Virtual Seminar on Climate Economics
Federal Reserve Bank of San Francisco

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Are economists getting climate dynamics right and does it matter?

Simon Dietz\textsuperscript{1,2}, Frederick van der Ploeg\textsuperscript{2,3,4}, Armon Rezai\textsuperscript{2,5} and Frank Venmans\textsuperscript{6,1}


30 July 2020
Section 1

Motivation/background
Economists’ models of climate change, a.k.a. integrated assessment models (IAMs)

This talk is about IAMs built by economists for cost-benefit analysis of climate change:

- Quantitative IAMs, e.g. **Nordhaus’ DICE model**, FUND (Anthoff & Tol) and PAGE (Hope)
- Analytical IAMs, e.g. **Golosov et al. (2014 in ECTA)**, Lemoine and Rudik (2017 in AER), Gerlagh and Liski (2018 in JEEA)

The term IAM is also used to describe other models that this paper is not concerned with, e.g.:

- Models of the energy system used to study how to meet exogenous/pre-determined carbon budgets
- Agricultural/land-use models used to study greenhouse gas emissions and climate impacts in that sector
Anatomy of a cost-benefit IAM

Consumption & welfare

Saving

Capital

Production/output

Emissions abatement

CO₂ emissions & removal

Atmospheric CO₂ concentration

Radiative forcing & heat exchange

Atmospheric temperature

Damages
The climate module within a cost-benefit IAM

Consumption & welfare

Saving → Capital

Production/output → Emissions abatement

Climate module

Carbon cycle model

CO₂ emissions & removal

Atmospheric CO₂ concentration

Warming model

Radiative forcing & heat exchange

Atmospheric temperature

Damages
Economists’ climate models in relation to climate scientists’ climate models

Economist’s climate module (DICE, left); general circulation model from climate science (schematic; right)
Parallel development of these models creates the potential for divergence.
Are economists getting climate dynamics right? No

We test the climate modules of a representative sample of IAMs against a large sample of climate science models and find:

- Almost all IAMs respond much too slowly to a CO$_2$ emission impulse
- Almost all IAMs imply removal of atmospheric CO$_2$ rises with atmospheric CO$_2$, whilst climate science models suggest it falls due to positive feedbacks
Does it matter? Yes:
- A sluggish temperature response to CO$_2$ emissions leads to carbon prices that are too low and too sensitive to the choice of discount rate
- Failing to account for positive feedbacks in the carbon cycle leads to carbon prices that are too low, especially when atmospheric CO$_2$ is high

Does it matter more than anything else? No:
- Other things matter too (e.g. damages and discounting)
- But climate dynamics are easy to fix and we make some suggestions as to how
Section 2

Two key tests of climate dynamics
Test 1: the temperature response to a CO$_2$ emission impulse

256 climate models from CMIP5
The step response of temperature to a CO$_2$ emission impulse

“it is a widely held misconception that the main effects of a CO$_2$ emission will not be felt for several decades” (Ricke and Caldeira, 2014, p1)
Test 1: the temperature response to a CO$_2$ emission impulse

256 climate models from CMIP5
Test 1: the temperature response to a CO$_2$ emission impulse

256 climate models from CMIP5 and six economic models
Test 2: Yearly uptake of CO$_2$ by carbon sinks as a function of atmospheric CO$_2$

FAIR model (best fit of CMIP5 ensemble plus calibrated feedback)
Why positive feedbacks in the carbon cycle produce this decreasing relationship

The amount of dissolved gas in a liquid is proportional to its partial pressure above the liquid.
Test 2: Yearly uptake of CO$_2$ by carbon sinks as a function of atmospheric CO$_2$

FAIR model (best fit of CMIP5 ensemble plus calibrated feedback)
Test 2: Yearly uptake of CO$_2$ by carbon sinks as a function of atmospheric CO$_2$

**FAIR model and six economic models**

![Graph showing yearly emissions absorbed by sinks as a function of CO2 in atmosphere (ppm)](image)

- FAIR
- DICE16
- FUND
- PAGE
- GHKT14
- GL18
- LR17

SD, RvdP, ARez, FVen

Are economists getting climate dynamics right and does it matter?
Section 3

Models of the carbon cycle and temperature dynamics
Decomposing the temperature impulse response to a CO\textsubscript{2} emission

Simple carbon cycle models partition the system into reservoirs/boxes, between which carbon is exchanged (e.g. atmosphere, upper ocean, deep ocean)

