Growth and Development:

The Economics of Climate Change

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Lecture Notes for PhD Growth and Development (EC8510)

Climate Change

- Humans have engaged in large-scale transformations of the natural environment for Millenia.
  - Stone Age hunting technologies led to extinctions of large mammals
  - Agricultural revolutions transformed forests into farmland
  - Dams and reservoirs manipulate the flow of almost all rivers
  - Synthetic fertilizers now flood the nitrogen cycle.
  - We consume about one lego brick of plastic a week.
- However, the restructuring of the global carbon cycle and the accompanying change to the climate stands apart in its scale, complexity, and economic significance.

Climate Change

- The average human contributes around 5 tonnes of CO_2 into the atmosphere every year (Le Quéré et al., 2018), about a quarter of which will remain in the atmosphere for over 1,000 years.
- This CO_2, together with other greenhouse gases, distort the planet's energy balance.
  - In steady state, the sunlight that makes it to the Earth's surface is absorbed and re-radiated back to space
  - The accumulation of GHG emissions blocks some of this re-radiation, redirecting energy back towards the earth's surface.
  - The resulting climate distortion affects not just temperatures, but also where clouds form, when it floods, the intensity and movement of cyclones, and the volume of water in the ocean.

A Brief Overview of Climate Science

- Climate is the joint probability distribution describing the state of the atmosphere, ocean, and freshwater systems.

- The idea that human activity could alter the climate has a long history, going back almost two centuries (Weart, 2018)

- It took focussed research to achieve the level of confidence we now possess that human activity is altering the climate.

    - The null hypothesis that humans have had no influence on global climate is now easily rejected given available data.

Planetary Energy Balance and GHGs

- Sunlight continuously enters our planet's atmosphere from space.
- In order to maintain a stable surface temperature, this flow of incoming energy must be balanced by a flow of energy leaving the atmosphere.
  - 30% of incident sunlight is immediately reflected back out to space
  - The remaining 70% is absorbed by the Earth's surface and atmosphere.
  - Without GHGs the equilibrium global mean surface temperature would be -18°C.
- GHGs distort the Earth's energy balance because they are transparent to incoming visible and UV light but absorb infrared radiation, hindering the return flow of energy back into space.
- This IR is re-emitted in all directions, sending part of this energy back to the surface.

Feedbacks

- In the absence of additional feedbacks, doubling CO_2 concentrations would lead to an effective radiating level about 200m higher, which would lead to an equilibrium surface warming of about 1.2°C.
- However, the warming surface and atmosphere trigger feedbacks.
  - The most important feedback is water vapor: a warmer atmosphere is a more humid atmosphere.
  - Other important feedbacks are sea ice, clouds, and the response of the ocean and land biospheres.
- These change the effective radiating level and consequent surface temperature.
- Estimates of equilibrium climate sensitivity that include feedbacks are generally 2-4.5°C

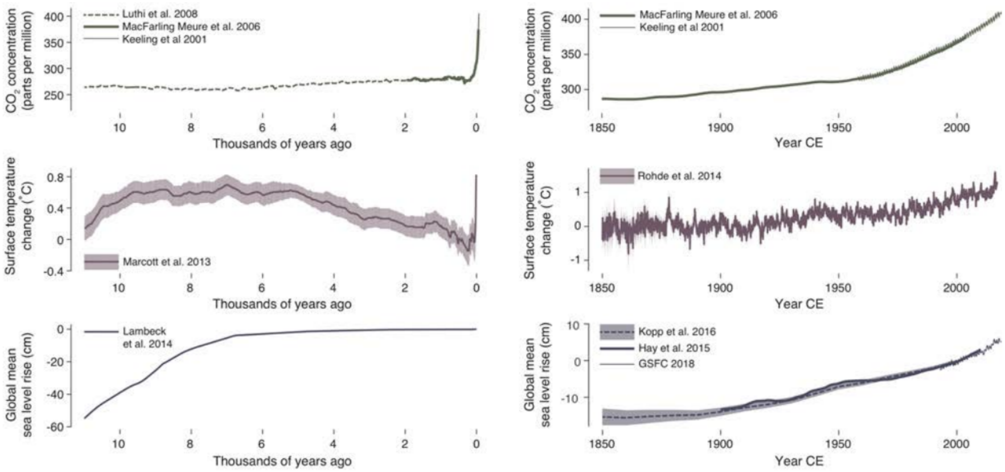
Radiative Forcing

- The influence of GHG on the climate is measured in units of "radiative forcing" = the extent to which the human-emissions distort the net flow of radiation into the atmosphere, relative to a pre-industrial baseline.
  - The historical baseline is estimated to be around 278 parts per million.
  - The current level is 424 parts per million.
  - The change has exerted ~ 2.2 W/m^2 of radiative forcing.
  - Central estimates of the equilibrium warming associated with a change in radiative forcing are 0.8°C per W/m^2 = 1.76°C.
- Radiative forcing does not translate immediately into surface warming, in part because the deep ocean takes centuries to warm.
- However, modeling suggests that most of the warming associated with a marginal increase in emissions occurs within a couple of decades and persists for millennia (Joos et al., 2013)

Establishing Baseline Climates

- Paleoclimatology is a well-developed subfield of climate science that focuses on the reconstruction of historical climates.
- This provides a baseline for explaining climate changes.
  - Gases trapped in air bubbles of ice contain information on atmospheric chemistry at the moment they froze.
  - The width of tree rings reflect growing-season temperatures and rainfall
  - Microscopic fossils in salt-marsh sediments reflect changes in salinity, and thus local sea level.
  - Relative abundances of different isotopes of oxygen in ocean sediments reflect the extent of "ice ages"
- Statistical methods + comparisons to physical models can be used to estimate global-mean values of quantities such as surface temperature and sea level from local data

Establishing Baseline Climates



Climate Models

- Climate models form the basis for inferring out the contribution of human activity to climate change.
- They represent our physical understanding of the climate system.
- They range from:
  - simple models that capture key aspects of the longer-term, global-scale response that enables more thorough qualifications of uncertainty
  - detailed, fully-complexity Earth system models that provide greater insight into processes at finer temporal and spatial scales (Hayhoe et al., 2017)
  - The most complex models can achieve resolutions of 10km $\times$ 10km.

Uncertainty

- Uncertainty arises from the imperfect representation of physical processes.
- Tiny errors in initial conditions can produce dramatically different forecasts within the same model – "the butterfly effect" (Lorenz, 1963)
- To account for this modeling teams run their model multiple times with perturbed initial conditions, creating a collection of results known as initial-conditions ensemble.
- Individual runs are never interpreted as literal forecasts; instead the ensemble as a whole is thought of as capturing the statistical properties of the climate system.
- Climate scientists prefer the term "projection" rather than "forecast" or "prediction".

Uncertainty

First Assessment Report (1990)	"Unequivocal detection of the enhanced greenhouse effect from observations is not likely for a decade or more."
Second Assessment Report (1995)	"The balance of evidence suggests a discernible human influence on global climate."
Third Assessment Report (2001)	"Most of the observed warming over the last 50 years is *likely** to have been due to the increase in greenhouse gas concentration."
Fourth Assessment Report (2007)	"Most of the observed increase in global average temperatures since the mid-20th century is *very likely* due to the observed increase in anthropogenic greenhouse gas concentrations."
Fifth Assessment Report (2013)	"It is *extremely likely* that human influence has been the dominant cause of the observed warming since the mid-20th century."

*The uncertainty language used by the IPCC is precisely defined: *likely* refers to an assessed probability of at least 66%, *very likely* implies at least 90%, and *extremely likely* means at least 95%.

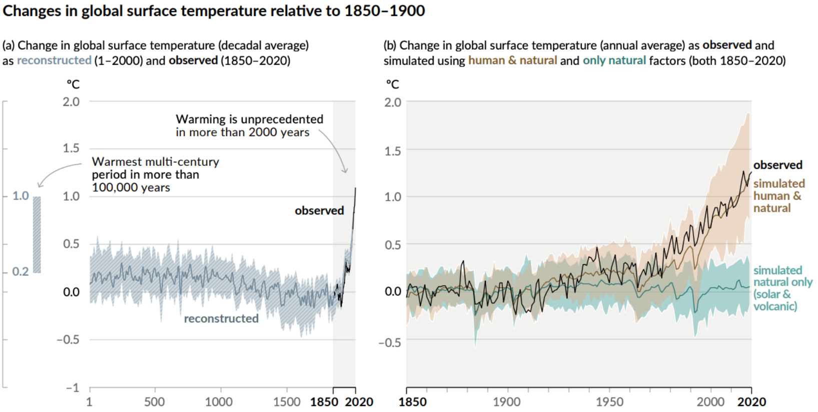
IPCC (2021)

"It is unequivocal that human influence has warmed the atmosphere, ocean, and land. Widespread and rapid changes in the atmosphere, ocean, cryosphere, and biosphere have occurred."

Observed and Projected Climate Changes

- A core objective of climate science is to detect changes in the climate and determine whether these changes can be attributed to human activity.
- i.e., has been an actual shift in the joint distribution of environmental variables that we refer to as the climate?
- Attribution refers to the inference problem of assigning a cause to observed changes.
  - Attribution studies simulate what counterfactual climates would look like in the absence of human activity, altering the model parameters that describe human inputs to the climate.
  - For example, human emissions of GHGs may be eliminated from the model.
  - If it is not possible that these human-free simulations can account for observed changes, then scientists attribute these changes to human activity.

