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[1,2], Frederick van der Ploeg[2,3,4], Armon Rezai[2,5] and Frank Venmans[6,1]

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30 July 2020

Section 1

Motivation/background

Economists' models of climate change, a.k.a. integrated assessment models (IAMs)

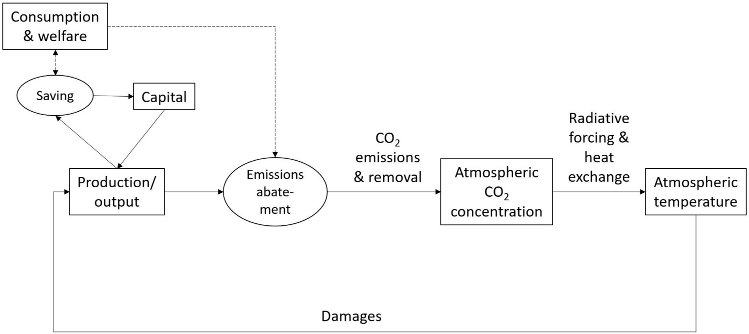
This talk is about IAMs built by economists for cost-benefit analysis of climate change:

- 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*)

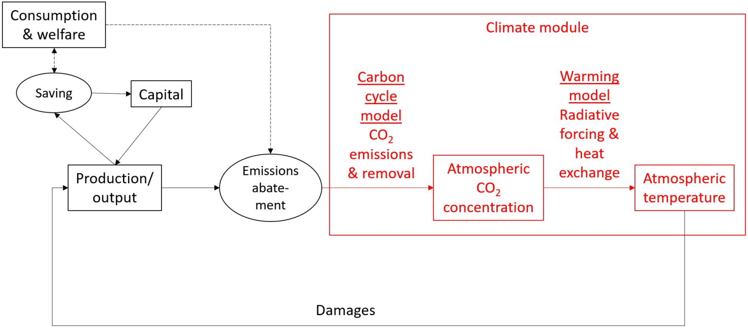
The term IAM is also used to describe other models that this paper is **not** concerned with, e.g.:

- 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



The climate module within a cost-benefit IAM



Economists' climate models in relation to climate scientists' climate models

Economist's climate module (DICE, left); general circulation model from climate science (schematic; right)

$$(A.12)\quad E(t) = E_{Ind}(t) + E_{Land}(t)$$

$$(A.13)\quad M_{AT}(t) = E(t) + \phi_{11} M_{AT}(t-1) + \phi_{21} M_{UP}(t-1)$$

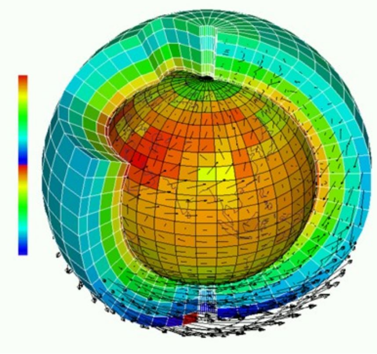
$$(A.14)\quad M_{UP}(t) = \phi_{12} M_{AT}(t-1) + \phi_{22} M_{UP}(t-1) + \phi_{32} M_{LO}(t-1)$$

$$(A.15)\quad M_{LO}(t) = \phi_{23} M_{UP}(t-1) + \phi_{33} M_{LO}(t-1)$$

$$(A.16)\quad F(t) = \eta\{log_2[M_{AT}(t)/M_{AT}(1750)]\} + F_{EX}(t)$$

$$(A.17)\quad T_{AT}(t) = T_{AT}(t-1) + \xi_1\{F(t) - \xi_2 T_{AT}(t-1) - \xi_3[T_{AT}(t-1) - T_{LO}(t-1)]\}$$

$$(A.18)\quad T_{LO}(t) = T_{LO}(t-1) + \xi_4\{T_{AT}(t-1) - T_{LO}(t-1)]\}$$



Parallel development of these models creates the potential for divergence

Image: Andy Beecroft

Preview of this paper

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

Preview of this paper

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:

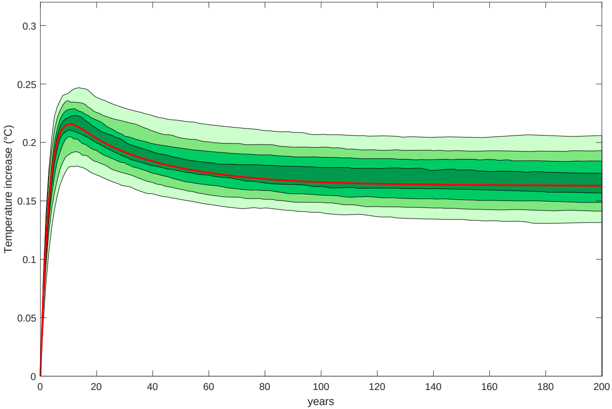
- Other things matter too (e.g. damages and discounting)
- But climate dynamics are easy to fix and we make some suggestions as to how

Section 2

Two key tests of climate dynamics

Test 1: the temperature response to a CO_2 emission impulse

256 climate models from CMIP5

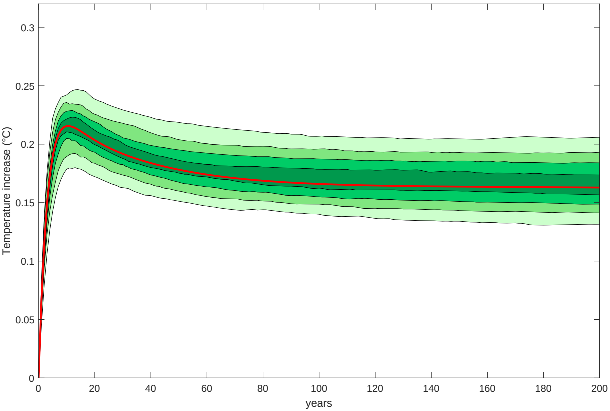


The step response of temperature to a CO_2 emission impulse

"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)

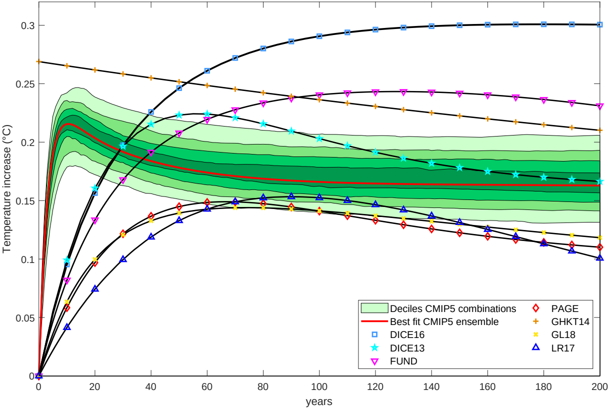
Test 1: the temperature response to a CO_2 emission impulse

256 climate models from CMIP5



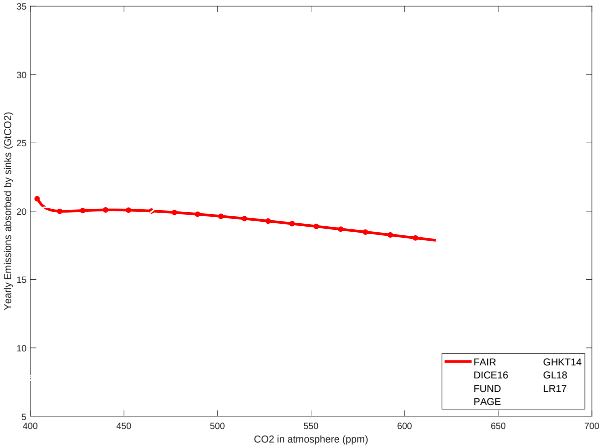
Test 1: the temperature response to a CO_2 emission impulse