Similarly, simple warming models partition the system into boxes, between which heat is exchanged (e.g. atmosphere/upper ocean, deep ocean)

We use spectral decomposition to translate these models into impulse response functions with a common structure

Start by writing the overall temperature impulse response to a CO\textsubscript{2} emission:

\[
\frac{\Delta T_t}{\Delta E_1} = \sum_{s=1}^{t} \frac{\Delta T_t}{\Delta F_s} \frac{\Delta F_s}{\Delta M_s} \frac{\Delta M_s}{\Delta E_1}
\]
Decomposing the temperature impulse response to a CO$_2$ emission

The carbon cycle model determines the CO$_2$ concentration impulse response,

$$\frac{\Delta M_t}{\Delta E_1} = \sum_{j=1}^{n} \psi_j \lambda_j^{t-1} = \psi_1 + \sum_{j=2}^{n} \psi_j \lambda_j^{t-1},$$

where $j = 1$ denotes the permanent box. The warming model determines the temperature impulse response to forcing, which is

$$\frac{\Delta T_t}{\Delta F_s} = \sum_{s=1}^{t} \sum_{i=1}^{2} \psi_i^T \lambda_i^T t-s.$$
Decomposing the temperature impulse response to a CO₂ emission

Together with \( \frac{\Delta F_s}{\Delta M_s} = \frac{F_{2 \times CO_2}}{\ln 2} \frac{1}{M_s} \), which we harmonise across the models, these can be convoluted into the overall temperature impulse response to a CO₂ emission:

\[
\frac{\Delta T_t}{\Delta E_1} = \frac{F_{2 \times CO_2}}{\ln 2} \sum_{s=1}^{t} \sum_{i=1}^{2} \psi_i T \lambda_i^T t^{-s} \frac{1}{M_s} \left( \psi_1 + \sum_{j=2}^{n} \psi_j \lambda_j^s \right)
\]

n.b. carbon cycle feedbacks are modelled separately, in effect by introducing a dependency between \( \lambda_j \) and cumulative CO₂ uptake and temperature
CO$_2$ concentration impulse response, $\Delta M_t / \Delta E_1$

Best fit carbon cycle model
CO$_2$ concentration impulse response, $\Delta M_t/\Delta E_1$

Best fit carbon cycle model and six economic models
Dynamic temperature response to a constant increase in atmospheric CO$_2$, i.e. step increase in forcing $\Delta T(t)/\Delta F$

Best fit CMIP5 ensemble
Dynamic temperature response to a constant increase in atmospheric CO$_2$, i.e. step increase in forcing $\Delta T(t)/\Delta F$
Section 4

Economic policies with different climate models, a.k.a. does all this matter?
Making a controlled comparison of the effects of different climate modules

We couple the economic module of DICE 2016 to five different climate modules, including four climate modules from IAMs, and the benchmark climate science model

<table>
<thead>
<tr>
<th>Model</th>
<th>Description</th>
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<tbody>
<tr>
<td>DICE 2016</td>
<td>Standard DICE 2016 economy and climate</td>
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<td>DICE-GHKT14</td>
<td>DICE 2016 economy with the Golosov et al. (2014) climate module</td>
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<td>DICE-GL18</td>
<td>DICE 2016 economy with the Gerlagh and Liski (2018) climate module</td>
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<td>DICE-LR17</td>
<td>DICE 2016 economy with the Lemoine and Rudik (2017) climate module</td>
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<tr>
<td>DICE-FAIR-Geoffroy</td>
<td>DICE 2016 economy with the FAIR carbon cycle and the Geoffroy et al. (2013) warming model</td>
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</tbody>
</table>
Different climate modules result in a wide range of carbon prices
Welfare maximising CO₂ emissions

Consequently different climate modules yield a wide range of CO₂ emissions
Welfare maximising temperatures

Optimal warming in 2100 ranges from 2°C to 4°C

SD, RvdP, ARez, FVen Are economists getting climate dynamics right and does it matter? 32
Again, different climate modules result in a wide range of carbon prices, especially mid-century, before the backstop technology kicks in.
2°C cost-minimising carbon prices

The time at which ‘net zero’ needs to be achieved ranges from before 2050 to after 2100
Although warming is limited to $2^\circ$C, the temperature trajectory shows significant variation across the models, particularly in mid-century.
Isolating the effect of excessive delay on welfare-maximising paths

