A New Path Forward
for an Empirical Social Cost of Carbon

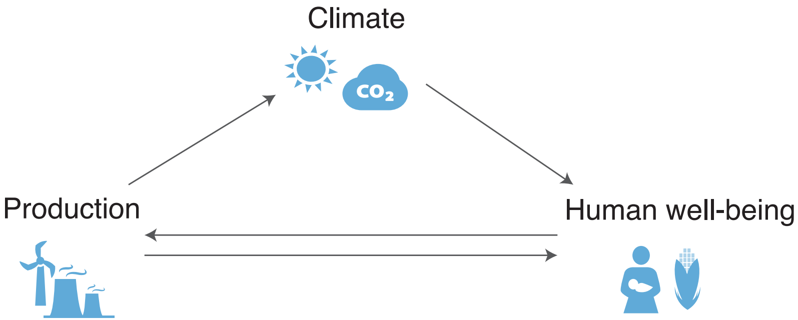
Michael Greenstone

Milton Friedman Professor of Economics, University of Chicago

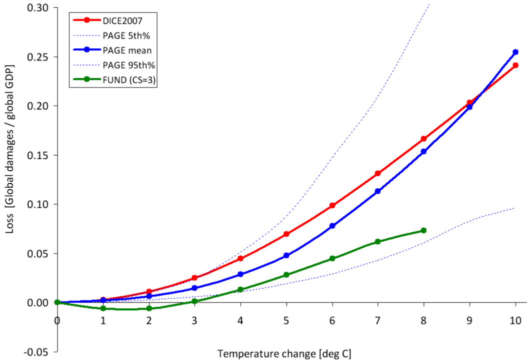
May 5th, 2016

History

The Integrated Assessment Models (e.g. Nordhaus, 1994) provided a monumental step forward in understanding the complex relationship between CO_2 emissions and human well-being.



Climate damages



Source: Interagency Working Group on Social Cost of Carbon, 2010

Two proposed criteria for a damage function

We propose that the estimates that underlie any reliable damage function <u>must</u> satisfy two key criteria:

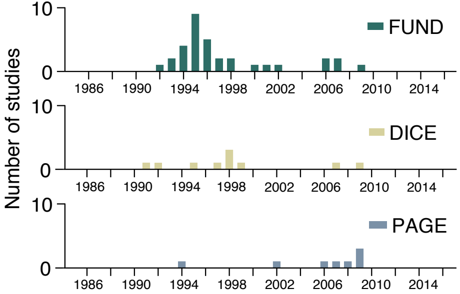
1. **Plausibly causal:** Damage functions should be derived from empirical estimates that are purged of sources of unobserved heterogeneity and are plausibly causal
2. **Reflect adaptation and its costs:** Damage functions should reflect that agents choose optimal adaptation opportunities and incur the costs of compensatory investments

Additional criteria for developing damage functions

We propose the following additional criteria for judging whether a damage function is reliable:

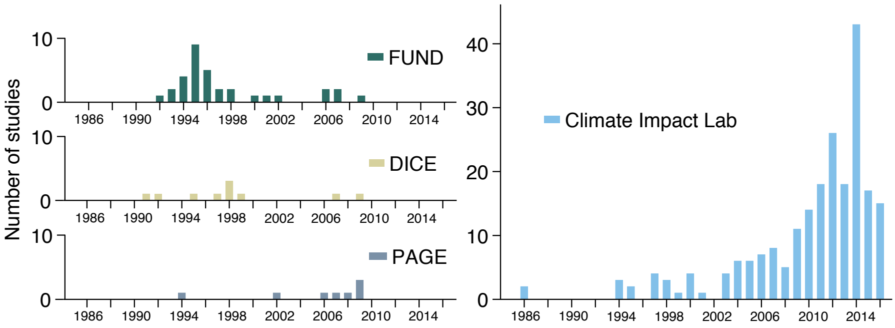
- **Representative:** Estimate should be representative of the population that it is applied to
- **Flexible:** Allow for non-linearity using semi-parametric approaches
- **Non-market valuations:** Allow for valuations of market and non-market impacts
- **Risk and inequality:** Capture distributional effects of climate impacts
- **Updatable and transparent:** SCC estimating framework should be easily updatable to incorporate the latest research, be replicable, and transparent

Literature



Number of studies
10
0
FUND
DICE
PAGE
1986
1990
1994
1998
2002
2006
2010
2014

Literature



A brief history of damage function estimation

	Research Advances	Causal	Adaptation
v1.0	Functional form assumptions about the shape of GDP-temperature response function		
v2.0	Greenhouse experiments of the response of crop yields to temperature	✓	
v3.0	Cross-sectional hedonic equation (e.g., Mendelsohn, Nordhaus, & Shaw AER 1994)		✓
v4.0	Exploit inter-annual variation in weather (e.g., Deschenes & Greenstone AER 2007)	✓	
v5.0	Exploit inter-annual variation and directly model adaptation as function of observables (e.g., Auffhammer & Aroonruengsawat CEC 2012)	✓	✓

Version 5.0 in action: Climate Impact Lab

Preliminary Results

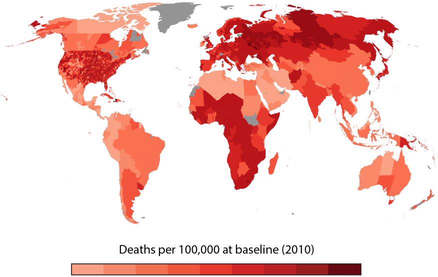
Climate Impact Lab

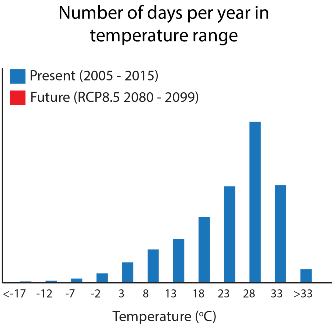
M. Greenstone	T. Houser	S. Hsiang	R. Kopp
T. Carleton	M. Delgado	R. Goyal	A. Jina
T. Kulczycki	M. Landin	K. Larsen	S. Mohan
I. Nath	S. Ori	S. Phan	D. Rasmussen
J. Rising	A. Rode	J. Yuan	

Climate Impact Lab Cookbook

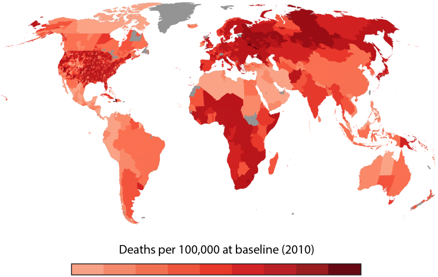
1. Develop “plausibly causal” estimates of relationship between measures of climate and human welfare in multiple sectors using continuously updating estimates
   - Reanalyze studies to ensure estimates meet research criteria
   - Conduct new analyses to achieve representative coverage
   - Incorporate results from new studies as they emerge
2. Build a model of direct responses based on historical adaptation and interpolate around the world, where no studies exist
3. Project responses into the future using high resolution climate projections
   - Develop cost estimates of compensatory investments
4. Obtain empirical damage function that accounts for multiple sources of uncertainty to **calculate an SCC that meets all criteria**

