Tipping points in the climate system and the economics of climate change

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Disclaimer: This research does not necessarily represent the views of the European Commission. All views are our own.

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Tipping points in the climate system are one of the principal reasons for concern about climate change (e.g. IPCC AR5).

In spite of this, leading economic estimates of the cost of climate change EITHER ignore these tipping points OR represent them in a highly simplified way that is impossible to calibrate.

But all is not lost: an emerging literature incorporates individual tipping points in IAMs (e.g. Nordhaus on the GIS in PNAS, 2019).

Our aim is to bring this literature closer to incorporation in leading economic estimates of climate costs, by

- Reviewing and synthesising this literature
- Building a meta/structural model capable of incorporating all the tipping points studied so far and estimating the overall contribution to the social cost of carbon.
TPs covered in this study collectively increase the social cost of carbon (SC-CO\textsubscript{2}) by 28\% in our main specification.

A so-far incomplete sensitivity analysis indicates the corresponding range is 2-71\%.

Main contributors are the methane feedbacks, i.e. permafrost melting (+10.6\%) and dissociation of ocean methane hydrates (+9.4\%).
What do you mean by tipping points in the climate system?

Source: Lenton et al. 2008 PNAS.
## Models synthesised in this study

<table>
<thead>
<tr>
<th>Tipping point</th>
<th>Papers</th>
<th>IAM</th>
<th>Model of TP</th>
<th>Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>OMH</td>
<td>Ceronsky et al. (2011, unpublished)</td>
<td>FUND</td>
<td>Tipping event</td>
<td>Deterministic &amp; MC</td>
</tr>
<tr>
<td></td>
<td>Whiteman et al. (2013, <em>Nature</em>)</td>
<td>PAGE09</td>
<td>Tipping event</td>
<td>MC</td>
</tr>
<tr>
<td>GIS disintegration</td>
<td>Nordhaus (2019, <em>PNAS</em>)</td>
<td>DICE</td>
<td>Process-based</td>
<td>Deterministic</td>
</tr>
<tr>
<td>WAIS disintegration</td>
<td>Diaz and Keller (2016, <em>AER P&amp;P</em>)</td>
<td>DICE</td>
<td>Tipping event</td>
<td>Survival analysis</td>
</tr>
<tr>
<td>AMOC slowdown</td>
<td>Anthoff et al. (2016, <em>AER P&amp;P</em>)</td>
<td>FUND</td>
<td>Tipping event</td>
<td>Deterministic</td>
</tr>
</tbody>
</table>
Can’t you just pull numbers from these papers?

Papers use different boundary conditions (e.g. emissions), model structures, make divergent choices on common parameters (e.g. discount rate) and even report different welfare metrics (this last one is avoidable!) + TPs interact
A meta/structural economic model of climate change including tipping points

We replicate the TP modules in each of these papers

Then we build a meta/structural model of emissions \(\rightarrow\) temperatures \(\rightarrow\) damages that can accommodate all of the replica TP modules in a consistent framework

General features of the structural model:

- 4 x RCP-SSP emissions scenarios
- Climate dynamics that conform with current climate science
- Damages from climate econometrics lit.

Features of the structural model informed by tipping points:

- PCF and OMH \(\Rightarrow\) explicit methane cycle
- GIS and WAIS \(\Rightarrow\) explicit SLR damages
- AMOC and ISM \(\Rightarrow\) national-level damages for c. 180 countries
Climate model

Global mean surface temperature

\[ F(t) = F_{\text{CO}_2}(t) + F_{\text{CH}_4}(t) + F_{\text{EX}}(t) \]

Total radiative forcing

\[ F_{\text{CO}_2}(t) \] Radiative forcing from CO$_2$

\[ F_{\text{CH}_4}(t) \] Radiative forcing from CH$_4$

\[ F_{\text{EX}}(t) \] Exogenous radiative forcing

2 box warming model

\[ \Delta T_{AT}(t) \] Global mean surface temperature

Carbon dioxide

\[ \text{CO}_2_{\text{EX}}(t) \]
RCP-SSP database

FAIR carbon cycle & log forcing

\[ F_{\text{CO}_2}(t) \]
Radiative forcing from CO$_2$

Methane

\[ \text{CH}_4_{\text{EX}}(t) \]
RCP-SSP database

1 box CH$_4$ cycle & v forcing with N$_2$O dependence

\[ F_{\text{CH}_4}(t) \]
Radiative forcing from CH$_4$

Other GHGs and forcing agents

\[ F_{\text{EX}}(t) \]
Exogenous radiative forcing

FAIR carbon cycle & log forcing
Climate model including carbon-cycle feedbacks

\[ \Delta T_{AT}(t) \]