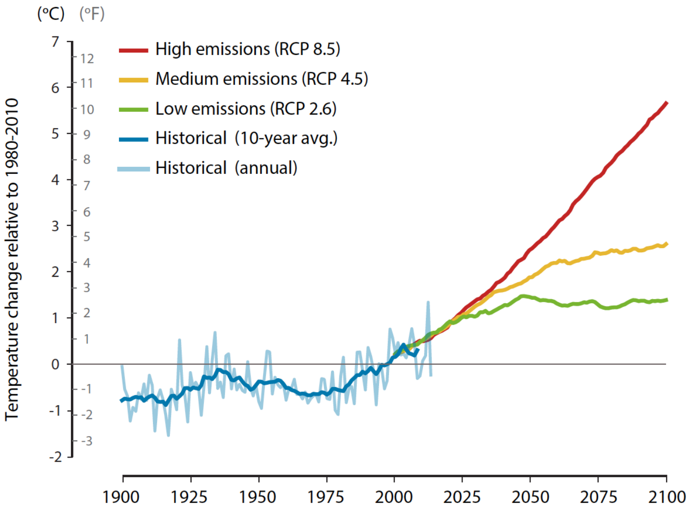
Observed Climate Changes



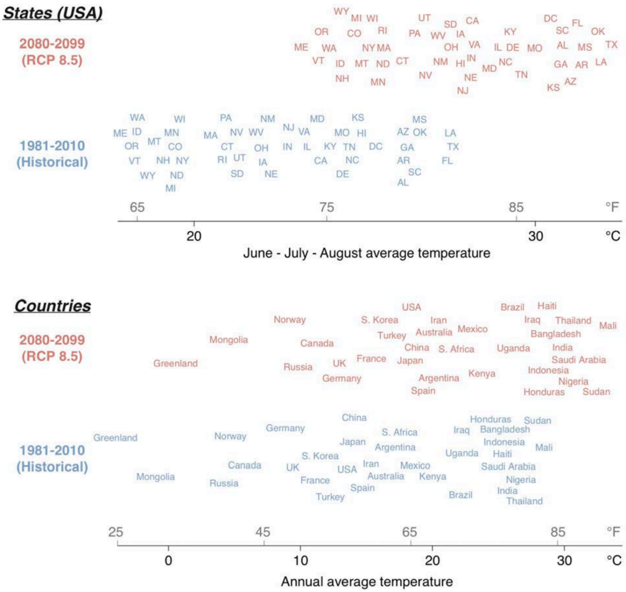
Temperature

- It is virtually impossible to explain current temperatures in the absence of human activity.
- Almost every location on the planet has exhibited an increasing temperature trend since the late 19th Ce.
- Land has warmed by 1.4°C, whereas the oceans have warmed by roughly 0.6°C.
- Since 1980, the most rapid warming has occurred in the far north, where the replacement of highly reflective summer sea ice with dark, open ocean, rapidly reduced albedo.

Projected Temperature Changes



Projected Temperature Changes



Projected Precipitation Changes

- A warmed atmosphere is capable of holding more water vapor
- Heavy precipitation events have increased since the 1950s.
- However, the atmospheric dynamics that govern precipitation occur at scales well below the spatial resolution of many climate models and so are more challenging to model than temperature.
- Dry regions are likely to become drier and wet regions are likely to become wetter...

Projected Changes in Humidity

- Relative humidity is the ratio of specific humidity (the total moisture content of air) to a theoretical maximum moisture capacity.
- This rises exponentially as temperature increases.
- Global mean specific humidity has increases since the 1970s, but there appears to be little evidence of an increase in global mean relative humidity.
- Humidity is economically important as it affects human health,
  - higher humidity levels make it more difficult for the human body to cool itself.
  - Dangerously hot and humid conditions are projected to become more likely in several regions, making it more difficult for humans to survive unassisted for long periods outdoors (Sherwood and Huber, 2010)

Projected Changes in Tropical Cyclones

- Tropical cyclones are the class of phenomena that include tropical storms, typhoons, hurricanes, and cyclones.
- They are driven by the temperature differences between the warm ocean surface and cooler temperatures higher in the atmosphere.
- The warm ocean moistens overlying air, which rises and cools, releasing energy and rain.
- Climate change is thought to have countervailing effects on storms.
- Broad agreement that the frequency of intense tropical cyclones, as well as the average intensity of their associated rainfall is projected to increase (Kossin et al., 2017).
- The effect on the total number of storms remains uncertain, though most studies suggest a stable or decreasing quantity of lower intensity storms.

Projected Changes in Sea Level Rise

- Global-mean sea-level rise is driven by two processes:
  - an increase in the volume of water already in the ocean, which occurs as the water warms and expands
  - an increase in the mass of water in the ocean, primarily from the melting of ice on land.
- Since 1990, global-mean sea-level has increased by about 18-21cm.
- A substantial fraction of this is attributable to human-caused climate change (Sweet et al., 2017)
- Due to the slow response time of the oceans and ice sheets, sea-level rise is fairly insensitive to alternative emissions scenarios up to 2050 – median projections = 20-30cm.
- Post 2050 projections become very uncertain (Kopp et al., 2017) – median projection range from 40 - 250cm by 2100.

Projected Changes in Droughts and Floods

- By altering temperature and precipitation patterns, climate change alters the frequency and intensity of extreme moisture conditions.
- There is a limited but increasing ability to attribute intensifying extreme floods and droughts to human activity
  - Emanuel (2017) estimates that climate forcing by human amplified the probability of rainfall experienced by Texans during Hurricane Harvey six-fold.
- The frequency of droughts is expected to increase in dry regions (Collins et al. 2013)
- Regions with more vegetation are projected to see an increase in the frequency of wildfires (Abatzoglou and Williams, 2016)
- Projected increases in precipitation and shorter-lived snowpack are likely to increase the frequency of inland flooding.
- Changing patterns of flood risk are of particular economic importance as floods are recognized as the costliest of natural disasters.

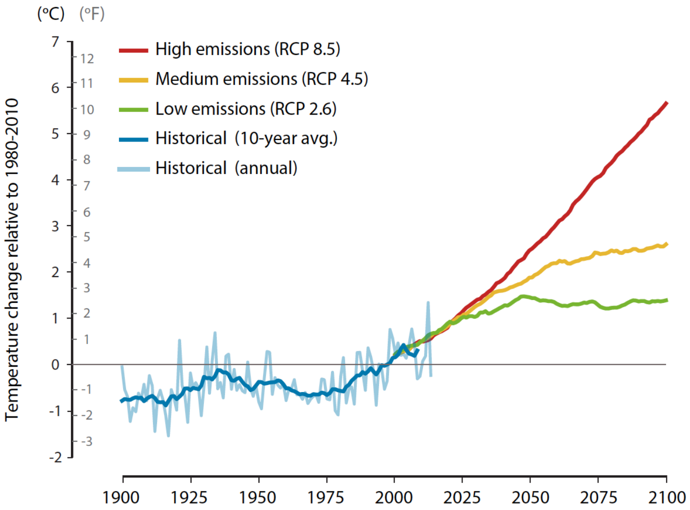
Tipping Elements and Critical Thresholds

- Nonlinearities and feedbacks in the Earth systems give rise to the potential for multiple steady states.
- If critical thresholds are crossed then rapid lock-in can occur.
- These parts of the Earth system are often called tipping elements and the thresholds tipping points.
- Tipping points don't necessarily imply "rapid change", they are just rapid relative to other changes in Earth systems.

Tipping Elements and Critical Thresholds

- Tipping elements can exist in atmosphere and ocean circulation.
  - Climate Oscillations such as El Niño occur due to tipping elements.
  - Patterns of Ocean circulation, such as the Atlantic Meridional Overturning Circulation are subject to tipping elements.
- Positive feedbacks between ocean-ice sheet interactions might commit the Antarctic to sustained ice sheet loss, raising global mean-sea level by multiple meters or tens of meters.
- Warming of previously frozen soils is allowing microbes to decompose freshly unfrozen organic materials into CO_2 and methane.

Like all of economics, climate change is about tradeoffs

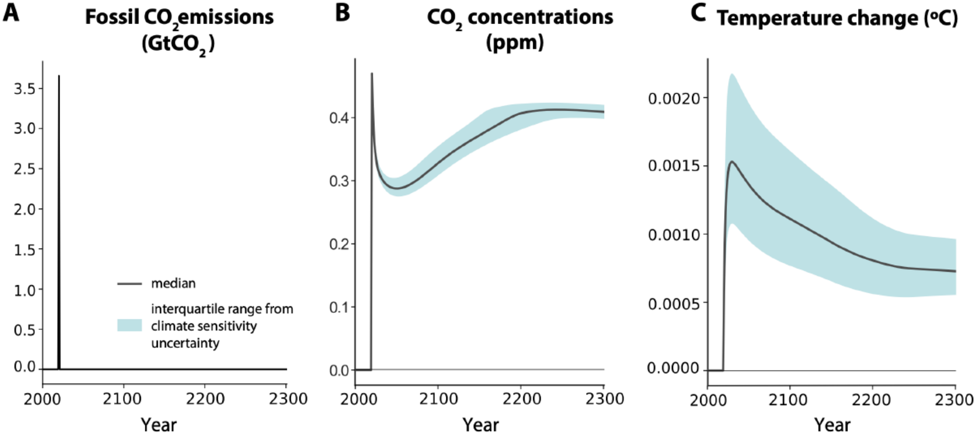


Nordhaus (1977, AER)

- "Economic Growth and Climate: The Carbon Dioxide Problem"
  - Uses an energy-systems model to produce first (?) estimates of global carbon tax schedules to keep CO_2 emissions from doubling
  - Visionary!
  - But somewhat arbitrary.
  - What would the social welfare-maximizing policy (target) be?

Putting some structure on the problem

- The global social planner gets utility from emitting in time t: $U(E_t)$
- But those emissions E_t cause a long trajectory of temperature changes: $T_t(\sum_{s=0}^{t} E_s)$



Putting some structure on the problem

- These temperature changes are (generally) damaging.
- Denote damages $D(\cdot)$.
- The global social planner's problem is to choose a trajectory of emissions, $\vec{E} = \{E_1, E_2, \ldots\}$, that maximizes utility net of (discounted) climate change damages:

$$\max_{\vec{E}} \sum_{t}^{\infty} [U(E_t) - D(T_t(\sum_{s=0}^{t} E_s))]\delta_t$$

where E= emissions, $D(T)$ = damages, and δ_t= discount factors.

Putting some structure on the problem

- Optimal E_t^* equates marginal benefits and marginal damages,

$$\frac{\partial U(E_t^*)}{\partial E_t}\delta_t = \sum_{s=t}^{\infty}\delta_s \frac{\partial D(T_s(\sum E^*))}{\partial T_S}\frac{\partial T_s(\sum E^*)}{\partial E_t}$$

  - Temperature more sensitive to emissions? $\rightarrow$ emit less
  - Temperature more damaging to society? $\rightarrow$ emit less
  - Higher discount rate (lower δ)? $\rightarrow$ emit more today

- Optimal emissions are determined by marginal damages evaluated along the optimal emissions trajectory $\vec{E}^*$.

