Are Economists Getting Climate Dynamics Right?

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The models are getting it wrong

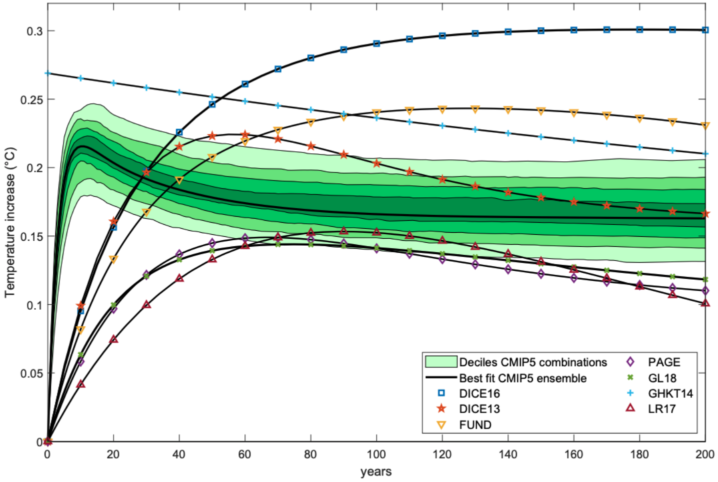
In this paper Dietz et. al. claim climate dynamics aren't accurately modelled in economics papers. Economists are getting predictions wrong in two major ways:

1. They underestimate how quickly temperatures will rise as a result of an emissions impulse;
2. They don't correctly model the saturation of carbon sinks

Temperature Response Experiment

- Performed an experiment exposing climate models from DICE16, DICE13, FUND, PAGE, GL18, GHKT14, and LR17 to a 100 GtC (367 $GtCO_2$) emissions impulse against a background CO_2 concentration of 389ppm
- Roughly equivalent to introducing 10 years of carbon emissions to the atmosphere from 2010
- Compared to an average model from an ensemble of 256 models from climate science (CMIP5)

Figure: Dynamic temperature responses of economics models and CMIP5



What's going on?

- CMIP5 resembles a step function quickly increasing and then flattening out
- All the economics models (besides GHKT14) increase temperatures much more slowly and don't stabilize as much
- Predictions diverge severely 2 centuries out

Why this is happening

- The change in temperature from an emission impulse is modelled by
$$\frac{\Delta T_t}{\Delta E_0} = \int_0^t \frac{\Delta T_t}{\Delta M_s} \frac{\Delta M_s}{\Delta E_0} ds$$
- In CMIP5, $\frac{\Delta T_t}{\Delta M_s}$ is slowly increasing and $\frac{\Delta M_s}{\Delta E_0}$ is slowly decreasing, which results in an initial gain in temperature followed by almost perfect offsetting
- Furthermore economics models end up reaching peak temperatures much later due to their incorrect models
  - 55, 68, 75, 92, 128, and 180 years out vs 10 years out in CMIP5

Implications

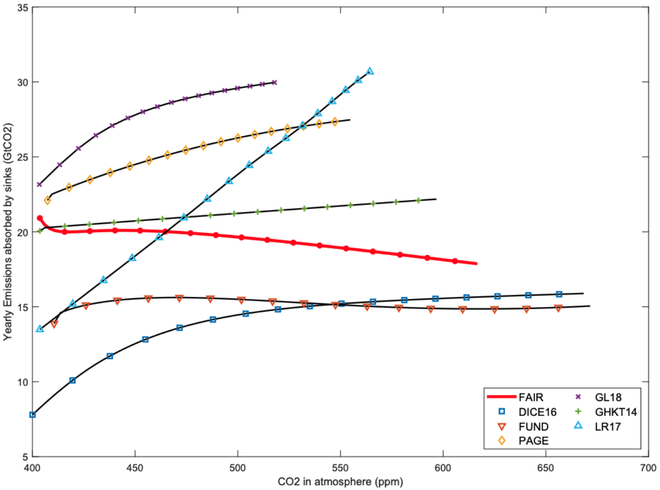
- Delayed temperature responses means costs of carbon that are incurred further into the future
- This results in undervaluation of costs an increased sensitivity to discount rates

We'll elaborate soon, now we'll talk about the other shortcoming

Undervaluation of Carbon Sink Saturation

- Carbon sinks get saturated as CO_2 concentrations increase
- Economics models don't capture this positive feedback in the carbon cycle which causes overly optimistic estimates of emissions removal
- To show this, Dietz et. al. performed the same experiment as before but looked at absorption of carbon into sinks
- They compared economics models to FAIR which is a model from climate science with decreasing marginal carbon absorption as concentrations of CO_2 increase

Figure: Emissions absorbed by sinks plotted against atmospheric CO_2



What's going on?