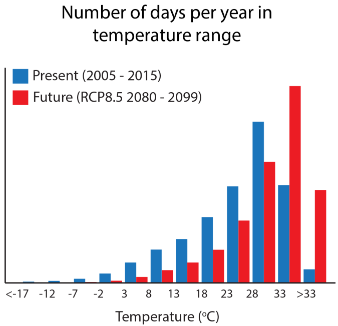
Case study: Mortality





Case study: Mortality





Climate Impact Lab Cookbook

1. Develop "plausibly causal" estimates of relationship between measures of climate and human welfare in multiple sectors using continuously updating estimates
   - Reanalyze studies to ensure estimates meet research criteria
   - Conduct new analyses to achieve representative coverage
   - Incorporate results from new studies as they emerge
2. Build a model of direct responses based on historical adaptation and interpolate around the world, where no studies exist
3. Project responses into the future using high resolution climate projections
   - Develop cost estimates of compensatory investments
4. Obtain empirical damage function that accounts for multiple sources of uncertainty to **calculate an SCC that meets all criteria**

Data

Mortality data

- Universe of mortality data from 6 countries, 46.7% of global population

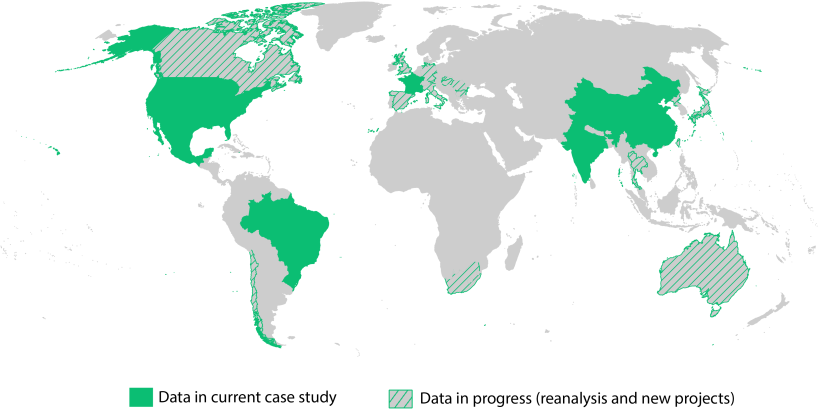
Climate data

- Daily historical county temperature and precipitation
- High-resolution projections of ~ 20 GCMs to 2100
- RCPs 4.5, 8.5, approx. 100 datasets of daily future weather

Covariate data for interpolation

- Income and population for 25,000 regions
- Nightlights for high resolution income

Mortality data covers 46.7% of global population



Estimating direct local mortality-temperature relationships

$$\underbrace{M_{it}}_{\text{mortality rate}} = \underbrace{\sum_k \beta_j^k T_{it}^k}_{\text{binned daily temp}} + g_j(precip_{it}) + \underbrace{\gamma_i + \delta_j \times t}_{\text{fixed effects \& trends}} + \varepsilon_{it}$$

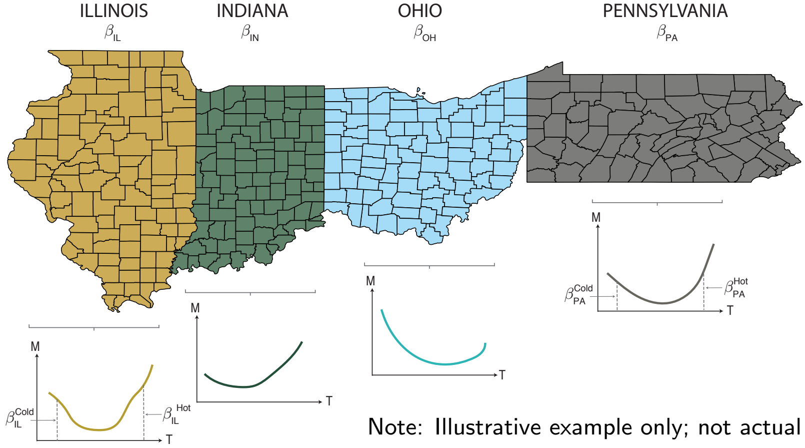
Our state-level estimation

For each state j in **6 countries**, we estimate this nonparametric temperature response using annual mortality data for counties i and **daily** temperature data, **saving k temperature coefficients** for each state.

▸ More details

Estimating direct local mortality-temperature relationships

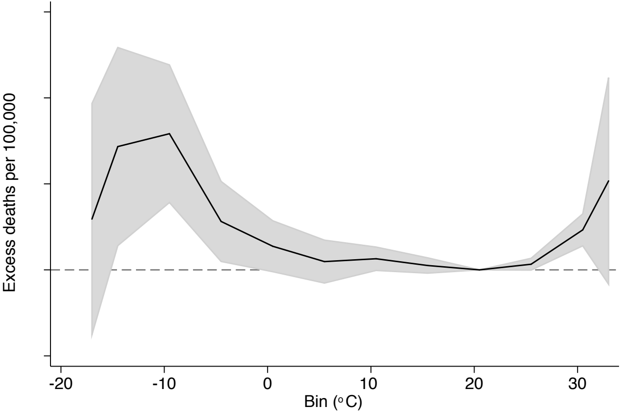
$$\underbrace{M_{it}}_{\text{mortality rate}} = \underbrace{\sum_k \beta_j^k T_{it}^k}_{\text{binned daily temp}} + g_j(precip_{it}) + \underbrace{\gamma_i + \delta_j \times t}_{\text{fixed effects \& trends}} + \varepsilon_{it}$$



Note: Illustrative example only; not actual data.

▸ Exact specification

The global mortality-temperature relationship



Note: Precision weighted estimates from global regression on state level coefficients.

→ **Full adaptation would imply a <u>flat line</u>**

Climate Impact Lab Cookbook

1. Develop “plausibly causal” estimates of relationship between measures of climate and human welfare in multiple sectors using continuously updating estimates
    - Reanalyze studies to ensure estimates meet research criteria
    - Conduct new analyses to achieve representative coverage
    - Incorporate results from new studies as they emerge
2. Build a model of direct responses based on historical adaptation and interpolate around the world, where no studies exist
3. Project responses into the future using high resolution climate projections
    - Develop cost estimates of compensatory investments
4. Obtain empirical damage function that accounts for multiple sources of uncertainty to **calculate an SCC that meets all criteria**

Modeling adaptation

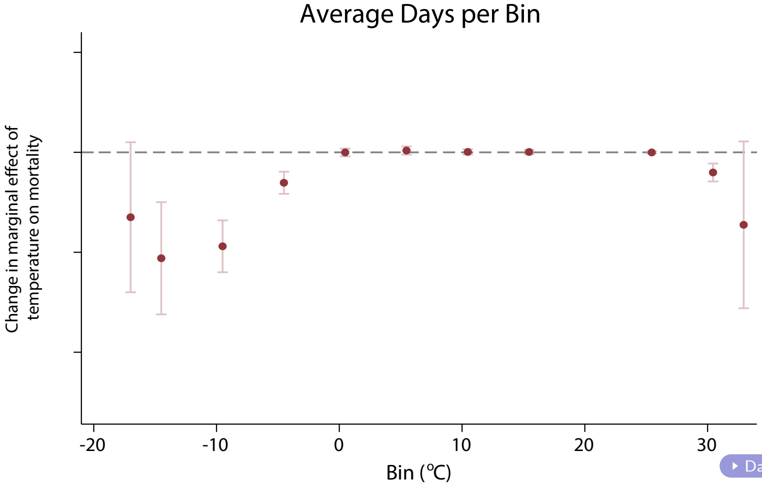
$$\hat{\beta}_j^k = \alpha^k + \underbrace{\gamma_1^k Avg\_days\_bin\_k_j}_{\substack{\text{adaptation due to} \\ \textbf{CLIMATE} \text{ directly}}} + \underbrace{\gamma_2^k \log(GDP\_pc_j)}_{\substack{\text{adaptation due to} \\ \textbf{INCOME} \text{ changes}}} + \underbrace{\gamma_3^k \log(Pop\_density_j)}_{\substack{\text{adaptation due to} \\ \textbf{POPULATION} \text{ changes}}} + \varepsilon_j^k$$