- Optimal policy sets a global carbon price, P^* = marginal damages at E^*.

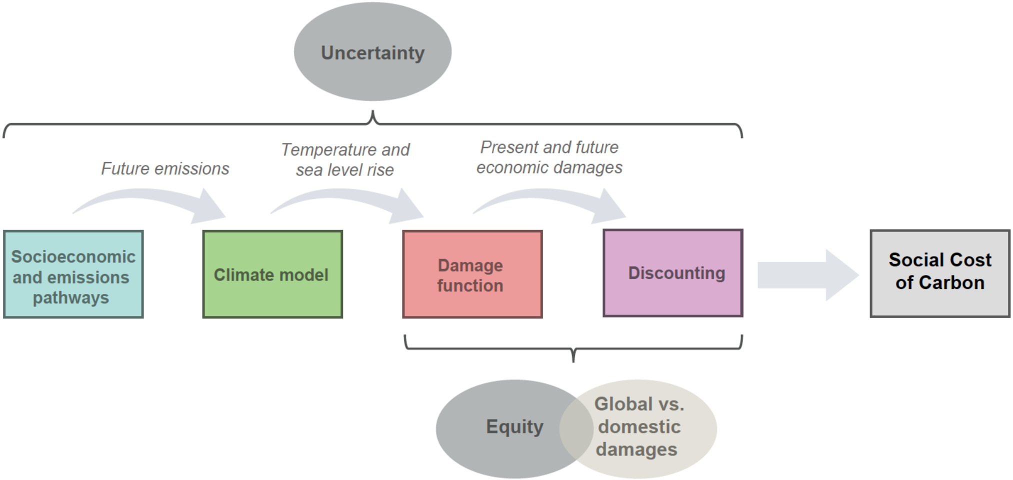
The SCC: climate policy without the global planner

- **Definition:** The SCC is the discounted stream of damages caused by the release of one additional ton of carbon dioxide (i.e., a one unit change in E)

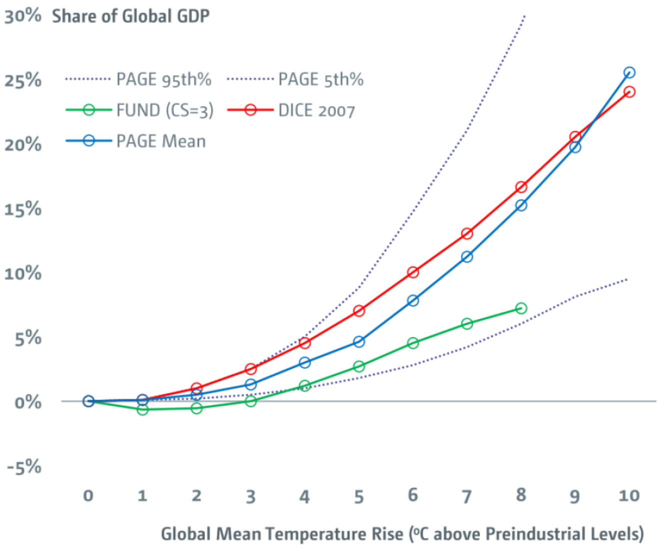
$$SCC_t = \sum_{s=t}^{\infty} \delta_s \frac{\partial D(T_s(\sum E))}{\partial T_S} \frac{\partial T_s(\sum E)}{\partial E_t}$$

- Depends on an exogenous trajectory of emissions
- SCC evaluated at $\vec{E}^*$ is the optimal carbon price. But in general these are not the same thing.
- Using the SCC for $\vec{E} \neq \vec{E}^*$ for policy making is sensible *only when the emissions change induced by policy is marginal.*
  - Climate damage functions are widely thought to be nonlinear, i.e., marginal damages are higher at higher E.
  - Damages may not be convex.

How Do We Estimate the SCC?



Damage function(s) are integral to any SCC calculation



Assessing Climate Change Damages

1) "Integrated Assessment Models" with endogenous equilibria $\rightarrow$ optimal climate policy
   - Derive fundamental aspects of the climate change problem (e.g. risk premium)
   - Guides optimal policy stringency
2) Scenario-driven "applied policy" models
   - Assume the trajectory of global economy & emissions
   - Endogenize key feedbacks
   - Can be globally comprehensive & capture many sectors
   - Allows us to explore several immediately policy-relevant outputs
3) Empirical estimates of climate damages
   - Focus on identification & measurement
   - Generally local & sector-specific
   - Challenge: weather $\neq$ climate change
   - Difficult to connect directly to policy

The DICE Model (1993-present)

- Social planner maximizes global dynastic rep. household utility:

$$W = \max \sum_{t=0}^{\infty} \beta^t L_t U(c_t)$$

$\beta \sim$ utility discount factor, $L_t \sim$ pop., $c_t \equiv$ p.c. consumption

- World GDP depends on L_t, capital, K_t, and exogenous technology,

$$Y_t^{gross} = A_t(K_t^{\alpha} L_t^{1-\alpha})$$

- Industrial carbon emissions are proportional to gross output,

$$E_t = \sigma_t \cdot Y_t^{gross}$$

$\sigma_t \sim$ projected BAU emissions intensity (exog.)

The DICE Model (1993-present)

- Society can reduce carbon emissions by fraction μ_t:

$$\tilde{E}_t = (1 - \mu_t) E_t$$

- Abatement μ_t costs a fraction of GDP:

$$\frac{AbtCost_t}{Y_t^{gross}} = \theta_{1t} (\mu_t)^{\theta_2}$$

- Emissions enter atmosphere, carbon cycle, change climate T_t:

$$T_t = F(S_0, \tilde{E}_0, \tilde{E}_1, \ldots, \tilde{E}_t, \eta_0, \ldots, \eta_t)$$

$T_t \sim$ mean atmospheric temperature increase; $S_0 \sim$ initial conditions, $\eta_t \sim$ exogenous shifters (e.g. land-based emissions)

The DICE Model (1993-present)

- Climate change effects summarized by the damage function $D(T_t)$

$$Y_t^{net} = (1 - D(T_t)) \cdot Y_t^{gross}$$

- Damages are expressed as % GDP-equivalent loss
    - Actual GDP effects + value of non-market effects
- Aggregate global damages $D(T_t) \sim$ sum of effect estimates across regions and sectors

The DICE Model (1993-present): Summary

$$W = \max \sum_{t=0}^{\infty} \beta^t L_t U\left(\frac{C_t}{L_t}\right)$$

subject to, $\forall t \geq 0$:

$$\begin{aligned}
C_t + I_t &= (1 - D(T_t))Y_t^{gross} - AbtCost_t(\mu_t) \\
Y_t^{gross} &= A_t(K_t^{\alpha} L_t^{1-\alpha}) \\
K_{t+1} &= K_t(1-\delta) + I_t \\
\tilde{E}_t &= (1-\mu_t) \cdot [\sigma_t Y_t^{gross}] \\
T_t &= F(S_0, \tilde{E}_0, \tilde{E}_1, \ldots, \tilde{E}_t, \eta_0, \ldots, \eta_t)
\end{aligned}$$

with K_0 and S_0 given

The DICE Model (1993-present): Social Cost of Carbon

$$SCC_t = \sum_{j=0}^{\infty} \underbrace{\beta^j \frac{U'C_{t+j})}{U'(C_t)}}_{\text{value today of output loss at t+j}} \underbrace{\frac{\partial D(T_{t+j})}{\partial T_{t+j}} Y_{t+j}(K_{t+j}, L_{t+j})}_{\text{marginal damages at t+j}} \underbrace{\frac{\partial T_{t+j}}{\partial \tilde{E}_t}}_{\Delta \text{ climate at t+j from +1 ton emissions today}}$$

- A lot of assumptions are required to calculate the SCC.
- The biggest three factors are the choice of discount rather, which sectors are omitted, and whether to consider domestic or global damages.
  - The Obama administration set this value at approximately \$40 per ton (3% discount rate).
  - The Trump administration set this value at approximately \$1 per ton by using a discount rate of 7% and focusing on domestic damages.

The Damage Function

- DICE assumes a quadratic damage function:

$$D(T_t) = \frac{1}{1 + \theta_1 (T_t)^{\theta_2}}$$

- 2016 DICE has $\theta_1 = 0.00236$, $\theta_2 = 2 \Rightarrow D(3^\circ C) \sim 2.1\%$ loss
- FUND (Tol, 2013): $D(3.5^\circ C) \sim 1.2\%$ loss (Global)
- PAGE-2002: $D(3.5^\circ C) \sim 6.4\% (Global), 1.5\%$ loss (U.S.)
- By comparison: Great recession real GDP loss in 2009 $\sim 2.8\%$

Concerns?

> *"A plethora of integrated assessment models (IAMs) have been constructed and used to estimate the social cost of carbon (SCC) and evaluate alternative abatement policies... the models' descriptions of the impact of climate change are* **completely ad hoc, with no theoretical or empirical foundation.**"
>
> – R. Pindyck (2013)

- The majority of the literature used to justify the damage functions used in in DICE, FUND, and PAGE are from the early and mid-1990s.
- The most recent citations are prior to 2010.
- Overall very few studies are cited.

New Directions

- Building on the Social Cost of Carbon approach:
  - The “Modern Macro” approach
  - The “Bottom-Up” Micro approach
- A Budget Approach (Colmer and Malmberg, 2021)
  - Reframing the problem/role of economists
  - Also a “Modern Macro” approach that requires “Bottom-Up” Micro-inputs.