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

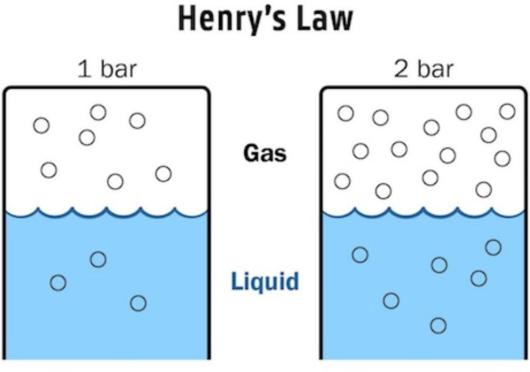


Image: rateyourdive.com

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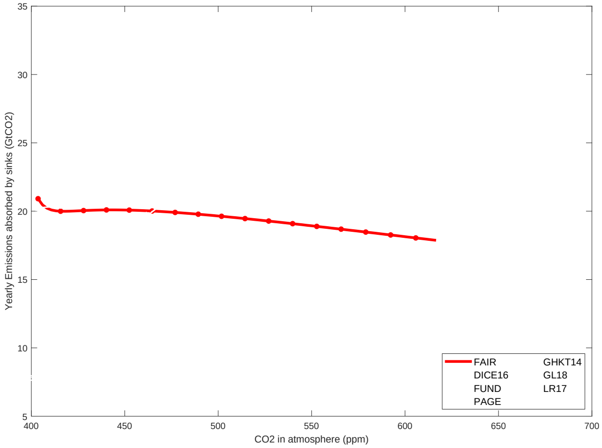
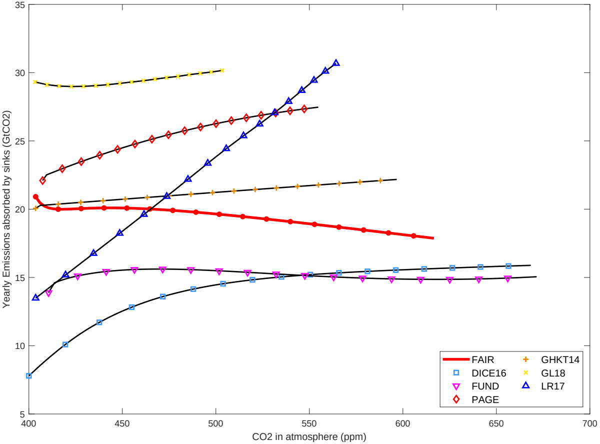


Test 2: Yearly uptake of CO_2 by carbon sinks as a function of atmospheric CO_2

FAIR model and six economic models



Section 3

Models of the carbon cycle and temperature dynamics

Decomposing the temperature impulse response to a CO_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_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 CO_2 emission

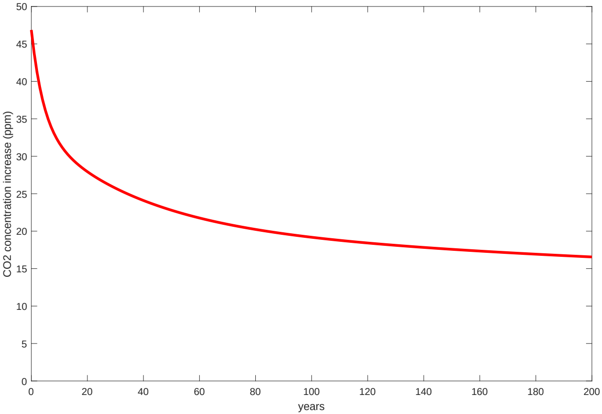
Together with $\Delta F_s / \Delta M_s = \frac{F_{2\times CO_2}}{\ln 2} \frac{1}{M_s}$, which we harmonise across the models, these can be convoluted into the overall temperature impulse response to a CO_2 emission:

$$\frac{\Delta T_t}{\Delta E_1} = \frac{F_{2\mathrm{xCO}_2}}{\ln 2} \sum_{s=1}^{t} \sum_{i=1}^{2} \psi_i^T \lambda_i^{T\ t-s} \frac{1}{M_s} \left(\psi_1 + \sum_{j=2}^{n} \psi_j \lambda_j^s \right)$$

n.b. carbon cycle feedbacks are modelled separately, in effect by introducing a dependency between λ_j and cumulative CO_2 uptake and temperature

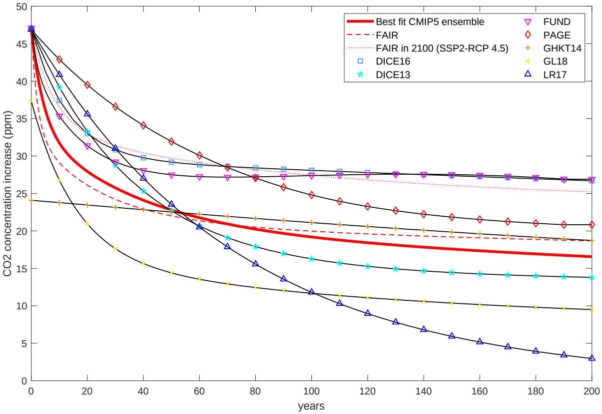
CO_2 concentration impulse response, $\Delta M_t / \Delta E_1$

