NATIONAL ACADEMIES *Sciences Engineering Medicine*

Incorporating Climate into Macroeconomic Modeling

Workshop | June 14–15, 2023

JUNE 2023

Session 3:
Economic Impacts, Damages, and Risks of Climate Change

NATIONAL ACADEMIES *Sciences Engineering Medicine*

Data-driven estimates of physical climate risks in the US and globally

Marshall Burke

Doerr School of Sustainability, Stanford

NAS Macro workshop, Jun 14 2023

Estimating physical risks from climate

Option 1: **bottom up, or “enumerative”**

- Uses trusted micro-data, causal econometrics
- Almost always sectorally focused, so requires (a) explicitly enumerating measurement of affected sectors, and (b) integration of many partial equilibrium estimates over sectors and across space

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Option 2: **top down**

- Study aggregates (e.g. GDP)
- Adding up is done for you, many costs/benefits of adaptation (e.g. sectoral reallocation) are embedded
- Will miss stuff not in GDP (e.g. mortality VSL)

Growth effects of temperature

Simple thought experiment: in a year that is hotter than average, does US economy grow faster or slower in that year (and subsequent)?

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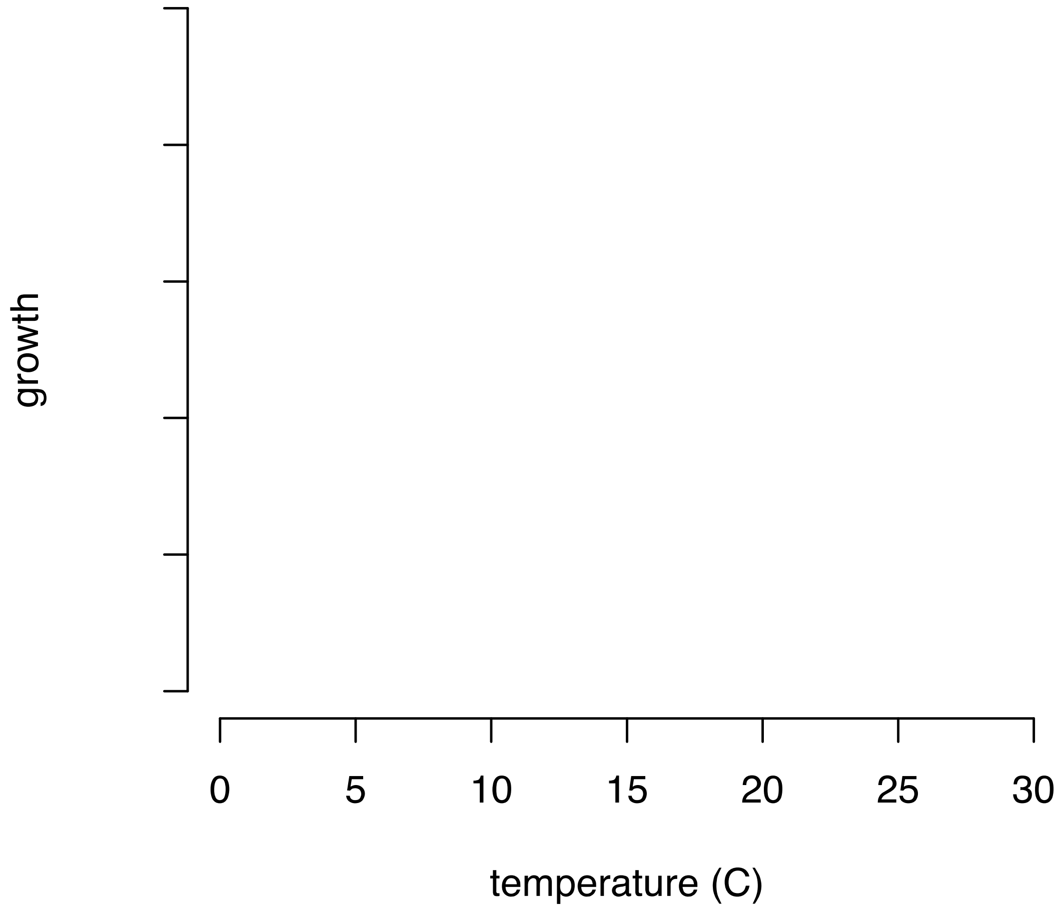
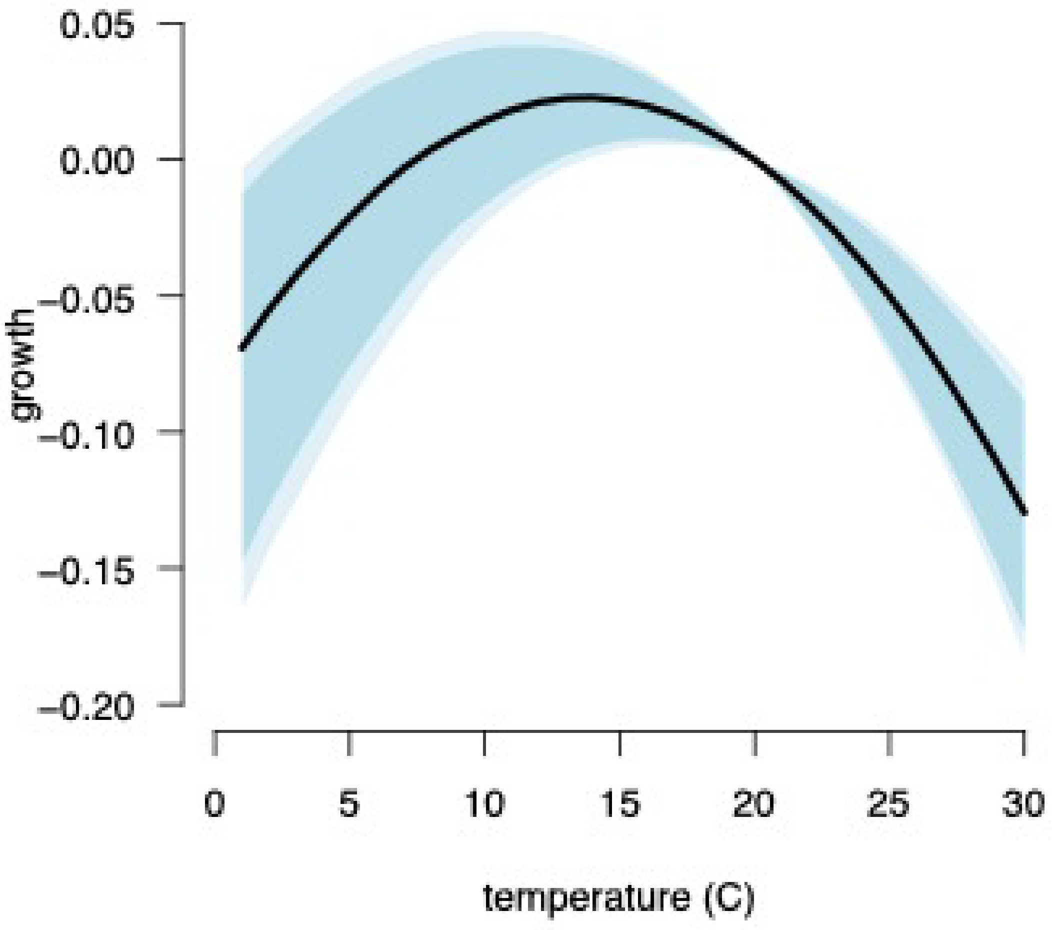


Data

- Per capita GDP growth since 1960, 190 countries
- Temp/precip data over same period

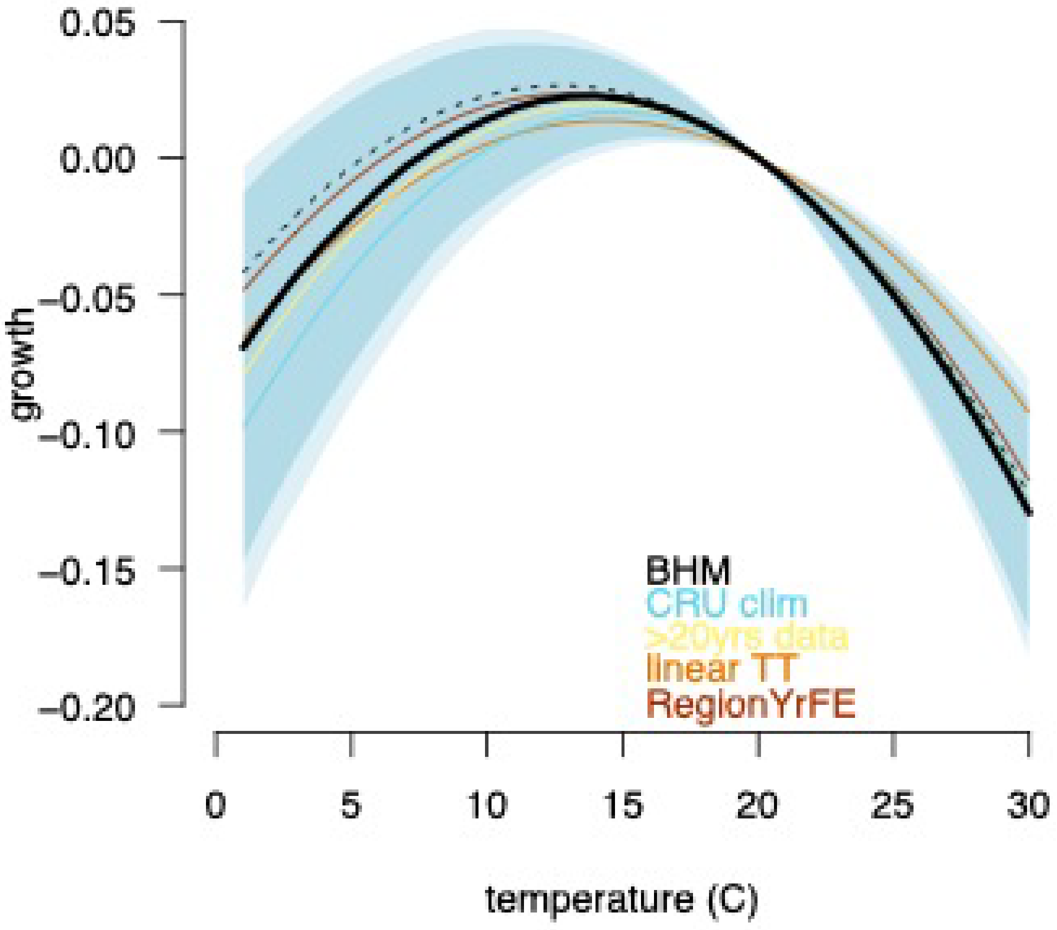
Panel regression that uses “within” variation

