A New Path Forward for an Empirical Social Cost of Carbon

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May 5th, 2016
The Integrated Assessment Models (e.g. Nordhaus, 1994) provided a monumental step forward in understanding the complex relationship between CO₂ 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 must 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.
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
Literature

The figure shows the number of studies published from 1986 to 2014 for three different climate impact models: FUND, DICE, and PAGE. The x-axis represents the years, while the y-axis represents the number of studies. The data is categorized by the year of publication, with increments of 2 years (1986, 1990, 1994, 1998, 2002, 2006, 2010, 2014). The number of studies for each model varies across the years, with some peaks and troughs. For instance, FUND shows a significant increase in studies from 2010 onwards, while DICE and PAGE have more consistent publication patterns throughout the years.
A brief history of damage function estimation

<table>
<thead>
<tr>
<th>Research Advances</th>
<th>Causal</th>
<th>Adaptation</th>
</tr>
</thead>
<tbody>
<tr>
<td>v1.0  Functional form assumptions about the shape of GDP-temperature response function</td>
<td></td>
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</tr>
<tr>
<td>v2.0  Greenhouse experiments of the response of crop yields to temperature</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>v3.0  Cross-sectional hedonic equation (e.g., Mendelsohn, Nordhaus, &amp; Shaw AER 1994)</td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td>v4.0  Exploit inter-annual variation in weather (e.g., Deschenes &amp; Greenstone AER 2007)</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>v5.0  Exploit inter-annual variation and directly model adaptation as function of observables (e.g., Auffhammer &amp; Aroonruengsawat CEC 2012)</td>
<td>✓</td>
<td>✓</td>
</tr>
</tbody>
</table>
Version 5.0 in action: Climate Impact Lab

Preliminary Results
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

Number of days per year in temperature range

Deaths per 100,000 at baseline (2010)

Temperature (°C)

Future (RCP8.5 2080 - 2099)
Climate Impact Lab Cookbook

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## 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

\[ M_{it} = \sum_k \beta_j^k T_{it}^k + g_j(\text{precip}_{it}) + \gamma_i + \delta_j \times t + \varepsilon_{it} \]

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.
Estimating direct local mortality-temperature relationships

\[ M_{it} = \sum_{k} \beta_{jk} T_{it}^k + g_j(precip_{it}) + \gamma_i + \delta_j \times t + \varepsilon_{it} \]

Note: Illustrative example only; not actual data.
The global mortality-temperature relationship

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

→ Full adaptation would imply a flat line
Climate Impact Lab Cookbook

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Modeling adaptation

\[ \hat{\beta}_j^k = \alpha^k + \gamma_1^k \text{Avg}_{-days\_bin\_k_j} + \gamma_2^k \log(GDP\_pc_j) + \gamma_3^k \log(Pop\_density_j) + \varepsilon_j^k \]

adaptation due to CLIMATE directly
adaptation due to INCOME changes
adaptation due to POPULATION changes

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

\[
\hat{\beta}_j^k = \alpha_k^k + \gamma_1^k \text{Avg\_days\_bin\_}k_j + \gamma_2^k \log(GDP_{pc_j}) + \gamma_3^k \log(Pop\_density_j) + \varepsilon_j^k
\]
Modeling adaptation

\[ \hat{\beta}_j^k = \alpha^k + \gamma_1^k \text{Avg\_days\_bin}_k + \gamma_2^k \log(GDP_{pcj}) + \gamma_3^k \log(Pop\_density_{ij}) + \epsilon_j^k \]
Modeling adaptation

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Predicting marginal effects where no data exist

→ Marginal effects vary with climate, income, and population density
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Adaptation over time

Mortality-temperature response function
(for Firozapur, Haryana, India)

Change in death rate (deaths per 100,000)

Temperature (°C)

2001-2020

→ Marginal effects vary with climate, income, and population density
Adaptation over time

Mortality-temperature response function
(for Firozapur, Haryana, India)