Best fit carbon cycle model



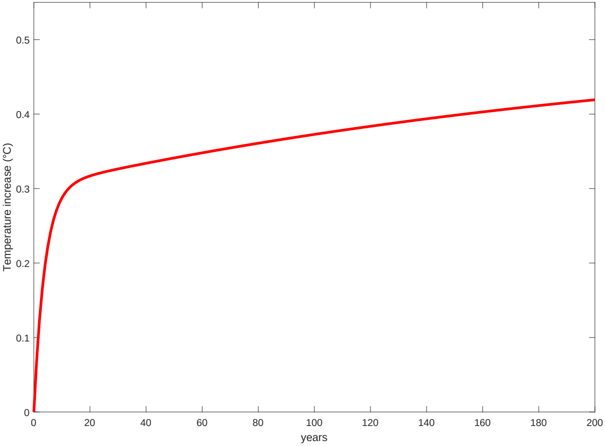
CO_2 concentration impulse response, $\Delta M_t / \Delta E_1$

Best fit carbon cycle model and six economic models



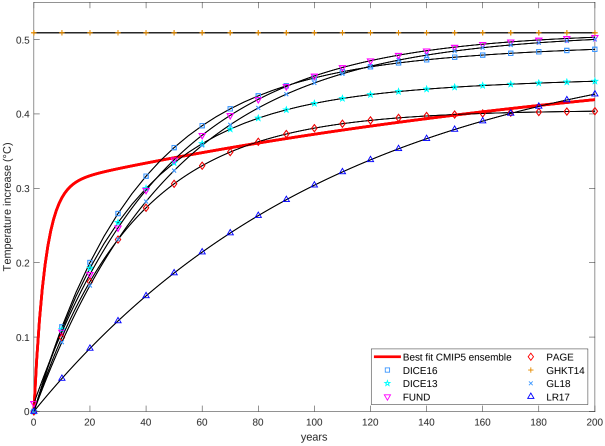
Dynamic temperature response to a constant increase in atmospheric CO_2, i.e. step increase in forcing $\Delta T(t)/\Delta F$

Best fit CMIP5 ensemble



Dynamic temperature response to a constant increase in atmospheric CO_2, i.e. step increase in forcing $\Delta T(t)/\Delta F$

Best fit CMIP5 ensemble and six economic models



Section 4

Economic policies with different climate models, a.k.a. does all this matter?

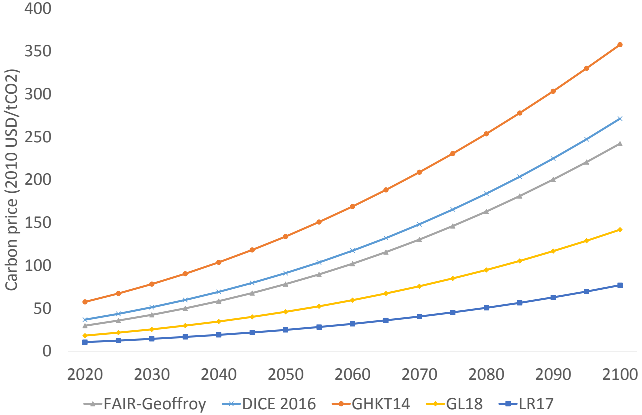
Making a controlled comparison of the effects of different climate modules

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

Model	Description
DICE 2016	Standard DICE 2016 economy and climate
DICE-GHKT14	DICE 2016 economy with the Golosov et al. (2014) climate module
DICE-GL18	DICE 2016 economy with the Gerlagh and Liski (2018) climate module
DICE-LR17	DICE 2016 economy with the Lemoine and Rudik (2017) climate module
DICE-FAIR-Geoffroy (best fit CMIP5 ensemble)	DICE 2016 economy with the FAIR carbon cycle and the Geoffroy et al. (2013) warming model