Growth effects of temperature



Global, non-linear response of GDP growth to temperature

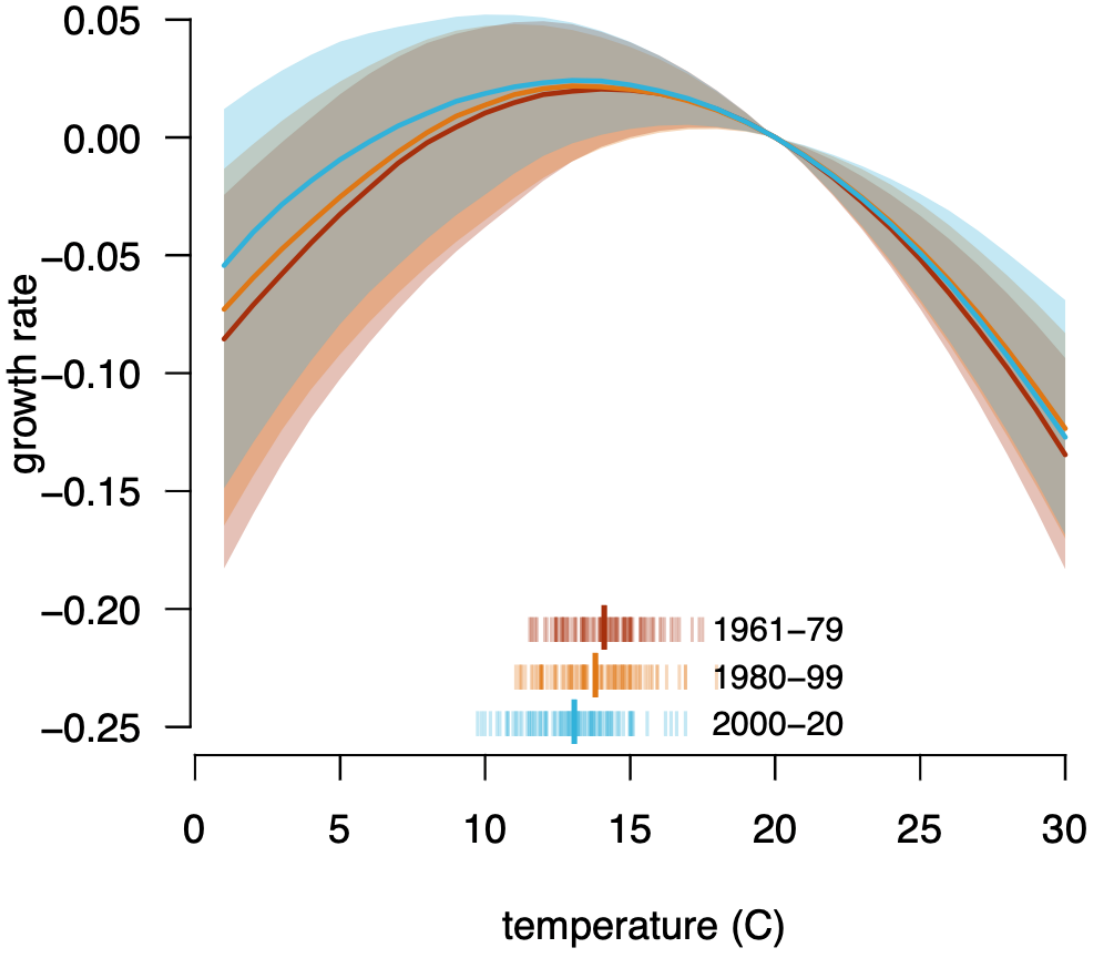
Growth effects of temperature



Global, non-linear response of GDP growth to temperature

Robust to alternate controls, functional forms, climate data

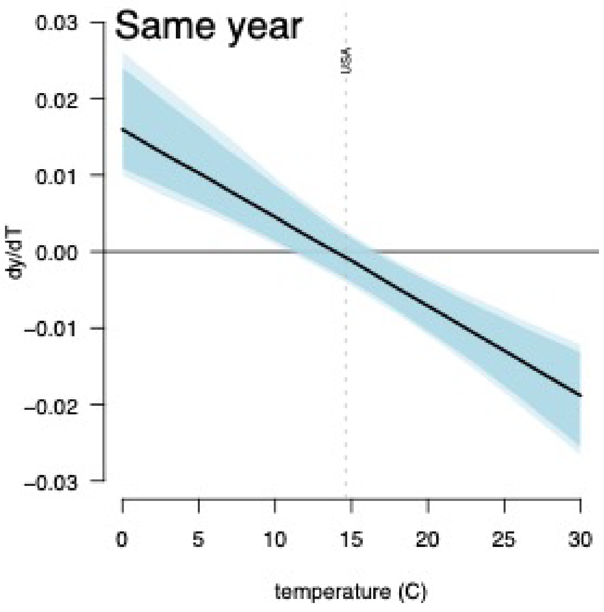
No clear evidence of adaptation



Response not flattening over last 6 decades

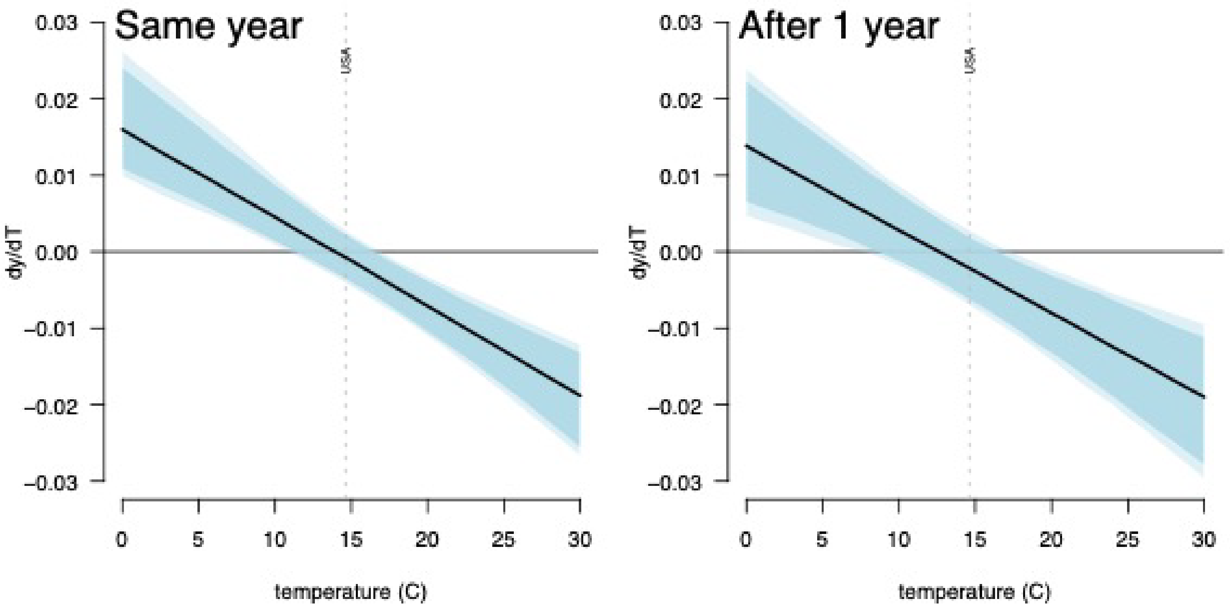
(Global real GDP/cap gone up >3x during this period)

One hot year affects growth for multiple years



"Marginal effect" = derivative of response function

One hot year affects growth for multiple years



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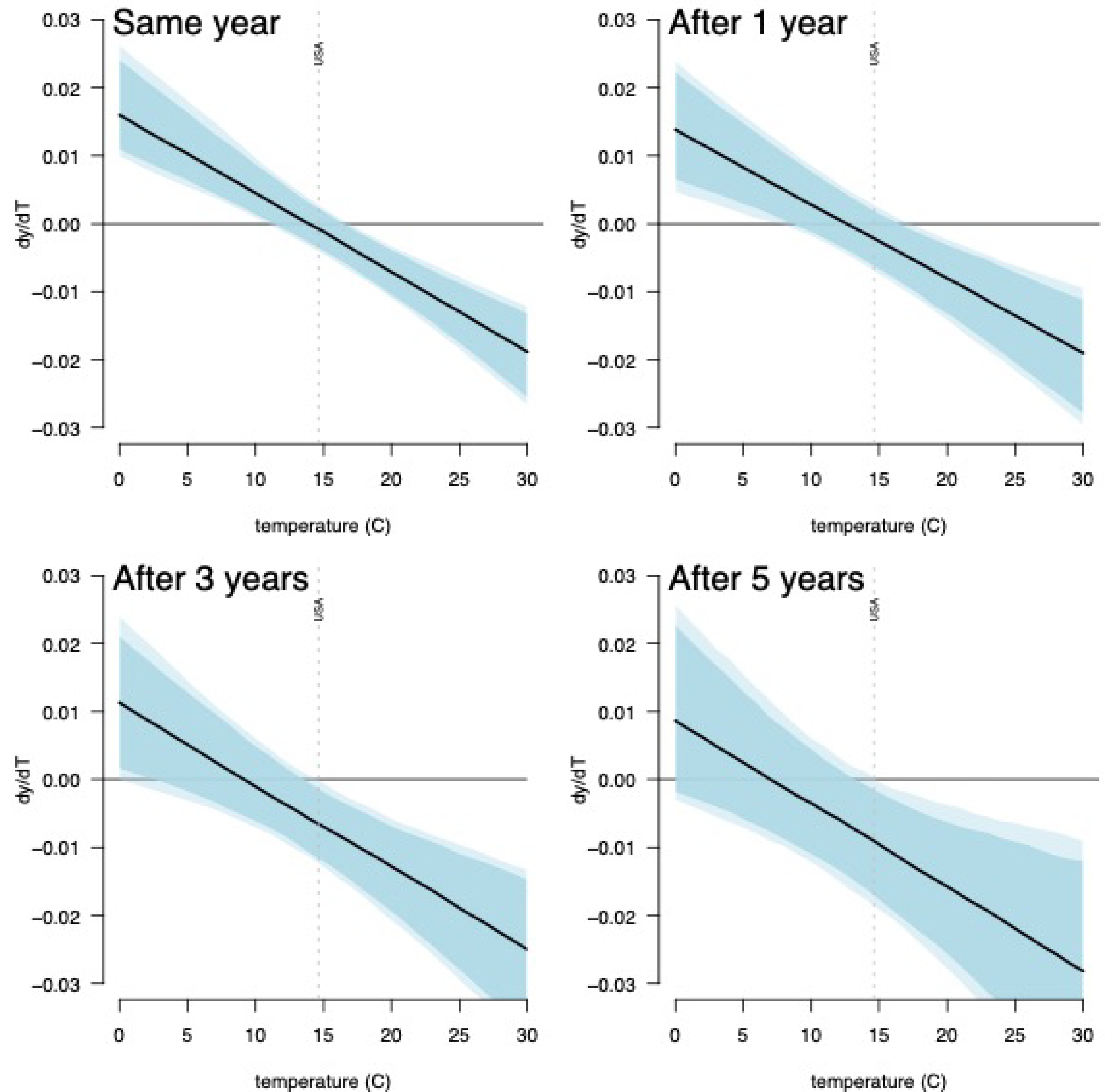


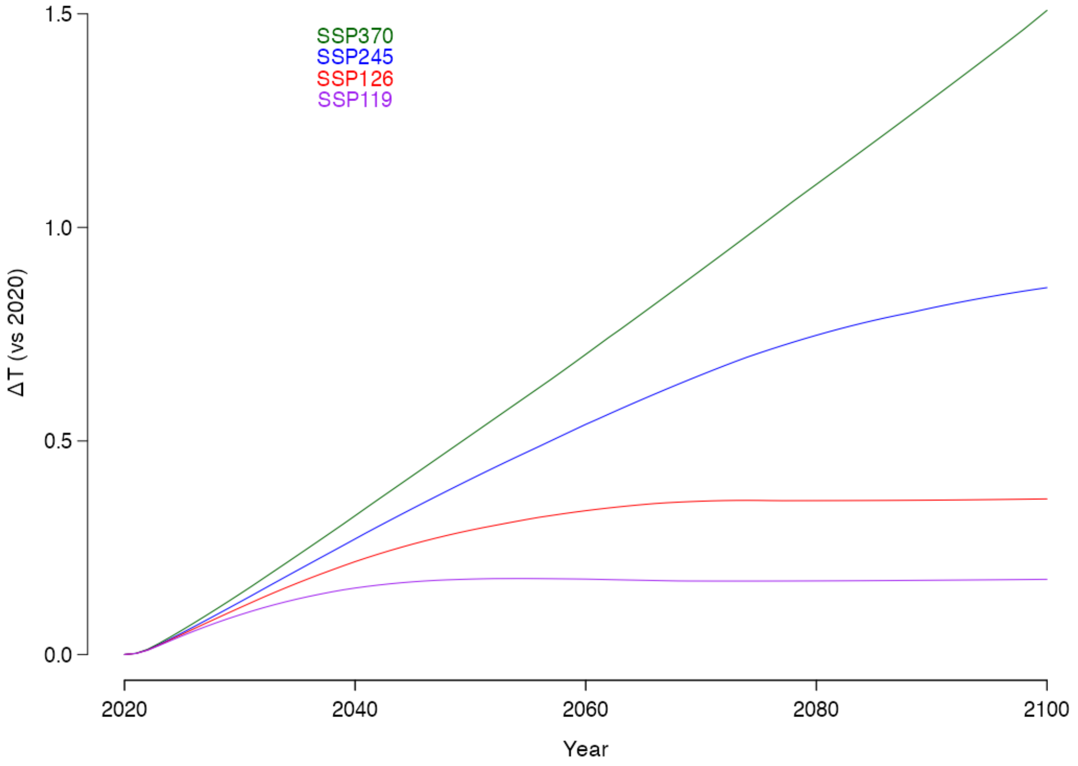
Cumulative effects of one hot year increasingly negative for most of the world, US included

Implications for near-term GDP

Run world forward, assuming baseline growth rate of 2%

Compute impact of different amounts of warming

Change in global temperature (relative to 2020)



