Are Economists Getting Climate Dynamics Right and Does It Matter ?

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Macro Reading Group

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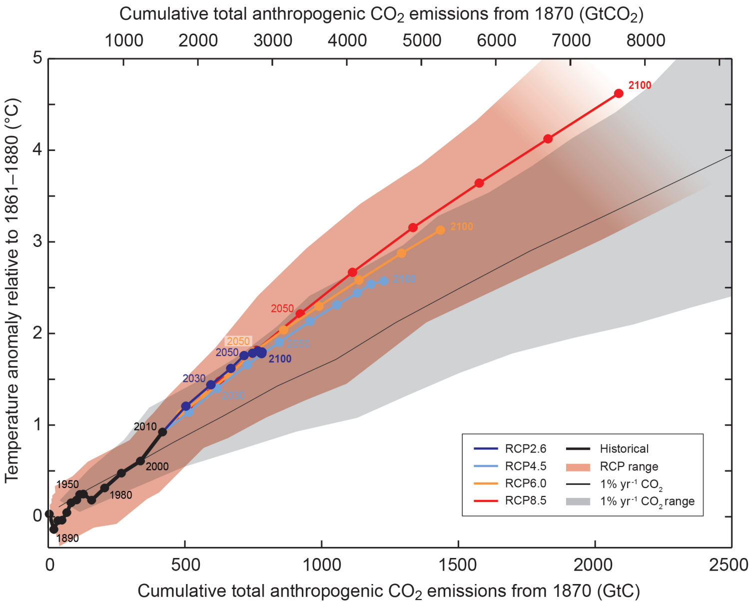
Cumulative total anthropogenic CO_2 emissions from 1870 ($GtCO_2$)
1000
2000
3000
4000
5000
6000
7000
8000
Temperature anomaly relative to 1861–1880 (°C)
0
1
2
3
4
5
0
500
1000
1500
2000
2500
Cumulative total anthropogenic CO_2 emissions from 1870 (GtC)
1890
1950
1980
2000
2010
2030
2050
2100
RCP2.6
RCP4.5
RCP6.0
RCP8.5
Historical
RCP range
1% yr^{-1} CO_2
1% yr^{-1} CO_2 range

Introduction

- This paper compares the climate dynamics predictions of two sets of models :
  - IAMs : Nordhaus' DICE-2016, GHKT 2014, FUND, PAGE, etc
  - Climate sciences models : IRF-MIP/CMIP5

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- What are the key differences in climate, carbon cycle response and temperature predictions
  - (i) delay between CO2 emissions and warming (too long for IAMs)
  - (ii) positive carbon cycle feedbacks are mostly absent (sink absorbs CO_2 too fast in IAMs)

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- What are the key differences in climate, carbon cycle response and temperature predictions
  - (i) delay between CO2 emissions and warming (too long for IAMs)
  - (ii) positive carbon cycle feedbacks are mostly absent (sink absorbs CO_2 too fast in IAMs)
- Are these differences important for policy decisions ?
  - Evaluation with damage function as in Nordhaus' DICE model
  - Implications for carbon price (welfare-maximizing vs. cost-minimizing)
  - Slow temperature response lowers the price of carbon & increases emissions !
  - Matters for the likelihood of staying under $2°C$

Climate dynamics in IAMs : two key differences

- Same experiment as last week (Ricke and Caldeira 2014)
  - Impulse of 100 GtC, with CO_2 concentration of 389 ppm (2010)
  - Temperature impulse response of 256 reduced forms climate sciences models :
  - CMIP5 ensemble, c.f. Joos et al 2013. (16 models of the carbon cycle) + Geoffroy et al. 2013 (16 models of temperature)
- Comparison with Integrated assessment models (IAMs)
  - Nordhaus' DICE (2013, 2016), FUND (Waldhoff et al 2014), PAGE (Hope 2013)
  - Analytical models : Golosov et al. 2014 (GHKT), Lemoine and Rudik 2017 (LR) ; Gerlagh and Liski 2018 (GL)