Determining adaptation response

- **Temperature:** People adapt to temperature directly, based on average exposure (e.g., Auffhammer & Aroonruengsawat, 2012)
- **Income:** Richer people are more able to make adaptive investments (e.g., Hsiang and Narita, 2012)
- **Population density:** Urban infrastructure decreases temperature sensitivity (e.g., Burgess et al., 2016)

Modeling adaptation

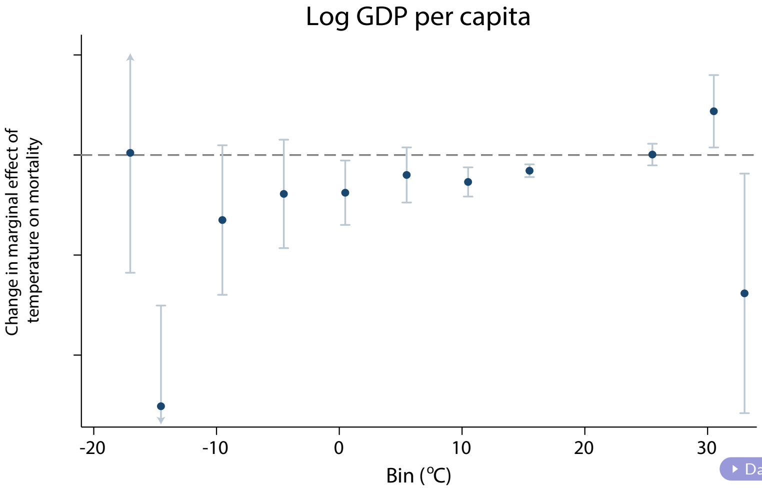
$$\hat{\beta}_j^k = \alpha^k + \boxed{\gamma_1^k Avg\_days\_bin\_k_j} + \gamma_2^k \log(GDP\_pc_j) + \gamma_3^k \log(Pop\_density_j) + \varepsilon_j^k$$



▸ Data

Modeling adaptation

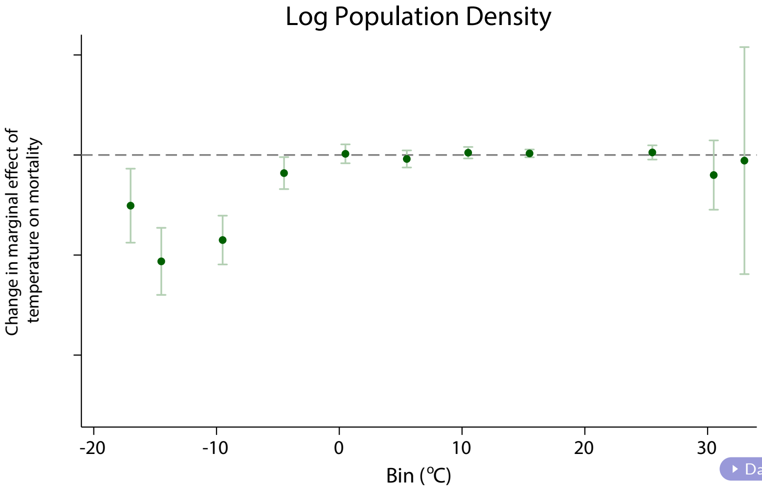
$$\hat{\beta}_j^k = \alpha^k + \gamma_1^k Avg\_days\_bin\_k_j + \gamma_2^k \log(GDP\_pc_j) + \gamma_3^k \log(Pop\_density_j) + \varepsilon_j^k$$



Data

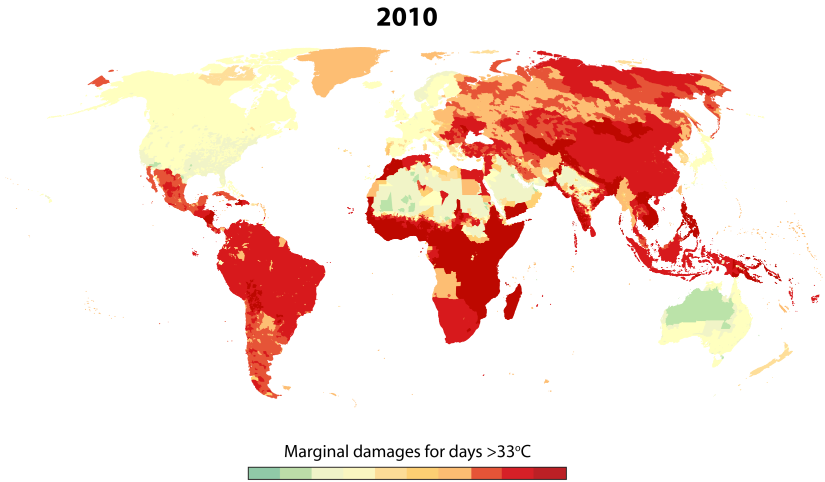
Modeling adaptation

$$\hat{\beta}_j^k = \alpha^k + \gamma_1^k Avg\_days\_bin\_k_j + \gamma_2^k \log(GDP\_pc_j) + \gamma_3^k \log(Pop\_density_j) + \varepsilon_j^k$$



Data

Predicting marginal effects where no data exist



→ Marginal effects vary with climate, income, and population density

Climate Impact Lab cookbook

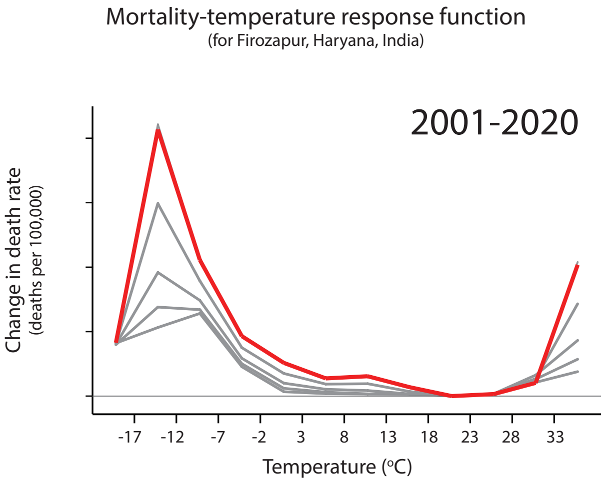
1. Develop “plausibly causal” estimates of relationship between measures of climate and human welfare in multiple sectors using continuously updating estimates
   - Reanalyze studies to ensure estimates meet research criteria
   - Conduct new analyses to achieve representative coverage
   - Incorporate results from new studies as they emerge