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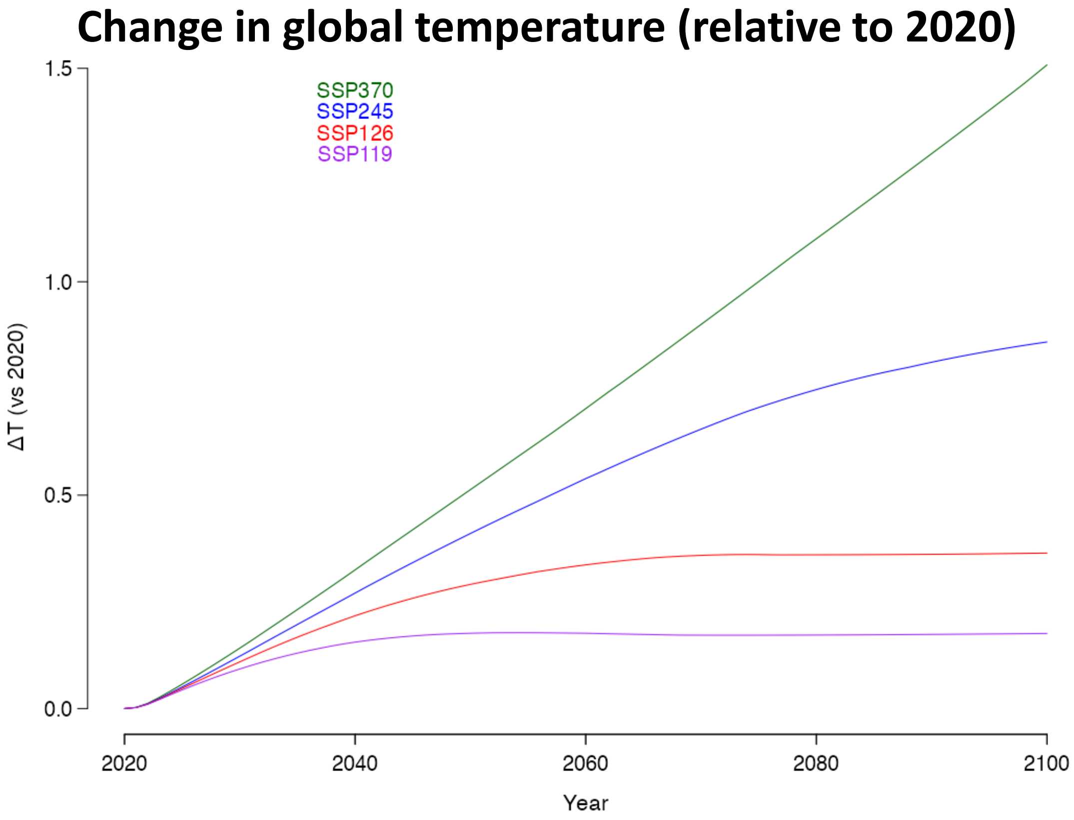

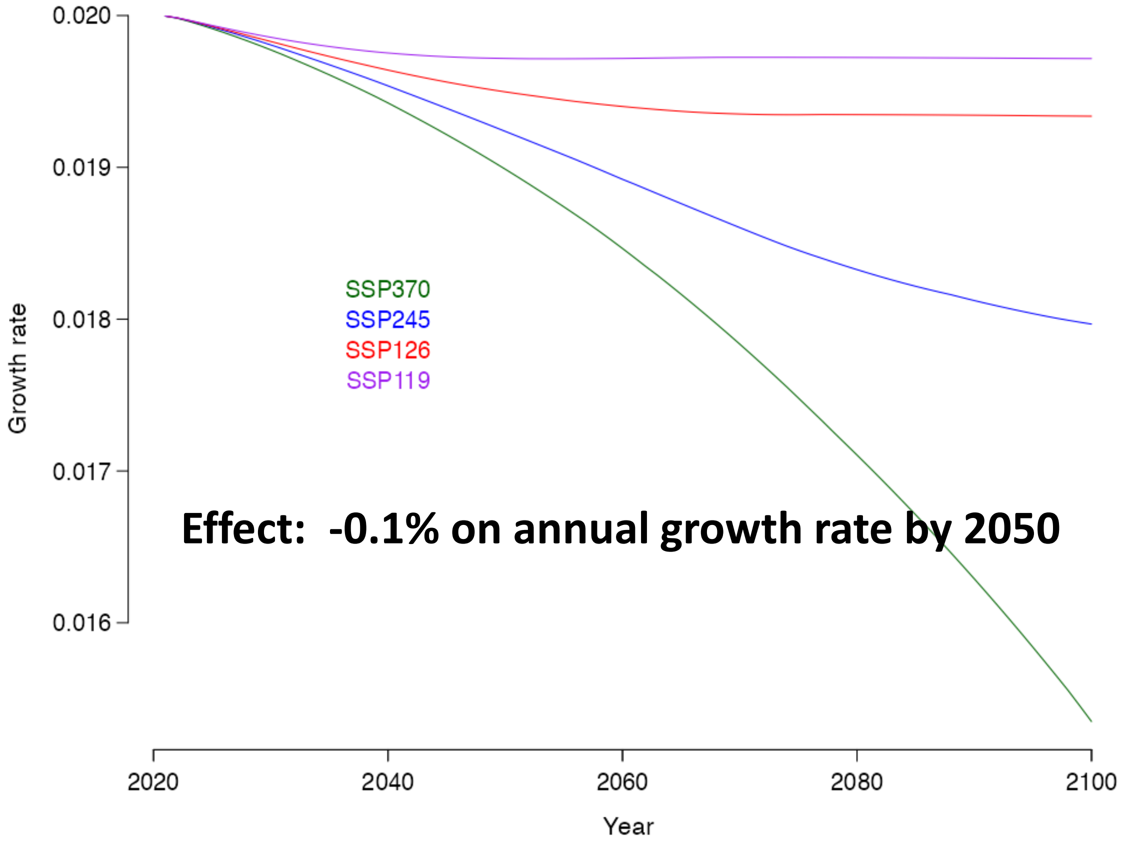

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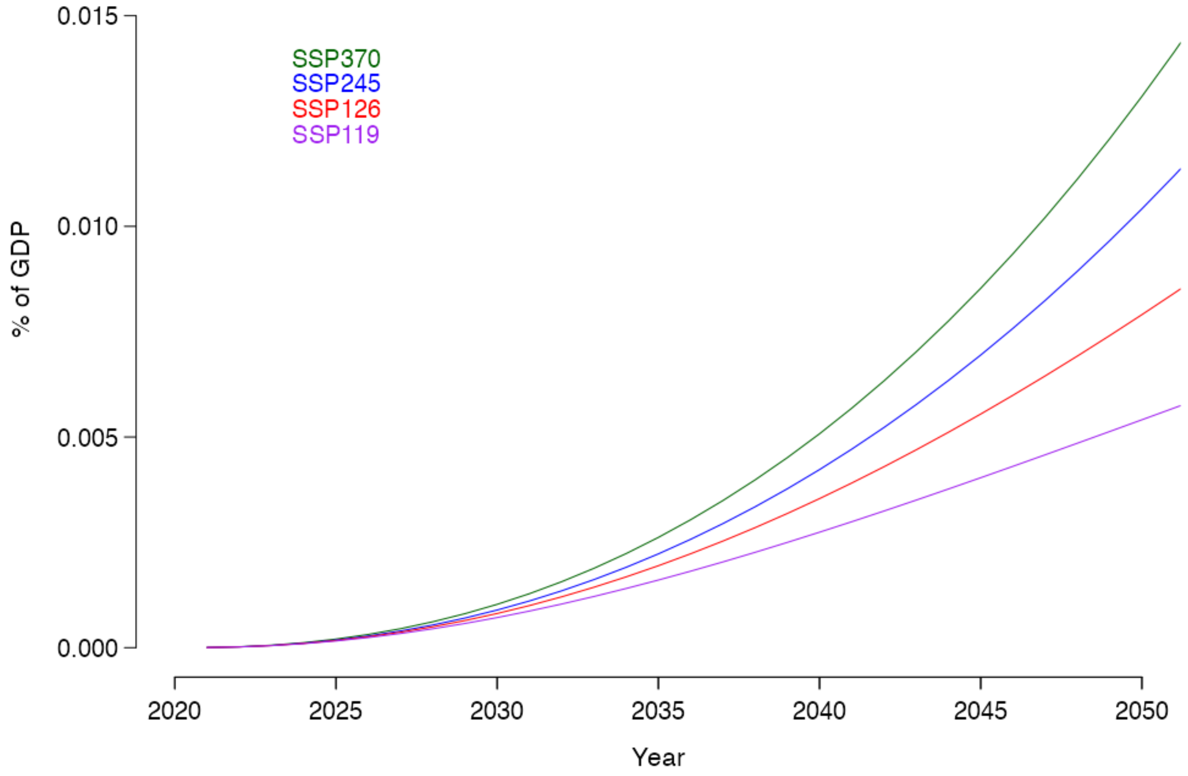

1.5% lower per cap GDP by 2050 under SSP3-7.0

Note: this is using "zero-lag" model; estimates more negative with additional lags.

How to integrate into long-run budget outlook?

Historical data offer an empirical constraint on *dGrowth/dTemp*

How to integrate into long-run budget outlook?

Historical data offer an empirical constraint on *dGrowth/dTemp*

These data suggest historical TFP slowdown <u>not</u> driven substantially by climate in US (we're near optimum temp)

- Implication: projections that reflect this slowdown are not already baking in climate impacts.

<u>Recommendation</u>: Take preferred model with TFP or factor-specific productivities, adjust productivities so model output matches these empirical constraints

Measuring the inequalities of climate change

The Climate Impact Lab
+
Tamma Carleton
Bren School of Environmental Science and Management
University of California, Santa Barbara & NBER

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National Academies of Sciences, Engineering, and Medicine

June 14^{th}, 2023

Climate change is a **global** challenge, but its impacts are felt **locally**

Source: Associated Press

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Accurate local damage estimates are critical to climate policy

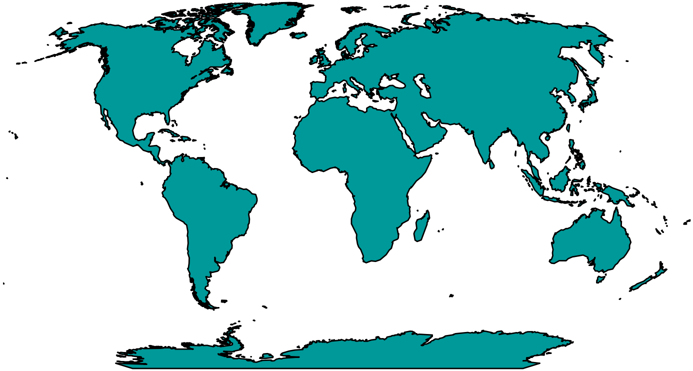
- **Mitigation:** Aggregate climate damages are inaccurate if heterogeneity is ignored
- **Adaptation:** Planning for climate impacts requires accurate local projections

Source: Associated Press

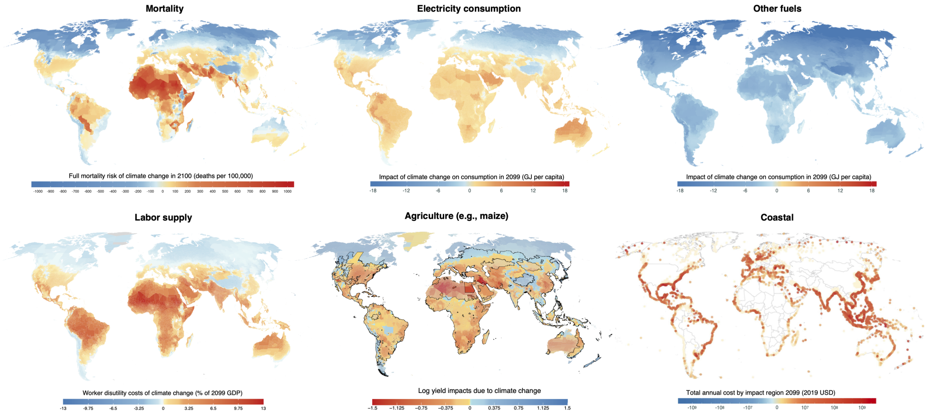
Early global climate damage assessments

"Estimating the damages from greenhouse warming has proved to be extremely difficult. The DICE model assumes that a 3°C warming would lower world output by **1.3 percent**."

–Nordhaus (AER, 1993)



A new era: high spatial resolution



Sources: Carleton et al. (2022); Rode et al. (2021, 2023); Hultgren et al. (2023); Depsky et al. (2023)

A new era: high spatial resolution

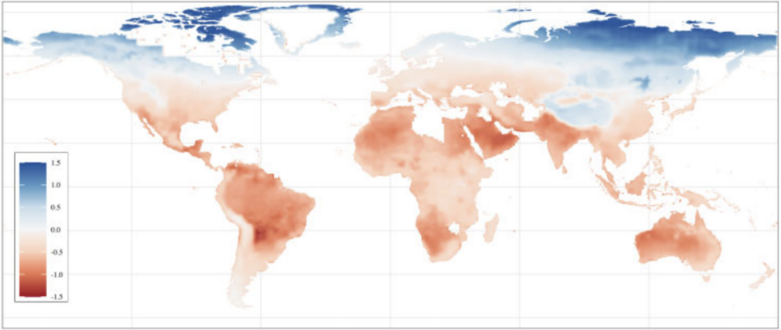
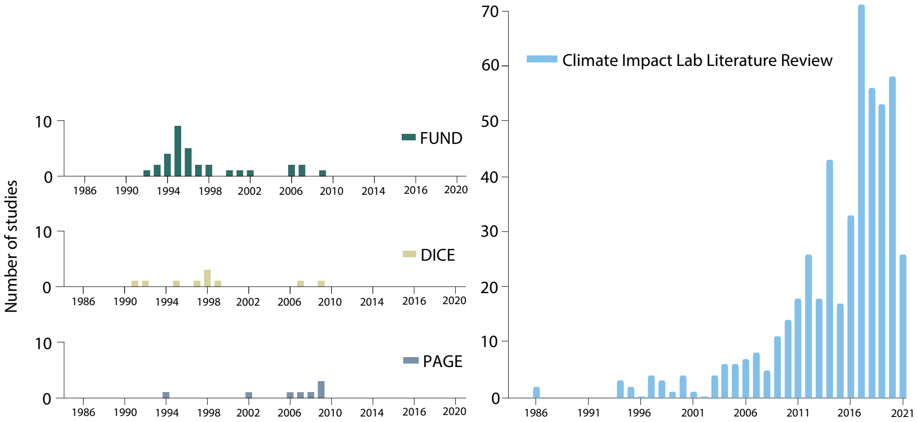


Figure 7. Effect of climate change on real output per capita in 2200
Note: The log of real output per capita under climate change minus the log of real output per capita under no climate change in period 200.