Golosov et al. (2014, Econometrica)

- Highly influential paper that makes two core contributions:
  1) Slightly more standard ‘modern macroeconomic’ extension of DICE
  2) Closed-form optimal carbon tax-GDP ratio given certain assumptions
- What do I mean by “modern macro"?
  - Decentralized economy modeled explicitly
  - Rational, forward-looking households
    - Given prices and policies, decide on savings, etc.
  - Profit-maximizing firms
    - Given prices and policies, decide on energy, factor inputs, etc.
  - Search for policies that can decentralize solution to planner’s problem
  - Dynamic general equilibrium

Golosov et al. (2014, Econometrica): Energy Sector

- Another GHKT (2014) element that has become standard is to microfound emissions/abatement via an explicit energy sector
- Economy has 4 sectors: Final goods production + 3 Energy sources:
  - Oil in finite supply $\bar{R}$ with zero extraction costs
  - Coal and clean energy produced from labor:

$$\begin{aligned} E_{coal,t} &= A_{coal,t} L_{coal,t} \\ E_{clean,t} &= A_{clean,t} L_{clean,t} \end{aligned}$$

    Final good production uses energy composite E_t:

$$E_t = (\kappa_1 E^{\rho}_{oil,t} + \kappa_2 E^{\rho}_{coal,t} + \kappa_3 E^{\rho}_{clean,t})^{1/\rho}$$

    with $\sum_{i=1}^{3} \kappa_i = 1$ and ρ the elasticity of substitution between $E_{i,t}$
  - Final goods production:

$$Y_t = (1 - D(\cdot)) A_{0,t} K_t^{\alpha} L_{0,t}^{1-\alpha-v} E_t^{v}$$

Energy and Emissions: DICE vs. GHKT

- DICE:

$$\begin{aligned} \tilde{E}_t &= (1-\mu_t)\sigma_t \cdot Y_t(A_t, K_t, L_t) \\ AbtCost(\mu_t) &= \theta_{1t}\mu_t^{\theta_2} \end{aligned}$$

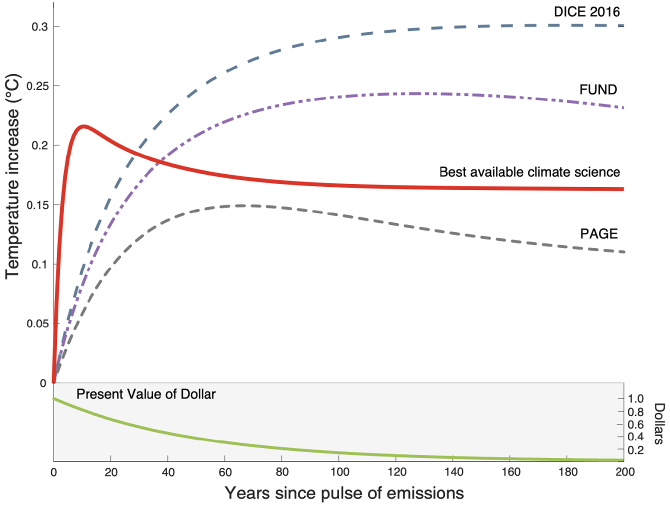
- GHKT:

$$\begin{aligned} \tilde{E}_t &= E_{oil,t} + E_{coal,t} \\ AbtCost &\sim \text{lost output from (i) reduced energy usage, and/or} \\ & \quad \text{(ii) higher (labor) cost of meeting energy needs via } E_{clean,t} \end{aligned}$$

Golosov et al. (2014, Econometrica): the Climate System

- One aspect of GHKT that remains debated (a good use of economists time?) is their specification of the climate system
  - GHKT assume no delays between emissions and warming
  - DICE ocean-atmosphere dynamics $\rightarrow$ peak warming delayed 30-60 years
- Results in large SCC differences (due to discounting)!
- Debate continues (Dietz and Venmans, 2020; Dietz et al., 2021)

From Carleton and Greenstone (2021)



Literature Extensions: Heterogeneity

- DICE and GHKT have served as the foundation for hundreds of papers on climate economics
- Areas of interest/focus:
  - Heterogeneity:
    - computationally prohibitive + assumption to gain tractability subject to own critique.
    - every country's wealth level becomes a state variable relevant to every other agent's decision problem at every point in time.
    - State-of-the-art: **Krussel-Smith Method**: 'Approximate Aggregation' – individual decision-makers focus only on first moment of future wealth distribution in forecasting future prices.

Literature Extensions: Uncertainty

- Initial efforts to study uncertainty based on monte carlo analysis of deterministic model outcomes (e.g., Nordhaus, 2008)
  - Problem: Does not actually model decision-making under uncertainty!
- Literature evolved to recursive dynamic programing methods, considering one source of uncertainty at a time, e.g,, climate sensitivity, damage coefficients, future economic growth, tipping points, etc.
- Implication for optimal policy are complex.
- Current frontier: multiple sources of uncertainty
  - Cai, Judd, Lontzek (2018, JPE) – Develop DSICE (S $\sim$ 'stochastic) model
  - Modeling climate and economic uncertainty *jointly* leads to very different SCC distributions that separate approach

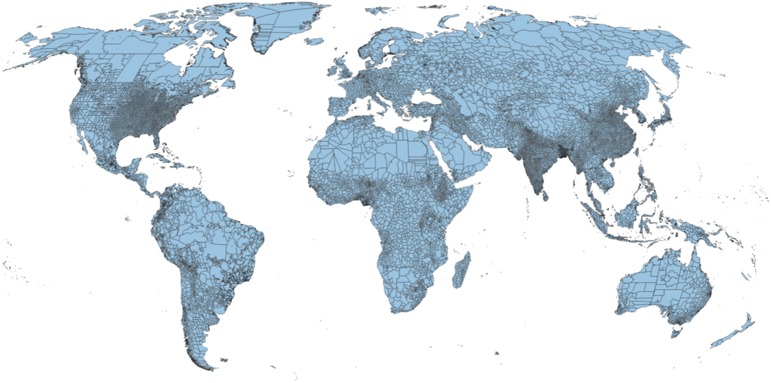
The “Micro Approach”: A Bottom-Up High-Resolution Approach to Estimating Damages

- Advances in statistical tools have increased opportunities to evaluate counterfactual outcomes and identify causal relationships.
- Advances in computer science and climatology that have improved our ability to parameterize and identify the components associated with climatological variations that are most relevant to society.
- A rapidly expanding literature within economics has sought to estimate the economics consequences of climate.

New Generation of Partial-SCC Calculations

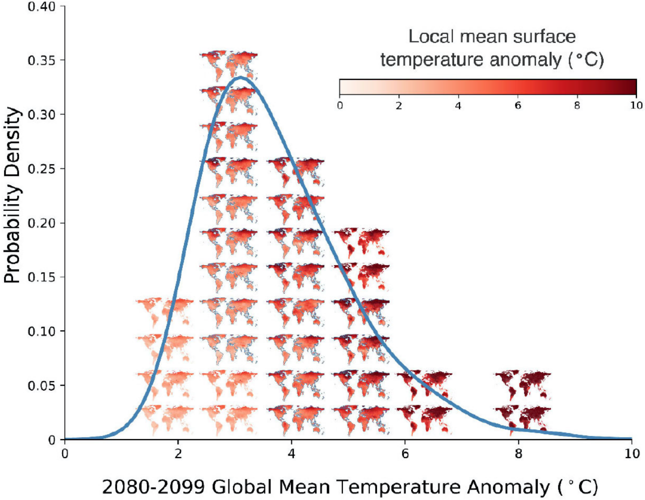
- **Guiding principles:** SCC calculations should ...
  - be based on best-available empirical evidence
  - be based on best-available climate models
  - be globally representative
  - account for adaptation and its costs
  - value uncertainty and engage with distributional considerations

Data-Driven Spatial Climate Impact Model (DSCIM)



24,378 regions capture subnational inequality of damages

Downscaled and Probabilistic Climate Model Representations



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*)

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*)

High risk labor
Low risk labor

Coastal — sea level rise and storm damages (Depsky et al, *in review*)

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

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

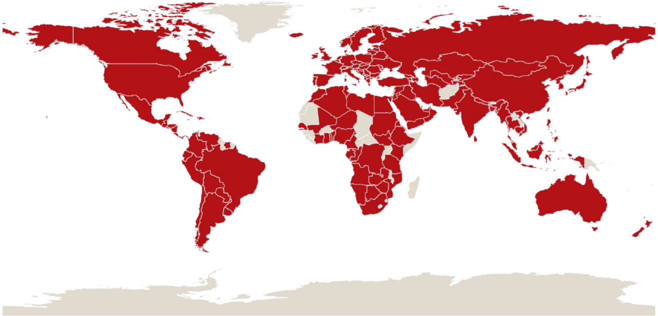
Intertemporal discounting
Valuing inequality
Pricing risk

Building a Data-Driven SCC in DSCIM

- **Step 1:** Collect and harmonize comprehensive data for each sector
- **Step 2:** Estimate causal relationships, accounting for key drivers of adaptation
- **Step 3:** Develop a revealed preference approach to infer costs of adaptation
- **Step 4:** Project impacts globally today and into the future using high resolution climate projections
- **Step 5:** Estimate empirical damage functions accounting for uncertainty, then calculate partial sector-specific SCC estimates
- **Step 6:** Integrate across sectors to build a full, multi-sector SCC

Comprehensive Data – Energy (Rode et al., Nature 2021)

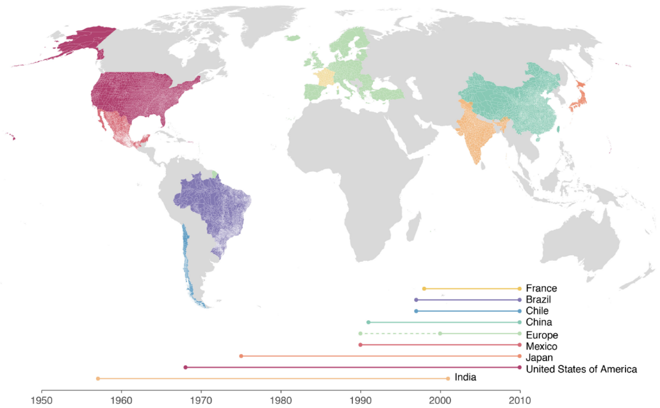
International Energy Agency (IEA) provides data from 146 Countries (1971-2012).