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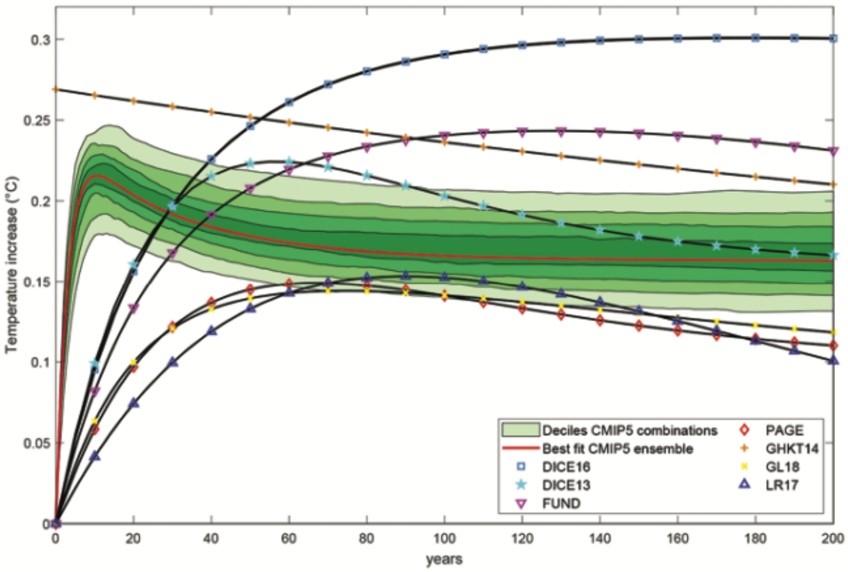
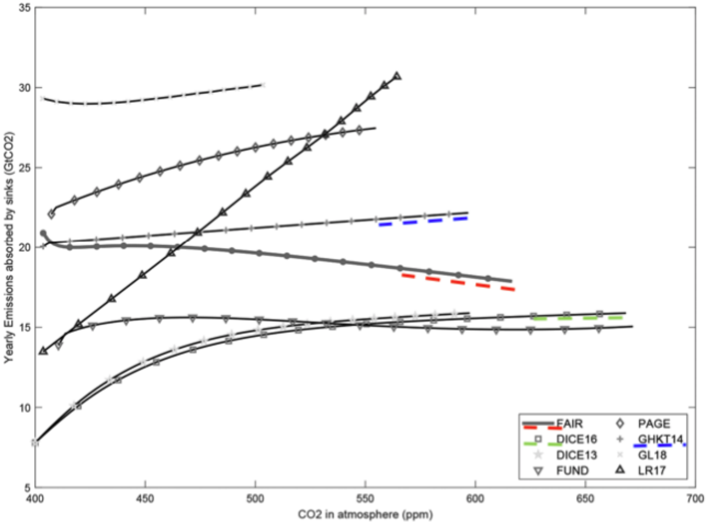
- Results (1) :
  - Response of temperature is fast : 10 years to reach peak temperature
  - Way too slow in IAMs (55-180 years to peak)
  - Robust : similar result (shape of IRF) for different sizes and consistent with observational data


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

Climate dynamics in IAMs : two key differences

- Same experiment as last week (Ricke and Caldeira 2014)
- Comparison with leading Integrated assessment models (IAMs)
- Experiment (2)
  - For constant emissions, how much CO_2 is absorbed by sinks ?
  - Comparison with FAIR model (Millar et al 2017), i.e. a CMIP5 model calibrated on IRFs of fig 1.
- Results (2) :
  - In FAIR/CMIP5 : uptake by carbon sinks decline as atmospheric CO_2 : positive feedback
  - Most IAMs do not include feedback from the carbon cycle


Yearly Emissions absorbed by sinks (GtCO2)
CO2 in atmosphere (ppm)
35
30
25
20
15
10
5
400
450
500
550
600
650
700
FAIR
DICE16
DICE13
FUND
PAGE
GHKT14
GL18
LR17

Decomposition of IRF

- Decompose temperature response to a CO_2 emission impulse in the models into IRF of (i) atmospheric CO_2 concentration M_s and (ii) temperature T_t.

$$\frac{\Delta T_t}{\Delta E_1} = \sum_{s=1}^{t} \frac{\Delta T_t}{\Delta F_s} \frac{\Delta F_s}{\Delta M_s} \frac{\Delta M_s}{\Delta E_1}$$

- First : Carbon cycle $\frac{\Delta M_s}{\Delta E_1}$
- Second : Radiative forcing and temperature dynamics $\frac{\Delta T_t}{\Delta F_s} \frac{\Delta F_s}{\Delta M_s}$