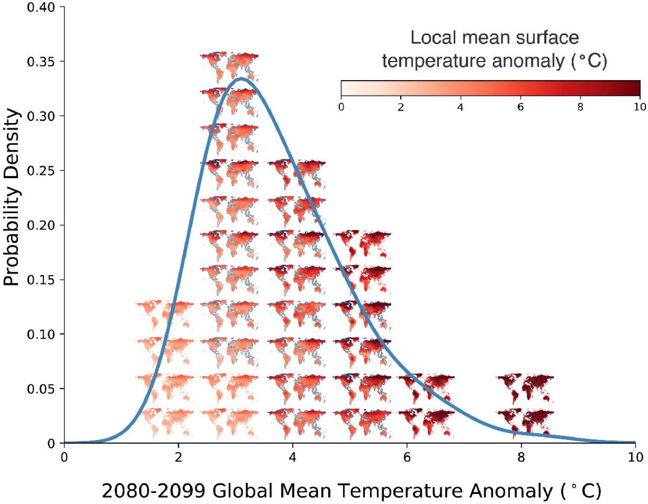
Conte, Desmet, Nagy, Rossi-Hansberg (J Econ Geo, 2021)

A new era: empirical foundations

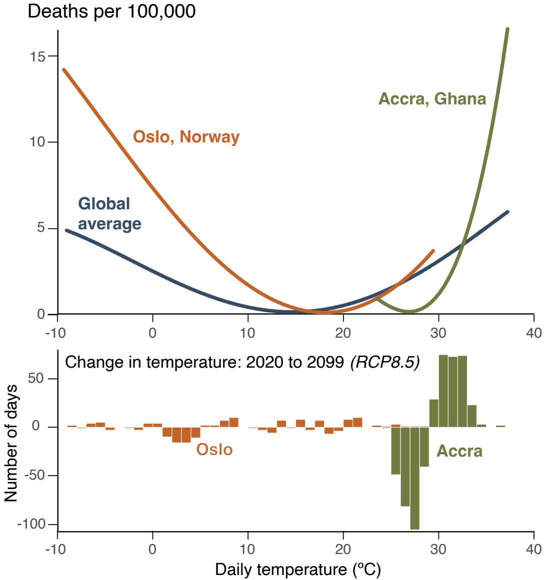


A new era: probabilistic projections

The probability distribution of estimated change in Global Mean Surface Temperature in 2080-2099 (CMIP5/SMME; RCP 8.5)



A new era: empirically-based adaptation



Carleton & Greenstone (*REEP*, 2022)

A new era for climate damage estimation

Climate damage calculations can now feasibly...

$\longrightarrow$ be based on best-available **empirical evidence** and **climate models**

$\longrightarrow$ be **globally representative**

$\longrightarrow$ account for **adaptation** and **its costs**

$\longrightarrow$ characterize and value **uncertainty**

Meeting these goals will provide the foundation for emerging equity-focused climate policies

Climate Impact Lab

Modular analysis

Mortality — heat and cold deaths (Carleton et al., *QJE 2022*)

All cause mortality (<5)   All cause mortality (>64)   All cause mortality (5-64)

Agriculture — crop yields (Hultgren et al., *WP 2023*)

Maize   Wheat   Rice

Soybean   Sorghum   Cassava

Energy — energy and electricity demand (Rode et al., *Nature 2021*)

Electricity consumption   Other fuels consumption

Labor — labor supply & disamenity (Rode et al., *WP 2023*)

High risk labor   Low risk labor

Coastal — sea level rise and storm damages (Depsky et al., *WP 2023*)

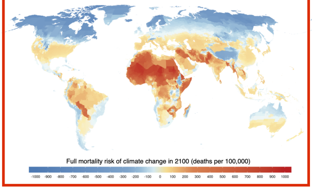
Sea level rise inundation   SLR $\times$ tropical cyclone surge

Integration — valuing marginal damages (Nath et al., *WP 2023*)

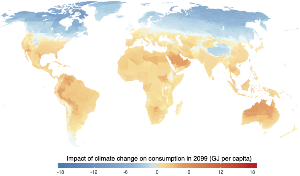
Intertemporal discounting   Valuing inequality   Pricing risk

Global climate change damages across sectors

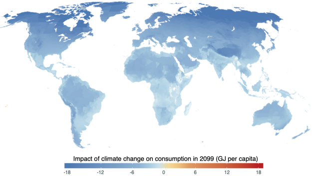
Mortality



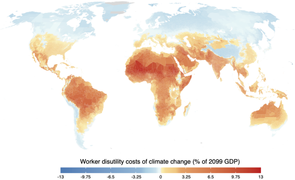
Electricity consumption



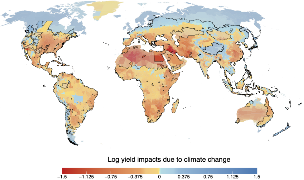
Other fuels



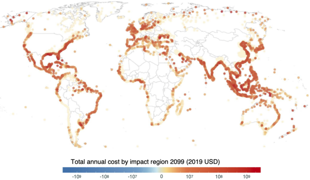
Labor supply



Agriculture (e.g., maize)

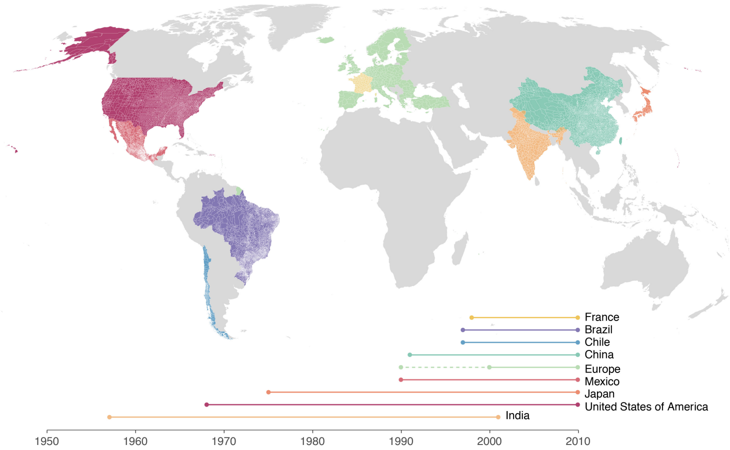


Coastal



Quantifying climate damages from mortality

Subnational mortality records covering 55% of the global population

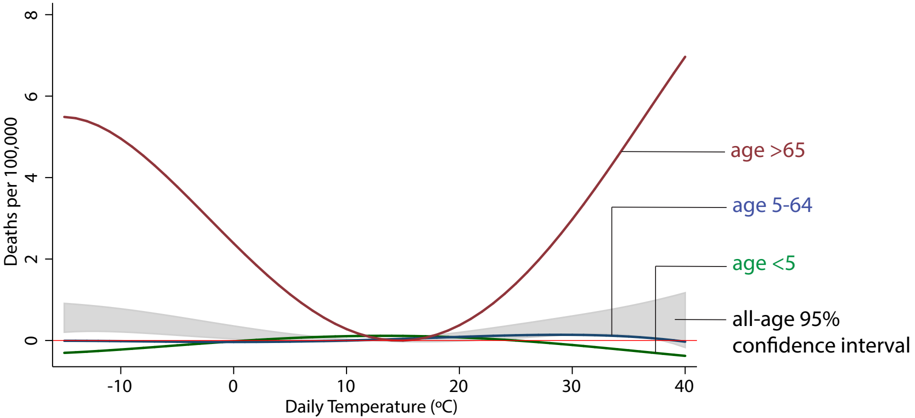


Age-specific annual mortality rates at ∼county level

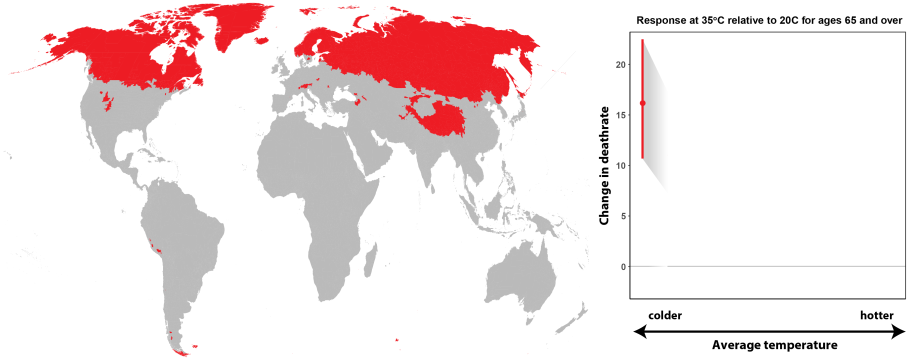
Carleton et al. (QJE, 2022)

Quantifying climate damages from mortality

Extreme heat and extreme cold impact mortality rates:

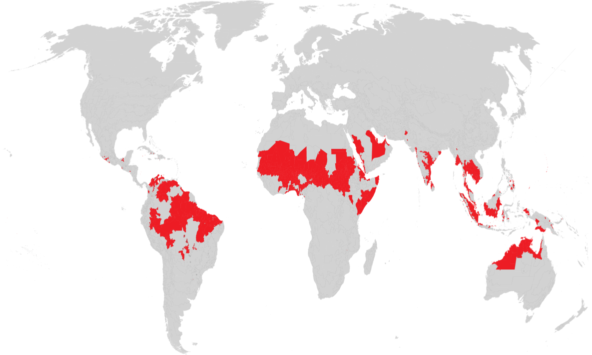


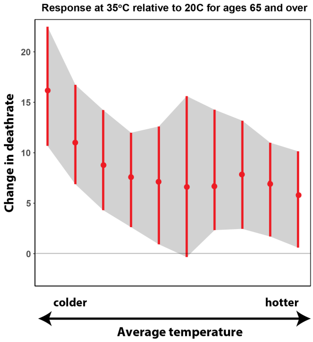
Mortality damages vary by climate



Effect day at 35°C relative to 20°C for ages 65 and over.
Coefficient calculated for deciles of *TMEAN* (red shaded area).