→ Marginal effects vary with climate, income, and population density
Adaptation over time

Mortality-temperature response function
(for Firozapur, Haryana, India)

2041-2060

→ Marginal effects vary with climate, income, and population density
Adaptation over time

Mortality-temperature response function
(for Firozapur, Haryana, India)

→ Marginal effects vary with climate, income, and population density
Adaptation over time

Mortality-temperature response function
(for Firozapur, Haryana, India)

→ 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

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Calculating the “full” mortality costs of climate change

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

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<th>Measuring adaptation costs</th>
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<td><strong>Challenge:</strong> Reduced form results reveal how mortality-temperature relationships evolve in response to adaptation. However, they do not reveal the costs of unobserved compensatory investments</td>
</tr>
</tbody>
</table>

⇒ 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 $\beta^k$ 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 $\beta^k$, 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 $\beta^k$ is defined by: $T^k = -C'(\beta^k)$

$\beta^k$ is lower when $T^k$ is higher (costs are decreasing in $\beta^k$)
Calculating the “Full” Mortality Costs

- 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 $\beta_1^k$ 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 $\beta_0^k$ at $T_1^k$
Linking to climate projections

Number of days above 28 °C in each region
1986-2005 average

Number of days above 28 °C in each region
RCP8.5 2080-2099 average
Projected impacts for USA under RCP8.5

Comparison of mortality impacts: United States

Heat and cold deaths per 100,000 per year

Year

2000 2025 2050 2075 2100

No adaptation
Projected impacts for USA under RCP8.5

Comparison of mortality impacts: United States

- No adaptation
- Income & urbanicity adaptation

Heat and cold deaths per 100,000 per year

Year

2000 2025 2075

2000 2025 2050 2075 2100
Projected impacts for USA under RCP8.5

Comparison of mortality impacts: United States

- No adaptation
- Income & urbanicity adaptation
- Climate, income & urbanicity adaptation

Heat and cold deaths per 100,000 per year

Year

2000 2025 2050 2075 2100
Comparison of mortality impacts: United States

Year

Heat and cold deaths per 100,000 per year

- No adaptation
- Income & urbanicity adaptation
- Climate, income & urbanicity adaptation
- Total mortality-related costs

2000 2025 2050 2075 2100

Projected impacts for USA under RCP8.5
Projected impacts for the globe under RCP8.5

Comparison of mortality impacts: Entire Globe

- No adaptation
- Income & urbanicity adaptation
- Climate, income & urbanicity adaptation
- Total mortality-related costs

Heat and cold deaths per 100,000 per year vs. Year (2000-2100)
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An illustrative empirical global MORTALITY damage function
Damage function comparison

Global MORTALITY damage function

- Median
- “Likely Range”

Anomaly from 1986-2005 average (°C)

Anomaly from pre-industrial average (°C)

Loss [Global damages / Global GDP]

Temperature change [deg C]
Apply procedure to other sectors

AGRICULTURE
CRIME & CONFLICT
LABOR
HEALTH
MIGRATION
COASTAL
ENERGY

NEW ANALYSES
REANALYZED STUDIES
INCORPORATED DIRECTLY

35
63
21
69
24
19
30
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

\[ M_{it} = \sum_k \beta^k_j T^k_{it} + g_j(precip_{it}) + \gamma_i + \delta_j \times t + \epsilon_{it} \]

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

GDP per capita at baseline (period 2005-2015)
Data for interpolation: Population Density
Data for interpolation and projection: Climate

(a) # days/year Tavg below 0°C in 1986-2005

(b) # days/year Tavg below 0°C in 2080-2099

(c) # days/year Tavg above 28°C in 1986-2005

(d) # days/year Tavg above 28°C in 2080-2099
Measuring adaptation cost with revealed preferences

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

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

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

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

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

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

\[
\implies -T_0 \frac{\partial \beta}{\partial \bar{T}} < C < -T_1 \frac{\partial \beta}{\partial \bar{T}}
\]