- FAIR has a negative slope indicating a decreasing marginal emissions uptake
- Economics models have largely linear emissions absorption which is far too optimistic when compared with FAIR
- None of the models except FUND have negative slope (FUND has a positive feedback mechanism)

Implications

- Overly optimistic emissions uptake results in underestimates of long-term CO_2 concentrations and inaccurate temperature responses
- This impacts welfare evaluations

Model considerations

There are 2 components in climate models to consider in comparisons:

1. Carbon cycle models
2. Temperature dynamics models

Linear Reservoir Carbon Cycles

- Most papers model carbon cycle as a diffusion model between reservoirs
- The reservoir concentrations are given by a linear equation:

$$\mathbf{m}_t = \mathbf{A}\mathbf{m}_{t-1} + \mathbf{b}E_t$$

- $\mathbf{m}_t$ is the vector of reservoir carbon stocks, E_t is the emissions during the period t and $\mathbf{A}$ is a matrix of diffusion coefficients
- Using spectral decomposition you can compute an impulse response that determines the aggregate carbon stock

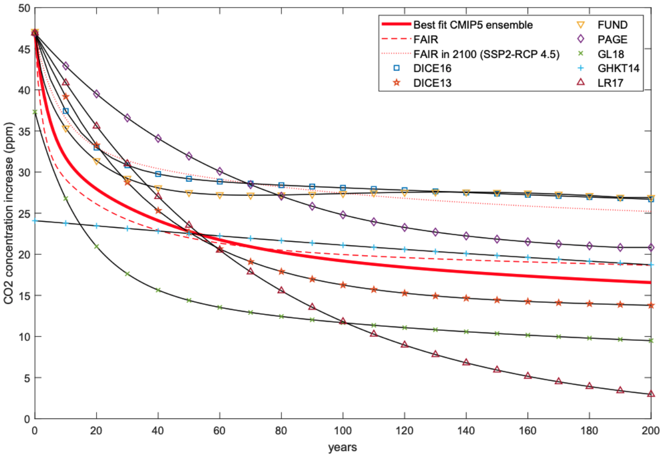
$$\frac{\Delta M_t}{\Delta E_1} = \psi_1 + \sum_{i=2}^{n} \psi_i \lambda_i^{t-1}$$

Table 1: Comparing key linear carbon cycle models

Model	Time step (years)	Box				
		1. Permanent	2. Temporary	3. Temporary	4. Temporary	5. Temporary
DICE 2016	5	22%	41%; 851 years	37%; 9 years		
FUND	1	13%	20%; 252 years	32%; 51 years	25%; 12 years	10%; 1.4 years
PAGE	varies	19%	43%; 73 years	38%; < 1 years		
GHKT14	10	20%	31%; 300 years	49%; < 10 years		
GL18	10	16%	18%; 91 years	44%; 11 years		
LR17	1		100%; 50 years			
Joos et al. (2013) / best fit CMIP5 ensemble	1	22%	22%; 277 years	28%; 25 years	28%; 3 years	

Key: the first figure in each cell is the fraction of emissions flowing into box i (ψ_i) and the second figure the time it takes for half of the carbon to have left box i ($\ln(0.5)/\lambda_i$ for Joos et al. (2013) and timestep $\times \ln(0.5)/\ln(\lambda_i)$ for the other models). Both FUND and PAGE include additional positive carbon cycle feedbacks that are not included in this table.

Figure: Emissions uptake as a result of removing a 100 GtC emissions impulse



What's going on?