2. Build a model of direct responses based on historical adaptation and interpolate around the world, where no studies exist

3. Project responses into the future using high resolution climate projections
   - Develop cost estimates of compensatory investments

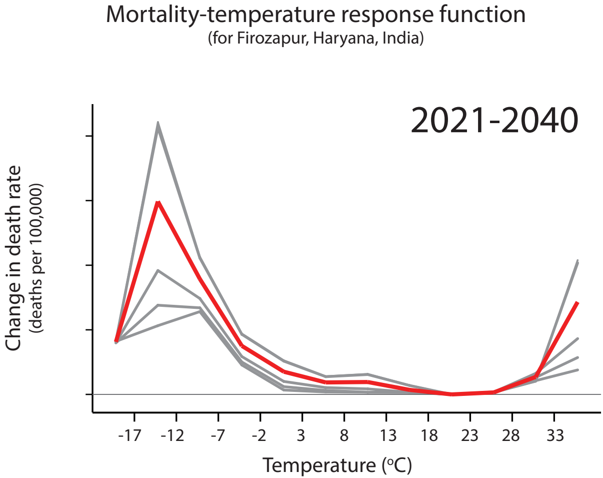
4. Obtain empirical damage function that accounts for multiple sources of uncertainty to **calculate an SCC that meets all criteria**

Adaptation over time



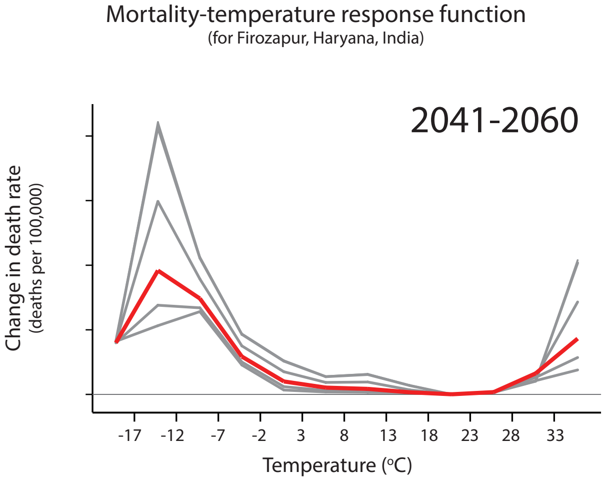
→ Marginal effects vary with climate, income, and population density

Adaptation over time



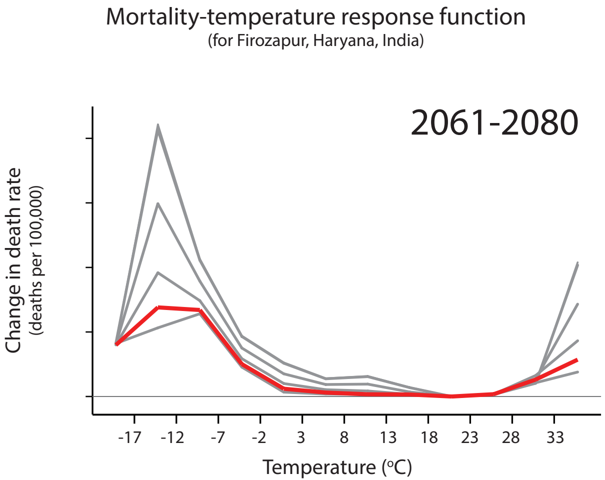
→ Marginal effects vary with climate, income, and population density

Adaptation over time



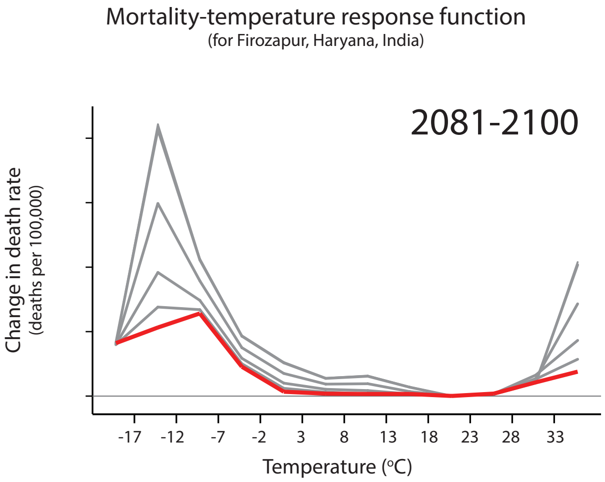
→ Marginal effects vary with climate, income, and population density

Adaptation over time



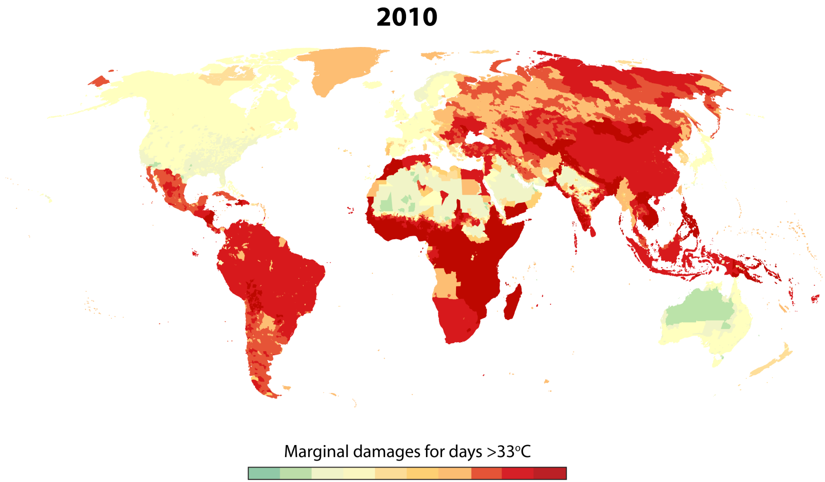
→ Marginal effects vary with climate, income, and population density

Adaptation over time



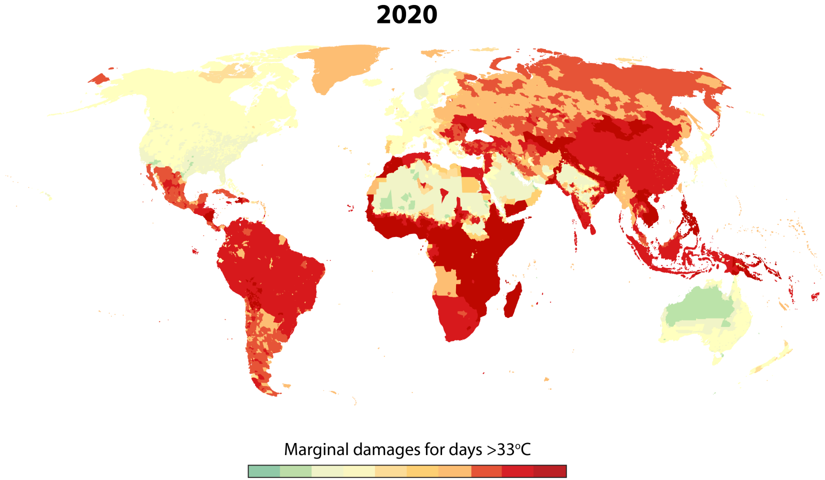
→ Marginal effects vary with climate, income, and population density

