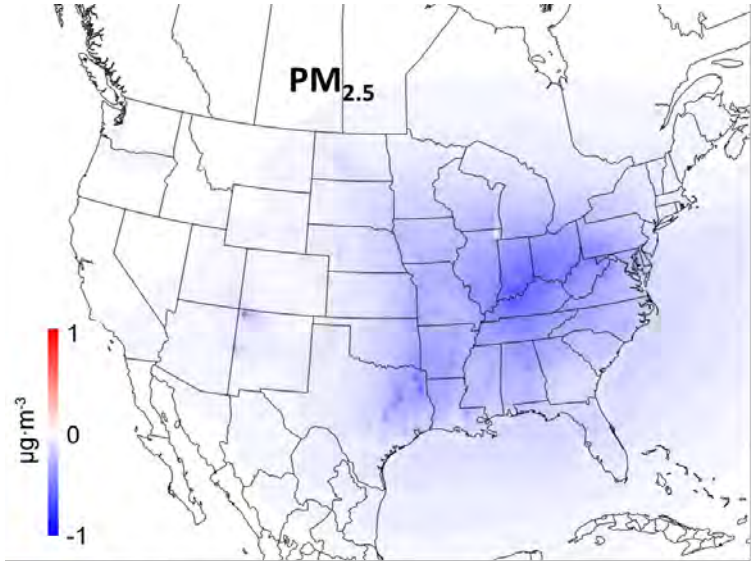
- Clean Energy Futures
  - Assess how policies to reduce CO2 from power plants will improve environmental (air+water) quality and health, simultaneously
    - JPB Foundation

- Monetization of emissions reductions
  - Assess the value of reducing traditional air pollutant emissions (NOx, SO_2, PM and ammonia) spatially across the US and Canada
    - Assess health benefits from reduced PM, mostly
  - Link how removing source emissions (including CO_2) would lead to "co-benefits"
    - Co-benefits: How much reducing "traditional" air pollutant emissions associated with 1 ton of CO_2 from that source would lead to health benefits
- Both of these use what is called a Value of Statistical Life (VSL)
  - About $12 million (depends on country, age, year of study)
- Social cost of carbon is (now) about $200/ton (RFF)
  - Estimates vary and are time dependent

Clean Energy Futures

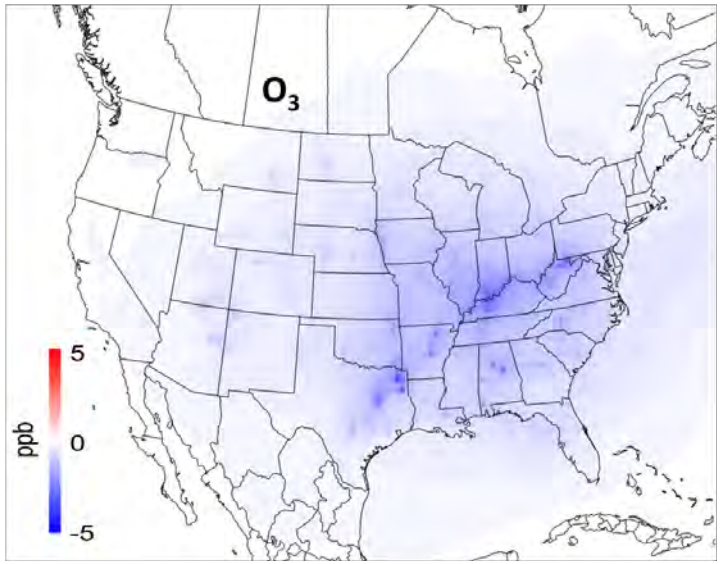
Co-benefits of zero emissions EGU (power plant) policies: Clean Energy Futures

- Drive towards 100% clean electricity generation by 2050
- While the main driver is CO_2 reductions, substantial co-benefits from ozone, $PM_{2.5}$ and sulfate can be realized
- Studied a variety of policy scenarios, and the future benefits the provide, with a main focus on a flexible policy with a target of 80% reduced CO_2 emissions generation by 2030, near 100% by 2050
  - Used IPM for EGU system modeling and optimization



Change in $PM_{2.5}$ (annual average of 24-h averages)

Change in average $PM_{2.5}$



Change in O_3 (O_3 season average of maximum daily 8-h averages)