Mortality damages vary by climate





Effect day at 35°C relative to 20°C for ages 65 and over.
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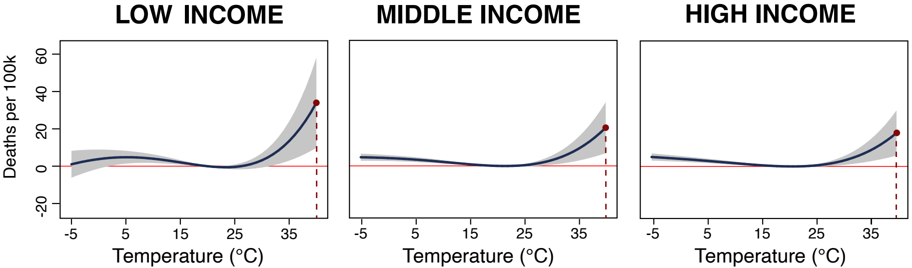
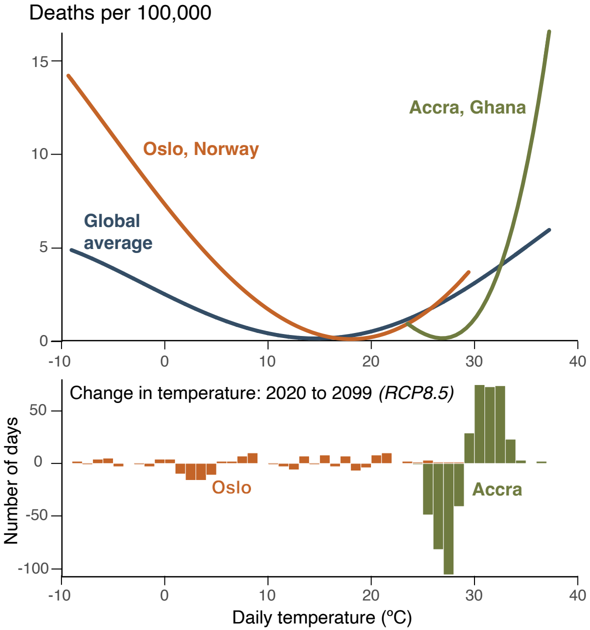
Mortality damages vary by income

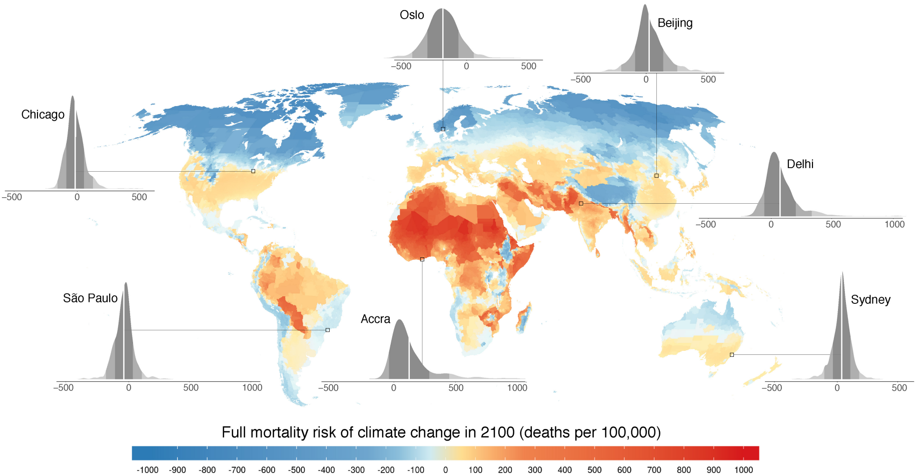


Quantifying climate change damages from mortality



T. Carleton + Climate Impact Lab

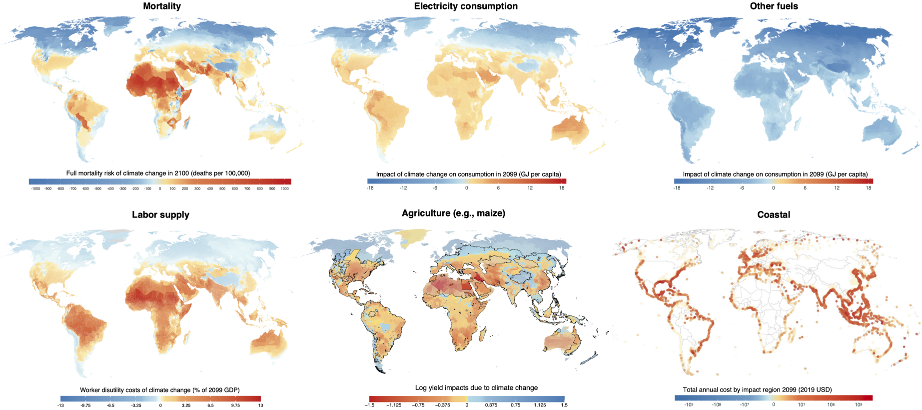
Mortality impacts are distributed unequally



Δ Mortality + adapt. costs due to warming; 2099, high-emissions scenario

T. Carleton + Climate Impact Lab

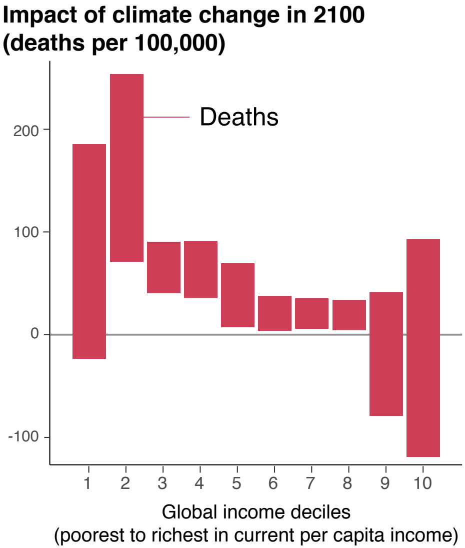
Impacts are distributed unequally across the globe



2099, high-emissions scenario

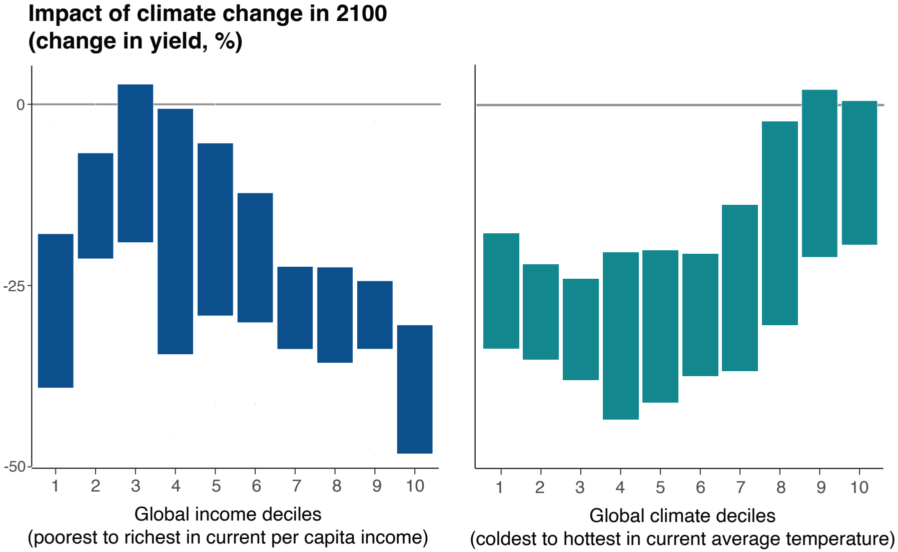
Uncertainty

Mortality: Distribution of burden by income



Carleton et al (2022)

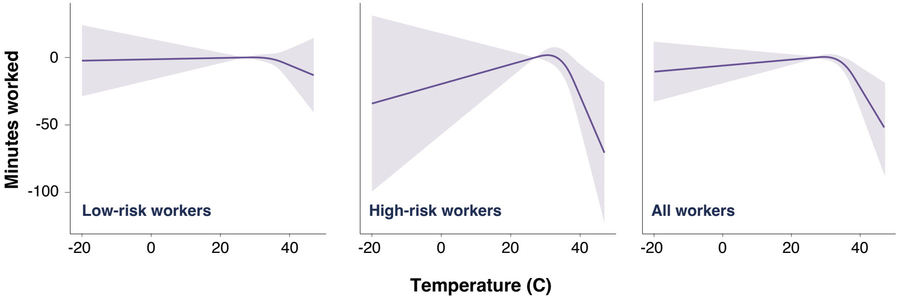
Agriculture: Losses greatest in breadbaskets



Hultgren et al (WP, 2023)

Labor: Damages fall on high-risk workers

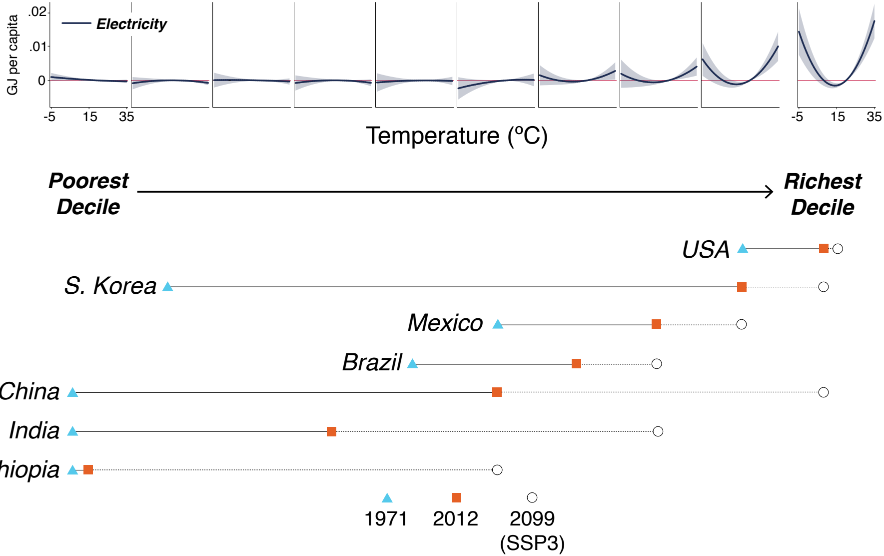
- **High risk workers:** Agriculture, mining, construction, manufacturing
- **Low risk workers:** All other sectors



⟶ Use labor supply response to derive compensating differential for extreme weather

Rode et al (WP, 2023)

Energy: Income shapes temperature response



Rode et al (Nature, 2021)

The Social Cost of Carbon

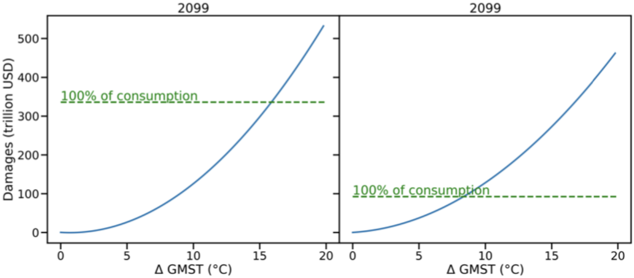
The Social Cost of Carbon (SCC) - the monetary value of the damages imposed by the release of one additional ton of carbon-dioxide.

The SCC enables analysis of policy tradeoffs involving climate change mitigation.

Accounting for inequality in the SCC calculation

Implementation: compute a **spatial certainty equivalent damage function** that places higher weight on damages accruing to poor regions, where each dollar is worth more utility (CRRA utility with $\eta = 2$)

Damage Functions Using Average Global Income (Left)
Versus Spatial Certainty Equivalent (Right)



Nath et al. (*WP, 2023*)

A Data-Driven Social Cost of Carbon

Sectors: Mortality, energy, labor, agriculture, coastal

	Constant discounting: $\delta = 2\%$			Endogenous discounting
	Mean over uncertainty	**Certainty equivalent**	**Equity weighting**	**Ramsey w/ uncertainty**
RCP4.5	\$43	\$58	\$77	\$156
RCP7.0	\$71	\$116	\$112	\$941

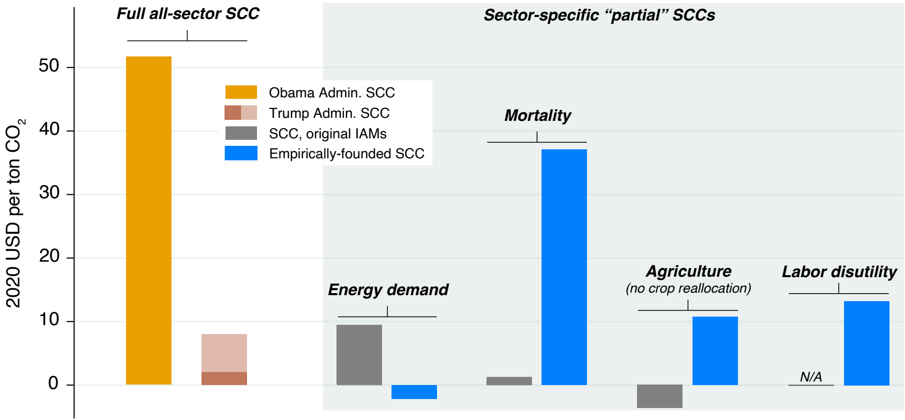
Assumptions: $\eta = 2$ and $\rho = 0$; SSP3 (constant δ); SSPs 2-4 (endog. discounting)

→ Many alternative valuation metrics presented in Nath et al (*WP, 2023*)

→ Integrating probabilistic socioeconomic and emissions trajectories

→ Also computing SC-methane and SC-nitrous oxide

Non-market damages dominate bottom-up SCC estimates



Source: *Climate Impact Lab*

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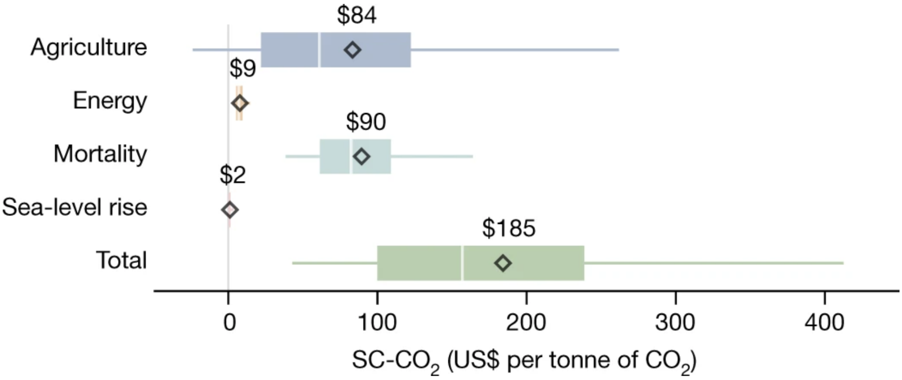
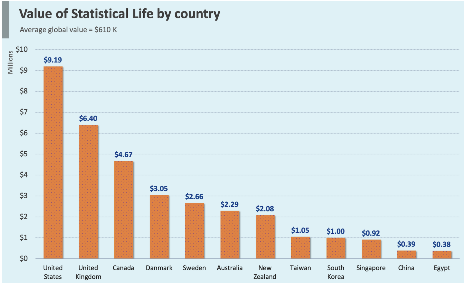


Source: Rennert et al. (2022)

Challenges in integrating local sectoral damages into aggregate damage metrics

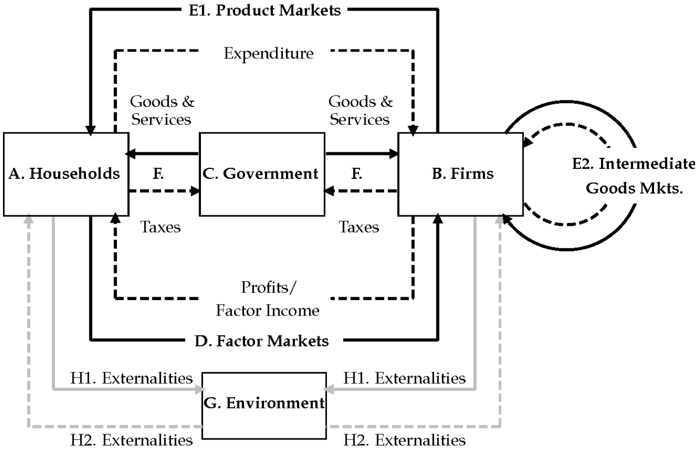
#1: Monetization Conversion from physical units $\longrightarrow$ $$ can be difficult and depend critically on strong assumptions.