Global mean surface temperature

Amazon rainforest dieback

Permafrost carbon feedback

Dissociation of ocean methane hydrates

\[ F(t) = F_{CO2}(t) + F_{CH4}(t) + F_{EX}(t) \]

Total radiative forcing

\[ F_{CO2}(t) \]
Radiative forcing from CO\(_2\)

\[ F_{CH4}(t) \]
Radiative forcing from CH\(_4\)

\[ F_{EX}(t) \]
Exogenous radiative forcing

\[ \Sigma CO_2(t) = CO_{2\,EX}(t) + CO_{2\,PF}(t) + CO_{2\,AMAZ}(t) \]
FAIR carbon cycle and log forcing

\[ \Sigma CH_4(t) = CH_{4\,EX}(t) + CH_{4\,PF}(t) + CH_{4\,OMH}(t) \]
1 box CH\(_4\) cycle and forcing with N\(_2\)O dependence

\[ CO_{2\,EX}(t) \]
RCP-SSP database

\[ CH_{4\,EX}(t) \]
RCP-SSP database

2 box warming model
Temperature and SLR damages

Temperature damages channel

\( \lambda(i,t) \)
Statistical downscaling

\( T_{AT}(i,t) \)
National mean surface temperature

Country-specific temperature damages
(Burke et al.)

\( D_{TEMP}(i,t) = \beta_1 T_{AT}(i,t) - \beta_2 T_{AT}(i,t)^2 \)
National temperature damages

SLR damages channel

\( \Delta T_{AT}(t) \)
Global mean surface temperature

Thermal expansion & melting of small ice caps & glaciers

SLR damages and coastal exposure by country

\( D_{SLR}(i,t) = \theta \mu(i) \sum \SigmaLR(t) \)
National SLR damages

Dietz, Rising, Stoerk, Wagner
Tipping points in the climate system and the economics of climate change
Temperature and SLR damages, income and welfare

Temperature damages channel

- $\lambda(i,t)$: Statistical downscaling
- $T_{AT}(i,t)$: National mean surface temperature
- $D_{TEMP}(i,t) = \beta_1 T_{AT}(i,t) - \beta_2 T_{AT}(i,t)^2$: National temperature damages
- $g_{EX}(i,t)$: Exogenous growth from RCP-SSP database
- Exogenous population from RCP-SSP database

SLR damages channel

- $\Delta T_{AT}(t)$: Global mean surface temperature
- Thermal expansion & melting of small ice caps & glaciers
- $SLR_{THERM}(t)$: Sea level rise
- $D_{SLR}(i,t) = \theta \mu(i) \sum SLR(t)$: National SLR damages

Utility and social welfare functions

- $c(i,t) = \left[1 - s(i)\right][\bar{y}(i,t - 1)\left[1 + g_{EX}(i,t) + D_{TEMP}(i,t)\right]\left[1 - D_{SLR}(i,t)\right]]$: National consumption per capita
- $W = (1 + \rho)^{-t} u(i,t)L(i,t)$: Discounted welfare

Country-specific temperature damages

(Burke et al.)

$D_{TEMP}(i,t) = \beta_1 T_{AT}(i,t) - \beta_2 T_{AT}(i,t)^2$
Plus ice-sheet disintegration and changes in large-scale circulation

Global mean surface temperature

\[ \Delta T_{AT}(t) \]

Statistical downscaling

\[ \lambda(i,t) \]

AMOC slowdown

\[ T_{AT}(i,t) \]

National mean surface temperature

Country-specific temperature damages
(Burke et al.)

\[ D_{TEMP}(i,t) = \beta_1 T_{AT}(i,t) - \beta_2 T_{AT}(i,t)^2 \]

National temperature damages

Exogenous growth from RCP-SSP database

\[ g_{EX}(i,t) \]

Exogenous population from RCP-SSP database

Exponential growth rate

\[ s(i) \]

Thermal expansion & melting of small ice caps & glaciers

GIS disintegration

WAIS disintegration

Total sea level rise

\[ \Sigma SLR(t) = SLR_{THERM}(t) + SLR_{GIS}(t) + SLR_{WAIS}(t) \]

SLR damages and coastal exposure by country

\[ D_{SLR}(i,t) = \theta \mu(i) \Sigma SLR(t) \]