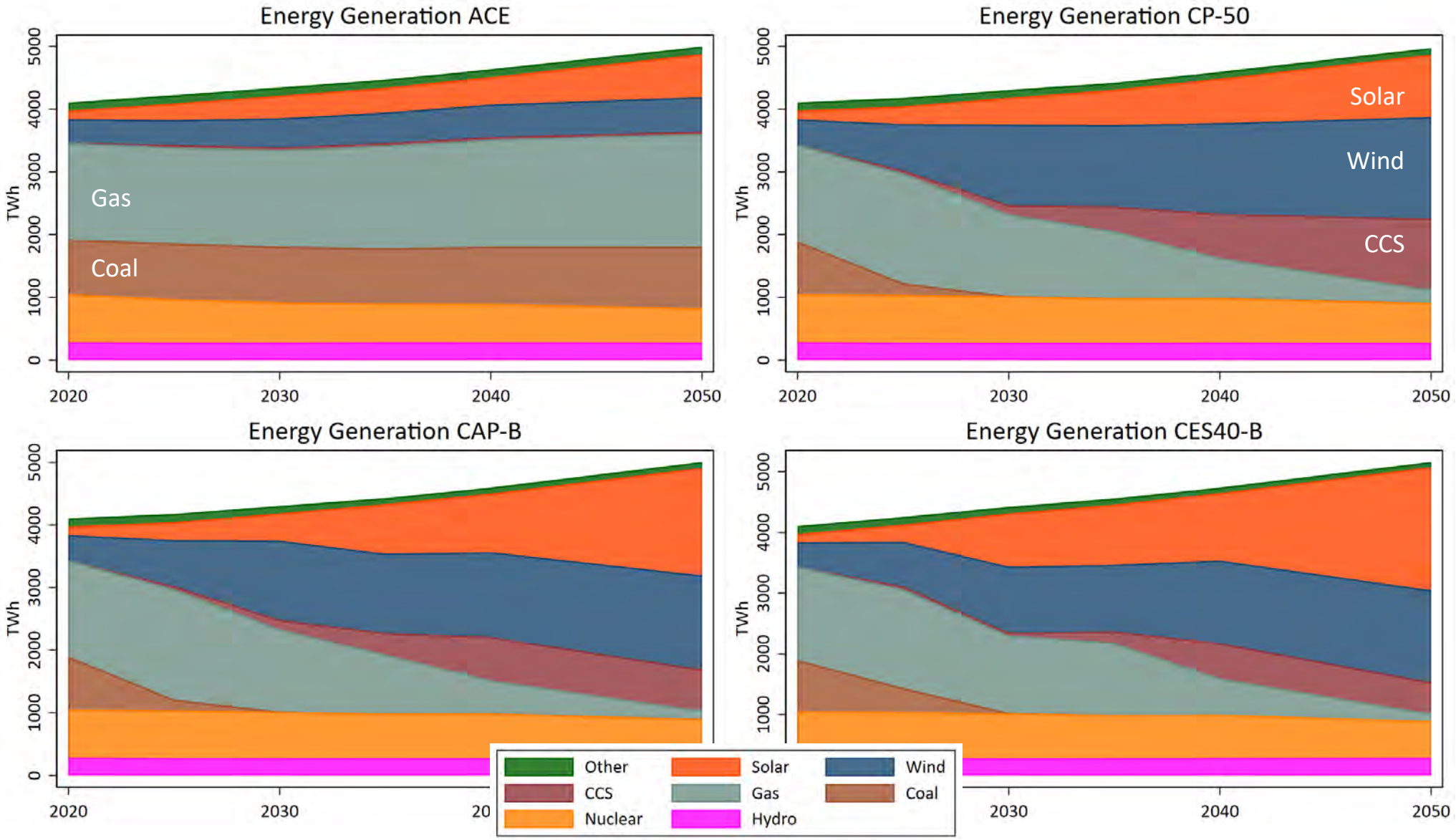
Change in max 8hr avgO_3

Vasilakos et al. 2022

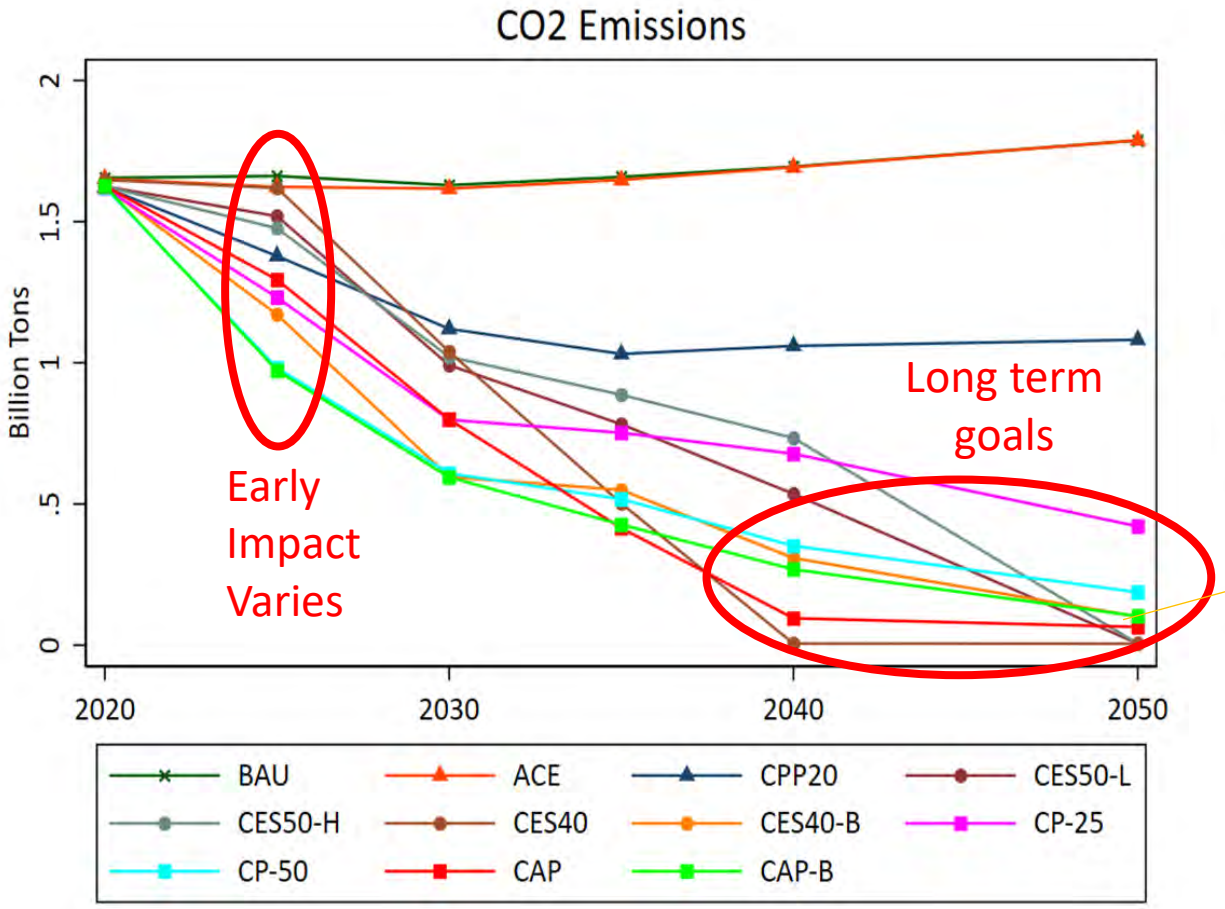
Compared 13 Electricity Sector Carbon Policies