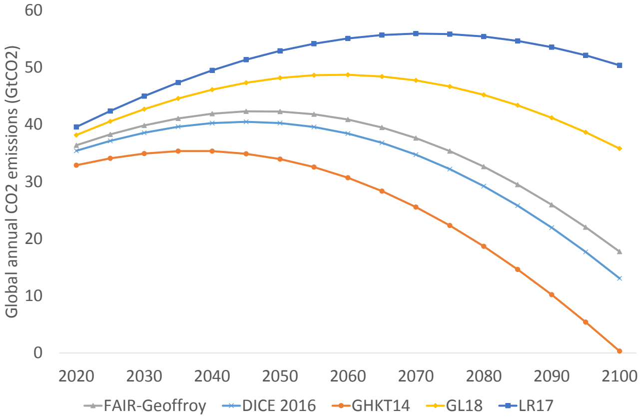
Welfare maximising carbon prices

Different climate modules result in a wide range of carbon prices



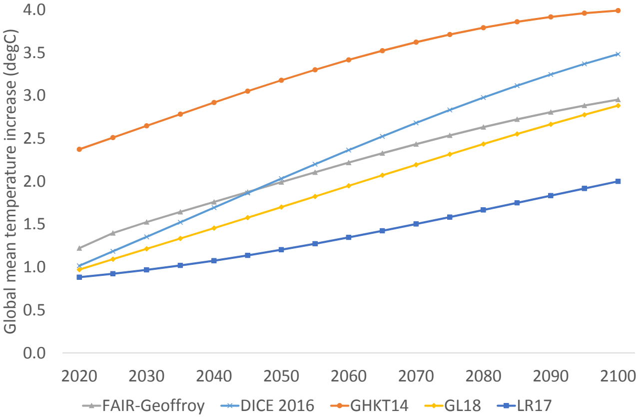
Welfare maximising CO_2 emissions

Consequently different climate modules yield a wide range of CO_2 emissions



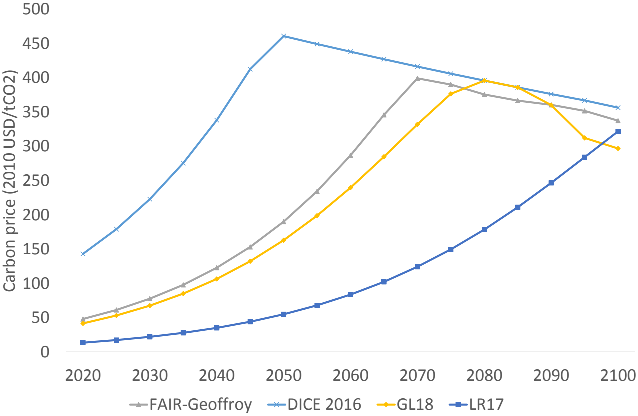
Welfare maximising temperatures

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



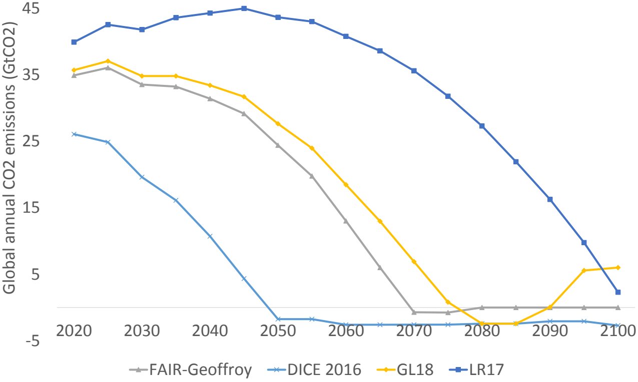
2°C cost-minimising carbon prices

Again, different climate modules result in a wide range of carbon prices, especially mid-century, before the backstop technology kicks in



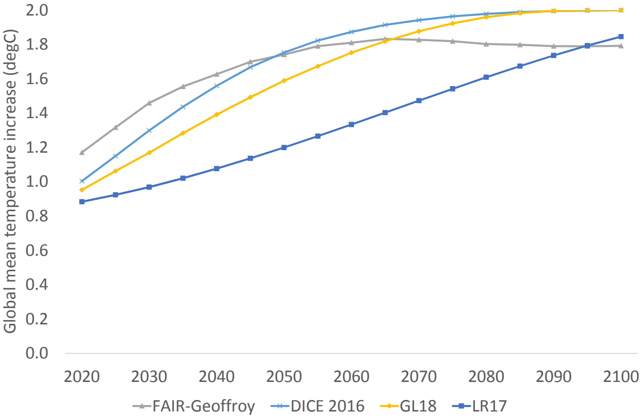
2°C cost-minimising carbon prices

The time at which 'net zero' needs to be achieved ranges from before 2050 to after 2100