Annual consumption of residential, commercial, and industrial electricity and other fuels

Comprehensive Data – Mortality (Carleton et al., QJE 2022)

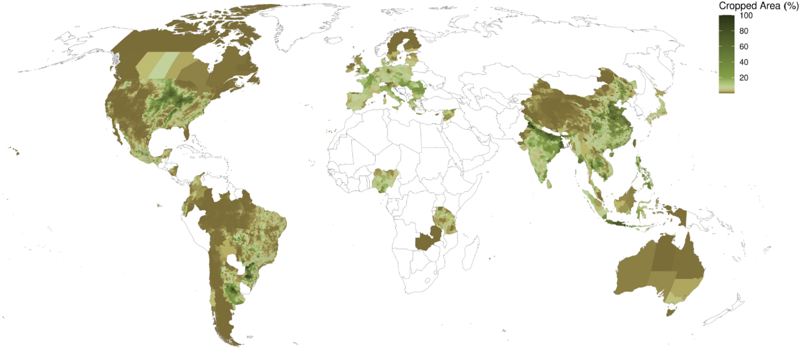
Subnational mortality records covering 55% of the global population



Age-specific annual mortality rates at ∼county level

Comprehensive Data – Agriculture (Hultgren et al., 2021)

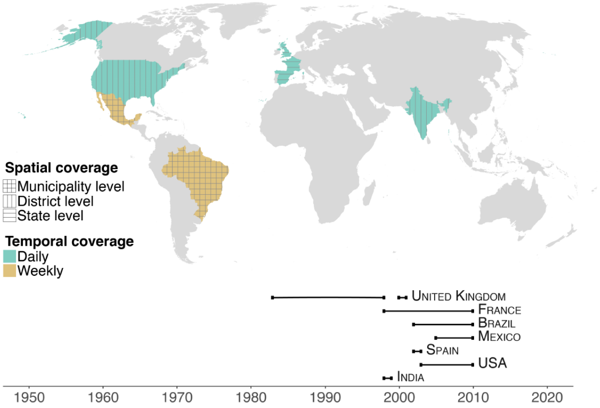
Collection of subnational crop production data covering 41,186 region × crop units



Annual yield for maize, soybean, rice, wheat, sorghum and cassava

Comprehensive Data – Labor (Rode et al., 2022)

Time use and labor force surveys representing ~30% of the global population



Minutes worked per day/week for labor force participants ages 15-65

Building a Data-Driven SCC in DSCIM

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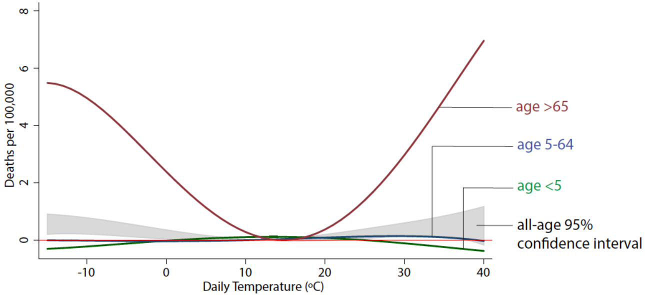
Estimating an Impact Relationship

- Use random variation in short-run weather to causally identify the effect of weather realizations on sector-specific outcomes

$$Mortality\_rate_{ait} = f_a(Temp_{it}, Precip_{it}) + \underbrace{\alpha_{ai} + \delta_{act}}_{\text{nonparametric location \& time controls}} + \varepsilon_{iat}$$



Heterogeneity in Responses

- We want the shape of the response function to be a function of conditions at that location (Hsiang & Jina, 2014; Heutel et al., 2021; Auffhammer, 2022; Carleton et al., 2022)

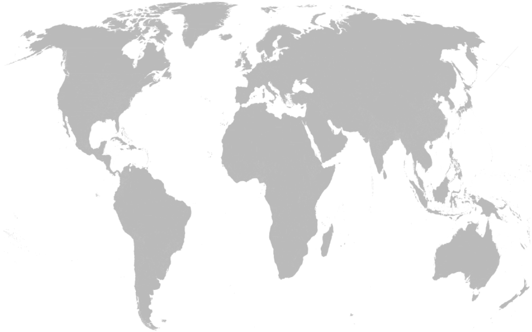
$$Outcome_{it} = \sum_p \beta^p \, Weather^p_{it} \, \ldots \, controls$$

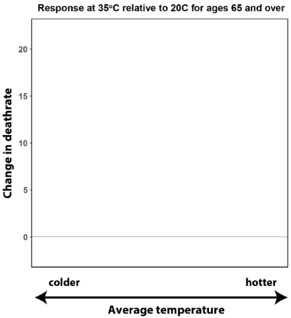
$$\uparrow$$

$$\beta^p(i) = \gamma^p_0 + \gamma^p_1 \, Climate_i + \gamma^p_2 \, \log(GDPpc)_i + \ldots$$

- **Covariates determining heterogeneity depend on sector**
  - $Climate_i$ = long-run avg. climate.
  - $log(GDPpc)_i$ = average log income per capita
  - $area_irrigated_i$ = share of area equipped for irrigation

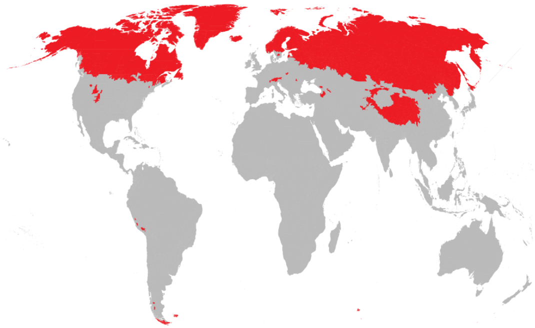
Mortality: Adaptation to Climate

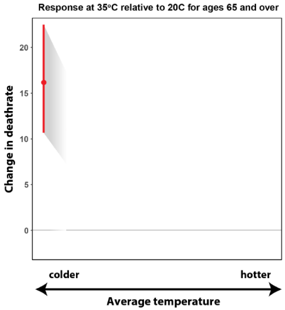




The estimated effect of a day at 35°C relative to 20°C for ages 65 and over. Coefficient calculated for deciles of *TMEAN* (red shaded area).

Mortality: Adaptation to Climate





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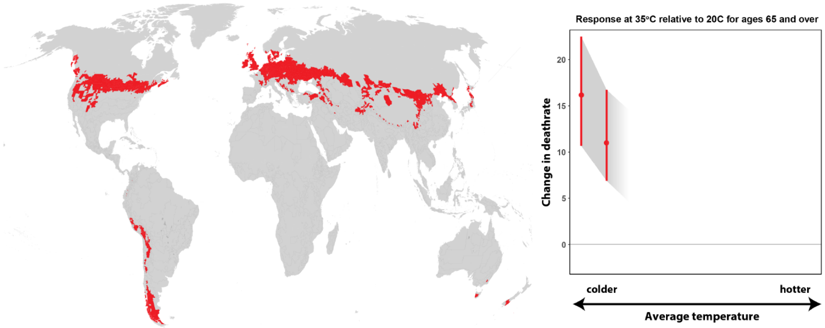

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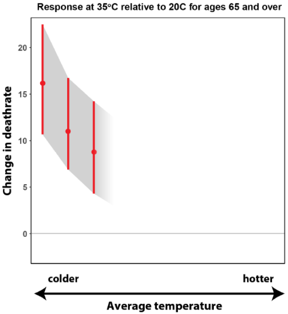

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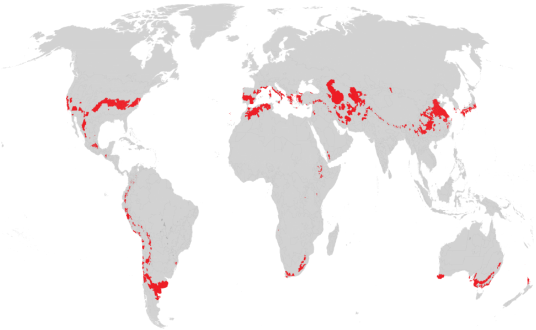

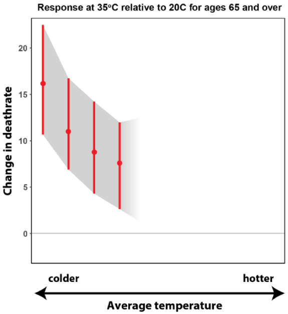

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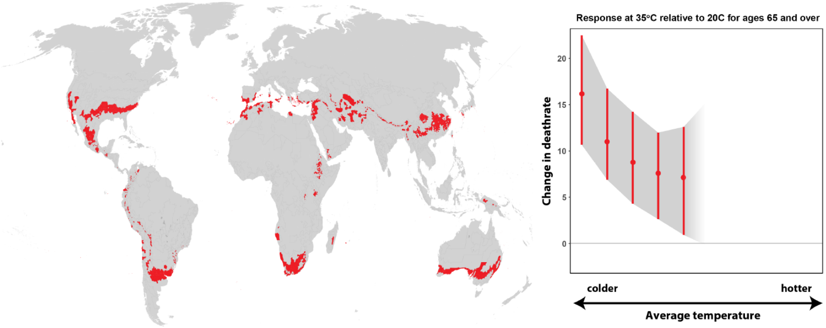

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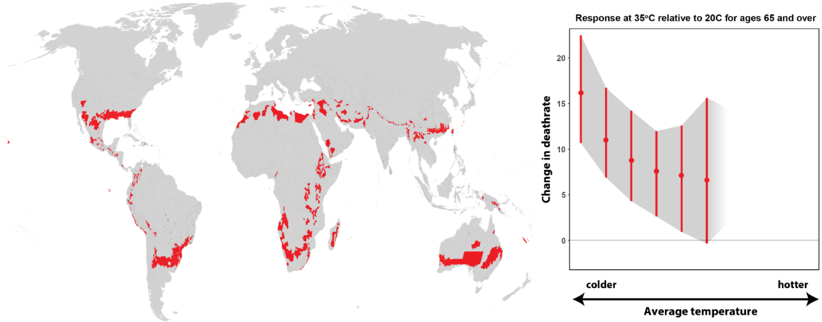

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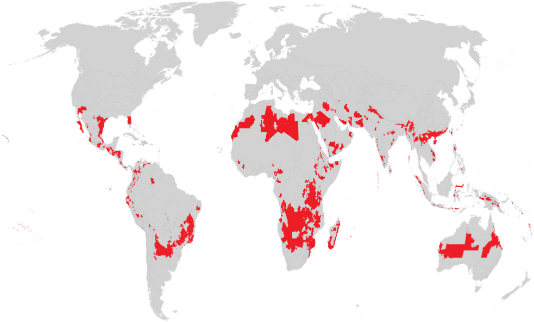