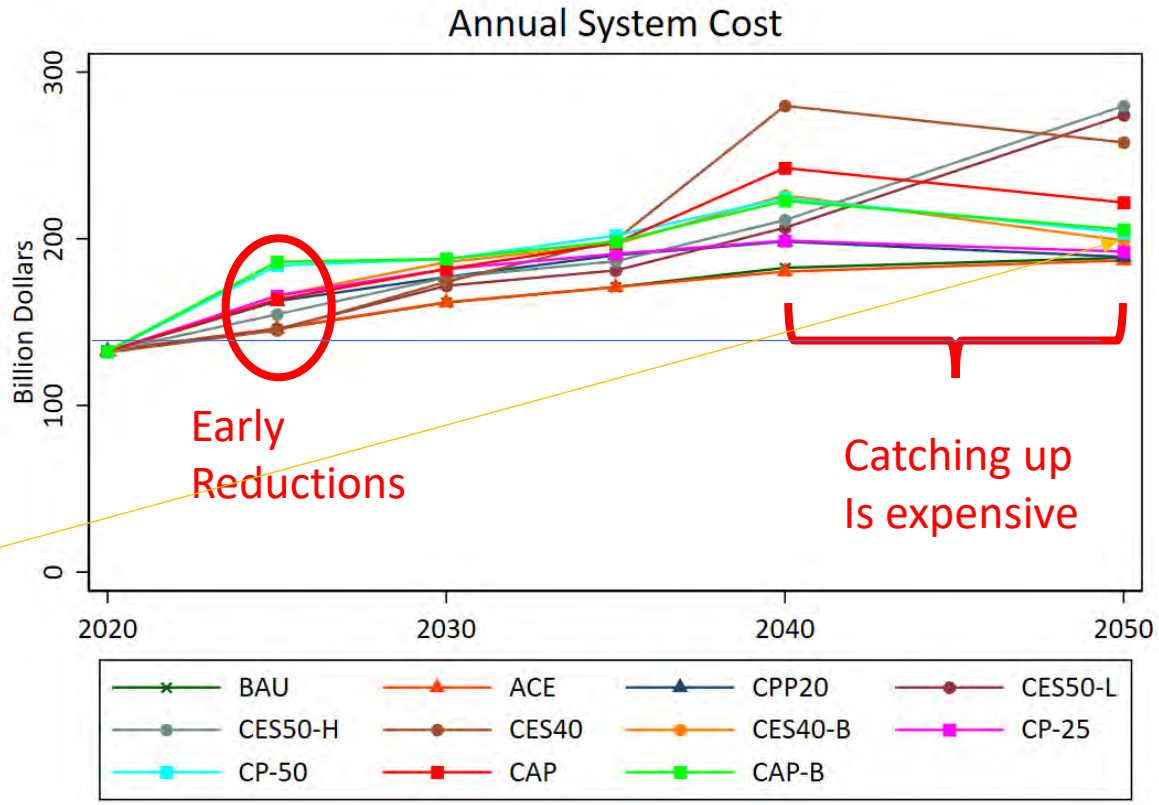
Policy Type	Code	Description
Reference case	**BAU**	Business as usual, no policy
Section 111 rules	**ACE**	Affordable Clean Energy – assumed 4.5% HRI for affected units
	CPP20	Updated Clean Power Plan - achieves 65% CO2 reduction from 2005 levels by 2035
	Cofiring	Rate-based and mass-based standards equivalent to 20% natural gas cofiring at (non-CHP) coal plants
Clean Energy Standard	CES40	100% clean in 2040, 0.82 metric tons/MWh, partial crediting, total generation, no banking
	CES40-B	**100% clean in 2040**, **0.82 metric tons/MWh**, partial crediting, total generation, **banking allowed**
	CES50-H	100% clean in 2050, high carbon intensity benchmark (0.82 metric tons/MWh), total generation, banking allowed until 2040
	CES50-L	100% clean in 2050, low carbon intensity benchmark (0.46 metric tons/MWh), total generation, banking allowed until 2040
Cap and Trade	CAP	Net 0 emissions in 2040, offsets allowed but no banking
	CAP-B	Net 0 emissions in 2040, banking allowed
Carbon Price	CP-25	Carbon price $25/ton rising at 5% per year
	CP-25u	Like CP-25 but units below 25 MW “unconstrained” (not held to BAU capacity factors)
	CP-50	Carbon price $50/ton rising at 5% per year
	CP-50u	Like CP-50 but units below 25 MW “unconstrained” (not held to BAU capacity factors)