National SLR damages

ISM variability

Utility and social welfare functions

\[ W = (1 + \rho)^{-t} u(i,t)L(i,t) \]

Discounted welfare

In India only

\[ y(IND, t) = \hat{y}(IND, t)[1 - D_{ISM}(IND, t)] \]

\[ D_{ISM}(IND, t) = f[P(t)] \]
### Results: main specification

<table>
<thead>
<tr>
<th>TP</th>
<th>SC-CO₂ (USD/tCO₂)</th>
<th>% increase due to TP</th>
</tr>
</thead>
<tbody>
<tr>
<td>None</td>
<td>49.07</td>
<td>-</td>
</tr>
<tr>
<td>PCF</td>
<td>54.28</td>
<td>10.6</td>
</tr>
<tr>
<td>OMH</td>
<td>53.68</td>
<td>9.4</td>
</tr>
<tr>
<td>Amazon</td>
<td>49.47</td>
<td>0.8</td>
</tr>
<tr>
<td>GIS</td>
<td>49.69</td>
<td>1.3</td>
</tr>
<tr>
<td>WAIS</td>
<td>49.32</td>
<td>0.5</td>
</tr>
<tr>
<td>AMOC</td>
<td>48.33</td>
<td>-1.5</td>
</tr>
<tr>
<td>ISM</td>
<td>49.89</td>
<td>1.7</td>
</tr>
<tr>
<td>All</td>
<td>62.98</td>
<td>28.3</td>
</tr>
</tbody>
</table>

\[ \sum \text{‘main effects’} = 22.7 \]

*Note:* RCP4.5/SSP2; Kessler main PCF; Whiteman et al. main OMH; IPSL AMOC hosing
### Different PCF scenarios

<table>
<thead>
<tr>
<th>PCF scenario</th>
<th>W/o PCF</th>
<th>With PCF</th>
<th>% increase</th>
</tr>
</thead>
<tbody>
<tr>
<td>None</td>
<td>49.07</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Kessler (main)</td>
<td>-</td>
<td>54.28</td>
<td>10.6</td>
</tr>
<tr>
<td>Hope and Schaefer</td>
<td>-</td>
<td>52.63</td>
<td>7.2</td>
</tr>
<tr>
<td>Yumashev et al.</td>
<td>-</td>
<td>51.71</td>
<td>5.4</td>
</tr>
<tr>
<td><strong>Average</strong></td>
<td>-</td>
<td>52.87</td>
<td>7.8</td>
</tr>
<tr>
<td>Kessler 2.5%</td>
<td>-</td>
<td>53.18</td>
<td>8.4</td>
</tr>
<tr>
<td>Kessler 97.5%</td>
<td>-</td>
<td>56.95</td>
<td>16.1</td>
</tr>
</tbody>
</table>

*Note: RCP4.5/SSP2*
## Different OMH scenarios

<table>
<thead>
<tr>
<th>OMH scenario</th>
<th>W/o OMH</th>
<th>With OMH</th>
<th>% increase</th>
</tr>
</thead>
<tbody>
<tr>
<td>None</td>
<td>49.07</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Whiteman et al.</td>
<td>-</td>
<td>53.68</td>
<td>9.4</td>
</tr>
<tr>
<td>Ceronsky et al. 0.2Gt/yr</td>
<td>-</td>
<td>50.14</td>
<td>2.2</td>
</tr>
<tr>
<td>Ceronsky et al. 1.8Gt/yr</td>
<td>-</td>
<td>56.54</td>
<td>15.2</td>
</tr>
<tr>
<td>Ceronsky et al. 7.8Gt/yr</td>
<td>-</td>
<td>74.53</td>
<td>51.9</td>
</tr>
</tbody>
</table>

*Note: RCP4.5/SSP2*
### Different AMOC scenarios

<table>
<thead>
<tr>
<th>AMOC scenario</th>
<th>W/o PCF</th>
<th>With PCF</th>
<th>% increase</th>
</tr>
</thead>
<tbody>
<tr>
<td>None</td>
<td>49.07</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>HADCM 7%</td>
<td>-</td>
<td>48.51</td>
<td>-0.6</td>
</tr>
<tr>
<td>BCM 24%</td>
<td>-</td>
<td>48.77</td>
<td>-0.6</td>
</tr>
<tr>
<td>IPSL 27%</td>
<td>-</td>
<td>48.33</td>
<td>-1.5</td>
</tr>
<tr>
<td>Hadley 67%</td>
<td>-</td>
<td>46.14</td>
<td>-6.0</td>
</tr>
</tbody>
</table>