Projecting sensitivity to temperature into the future



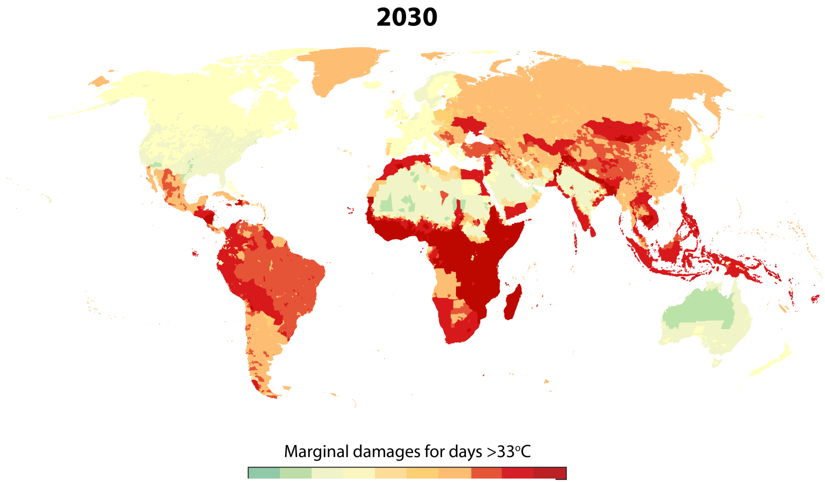
→ Marginal effects vary with climate, income, and population density

Projecting sensitivity to temperature into the future



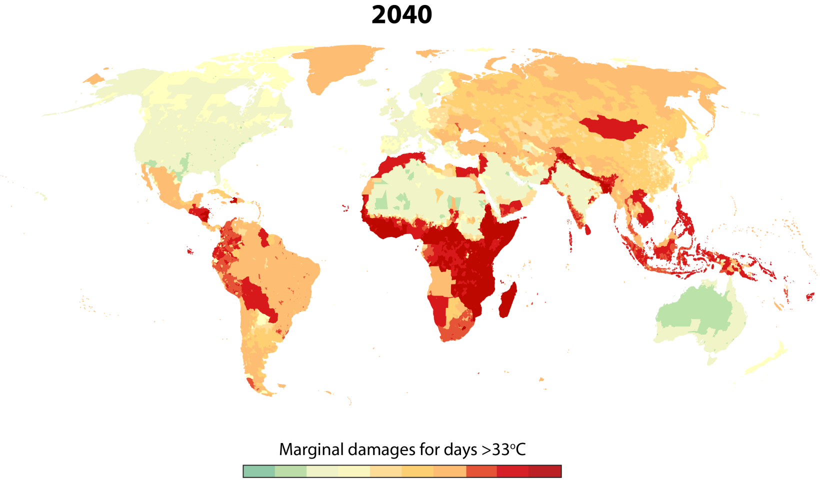
→ Marginal effects vary with climate, income, and population density

Projecting sensitivity to temperature into the future



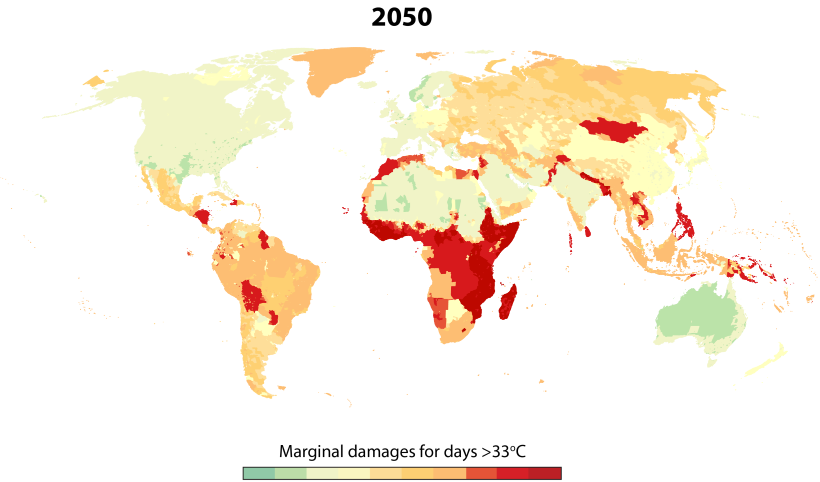
→ Marginal effects vary with climate, income, and population density

Projecting sensitivity to temperature into the future



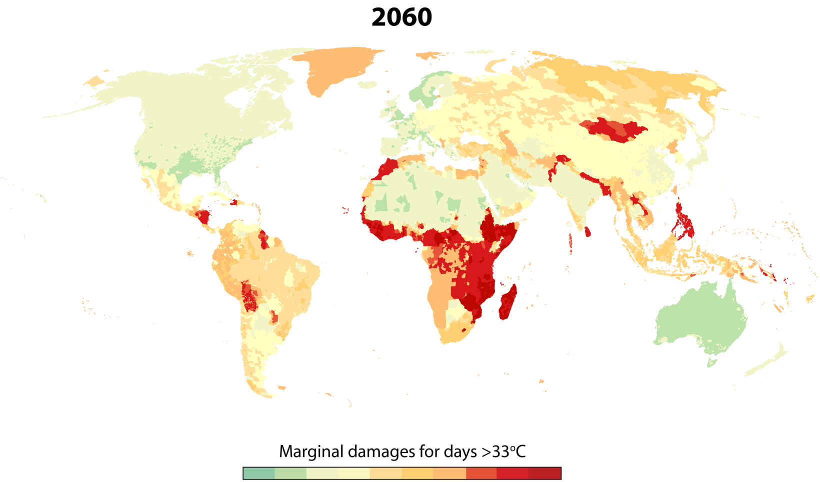
→ Marginal effects vary with climate, income, and population density

Projecting sensitivity to temperature into the future



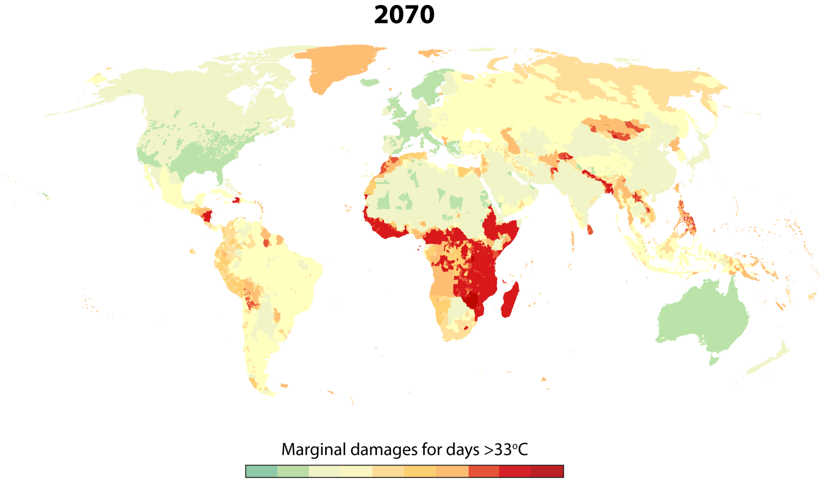
→ Marginal effects vary with climate, income, and population density