Technologies Utilized Vary with Policy



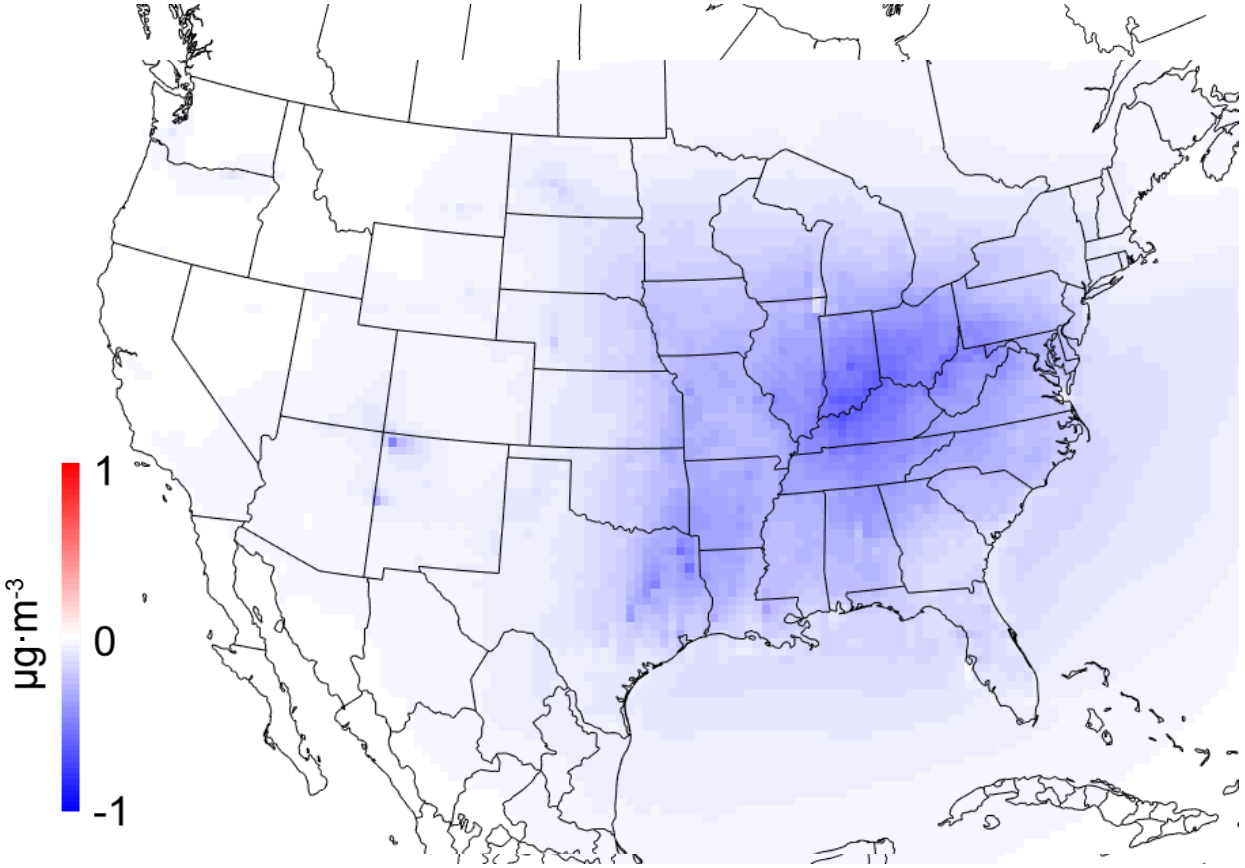
CO_2 Impacts and Costs



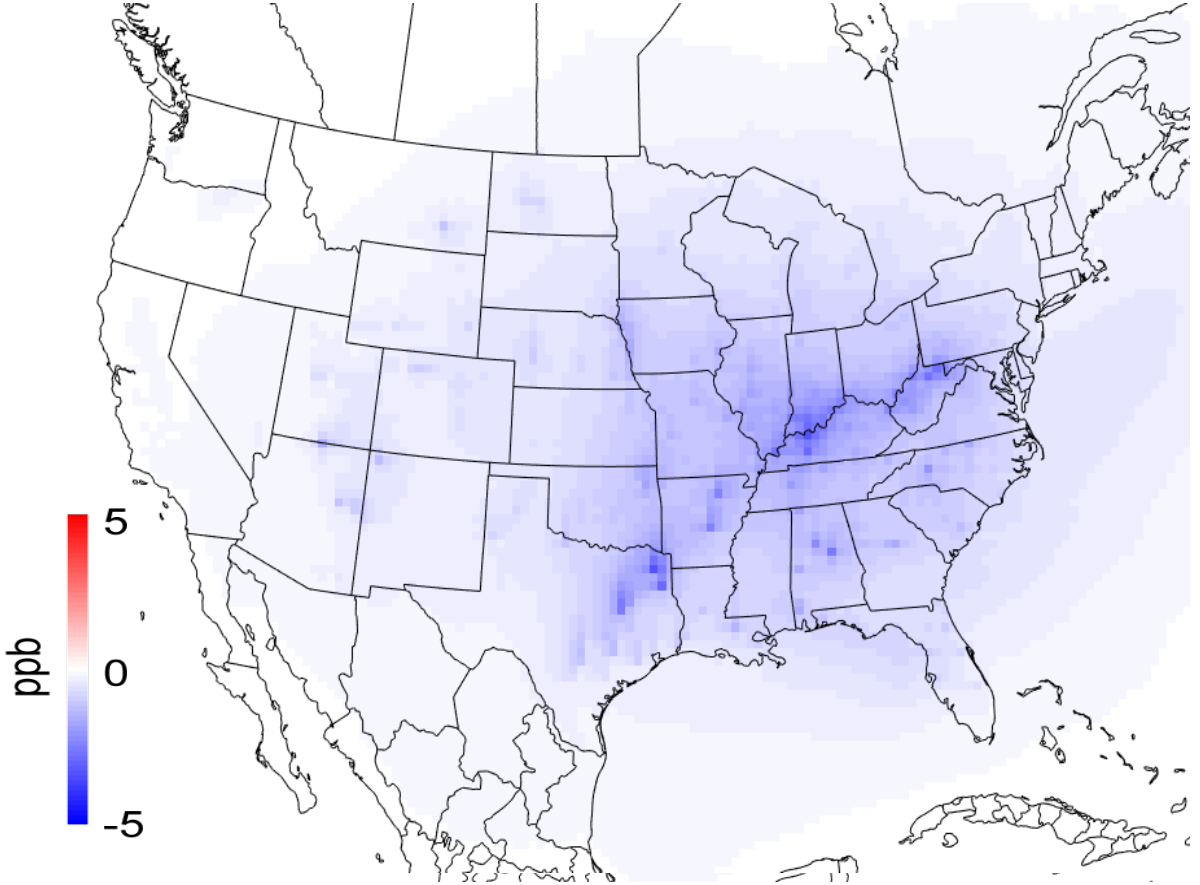


Air Quality Benefits (CES-40B)

Applied CMAQ



Change in $PM_{2.5}$ (annual average of 24-h averages)

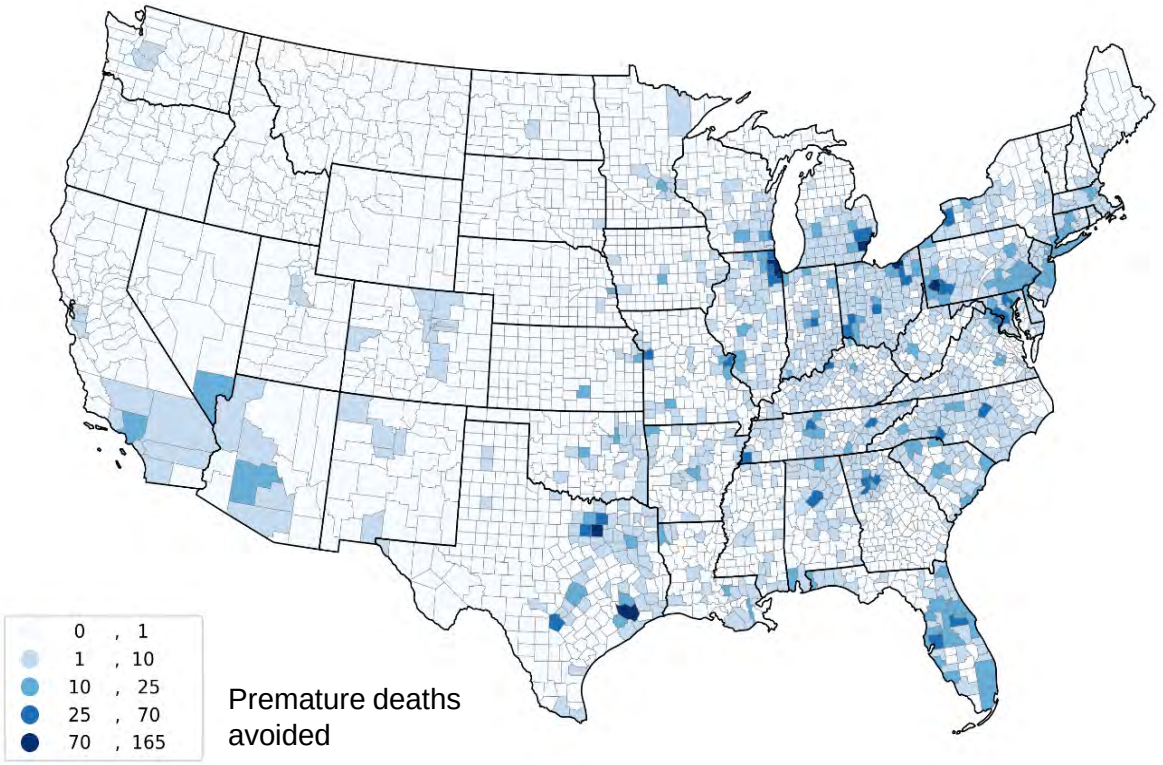


Change in O_3 (O_3 season average of maximum daily 8-h averages)