- **Mortality:** Whether and how to use an income elasticity of the VSL? (Carleton et al., 2022)
- **Labor:** Disutility estimates depend on a set of stylized assumptions (Rode et al., 2023)
- **Crime and conflict:** ?? **Mental health:** ??



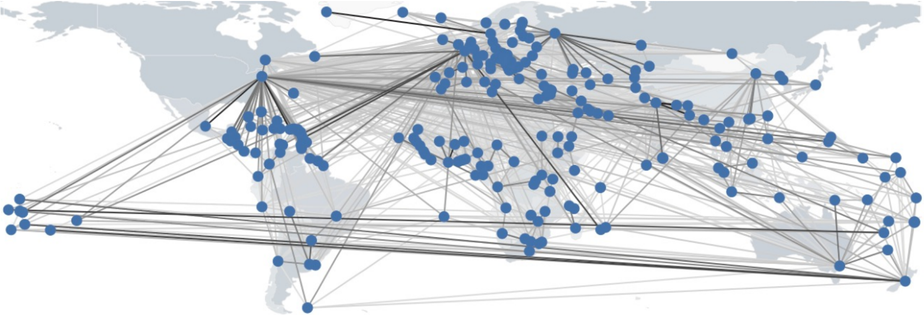
Challenges in integrating local sectoral damages into aggregate damage metrics

#2: Feedbacks Interactions and feedbacks are poorly characterized



Challenges in integrating local sectoral damages into aggregate damage metrics

#3: Migration Migration is likely first-order but a very difficult problem



- Inherently a general equilibrium problem $\longrightarrow$ difficult to characterize with reduced form approaches
- Climate-driven expectation formation poorly understood

Thank you!

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www.impactlab.org

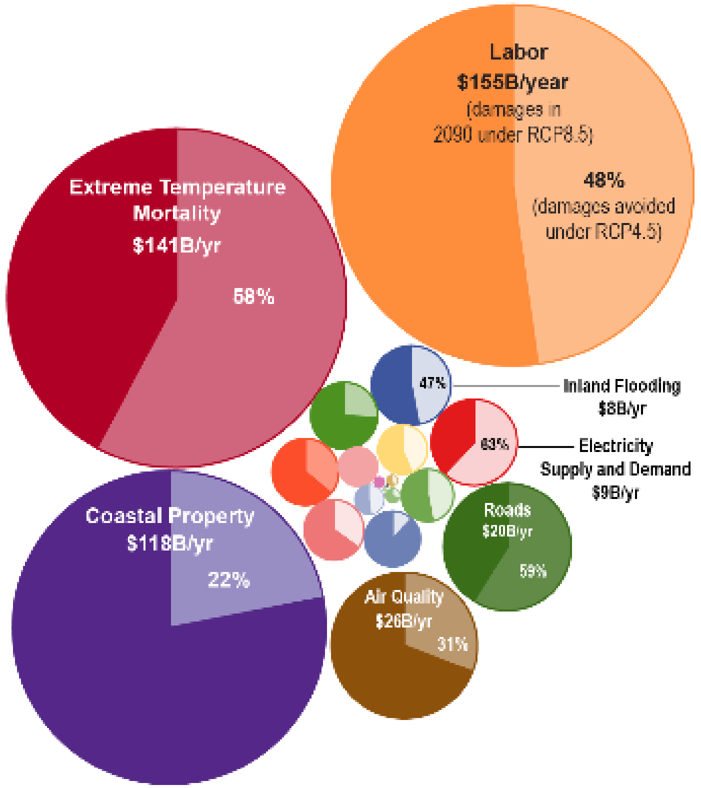
Modeling Future U.S. Climate Impacts using FrEDI

Jeremy Martinich
USEPA Climate Change Division

NAS workshop on
Incorporating Climate into Macroeconomic Modeling

The Climate change Impacts and Risk Analysis (CIRA) Project

- **CIRA Purpose: To quantify and monetize climate change impacts across sectors of the U.S., including how risks can be reduced through GHG mitigation and adaptation.**
  - Approach uses a common modeling framework (consistent inputs and assumptions) to evaluate impacts across sectors under specific future emission scenarios (e.g., RCPs), supported by peer-reviewed climate impact literature (>50 journal articles since 2010)
  - CIRA has been coordinated by EPA for >13 years, and involves researchers from other agencies (e.g., NOAA, CDC, DOE), consultants, and academics.
- **CIRA fills an important gap in U.S. climate assessments.**
  - The CIRA project is one of the only impact models of this scale (geographic & number of impacts)
  - It creates a framework to estimate and compare the economic impacts across sectors and identify ways to reduce risk.
- **CIRA is scenario specific and resource intensive.**
  - Modeling phases take ~***12-15 months***, have involved ***50-60 modelers*** (most external to EPA), and each study only considered a limited set of specific emission scenarios.



NCA4 Fig. 29.2: Projected Damages and Potential for Risk Reduction by Sector

www.epa.gov/cira

Creating a More Flexible Climate Impacts Framework: The Framework for Evaluating Damages and Impacts (FrEDI)

FrEDI is a **reduced form framework** that draws upon detailed temperature-impact relationships from over 30 peer-reviewed studies, including from CIRA, to **rapidly estimate** climate change impacts and damages **under any custom emission or policy pathway**.

Inputs:

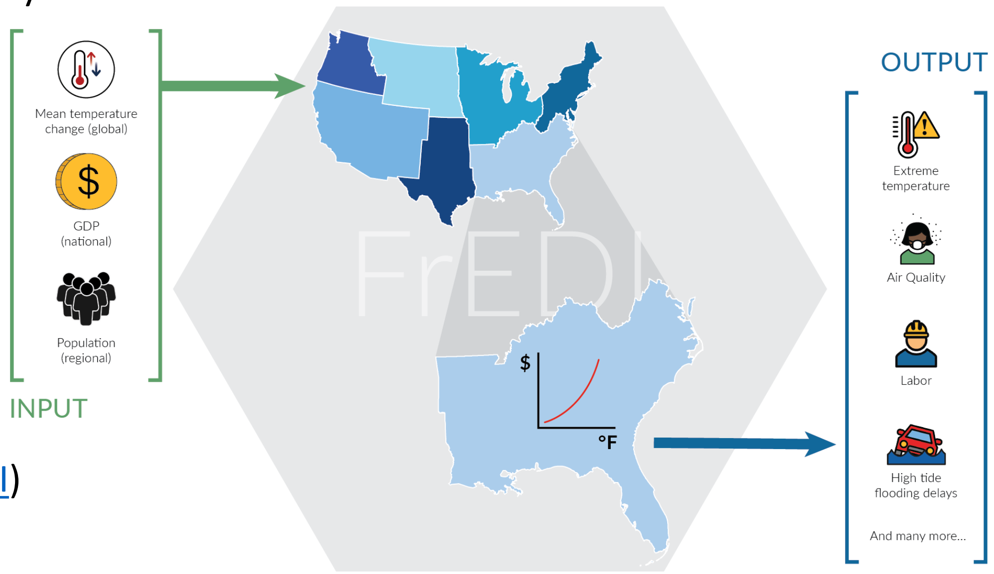
- Projections of any U.S. population, GDP, and global temperature scenario (from any emissions scenario from a simple climate model)

Outputs:

- Rapid estimates of physical and monetized climate impacts....
  - Across 20+ sectors
  - At the national or NCA region scale
  - Under multiple adaptation options
  - Across socially vulnerable populations
  - Accounting for important sources of uncertainty

Framework characteristics:

- Open-source and transparent (available on github: www.github.com/usepa/FrEDI)
- ISI-level peer and public reviews of technical documentation
- Robust and flexible modeling framework



https://www.epa.gov/cira/fredi

FrEDI Sectoral Coverage v3.0

Currently in Tool:
- Agriculture (CIL)*
- Asphalt Roads*
- Coastal property
- Electricity demand/supply
- Electricity trans/distribution infrastructure
- Extreme temperature mortality
- Extreme temperature mortality (CIL)*
- Extreme temperature mortality (ATS)*
- Hightide flooding and transportation
- Inland Flooding (residential)
- Labor allocation
- Marine fisheries
- Ozone/PM2.5 health effects
- Property & violent crime (CIL)*
- Rail infrastructure
- Road infrastructure
- Southwest dust
- Tropical Storm Wind *
- Urban drainage
- Water quality
- Wildfire/AQ health effects and suppression costs
- Winter recreation
- Valley Fever

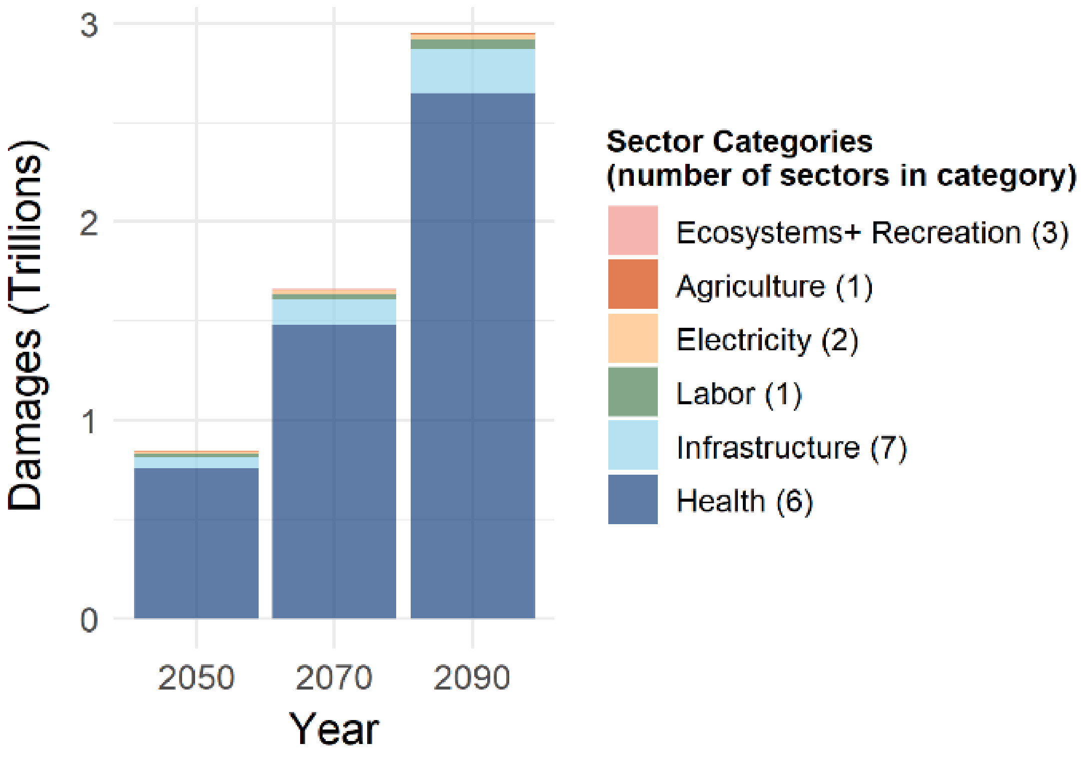
Coming Soon:
- Energy (CIL)*
- Coastal property (CIL)*
- Labor (CIL)*
- Suicide
- Forestry
- Recreation
- Agriculture
- Vibrio
- Coastal marsh loss