Projecting sensitivity to temperature into the future



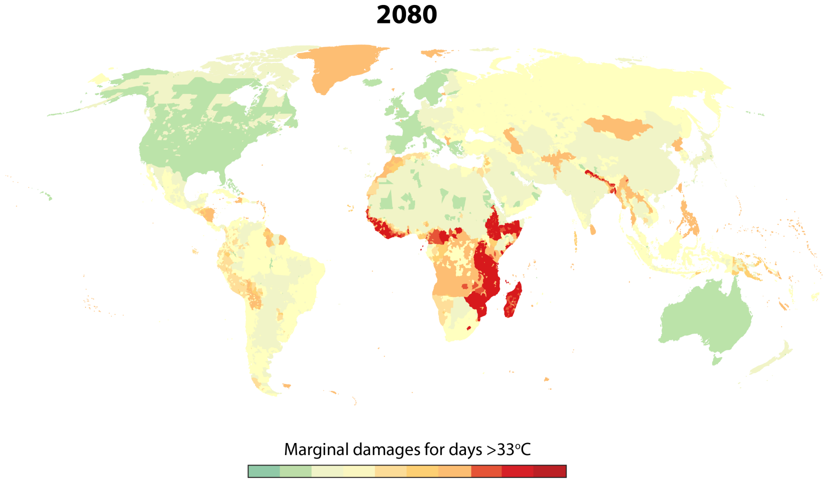
→ Marginal effects vary with climate, income, and population density

Projecting sensitivity to temperature into the future



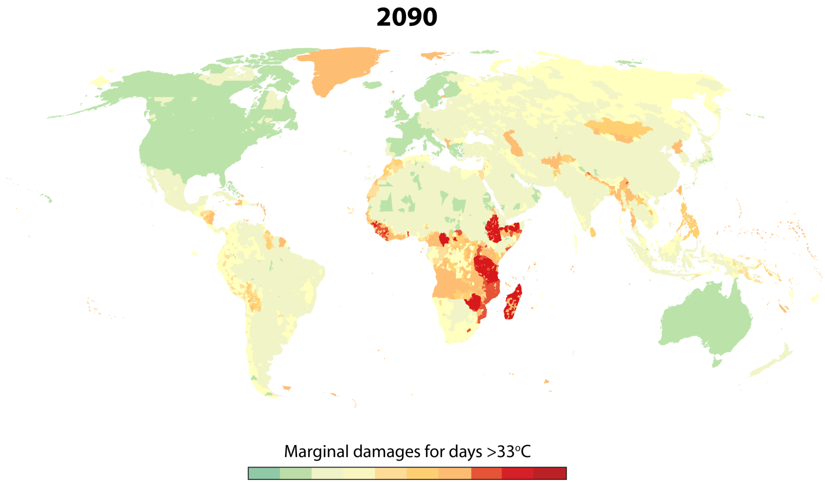
→ Marginal effects vary with climate, income, and population density

Projecting sensitivity to temperature into the future



→ Marginal effects vary with climate, income, and population density

Projecting sensitivity to temperature into the future



→ Marginal effects vary with climate, income, and population density

Climate Impact Lab cookbook

1. Develop "plausibly causal" estimates of relationship between measures of climate and human welfare in multiple sectors using continuously updating estimates
    - Reanalyze studies to ensure estimates meet research criteria
    - Conduct new analyses to achieve representative coverage
    - Incorporate results from new studies as they emerge
2. Build a model of direct responses based on historical adaptation and interpolate around the world, where no studies exist
3. Project responses into the future using high resolution climate projections
    - Develop cost estimates of compensatory investments
4. Obtain empirical damage function that accounts for multiple sources of uncertainty to **calculate an SCC that meets all criteria**

Calculating the "full" mortality costs of climate change

Adaptation reduces temperature sensitivity, but it requires costly compensatory investments (e.g. air conditioning).

Measuring adaptation costs

Challenge: Reduced form results reveal how mortality-temperature relationships evolve in response to adaptation. However, they do not reveal the costs of unobserved compensatory investments

$\Longrightarrow$ If adaptation were costless, there would be a flat relationship between mortality and temperature throughout the world

Solution: It is possible to bound adaptation costs in units of mortality by using a revealed preference argument

Revealed preference approach to measuring adaptation costs

- Let β^k be the increase in mortality caused by a day in bin k relative to a day in a neutral bin
- Let T^k be the number of days in bin k
- $C(\beta^k)$ are the compensatory investments required to realize β^k, the impact of temperature on mortality

Individual's cost minimization problem (for each bin):

$$\min_{\beta^k} \; \beta^k T^k + C(\beta^k)$$

- Optimal β^k is defined by: $T^k = -C'(\beta^k)$
- β^k is lower when T^k is higher (costs are decreasing in β^k)

Statement of problem
Exact calculation

Calculating the "Full" Mortality Costs back

- Climate change causes $T_0^k \rightarrow T_1^k$
- No Adaptation costs of climate change (e.g., Deschenes and Greenstone 2011):

$$\beta_0^k \times T_1^k - \beta_0^k \times T_0^k$$

- Full costs of climate change:

$$(\beta_1^k T_1^k - \beta_0^k T_0^k) + C(\beta_1^k) - C(\beta_0^k)$$

- Costs cannot be directly observed, but can be **bounded**:

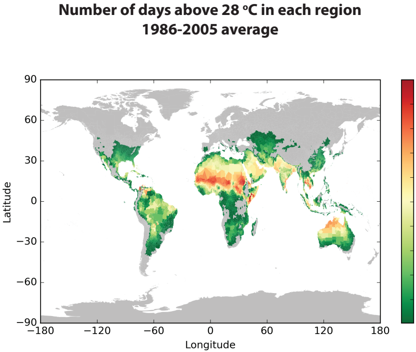
Lower bound: $C(\beta_1^k) - C(\beta_0^k) > (\beta_0^k - \beta_1^k) T_0^k$

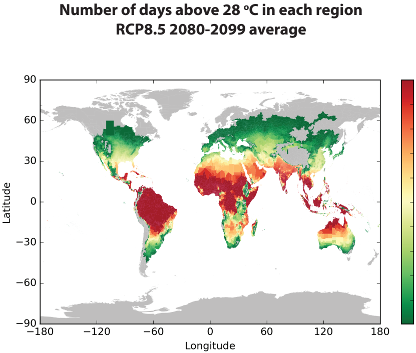
- Otherwise, Agents Would have Chosen β_1^k at T_0^k

Upper Bound: $C(\beta_1^k) - C(\beta_0^k) < (\beta_0^k - \beta_1^k) T_1^k$

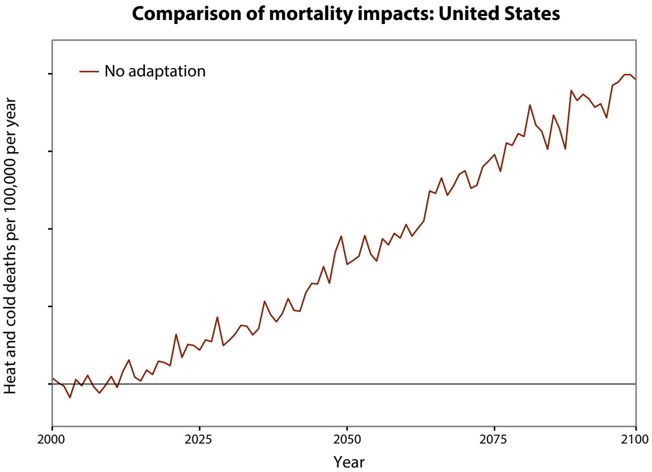
- Otherwise, Agents Would have Chosen β_0^k at T_1^k