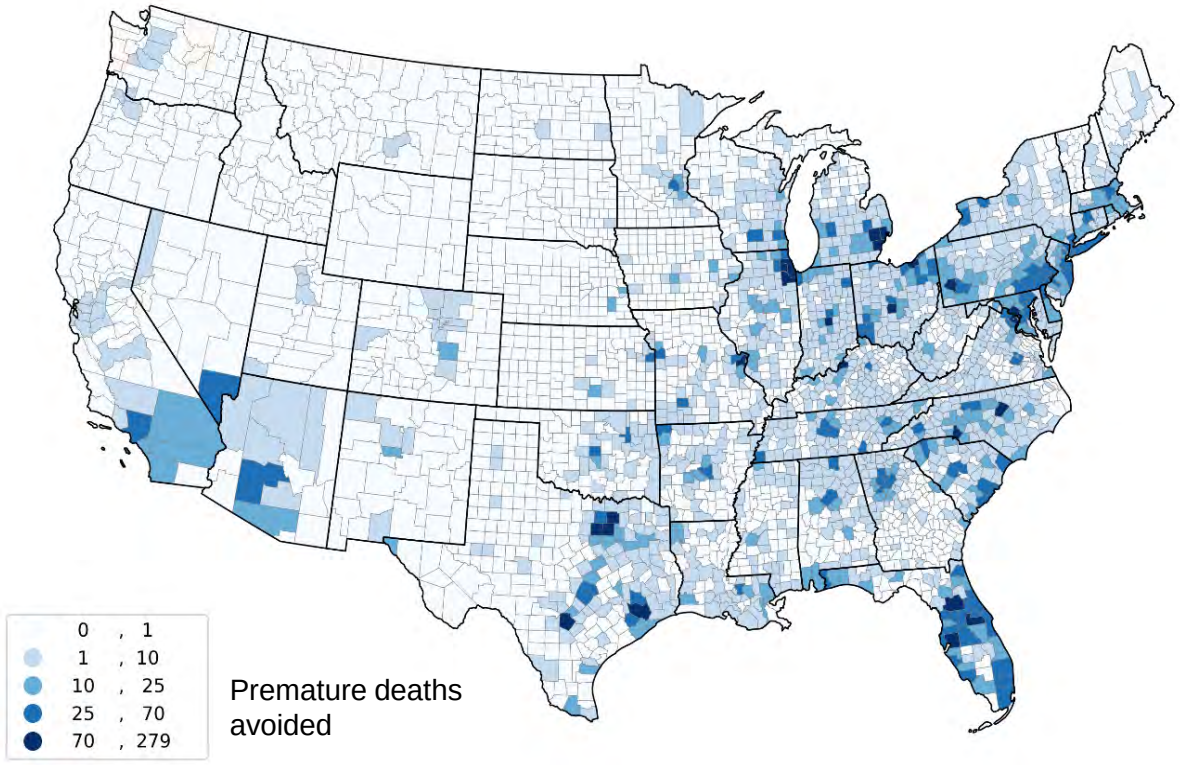
Clean Energy Futures, Driscoll et al.: See Vasilakos et al., 2022

Health Benefits Are Large and Widespread: 317,500 Premature Deaths Avoided Compared to No Policy (2020-2050)