- Economic models differ severely from the best fit model CMIP5, but FAIR is a good approximation
- To account for saturation, FAIR scales down carbon removal by a factor based on

$$\mathrm{iIRF}_{100} = r_{pi} + r_T T + r_C \left[\sum_{s=pi}^{t} E_s - (M_s - M_{pi}) \right]$$

  (r_{pi}, r_T, r_C are constants)
- Dietz does not elaborate on this, but the effect is replacing $\lambda_i \to \lambda_i / \alpha$ for some α based on iIRF_{100}

Temperature Models

- Most economic and climate models agree on a radiative forcing model that's linear in log emissions:

$$F_t = F_{j \times CO_2} \left(\log_j \frac{M_t}{M_{1750}} \right) + F_{\text{non}CO_2,t}$$

- Intercept ($F_{\text{non}CO_2,t}$) captures forcing by GHGs and other mechanisms that aren't CO_2
  - May be endogenous or exogenous (DICE is exogenous, FUND and PAGE are endogenous and model dynamics of other GHGs)
- Can be simplified into an expression that's similar to the one from carbon cycles:

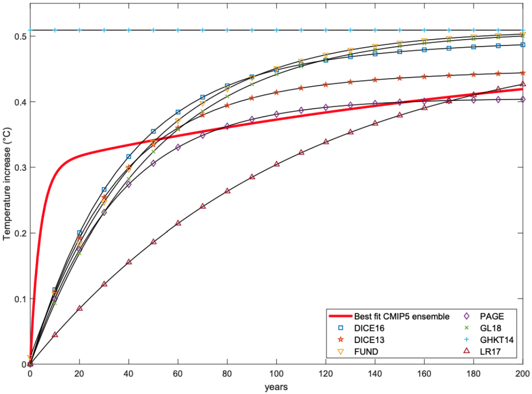
$$\Delta T_t = \sum_{s=1}^{t} \sum_{i=1}^{2} \psi_i^T (\lambda_i^T)^{t-s} \Delta F_s$$

Table 2: Comparing linear temperature-forcing responses

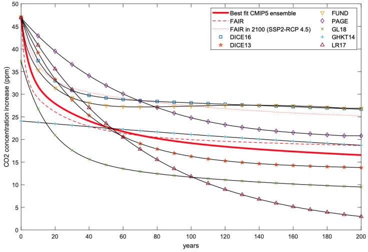
	Time step (years)	Box 1	Box 2
DICE 2016	5	9.9%; 25 years	0.2%; 150 years
FUND	1	100%; 31 years	
PAGE	varies	100%; 24 years	
GHKT14	10	n.a.	n.a.
GL18	10	100%; 34 years	
LR17	1	100%; 50 years	
Geoffroy et al. (2013) / best fit CMIP5 ensemble	1	13.5%; 3 years	0.2%; 167 years

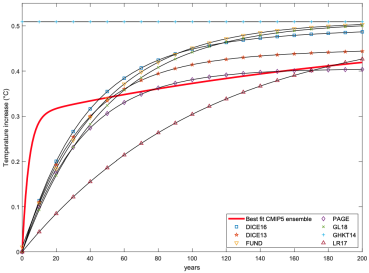
Key: The first figure in each cell is the weight of each mode and the second figure the half-life for each mode. PAGE models regional temperature and calculates global temperature as the area-weighted average.

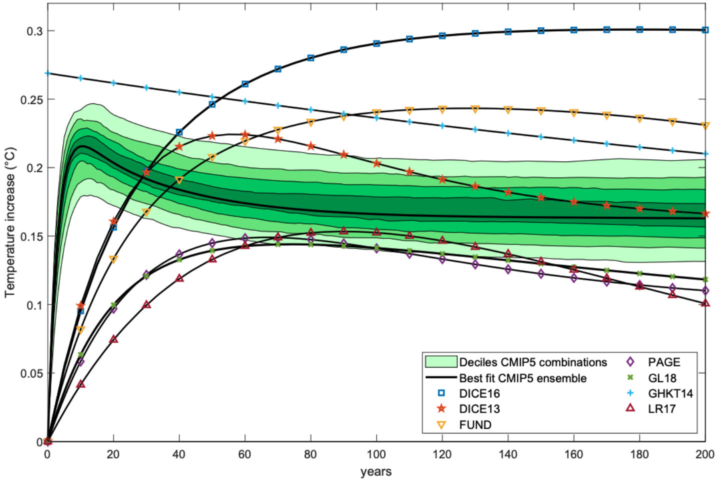
Figure: Dynamic temperature responses for different models