Linking to climate projections

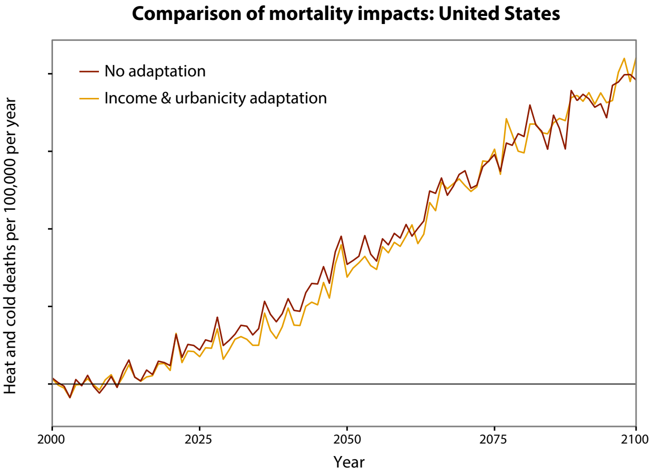




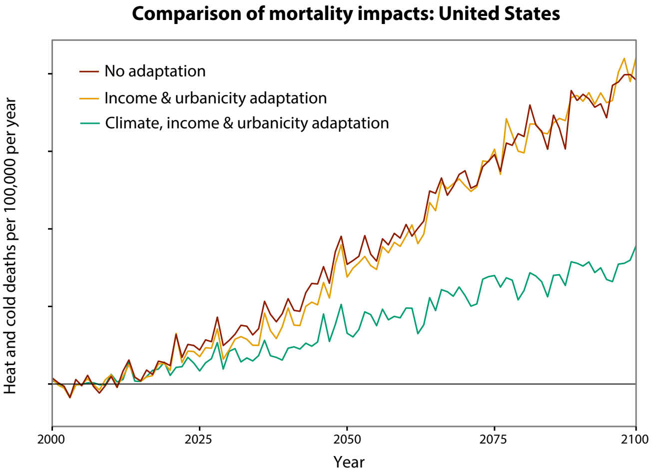
Projected impacts for USA under RCP8.5



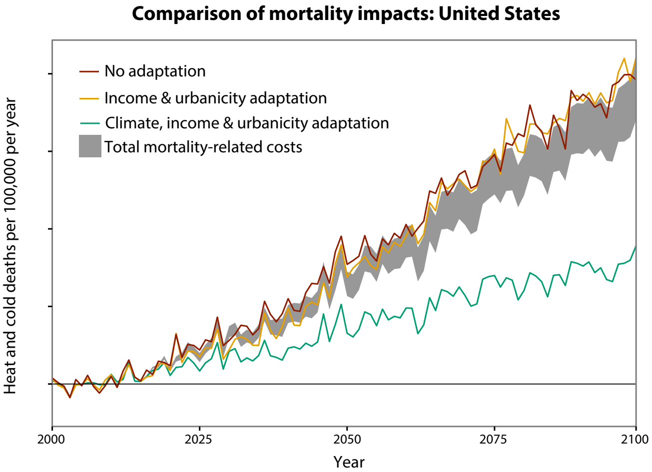
Projected impacts for USA under RCP8.5



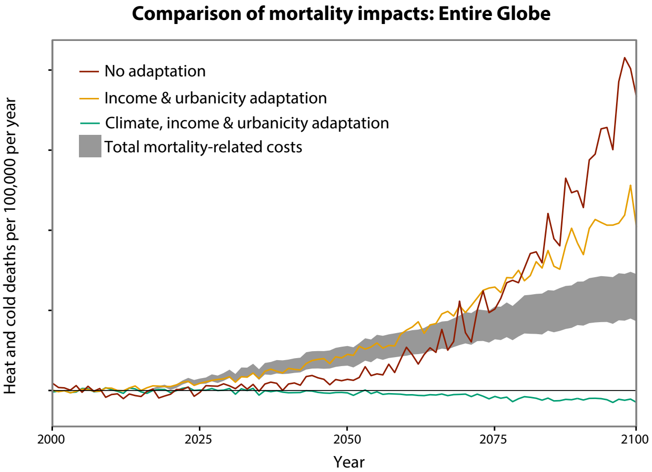
Projected impacts for USA under RCP8.5



Projected impacts for USA under RCP8.5



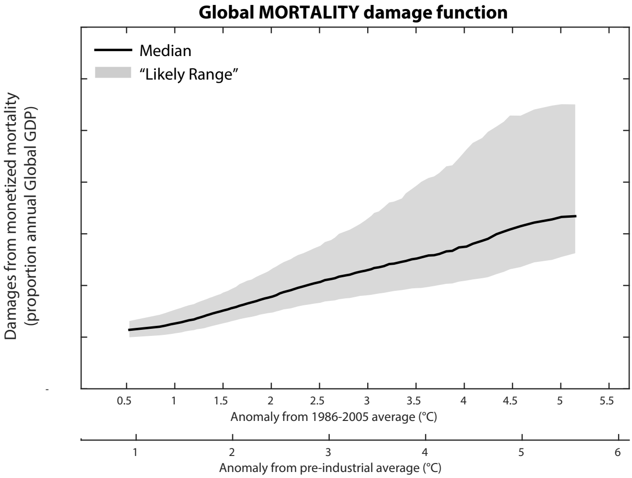
Projected impacts for the globe under RCP8.5



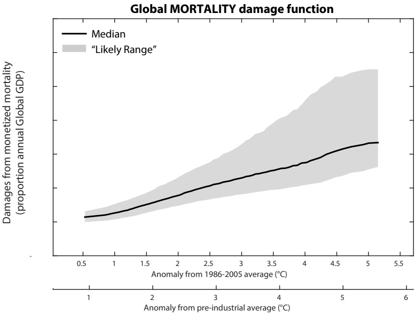
Climate Impact Lab cookbook

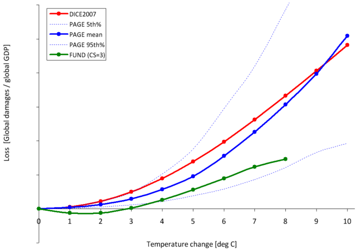
1. Develop "plausibly causal" estimates of relationship between measures of climate and human welfare in multiple sectors using continuously updating estimates
   - Reanalyze studies to ensure estimates meet research criteria
   - Conduct new analyses to achieve representative coverage
   - Incorporate results from new studies as they emerge
2. Build a model of direct responses based on historical adaptation and interpolate around the world, where no studies exist
3. Project responses into the future using high resolution climate projections
   - Develop cost estimates of compensatory investments
4. Obtain empirical damage function that accounts for multiple sources of uncertainty to **calculate an SCC that meets all criteria**