Premature Deaths Avoided in 2030: 9,200

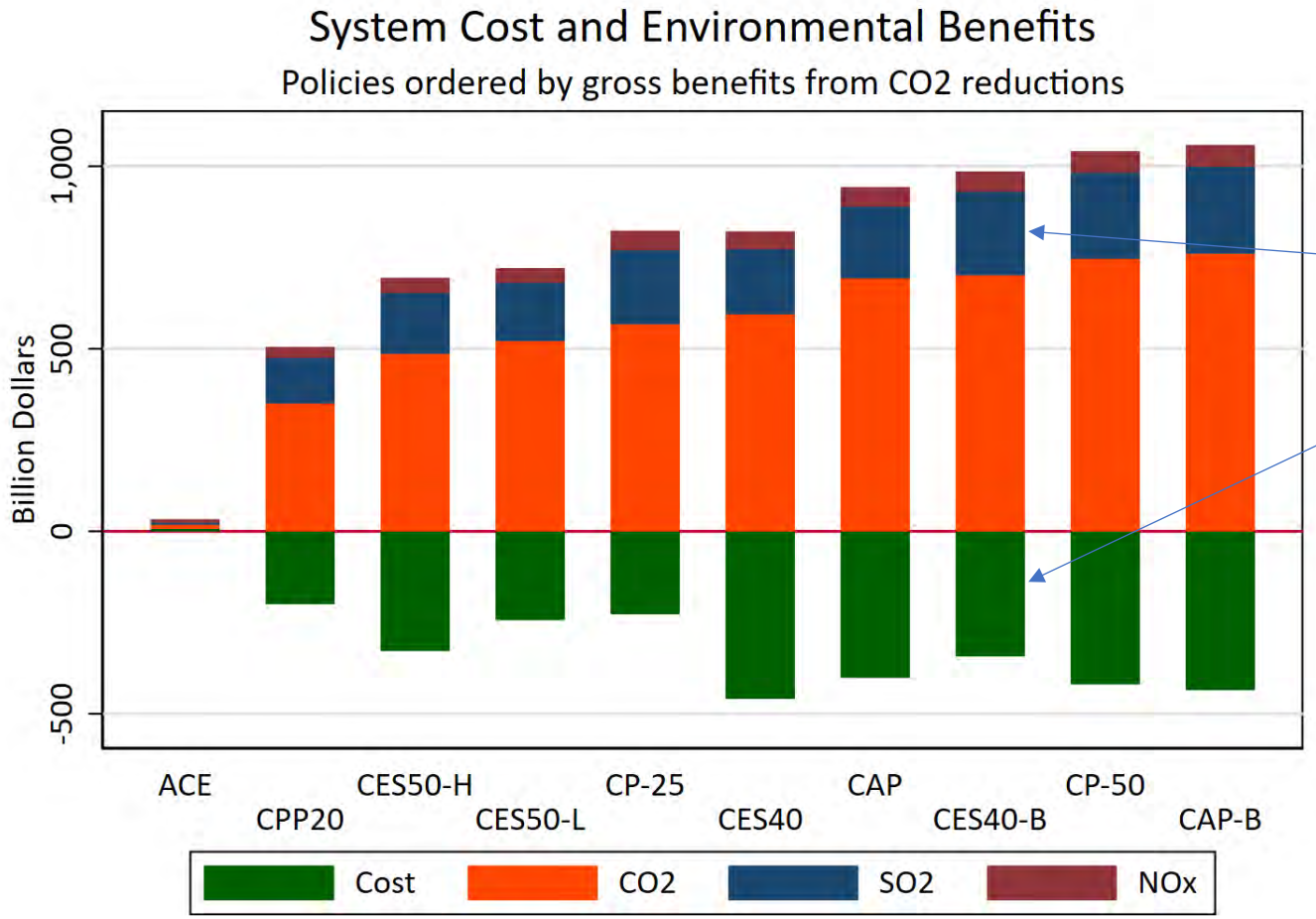


Premature Deaths Avoided in 2050: 17,000



Wilcoxen, Medhi, SU, CEF

Costs vs. Present Value Benefits by Policy



Control costs almost all offset by air quality benefits: CO2 reductions are almost “free”, and the air quality benefits are immediate.

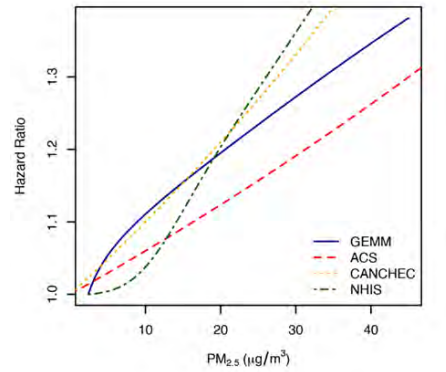
Health Effects Institute

Monetization of emissions reductions

- Used adjoint air quality model to quantify how spatial emissions of NOx, SO2, PM and ammonia impact PM levels, exposures, and premature deaths; used VSL to convert to monetized societal impact
  - Calculated the value of 1 ton of emissions across the US and Canada (not all of each country, but where most of the people are).
- Linked those with CO2 emissions from the same sources to fund the effective value of the reduction in CO2.
  - How to think about it: What are the air quality benefits from reducing, simultaneously, the associated traditional pollutants, along with a ton of CO2 from that source.
    - Say a source emits 1 ton of CO2, 0.01 tons of SO2, and 0.01 tons of NOx, this would be the monetized air quality benefit of removing 0.01 tons of SO2, and 0.01 tons of NOx
      - Does not include the benefits from removing 1 ton of CO2.

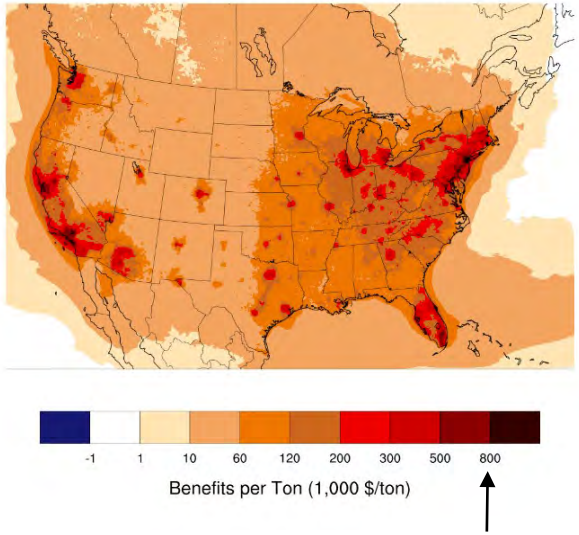
Monetary Valuation of Emission Reductions

- "Cost Function" $(\$'s) = V_{SL}\sum_i M_{0,i} \times P_i\left(1 - e^{-\theta T(z)}\right)$,
  - Value of reducing a ton of emissions
  - VSL: Value of statistical life, $M_{0,i}$: baseline mortality rate in location i, P_i: population, $\left(1 - e^{-\theta T(z)}\right)$: GEMM concentration response function, T(z) nonlinear function of $PM_{2.5}$ concentration