*Note: RCP4.5/SSP2*
## Sensitivity to emissions/socio-economic scenario

<table>
<thead>
<tr>
<th>RCP-SSP</th>
<th>W/o TPs</th>
<th>With all TPs</th>
<th>% increase</th>
</tr>
</thead>
<tbody>
<tr>
<td>RCP3-PD/2.6, SSP1</td>
<td>33.06</td>
<td>42.78</td>
<td>29.4</td>
</tr>
<tr>
<td>RCP4.5, SSP2</td>
<td>49.07</td>
<td>62.98</td>
<td>28.3</td>
</tr>
<tr>
<td>RCP6, SSP4</td>
<td>70.33</td>
<td>86.36</td>
<td>22.8</td>
</tr>
<tr>
<td>RCP8.5, SSP5</td>
<td>31.08</td>
<td>37.09</td>
<td>19.3</td>
</tr>
</tbody>
</table>

*Note: Kessler main PCF; Whiteman et al. main OMH; IPSL AMOC hosing*
Some further sensitivity analysis

<table>
<thead>
<tr>
<th>Sensitivity test</th>
<th>W/o TPs</th>
<th>With all TPs</th>
<th>% increase</th>
</tr>
</thead>
<tbody>
<tr>
<td>“Stern discounting”</td>
<td>83.08</td>
<td>109.23</td>
<td>31.5</td>
</tr>
<tr>
<td>“Nordhaus discounting”</td>
<td>38.95</td>
<td>49.55</td>
<td>27.2</td>
</tr>
<tr>
<td>Least sensitive climate</td>
<td>12.58</td>
<td>17.01</td>
<td>35.3</td>
</tr>
<tr>
<td>ACC2/GISS-E2-R</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Most sensitive climate</td>
<td>224.00</td>
<td>227.71</td>
<td>1.7</td>
</tr>
<tr>
<td>MESMO/HadGEM2-ES</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pure levels damages</td>
<td>25.13</td>
<td>32.41</td>
<td>28.9</td>
</tr>
<tr>
<td>Pure growth damages</td>
<td>2059.81</td>
<td>3513.08</td>
<td>70.6</td>
</tr>
</tbody>
</table>

Note: RCP4.5/SSP2; Kessler main PCF; Whiteman et al. main OMH; IPSL AMOC hosing
Conclusions

We built a meta/structural model to integrate different climate TPs, in order to estimate the overall effect on the SC-CO$_2$

Our central estimate so far is a 28% increase in the SC-CO$_2$, within a range of 2-71% (this is an incomplete estimate of the uncertainty)

- The largest contributions to the SC-CO$_2$ come from the PCF and OMH dissociation; the former seems much better constrained than the latter
- GIS and WAIS have small positive effect on SC-CO$_2$
- AMOC slowdown reduces the SC-CO$_2$
- ISM effect is large enough to register in global SC-CO$_2$
Our to-do list

Short to medium run
- Add Arctic sea-ice loss (surface albedo feedback)
- Maximally comprehensive sensitivity analysis
- Stochastic optimization of emissions

 Longer run
- Improve TP modules for e.g. OMH
- Integrate new TPs, e.g. Boreal Forest Dieback, ENSO, West African Monsoon
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Comments, suggestions, critiques:

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Where do emissions and growth rates come from?

Source: Carbon Brief.

Dietz, Rising, Stoerk, Wagner
Where do emissions and growth rates come from?

Where do emissions and growth rates come from?

Source: Carbon Brief.

Global population

Global GDP

Source: Carbon Brief.
\[ y(i, t) = \bar{y}(i, t - 1) \left[ 1 + g_{EX}(i, t) + D_{TEMP}(i, t) \right] \left[ 1 - D_{SLR}(i, t) \right], \]

where

\[ \bar{y}(i, t - 1) = \left[ \varphi y_{EX}(i, t - 1) + (1 - \varphi) y(i, t - 1) \right] \]

Two different interpretations of the empirical evidence on temperature damages.

1. \( (\varphi = 1) \) Temperatures impact the level of income in each year. The production possibilities frontier is assumed to evolve exogenously.

2. \( (\varphi = 0) \) Temperatures impact the growth rate of income by directly impacting the accumulation of factors of production and/or by impacting productivity growth.