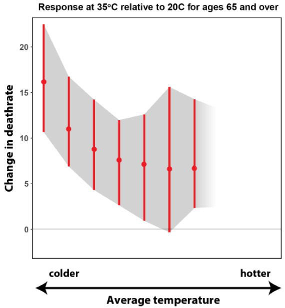

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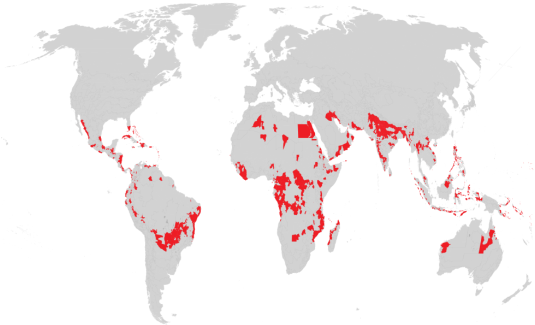

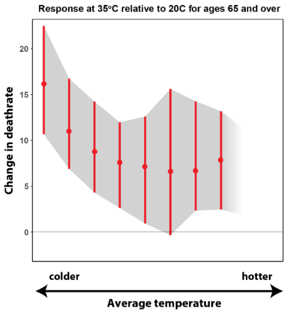

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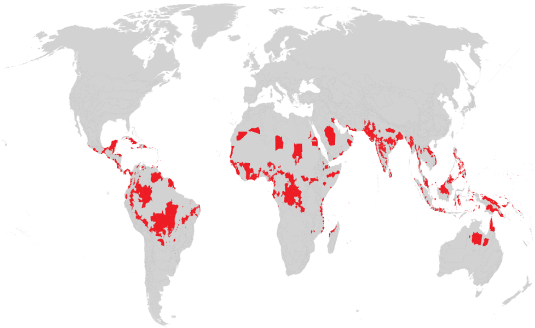

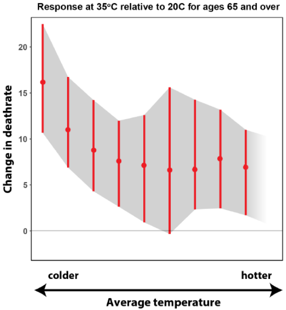

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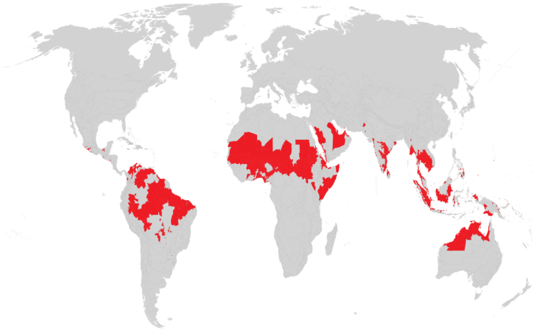

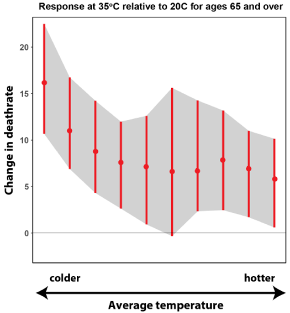

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Summary: Empirically Accounting for Adaptation

- The above approach:
  - Collects outcome data paired with high-resolution historical climate records
  - Estimates panel fixed effect regression models that:
    - Account for nonlinear relationships
    - Capture sector-specific drivers of adaptation
  - Enables climate change projections that account for adaptation (rather than using fixed response functions)
- Limitations:
  - Cross-sectional variation (sub-population heterogeneity NOT causal heterogeneity)
  - Applying these response functions to future projections assumes adaptation in the future will look like it has in the past

Building a Data-Driven SCC in DSCIM

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The "full" cost of climate change

- Adaptation reduces temperature sensitivity, but requires costly compensatory investments

- **No Adaptation**

$$\text{climate impacts without adaptation} = \beta_1 \, Temp_2 - \beta_1 \, Temp_1$$

- **Including adaptation benefits**

$$\text{climate impacts with adaptation} = \beta_2 \, Temp_2 - \beta_1 \, Temp_1$$

- **Accounting for adaptation benefits & costs**

$$\text{full value of climate impacts} = \underbrace{(\beta_2 \, Temp_2 - \beta_1 \, Temp_1)}_{\text{direct effect}} + \underbrace{A(\beta_2) - A(\beta_1)}_{\text{adaptation costs}}$$

Adaptation Costs via Revealed Preference

- Population solves $\beta^* = argmaxu(x)[1 - Mort(\beta, Temp)]$ s.t. budget constraint $A(\beta) + x = Y$.

$$\frac{\partial A(\beta^*)}{\partial \beta} = -VSL\frac{\partial Mort(\beta^*, Temp}{\partial \beta}$$

- Estimates of protective benefits, e.g., changes in sensitivity of outcomes to temperature as climate gradually warms,

$$-VSL\frac{\partial Mort(\beta^*, Temp}{\partial \beta} \approx -VSL\frac{\partial E[Mort]}{\partial TMEAN}$$

- Can use these measures to back out the costs,

$$A(\beta_1^*) - A(\beta_1^* = -\sum_{t=1}^{t=2} VSL_t\frac{\partial E[Mort]}{\partial TMEAN}(TMEAN_t - TMEAN_{t-1})$$

Limitations

- Requires restrictive assumptions, e.g.
  - Optimizing behavior of local agents
  - Perfect information
  - No adaptation dynamics
  - Shared cost of technology
- Relies on cross-sectional variation in revealed adaptive behavior.
- If identified, uses revealed preference of adapted populations today.
- Not feasible in all contexts.

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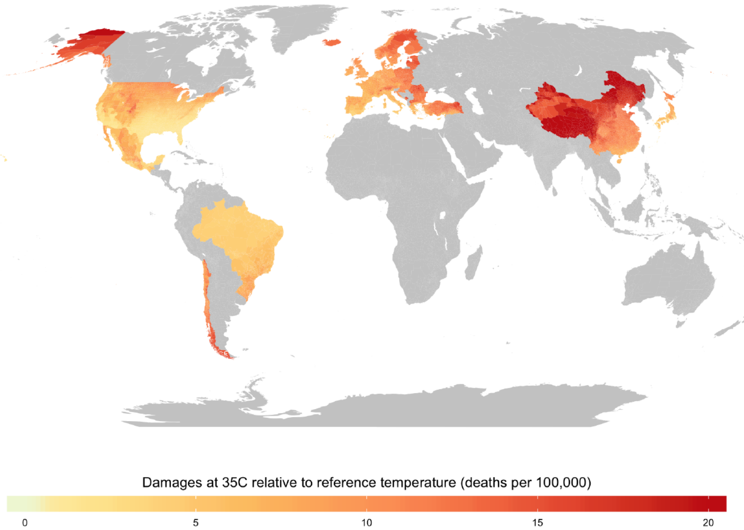
Generating High-Resolution Projections

- DCSIM Impact Regions are engineered to
  - Represent existing political units (e.g., counties)
  - be comparable in population size across regions
  - have internally homogenous climates within each region
- Interpolate response functions for each impact region using high-resolution covariate data

Example: Mortality Response to Hot Days in Sample (ages 65+)



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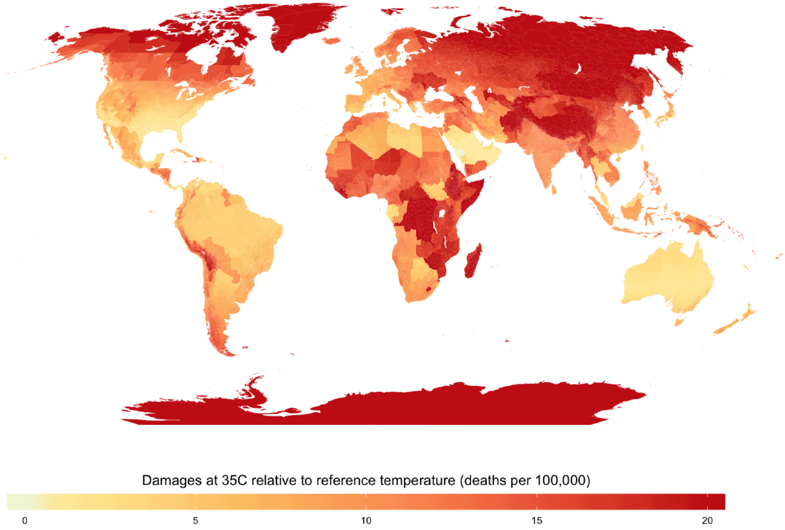
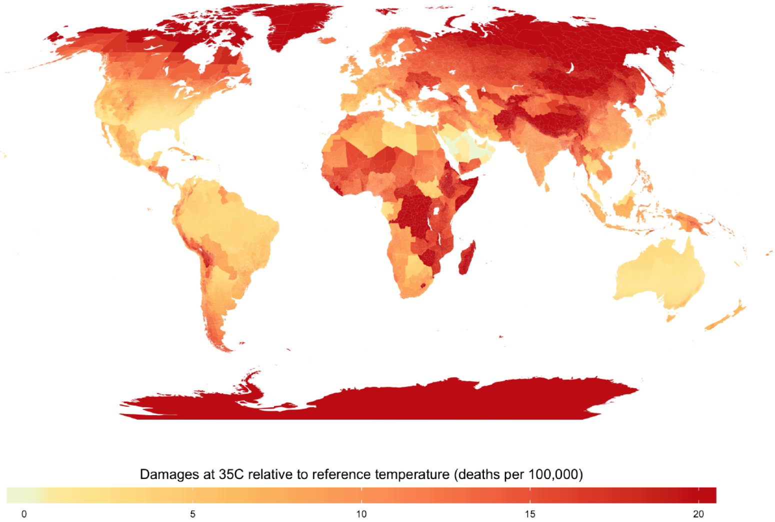
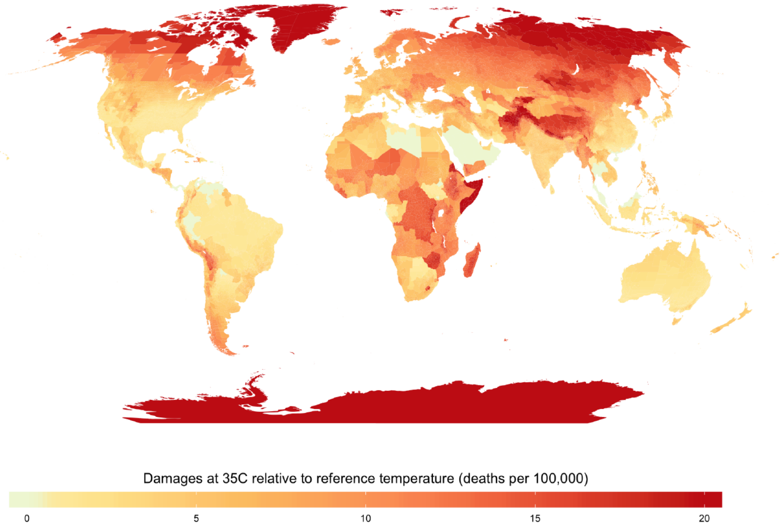