PM2.5 Emissions

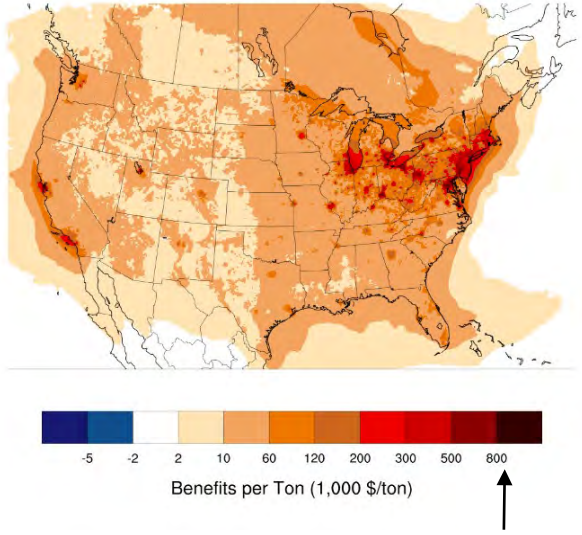
US.PM25.ANN.2016.GEMM.SURF



$800,000/ton

Ammonia Emissions

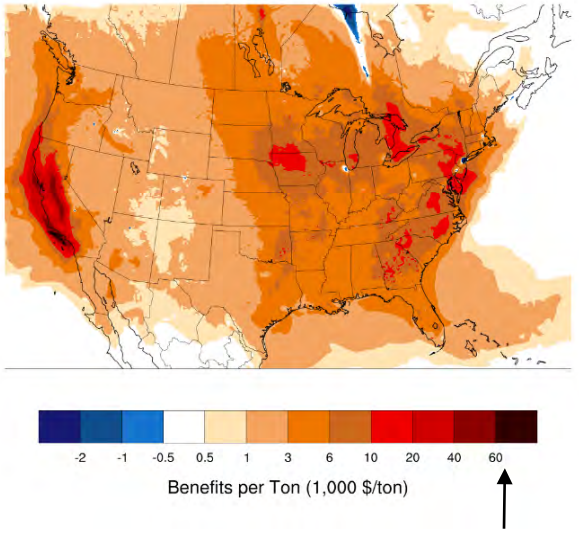
US.NH3.ANN.2016.GEMM.SURF



$800,000/ton

NOx Emissions

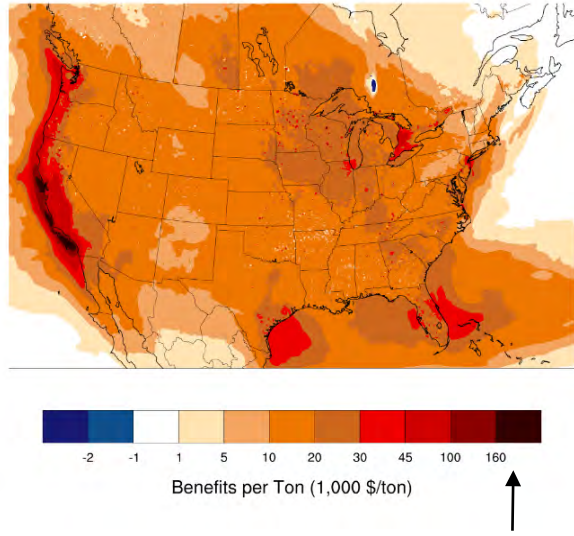
US.NOX.ANN.2016.GEMM.SURF



$60,000/ton

SO2 Emissions

US.SO2.ANN.2016.GEMM.SURF

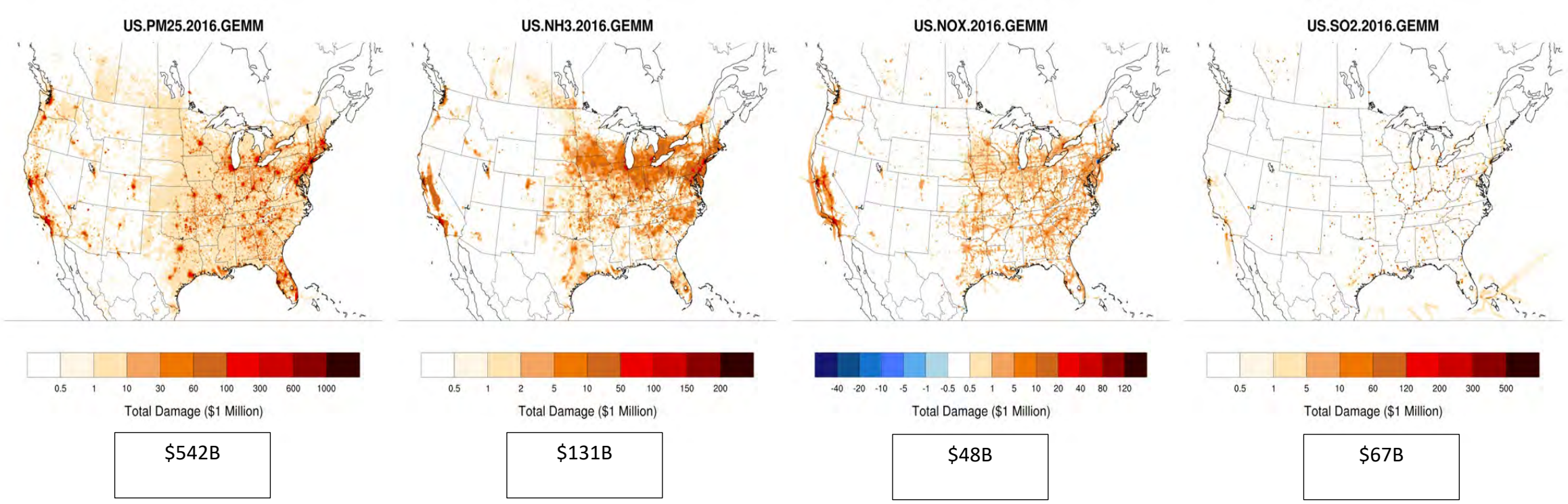


$160,000/ton

From Hakami, Russell, et al. (2023) HEI report

Valuation of Emissions at Each Location

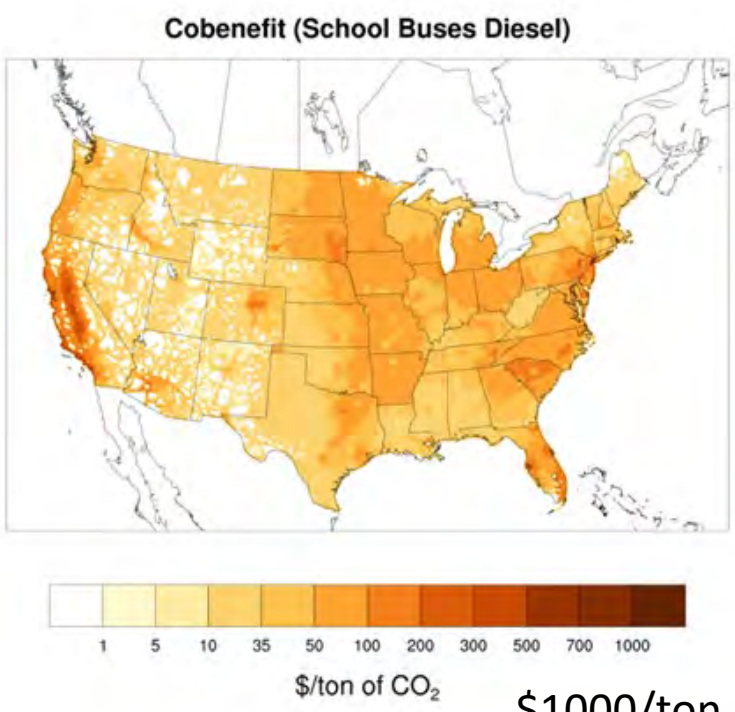
- Total value of emissions (by species) from each location
  - Assumes linearity