An illustrative empirical global MORTALITY damage function

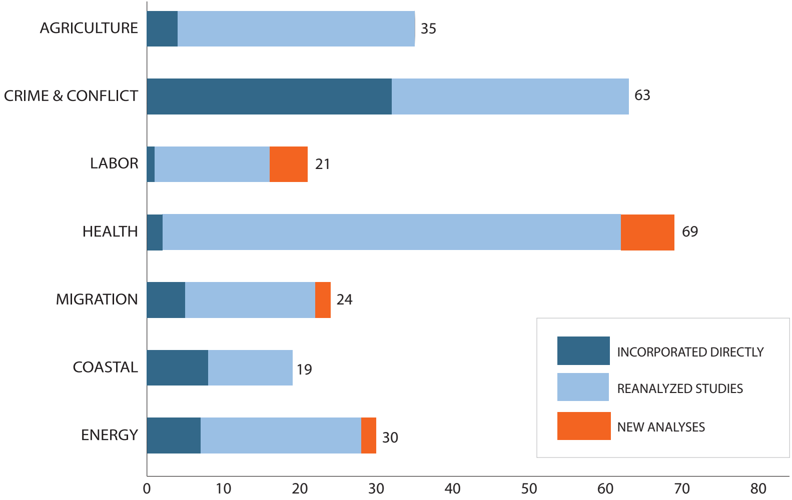


Damage function comparison





Apply procedure to other sectors



Conclusion

1. We recommend that damage functions be based on **plausibly casual empirical estimates** and reflect **adaptation costs**

2. We recommend that damage functions reflect a series of other **"best practices"** for modern empirical work, including taking full advantage of an exploding empirical climate damages literature

3. Climate Impact Lab work demonstrates that such damage functions will be available soon

Extra Slides

State-level mortality-temp specification

back

$$\underbrace{M_{it}}_{\text{mortality rate}} = \underbrace{\sum_k \beta_j^k T_{it}^k}_{\text{binned daily temp}} + g_j(precip_{it}) + \underbrace{\gamma_i + \delta_j \times t}_{\text{fixed effects \& trends}} + \varepsilon_{it}$$

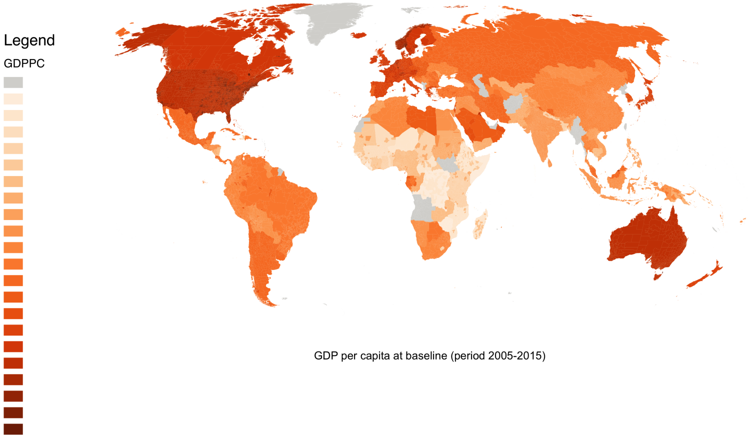
Our state-level estimation

For each state j in **6 countries**, we estimate this nonparametric temperature response using annual mortality data for counties i and **daily** temperature data, **saving k temperature coefficients** for each state.

- 3 months of lags are included in the lagged monthly regressions where monthly data are available
- County fixed effects are included, as well as linear time trends
- Standard errors are heteroskedasticity robust, but not clustered, due to small numbers of clusters (counties) in many countries

Data for interpolation: Income

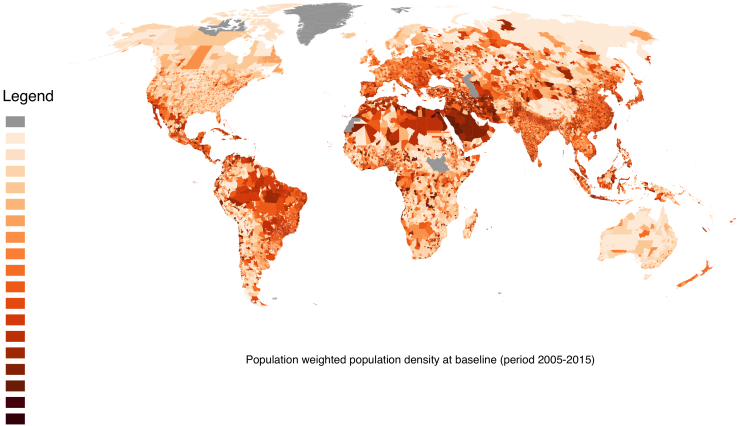
back



GDP per capita at baseline (period 2005-2015)

Data for interpolation: Population Density

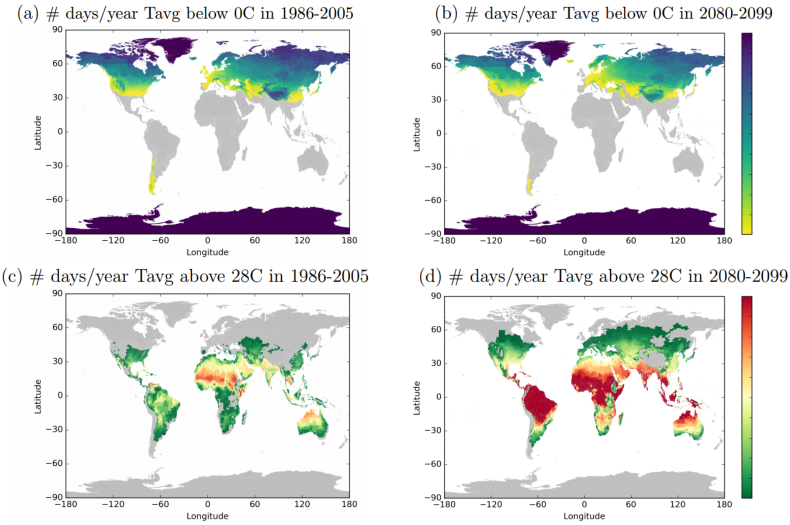
back



Population weighted population density at baseline (period 2005-2015)

Data for interpolation and projection: Climate

back



Measuring adaptation cost with revealed preferences

back

Damages today $<$ damages after adapting $+$ **costs of adaptation**

$$T_0 \cdot \beta(Y_0, P_0, \bar{T}_0) < T_0 \cdot \beta(Y_0, P_0, \bar{T}_1) + \mathbf{C}$$
$$T_0 \cdot \left[\beta(Y_0, P_0, \bar{T}_0) - \beta(Y_0, P_0, \bar{T}_1)\right] < \mathbf{C}$$

Damages tomorrow $+$ **costs of adaptation** $<$ unadapted damages tomorrow

$$T_1 \cdot \beta(Y_1, P_1, \bar{T}_1) + \mathbf{C} < T_1 \cdot \beta(Y_1, P_1 \bar{T}_0)$$
$$\mathbf{C} < T_1 \cdot \left[\beta(Y_1, P_1, \bar{T}_0) - \beta(Y_1, P_1, \bar{T}_1)\right]$$

$$\implies -T_0 \frac{\partial \beta}{\partial \bar{T}} < \mathbf{C} < -T_1 \frac{\partial \beta}{\partial \bar{T}}$$