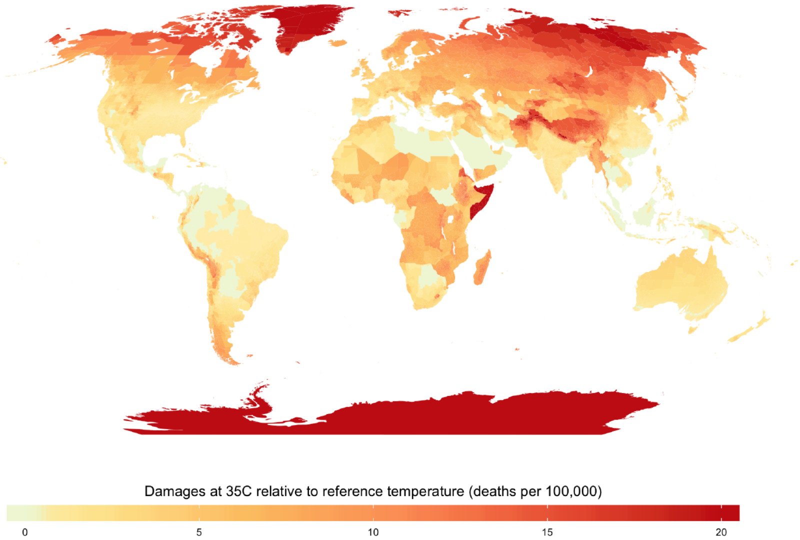
Example: Projecting Mortality Response to Hot Days (2020)



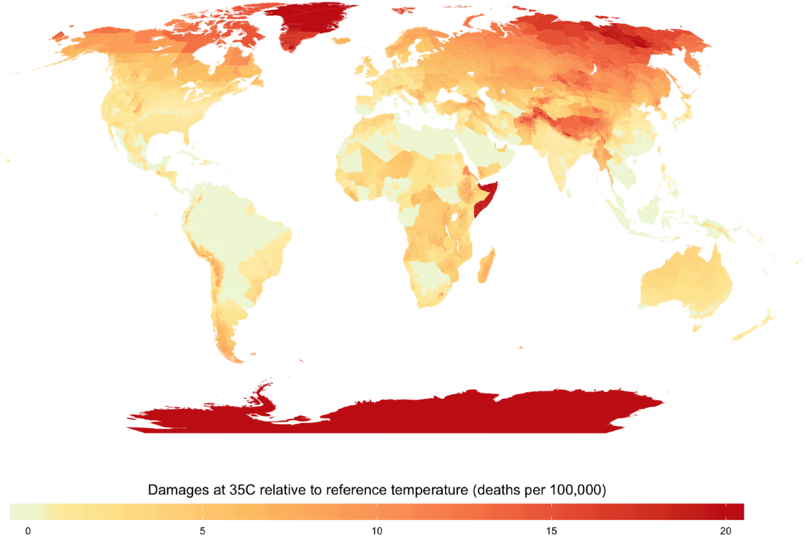
Example: Projecting Mortality Response to Hot Days (2050)



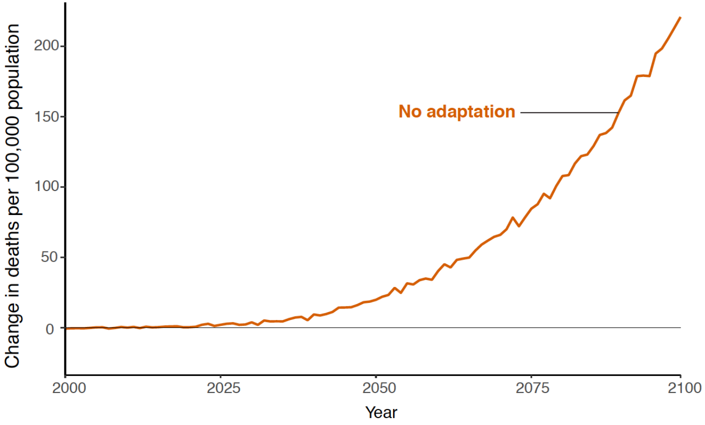
Example: Projecting Mortality Response to Hot Days (2080)



Example: Projecting Mortality Response to Hot Days (2100)



Mortality: Aggregate Impacts for the World



Scenario: RCP 8.5 (high emissions) & SSP3
Current global average mortality rate: 770 deaths per 100,000

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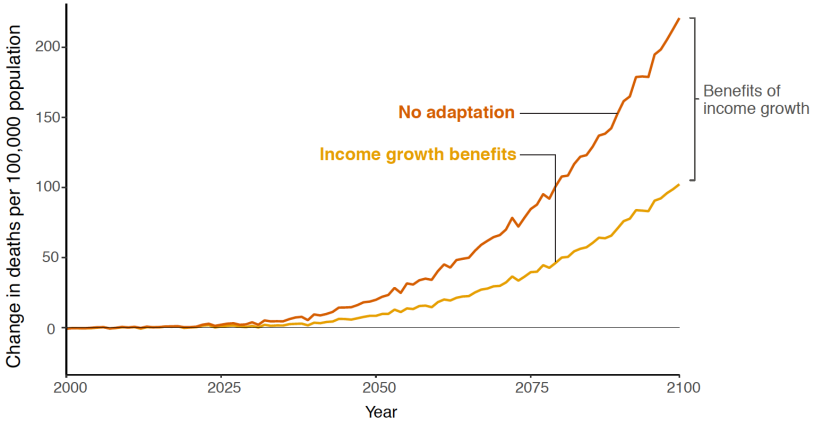

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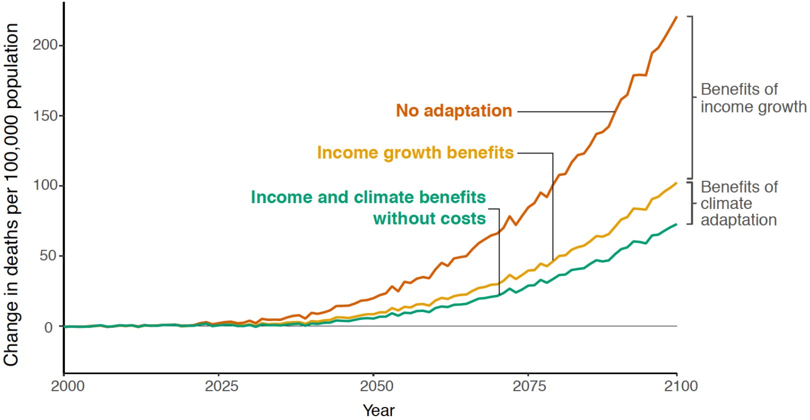

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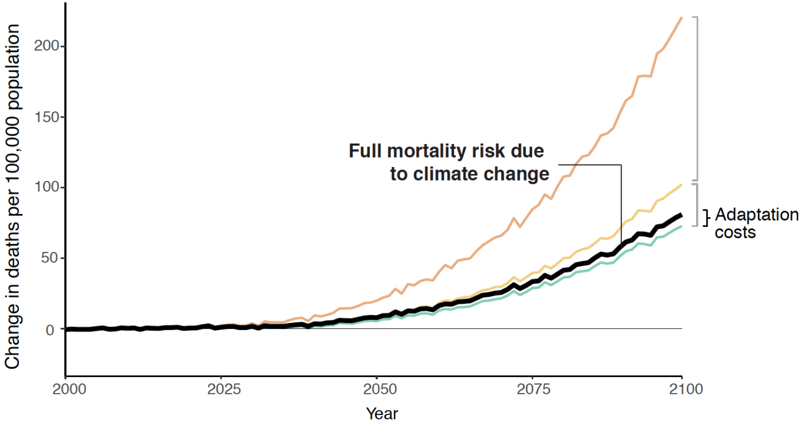

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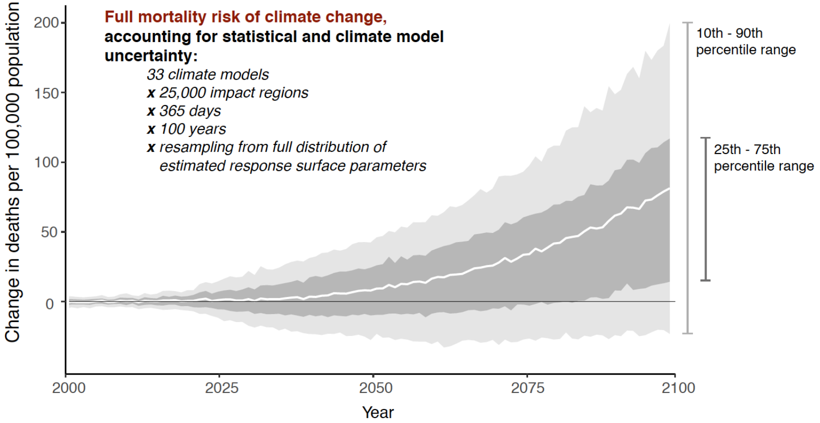

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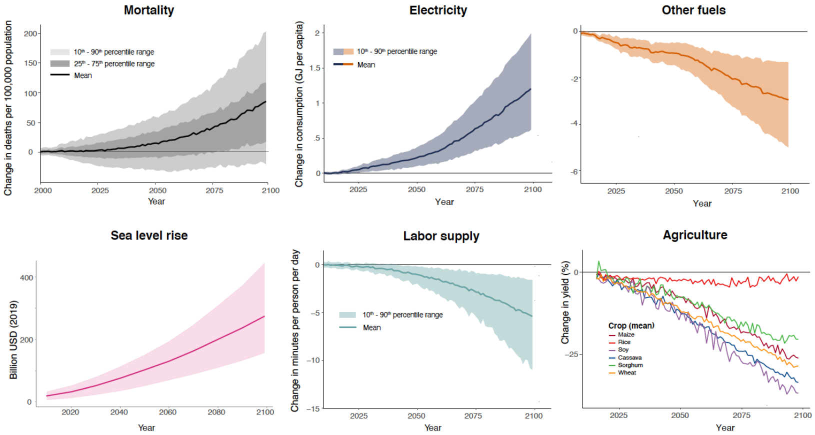