To isolate the effect of delay, we construct two artefact models, which have the same long-run temperature response to a CO₂ emission impulse, but reach it at very different speeds (5x and 10x delay)

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<tr>
<th></th>
<th>2020</th>
<th>2050</th>
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<tr>
<td>DICE-Joos-</td>
<td>26.97</td>
<td>66.53</td>
<td>197.61</td>
<td>36.76</td>
<td>44.23</td>
<td>25.28</td>
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<td>2.08</td>
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<td>Geoffroy</td>
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<td>Delay 56</td>
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<td>55.45</td>
<td>159.01</td>
<td>37.35</td>
<td>46.28</td>
<td>32.38</td>
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<td>Delay 112</td>
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<td>42.17</td>
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<td>38.19</td>
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<td>39.68</td>
<td>0.92</td>
<td>1.52</td>
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An implication of these results on excessive delay is that the optimal path is less sensitive to assumptions about the discount rate than previously thought.

<table>
<thead>
<tr>
<th>Model</th>
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<tr>
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<td>105.41</td>
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<td>156.41</td>
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<td>56.5</td>
<td>56.0</td>
<td>54.9</td>
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<td>51.3</td>
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Impact of positive carbon cycle feedback on welfare-maximising paths

We analyse how positive feedbacks in the carbon cycle affect optimal trajectories by comparing DICE-FAIR-Geoffroy (with feedbacks) and DICE-Joos-Geoffroy (without feedbacks).

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<td>(USD/tCO₂)</td>
<td>29.68</td>
<td>78.17</td>
<td>242.18</td>
<td>36.37</td>
<td>42.28</td>
<td>17.75</td>
<td>1.22</td>
<td>1.99</td>
<td>2.95</td>
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<tr>
<td>CO₂ emissions</td>
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<td>DICE-Joos-Geoffroy</td>
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Previous work with DICE 2016 found it is infeasible to limit warming to 2°C (Nordhaus, 2017). Our analysis suggests this is not the case if the climate system is appropriately responsive to CO₂ emissions.

<table>
<thead>
<tr>
<th>Model</th>
<th>Carbon- cycle feedback</th>
<th>Temp. model</th>
<th>Carbon price (USD/tCO₂)</th>
<th>CO₂ emissions (GtCO₂)</th>
<th>Warming (°C)</th>
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</thead>
<tbody>
<tr>
<td>DICE-FAIR- Geoffroy</td>
<td>Yes</td>
<td>Short delay</td>
<td>47.98 189.91 337.33</td>
<td>34.88 24.38 0.00</td>
<td>1.17 1.74 1.79</td>
</tr>
<tr>
<td>DICE 2016</td>
<td>No</td>
<td>Long delay + too hot later</td>
<td>142.95 460.68 356.31</td>
<td>26.05 -1.76 -2.71</td>
<td>1.00 1.67 2.00</td>
</tr>
</tbody>
</table>
Section 5

Discussion
Summary

Economic models respond too slowly to an impulse change in CO$_2$ emissions (except Golosov et al., 2014, by assumption)

- Most economic models remove CO$_2$ from the atmosphere too slowly initially
- Most economic models exhibit too much temperature inertia

Economic models also imply that the marginal removal of atmospheric CO$_2$ rises with atmospheric CO$_2$ (except for FUND), whilst climate science models suggest it falls

A sluggish temperature response to CO$_2$ emissions – excessive delay – leads to carbon prices that are too low and too sensitive to the choice of discount rate

Failing to account for positive feedbacks in the carbon cycle leads to carbon prices that are too low, especially when atmospheric CO$_2$ is high
Recommendations

Replace/revise the climate modules in economic models

- Models of the carbon cycle need to incorporate positive feedback effects, like FAIR/FUND do
- Models of temperature dynamics need to either be replaced or recalibrated so that they can reproduce the fast temperature response of climate science models to CO₂ emissions

This is doable. We provide code to do this in DICE, for example

For analytical models, where parsimony is key, an even simpler model where temperature is just a linear function of cumulative CO₂ emissions has been shown to suffice (provided future emissions are not too high)
Linear climate (IPCC AR5)
Are economists getting climate dynamics right and does it matter?

Simon Dietz\textsuperscript{1,2}, Frederick van der Ploeg\textsuperscript{2,3,4}, Armon Rezai\textsuperscript{2,5} and Frank Venmans\textsuperscript{6,1}


30 July 2020

Comments, suggestions, critiques:

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