- Every model has a temperature response that's too delayed


Best fit CMIP5 ensemble
FAIR
FAIR in 2100 (SSP2-RCP 4.5)
DICE16
DICE13
FUND
PAGE
GL18
GHKT14
LR17
CO2 concentration increase (ppm)
years


Best fit CMIP5 ensemble
DICE16
DICE13
FUND
PAGE
GL18
GHKT14
LR17
Temperature increase (°C)
years


Temperature increase (°C)
0.3
0.25
0.2
0.15
0.1
0.05
0
0
20
40
60
80
100
120
140
160
180
200
years
Deciles CMIP5 combinations
Best fit CMIP5 ensemble
DICE16
DICE13
FUND
PAGE
GL18
GHKT14
LR17

Effect on Economic models

This analysis looks at the following.

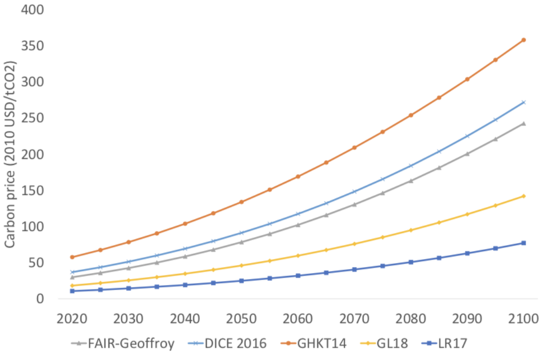
1. Optimal emissions (maximizing social welfare)
2. Limit warming to 2 degrees Celcius at minimum cost.

Table 3: List and description of models used for economic evaluation

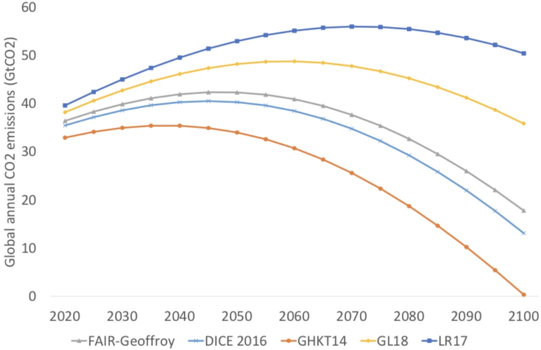
Model	Description
DICE 2016	Standard DICE 2016 economy and climate
DICE-GHKT14	DICE 2016 economy with the Golosov et al. (2014) climate model
DICE-GL18	DICE 2016 economy with the Gerlagh and Liski (2018) climate model
DICE-LR17	DICE 2016 economy with the Lemoine and Rudik (2017) climate model
DICE-FAIR-Geoffroy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

1. Economics parts of all the models are DICE.
2. Climate modules in DICE-FAIR-Geoffroy and DICE-Joos-Geoffroy represent recent climate science models.
3. Policies examined
    1. Optimal policies (maximizing social welfare)
    2. Efficiently limit warming to $2^o C$.

Figure: Welfare Maximizing Carbon Price (SCC)

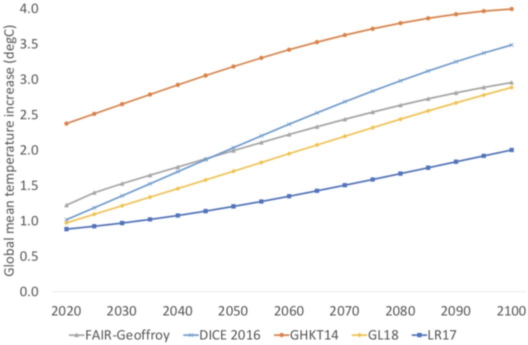


1. Science models are in the middle.
2. Initial welfare maximizing carbon price varies. \$57 in DICE-GHKT14, \$30 in DICE-FAIR-Geoffroy, \$11 in DICE-LR17. Unsurprisingly, the differences grow over time



Efficient carbon emissions.

Figure: Optimal Warming



1. Lowest optimal warming in 2100 is DICE-LR17, which has lowest carbon price and highest emissions. Why? Because it has slow temperature response when CO2 concentrations are high.
2. Warming is high in GHKT14 because it has no delay and exogenouus radiative forcing.