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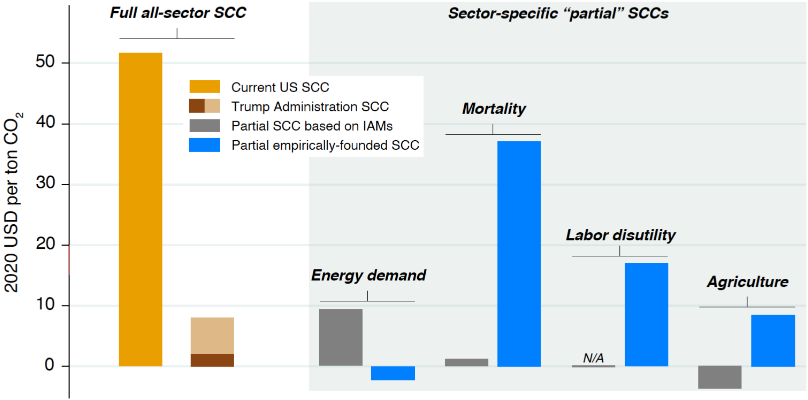
Empirically Founded SCCs vs. Current Policy



Scenario: high emissions
Discount rates: 3% (current, IAMs); 3%-7% (Trump Admin.), 2% (mortality, energy, labor, agric.).
Uncertainty: Mean estimates shown for empirical SCCs; full distribution resamples from damage function and climate uncertainty

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Accounting for joint impacts across sectors

- A social cost of carbon requires making key choices about how to measure welfare:
  - Uncertainty valuation (e.g. Barnett et al., 2020; Cai and Lontzek, 2016)
  - “Equity weighting” across contemporaneous individuals (e.g., Anthoff et al., 2009)
  - Discounting under uncertain economic growth (e.g. Gollier and Weitzman, 2010)
- Probabilistic, high-resolution climate damage estimates enable quantification of these prior theoretical insights

Welfare economics of climate change in DSCIM

- Choices about how to aggregate over time, space, and uncertain states of the world are fundamental to SCC calculations
- The “standard” calculation:
  - Deterministic growth, damages, climate ($\rightarrow$ risk neutrality)
  - Add up unweighted dollar value of damages across regions ($\rightarrow$ constant MU of consumption)
  - Use constant discount rate ($\rightarrow$ ignores future growth and damages)

Welfare economics of climate change in DSCIM

- How would a social planner weight damages across time, space, and uncertain states of the world?
  - Value the impacts of uncertainty in growth, damages, and climate on risk averse agents ($\rightarrow$ risk aversion)
  - Account for the different value of dollars to rich and poor within a generation ($\rightarrow$ declining MU of consumption)
  - Endogenous discounting ($\rightarrow$ accounts for future growth and damages)

Welfare economics of climate change in DSCIM

- New probabilistic emissions and socioeconomic scenarios (Rennert et al., 2021)
  - Dramatically improves the state-space of emissions and growth futures $\rightarrow$ better characterization of uncertainty and climate risk premium
  - Accounts for covariance between emissions trajectories and socioeconomic trajectories – “climate beta”, i.e., insurance value from investments in emissions reductions.

Figure 6. Average Projected Growth Rates of Global GDP per Capita

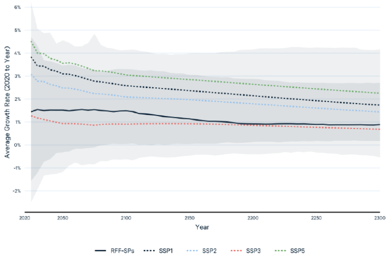
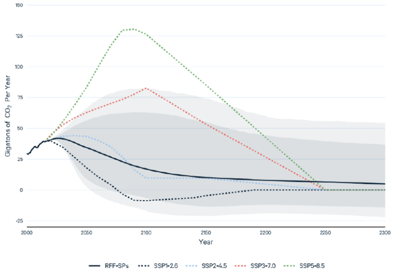


Figure 8. Net Annual Emissions of CO_2 from RFF-SPs and SSPs



Limitations of Empirical Sector-Specific Analysis

- Empirically-based SCCs don't currently address:
  - General equilibrium concerns
    - Need for macro-foundations of micro-facts.
    - Migration and trade
    - Endogenous sectoral reallocation
    - Other interactions between sectors/regions
  - Endogenous economic growth
  - Innovation
  - Tipping points
  - More sectors

Dynamic Programing and Accounting

- Dynamic optimization characterizes how intertemporal choices should be made given preferences and technologies
- In many cases, we want a low-dimensional representation of certain aspects of the dynamic problem – we call this “accounting”
- E.g.
  - Using a balance sheet to summarize a company’s state
  - Using GDP to summarize an economy’s performance
  - Using “shadow prices” to guide optimal decision making in terms of environmental resources
- Accounting has an important role:
  - It facilitates communication of intertemporal considerations beyond a technical audience
  - Provides “sufficient statistics” that guide decision making for multiple underlying models

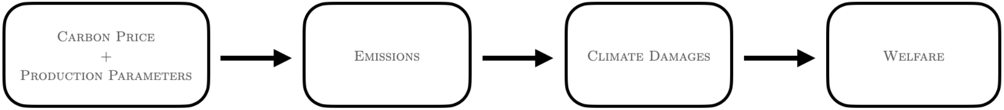
Dynamic Programing and Accounting

- But, accounting can be problematic if it fails to adequately capture key features of the underlying dynamic problem.
- Fortunately, every accounting scheme can be evaluated in light of a fully specified dynamic optimization problem.
  - The fully specified problem provides a rubric to grade different accounting schemes
  - An accounting system is good if it performs well under a reasonable range of underlying dynamic problems
  - Is the SCC a good accounting system?

Colmer and Malmberg (2021): A Budget Approach

- The SCC approach:
  - Estimate the marginal social cost of carbon emissions
  - Equate the pricing of carbon to the marginal social cost of carbon
- Carbon budgeting:
  - Set a maximum level of carbon emissions based on input from Climate scientists
  - Set a price needed to target this level of emissions
- What is the relationship between these two approaches?
  - We show that there is an equivalence between the two, but that each represent different ways to handle model uncertainty, non-convexities, relationship with climate science.
  - We argue that the carbon budget approach is more consistent with economists' comparative advantage, r.e., research and policy engagement.

Mapping between a Carbon Price and Welfare



- Each of these arrows is associated with potential uncertainties

- **Aim:** Specify an economic problem where the optimal carbon price is a function of these mappings.

A Static Framework[1]

- Assuming that output is strictly concave and private costs strictly convex, the planner's problem is

$$\tau^*[Y(\cdot), C(\cdot), D(\cdot), SC(\cdot)] = arg\max_{\tau} Y(E(\tau)) - SC(D(E(\tau)) - C(E(\tau))$$

where carbon price is mapped to emissions by private optimality,

$$E(\tau; Y(\cdot), C(\cdot)) = arg\max_{E} Y(E) - C(E) - \tau E$$

[1] For tractability, the plan is to show this within the GHKT (2014, Econometrica) structure.

SCC vs. Carbon Budgeting Price

- We define the Social Cost of Carbon as,

$$SCC[E; D(\cdot), SC(\cdot)] = SC'(D(E) \times D'(E)$$

- We define the carbon budgeting price of emissions as,

$$\tau^{budget}[E^*; Y(\cdot), C(\cdot)] = \min\{\tau : E[\tau; Y(\cdot), C(\dot{})] = E^*\}$$

- Both use emissions as an argument, but the two objects take *disjoint* primitives as an argument.
  - The SCC depends on: emissions $\rightarrow$ damages & damages $\rightarrow$ welfare.
  - τ^{budget} is independent of the climate block and is only a function of the relationship between production and emissions.

The Equivalence between SCC and Carbon Budgeting Price

- **Proposition:** Suppose $\tau^*, E^* \equiv E(\tau^*; Y, C)$ is a solution the planner's problem given SC, D, Y, C. If all functions are differentiable then,

$$SCC[E^*] = \tau^{budget}[E^*]$$

- If τ^* is optimal, it implies that the SCC is equal to this tax rate at the implied emissions level E^*.

- The converse, however, is not true.
  - For $SCC(E[\tau^{**}]) = \tau^{**}$, it might still be that τ^{**} is suboptimal.
  - The uniqueness of the solution requires that the welfare cost of carbon is convex, so that the SCC is uniformly increasing in E and uniformly decreasing in $E(\tau)$.
  - With tipping points, the SCC is non-monotonic.

An Irrelevance Theorem

- If:
  - economists have infinite research time
  - policy is implemented according to economists' definition/choice of social welfare function
  - economists fully understand the climate system and climate costs are convex (no tipping points)
- $\Rightarrow$ the two approaches should generate the same solution/answer.

The Importance of Research Time

- Despite being closely connected, the two approaches imply different roles for economists.
- Why? The two approaches can afford to neglect different aspects of the problem
- SCC approach:
  - To a first-order approximation the SCC doesn't need to know how responsive demand for carbon is to carbon prices.
  - We need to think very carefully about discount factors, treatment of uncertainty, and the precise working of the climate system
  - Assuming a constant SCC, set $\tau = SCC$ and the let the chips fall where they may in terms of emissions.
- The Carbon Budget:
  - The budget approach needs to know how responsive demand for carbon is to carbon prices.
  - Much less dependent on discount factors, risk valuation, and the details of the climate system.

What is Lost/Gained from Gravitating towards a "Carbon Budget" approach?

- Gained:
  - More focus/better understanding of the determinants/production function of carbon emissions and how to reduce them (IO/Macro)
  - More consideration of the effects of different policy initiatives (including second-best interventions) (Public Finance/Labor/Trade)
  - Aligns with target-based commitments on which policy is being formulated.
  - Better understanding of costs of action: conditional on commitments, what is the least cost path.
- Lost:
  - Less input into what temperature targets should be (do we have much input here?)
  - Less understanding of specific climate damages (well established literature? diminishing marginal returns?)