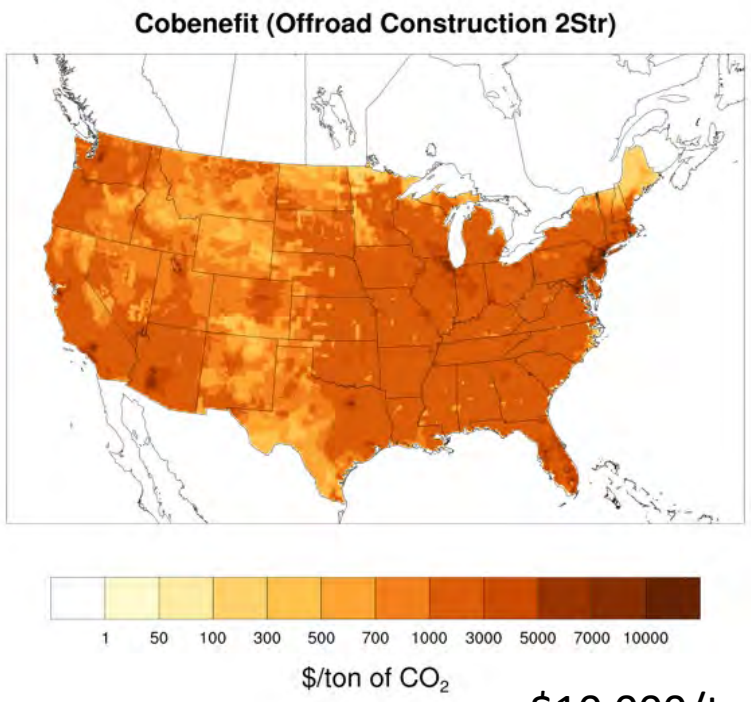
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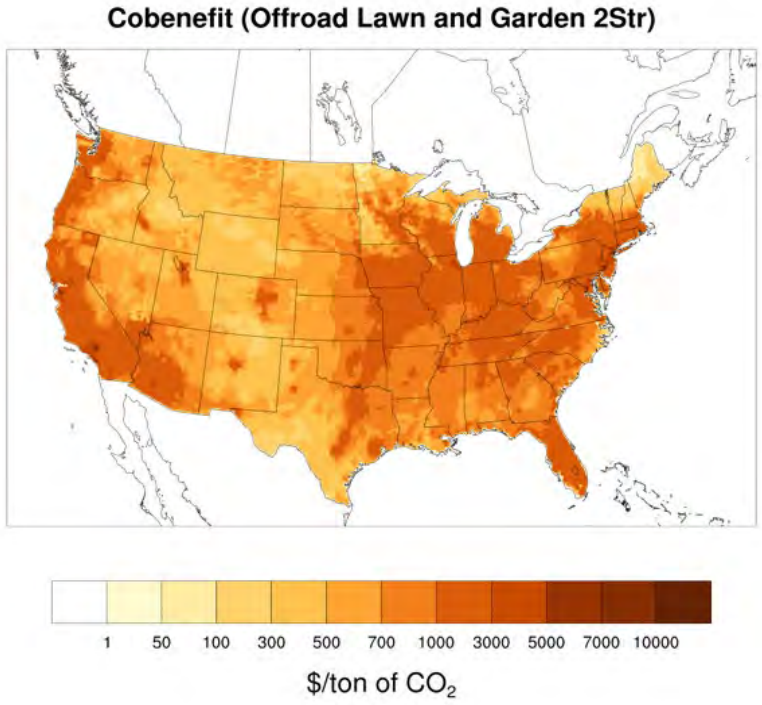
Co-benefits from CO2 reductions

- What are the air quality benefits from location-specific CO2 emissions reductions (and the associated traditional air pollutants) from specific sources
  - Accounts for how clean a vehicle is vs. fuel economy
  - Compare to Social Cost of Carbon: ($5-200+/ton)



$1000/ton





$10,000/ton

Benefits and co-benefits from cars

- Calculated model year specific CO_2 and traditional emissions

City	Co-benefit ($/ton-$CO_2$)					Per-vehicle damage ($/year)				
	1998	2002	2008	2012	2016	1998	2002	2008	2012	2016
Chicago	690	260	150	140	160	2100	900	700	700	700
Los Angeles	750	200	120	110	130	2200	700	500	500	600
New York	2060	840	490	450	530	6200	3100	2200	2100	2300
Seattle	280	110	60	60	60	800	400	300	300	300
Washington	340	130	80	80	80	1100	500	400	400	400

- Driving older cars have dramatically higher health impacts
  - ~$0.2/mile in a city (city dependent)

Call it a wrap

- Air quality continues to have an incredible, immediate and delayed impact on health
  - Silent, long term killer

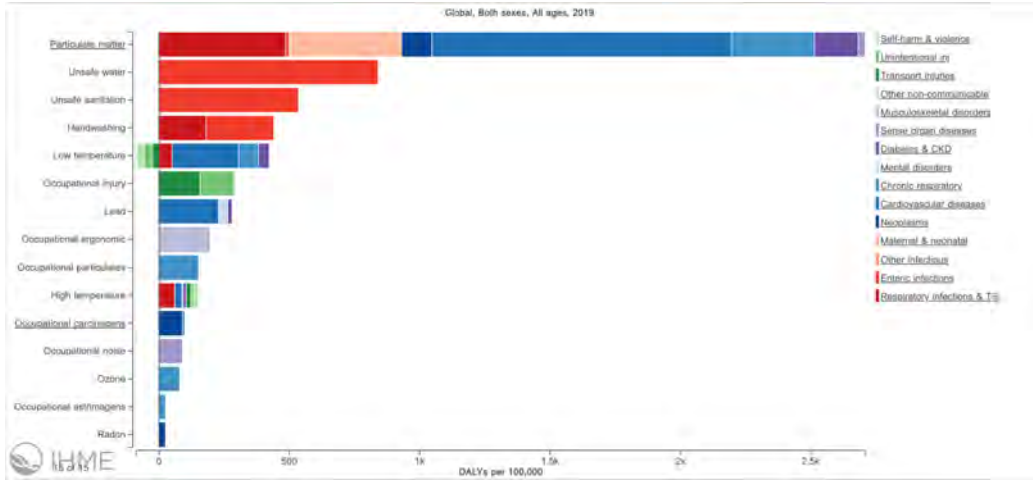
Main take-aways:

Climate and air quality linked (atmospherically and by control approaches)

Identifying controls to reduce both greenhouse gases (GHG) and traditional air pollutants can provide <u>immediate</u> health benefits and long-term climate benefits

The health benefits from reducing air pollution can help "pay for" (e.g., motivate) the GHG reductions

help "pay" for the reductions
- Plus: Air quality benefits are immediate



Thanks, and questions?

Feel free to contact me at ar70@gatech.edu