Additional Features:
- SV module
- Robust testing suite

Studies from non-CIRA work (*)

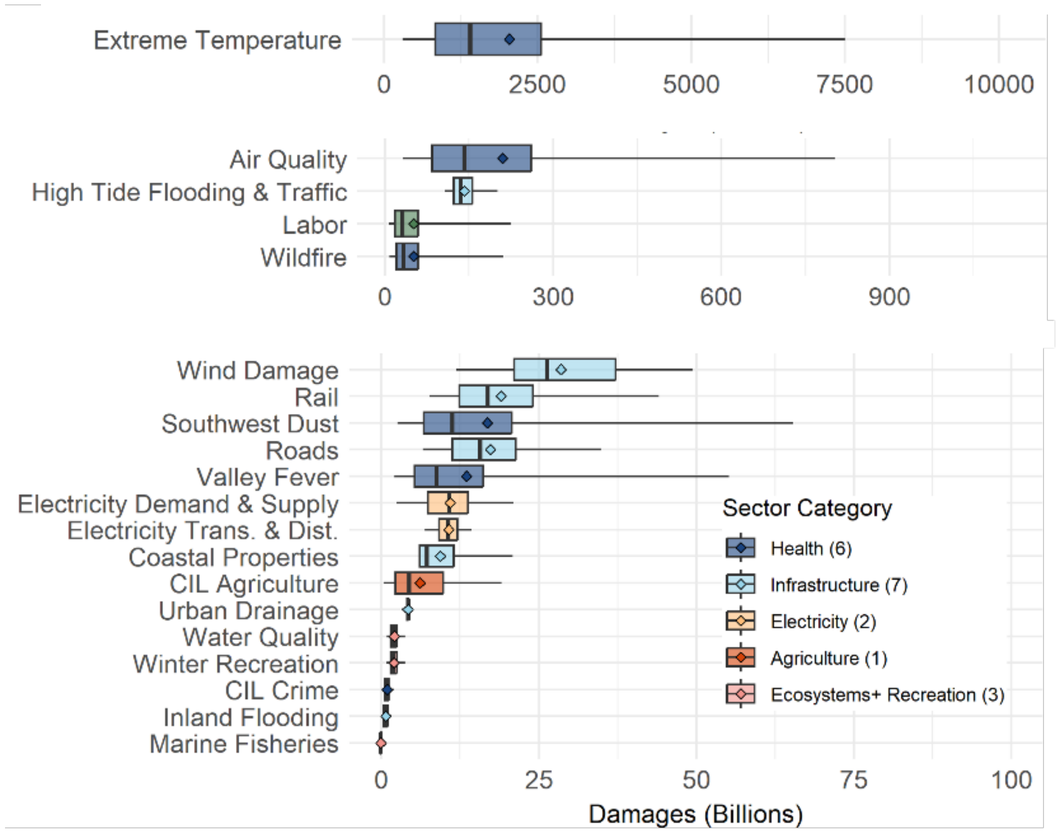
Example FrEDI Application #1:
Baseline Climate-Driven Damages (no additional mitigation)

Non-comprehensive Annual Climate-Driven Damages (Trillions$), by impact category



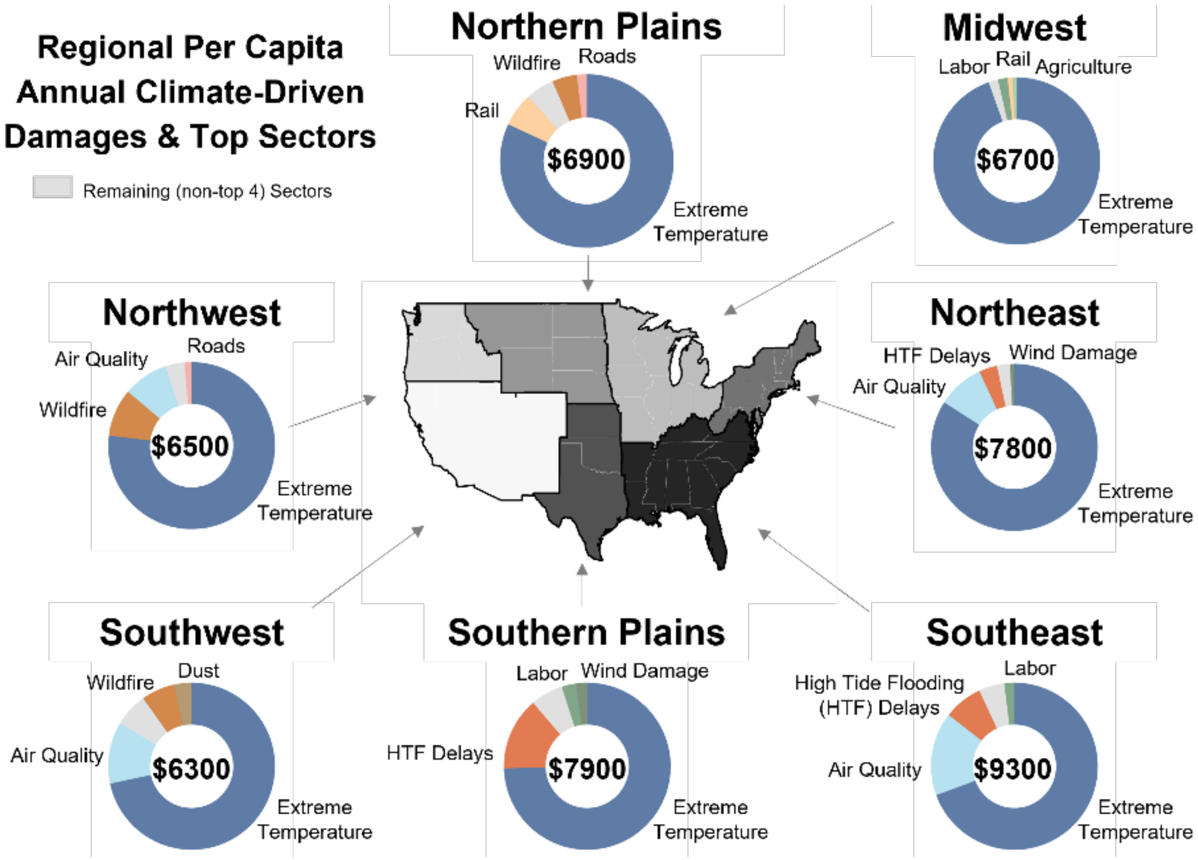
Figures from *Hartin et al., in discussion*

National Annual 2090 Climate-Driven Damages (Billions$), by impact sector



Example FrEDI Application #1:
Baseline Climate-Driven Damages (no additional mitigation)

Regional Annual 2090 Climate-Driven Damages ($/person), by largest impact sector (*not comprehensive*)



Relative Annual 2090 Climate-Driven Damages ($), by race/ethnicity

FrEDI Sectoral Coverage v3.0

Currently in Tool:

- Agriculture (CIL)
- Asphalt Roads
- Coastal property
- Electricity demand/supply
- Electricity trans/distribution infrastructure
- Extreme temperature mortality
- Extreme temperature mortality (CIL)
- Extreme temperature mortality (ATS)
- Hightide flooding and transportation
- Inland Flooding (residential)
- Labor allocation
- Marine fisheries
- Ozone/PM2.5 health effects
- Property & violent crime (CIL)
- Rail infrastructure
- Road infrastructure
- Southwest dust
- Tropical Storm Wind
- Urban drainage
- Water quality
- Wildfire/AQ health effects and suppression costs
- Winter recreation
- Valley Fever

Coming Soon:

- Energy (CIL)
- Coastal property (CIL)
- Labor (CIL)
- Suicide
- Forestry
- Recreation
- Agriculture
- Vibrio
- Coastal marsh loss

Sectors with at least some impacts to capital within contiguous U.S. borders

Sectors with non-capital effects most easily connected to macro models

Some Takeaways

- Our current levers into macro frameworks only capture a small portion of damages coming from FrEDI.
  - For example, FrEDI sectors with damages relevant to capital represent <15% of total damages in 2030 and <16% in 2090.
- FrEDI is far from comprehensive, with many important omitted impacts.
- Impacts captured in sectoral impact models continue to underrepresent extremes.
- Explicit focus on national macro effects (e.g., GDP) misses opportunities to communicate what people most easily understand about what climate change will mean to them (e.g., effects on income, costs of health insurance, delays, labor productivity, and the distribution of these effects).
  - Don’t forget the important timeframes involved with climate impacts.

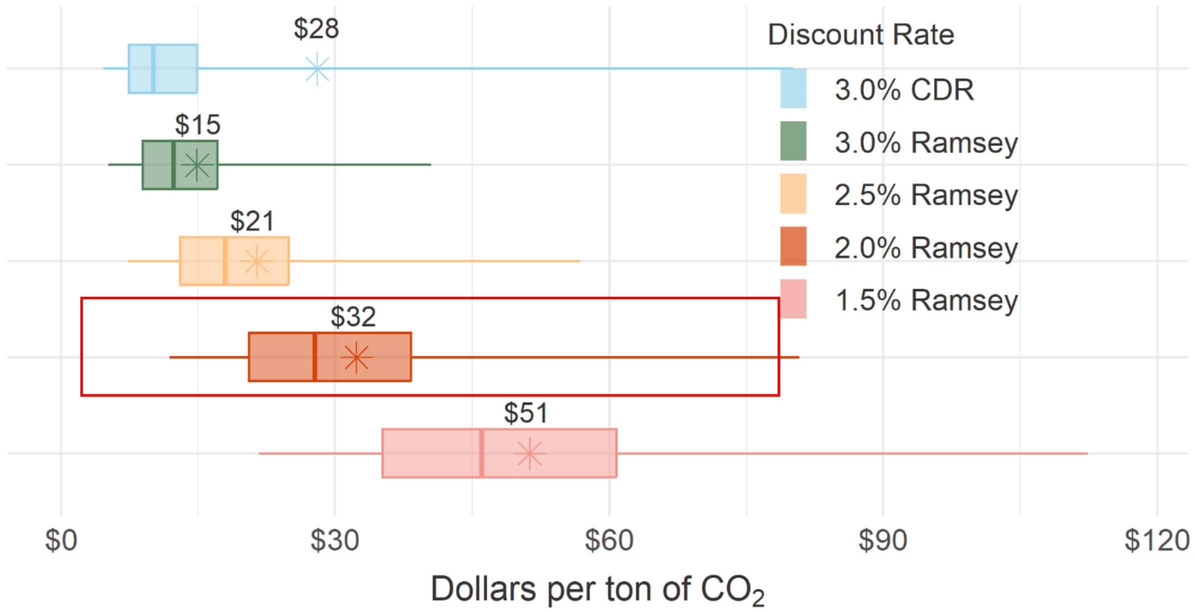
Extras

Important Uncertainties in Quantifying Climate Change Risks

- Future emissions, population, GDP –
  - can be assessed using different scenarios, like RFF-SPs
- Future temperature change associated with an emissions projection (i.e., climate model parameter uncertainty) –
  - can be assessed using multiple FaIR runs or multiple simple climate models
- Damage functions
- Future adaptation
- Interacting effects and/or tipping points
- Impacts outside U.S. borders
- Missing impact sectors

Example FrEDI Application #3: Social Cost of GHGs

FrEDI Net Present Damages ($/ton CO_2)



Hartin et al., in discussion

NPD is sensitive to discounting rate & method

FrEDI NPD Comparison ($/ton CO_2)

	Model	Mean SC-CO_2 ($/ton CO_2)	Discount Rate	% of Global
Global	DSCIM	$230	2% Ramsey	-
	GIVE	$220	2% Ramsey	-
Domestic	DSCIM	$14	2% Ramsey	5%
	GIVE	$11	2% Ramsey	6%
	FrEDI	**$32**	**2% Ramsey**	**14%**

- FrEDI domestic NPD is larger than DSCIM and GIVE domestic values
- FrEDI domestic NPD is >10% of global SC-GHG value

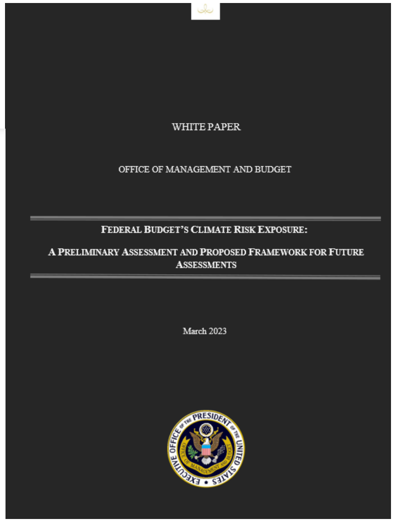
Timeline of FrEDI Development & Applications