Figure: Carbon prices to limit warming to 2 degrees C.

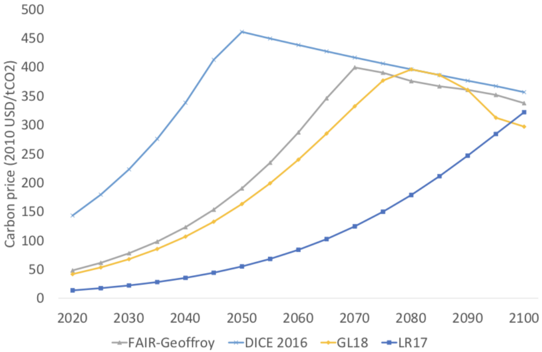


Figure: Achieving the $2^o C$ Constraint

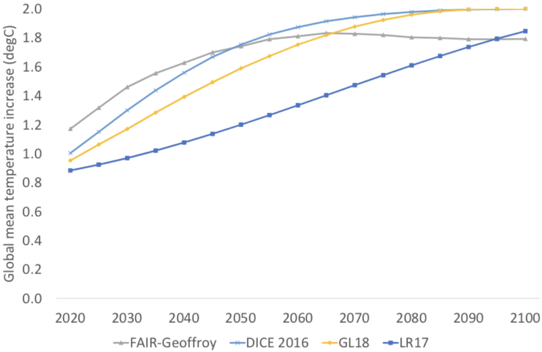
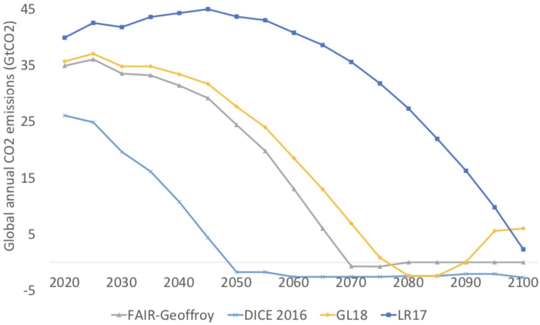


Figure: Emission Limites



1. Eventually, emissions have to become negative to achieve the 2^oC constraint.

Effects of Delayed Warming.

The longer the delay, the farther out in the future are the damages, which are **discounted**. Hence, delay will bias the SCC and optimal carbon taxes down.
There also seems to be a second-order effect from feedback or lack thereof.

	Model	Carbon-cycle feedback	Temp. model	Carbon price (USD/tCO_2) 2020	2050	2100	CO_2 emissions ($GtCO_2$) 2020	2050	2100	Warming (°C) 2020	2050	2100
1	DICE-FAIR-Geoffroy	Yes	Short delay	29.68	78.17	242.18	36.37	42.28	17.75	1.22	1.99	2.95
2	DICE-Joos-Geoffroy	No	Short delay	26.97	66.53	197.61	36.76	44.23	25.28	1.25	2.08	3.01
3	Delay 56	No	Long delay	23.02	55.45	159.01	37.35	46.28	32.38	0.98	1.81	2.93
4	Delay 112	No	Long delay	17.88	42.17	122.98	38.19	48.91	39.68	0.92	1.52	2.67
5	DICE 2016	No	Long delay + too hot later	36.72	91.04	271.34	35.40	40.25	13.07	1.02	2.03	3.48

Models for this analysis are DICE-Joos-Geoffroy. Models converge at different speeds to the same long-run temperature from an emissions impulse.

1. Delay 56: Peak warming is 56 years after the emission impulse.
2. Delay 112: Peak warming is 112 years after the emission impulse. Achieved by increasing the effective heat capacity of the ocean and decreasing the rate of CO2 removal.
3. DICE-FAIR-Geoffroy includes feedbacks (closest to science). DICE-Joos-Geoffry does not.
4. Long delay lowers carbon price.
5. Including the feedbacks raises carbon price.

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**

1. Examine optimal carbon tax sensitivity to the discount rate.
2. Rate of time preference: 1.5% (standard), 0.1% (public). Then combine with 2.5% per capita growth, discount rate becomes 5.1% (standard) and 3.5% (public).
3. Accounting faster reaction and feedbacks lowers the sensitivity. Why? Because costs are more heavily borne in the near term?