2°C maximising temperatures

Although warming is limited to 2°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 CO_2 emission impulse, but reach it at very different speeds (5x and 10x delay)

	2020	2050	2100	2020	2050	2100	2020	2050	2100
	Carbon price (USD/tCO_2)			CO_2 emissions (GtCO_2)			Warming (°C)		
DICE-Joos-Geoffroy	26.97	66.53	197.61	36.76	44.23	25.28	1.25	2.08	3.01
Delay 56	23.02	55.45	159.01	37.35	46.28	32.38	0.98	1.81	2.93
Delay 112	17.88	42.17	122.98	38.19	48.91	39.68	0.92	1.52	2.67

Sensitivity of welfare-maximising carbon prices to the discount rate

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

Model	Discount	2020	2030	2040	2050	2060	2070	2080	2090	2100
DICE-Joos-Geoffroy	Standard	26.97	37.55	50.64	66.53	85.52	107.86	133.86	163.72	197.61
	Public	40.45	53.20	71.53	94.24	121.13	152.31	187.95	228.20	273.12
	% diff.	**50.0**	**41.7**	**41.3**	**41.6**	**41.6**	**41.2**	**40.4**	**39.4**	**38.2**
Delay 56	Standard	23.02	31.79	42.54	55.45	70.73	88.55	109.12	132.57	159.01
	Public	36.59	47.44	63.25	82.70	105.50	131.68	161.29	194.30	230.49
	% diff.	**59.0**	**49.2**	**48.7**	**49.1**	**49.2**	**48.7**	**47.8**	**46.6**	**44.9**
Delay 112	Standard	17.88	24.38	32.41	42.17	53.82	67.56	83.57	102.00	122.98
	Public	30.07	38.09	50.46	65.93	84.25	105.41	129.46	156.41	186.10
	% diff.	**68.2**	**56.3**	**55.7**	**56.4**	**56.5**	**56.0**	**54.9**	**53.3**	**51.3**

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)

	2020	2050	2100	2020	2050	2100	2020	2050	2100
Model	Carbon price (USD/tCO_2)			CO_2 emissions ($GtCO_2$)			Warming ($^\circ C$)		
DICE-FAIR-Geoffroy	29.68	78.17	242.18	36.37	42.28	17.75	1.22	1.99	2.95
DICE-Joos-Geoffroy	26.97	66.53	197.61	36.76	44.23	25.28	1.25	2.08	3.01

Can we stay under 2°C in DICE?

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 CO_2 emissions

			2020	2050	2100	2020	2050	2100	2020	2050	2100
Model	Carbon-cycle feedback	Temp. model	Carbon price (USD/tCO_2)			CO_2 emissions (GtCO_2)			Warming (°C)		
DICE-FAIR-Geoffroy	Yes	Short delay	47.98	189.91	337.33	34.88	24.38	0.00	1.17	1.74	1.79
DICE 2016	No	Long delay + too hot later	142.95	460.68	356.31	26.05	-1.76	-2.71	1.00	1.67	2.00

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

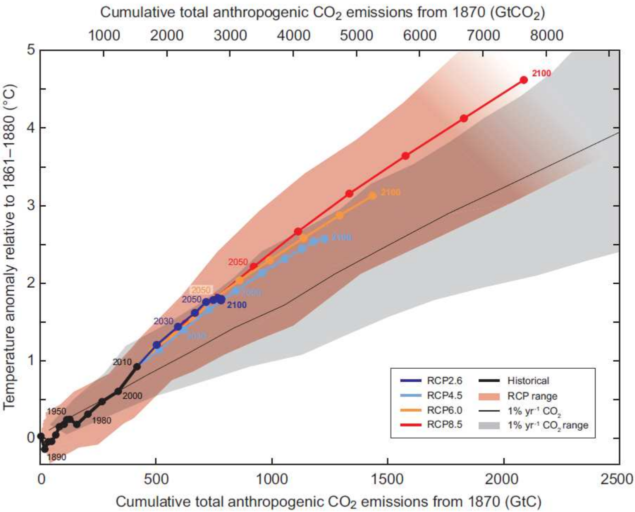
Replace/revise the climate modules in economic models

- 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 CO_2 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 CO_2 emissions has been shown to suffice (provided future emissions are not too high)

Linear climate (IPCC AR5)



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Comments, suggestions, critiques:

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