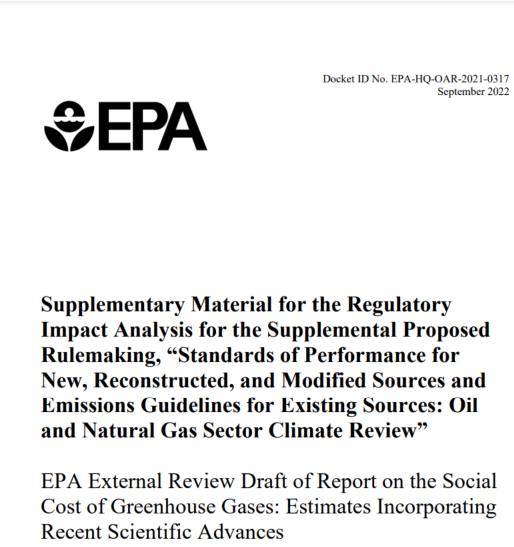
2023
- 111 Proposed Rule (Preamble)
- OMB Federal Financial Risk
- Hartin et al., *in discussion*

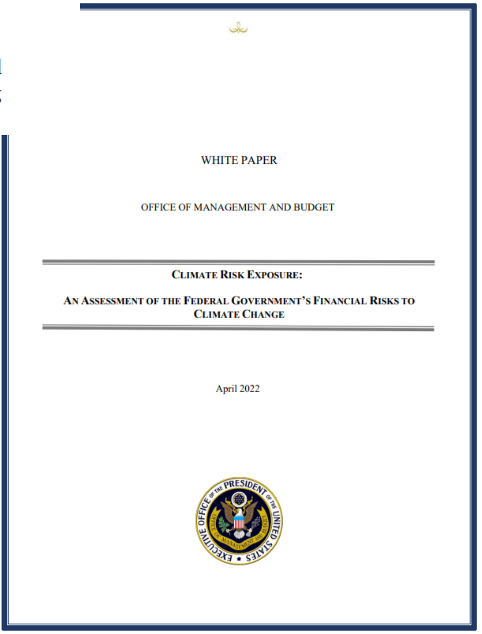
2022
- Social Cost of GHGs TSD (111 Oil & Gas Supplemental)
- OMB Climate Risk Exposure Report (health outcomes)

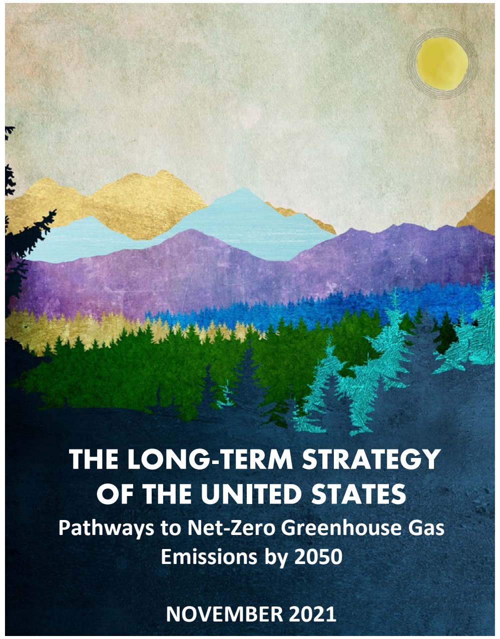
2021
- White House Long Term Strategy
- FrEDI Technical Documentation Published (ISI-level and external peer review)
- Sarofim et al., (temperature binning approach)

Starting in 2010
- CIRA & sectoral study development (precursor to FrEDI)









CIRA Bottom Up Sectoral Modeling – Climate Effects on Air Quality

GCM output RCP scenario

↓

Dynamic downscaling to simulate detailed meteorology

↓

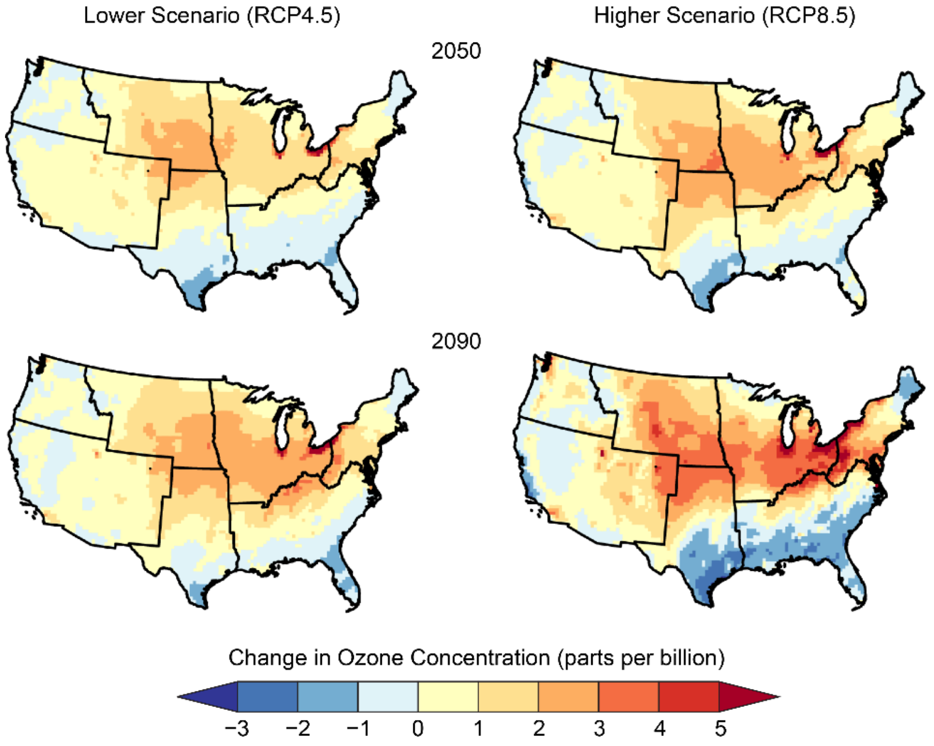
Atmospheric chemistry modeling

↓

Health impact modeling

↓

Valuation of mortality and morbidity



Change in Summer-Average Maximum Daily Ozone

Maps show the change in summer-average maximum daily 8-hour ozone concentrations (ppb) in 2050 (2045-2055) and 2090 (2085-2095) compared to 2000 (1995-2005).

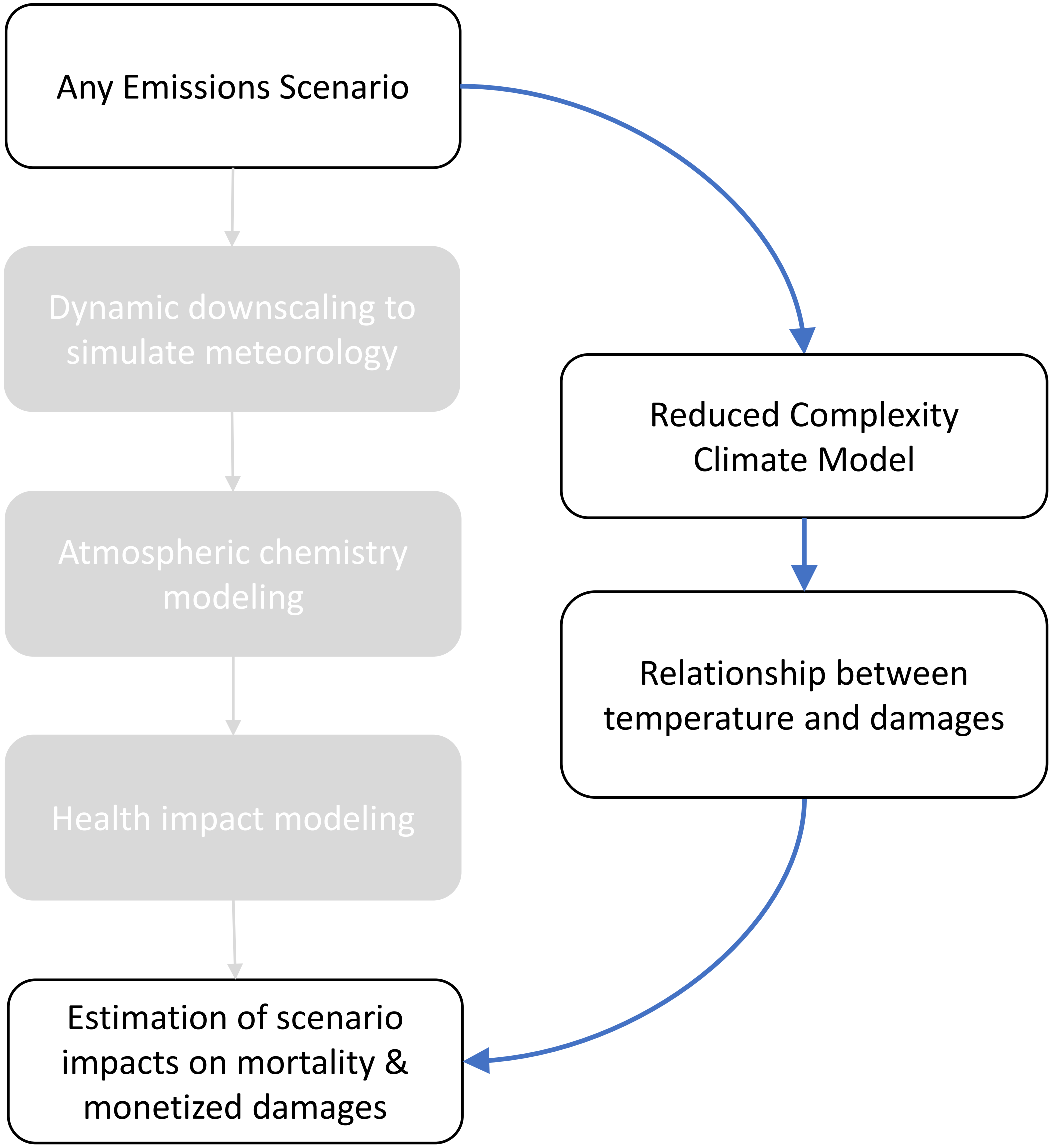
Figure 13.2 from NCA4 Volume II; Table from EPA, 2017

Table 3.2. Cost of Excess (or Avoided) Ozone-Related Premature Deaths

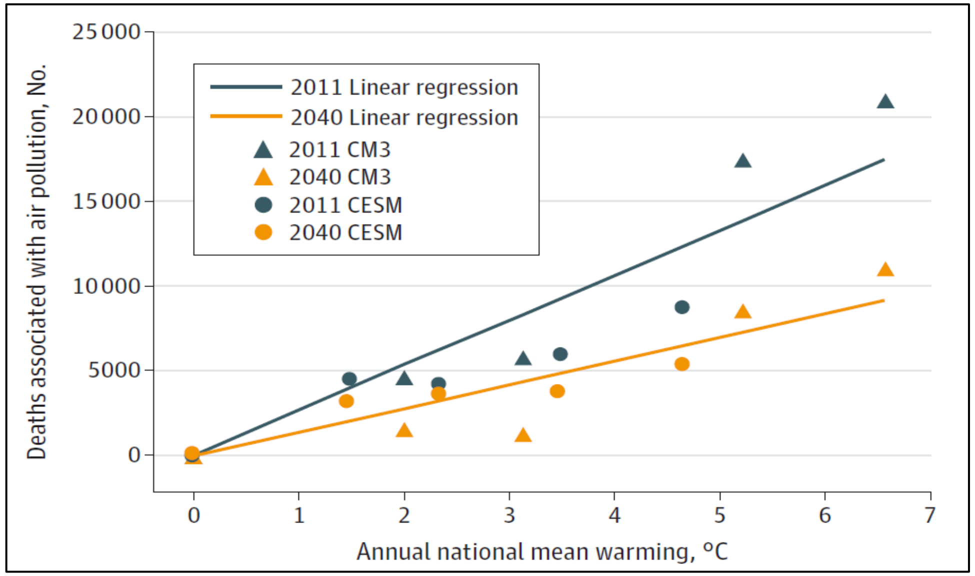
Deaths compared to 2000 (1995-2005). Units are millions of $2015

	2050		2090	
	RCP8.5	RCP4.5	RCP8.5	RCP4.5
Deaths	790 (420 to 1,200)	550 (300 to 810)	1,700 (920 to 2,500)	1,200 (630 to 1,700)
Estimated Value	$9,800 ($880 to $28,000)	$6,900 (-$900 to $21,000)	$26,000 (-$2,200 to $78,000)	$18,000 ($1,600 to $51,000)

FrEDI Sector Example – Climate Effects on Air Quality



Deaths Associated with O_3 and $PM_{2.5}$ by Temperature



Fann et al. 2021

We developed reduced form relationships between changes in temperature and the economic (or physical) damage from the detailed bottom-up sectoral studies using an impacts by degree approach.

Uncertainty Assumptions – 10,000 probable futures

- Same socio-economic (GDP, population, emissions) assumptions as SC-GHG, from RFF: 10,000 scenarios
- Same climate assumptions as SC-GHG (FaIR model): 2,237 possible parameter sets
- Same set of runs used in the SC-GHG TSD