Decomposition of IRF : 1. Carbon cycle

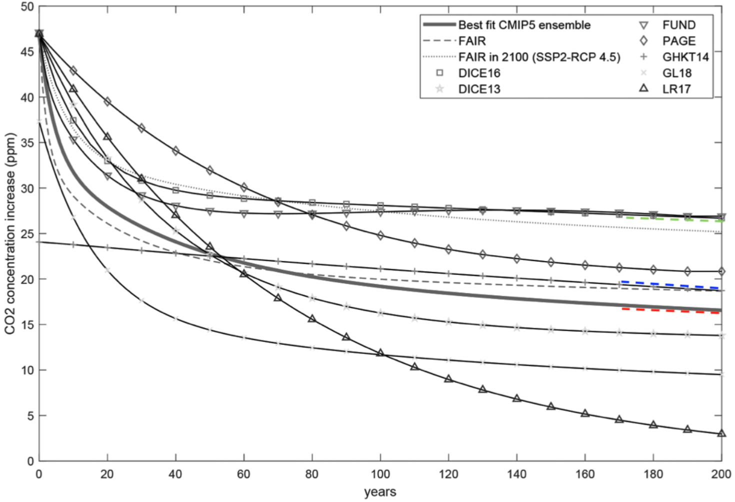
- Carbon cycle is modeled with different boxes (atmosphere, biosphere, and upper and lower oceans) as a system of equations :

$$\boldsymbol{m}_t = A\boldsymbol{m}_{t-1} + bE_t$$
$$M_t = d'\boldsymbol{m}_t$$

- Atmospheric CO_2 concentration :
  - sprectral decomposition, with n eigenvalues λ_i.
  - ψ_i : contribution to box i to M_t
  - $i = 1$ permanent box : 22% of M_t is due to ψ_1
  - Many slowly decaying boxes

$$\frac{\Delta M_t}{\Delta E_s} = d'A^{t-s}b = \sum_{s=1}^{t}\sum_{i=1}^{n}\psi_i\lambda_i^{t-s}$$

- Some IAMs do not have the same decomposition (sometimes half life $log(1/2)/\lambda_i$ too low)
- DICE do not remove enough CO_2 in the long-run


Best fit CMIP5 ensemble
FAIR
FAIR in 2100 (SSP2-RCP 4.5)
DICE16
DICE13
FUND
PAGE
GHKT14
GL18
LR17
CO2 concentration increase (ppm)
years
0
5
10
15
20
25
30
35
40
45
50
0
20
40
60
80
100
120
140
160
180
200

Decomposition of IRF : 2. Temperature dynamics

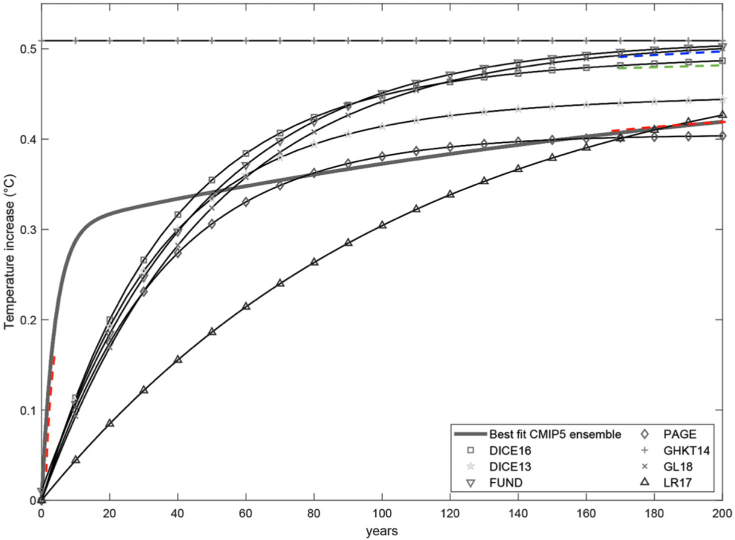
- Second : Radiative forcing F_s and temperature dynamics T_t
- Radiative forcing : simple physical relation :

$$\frac{\Delta F_s}{\Delta M_s} = \frac{F_{2\times CO_2}}{\ln(2)} \frac{1}{M_s}$$

- Warming models :
  - Impulse of $100GtC$ / 47 ppm
  - Decomposition, with n eigenvalues λ_i^T for each box
  - ψ_i^T : contribution to box i to T_t

$$\frac{\Delta T_t}{\Delta F_s} = \sum_{s=1}^{t} \sum_{i=1}^{n} \psi_i^T \lambda_i^{T\ \ t-s}$$

- Results :
  - IAM have too sluggish temperature
  - Heat up too much in the long-run


Temperature increase (°C)
years
0
0.1
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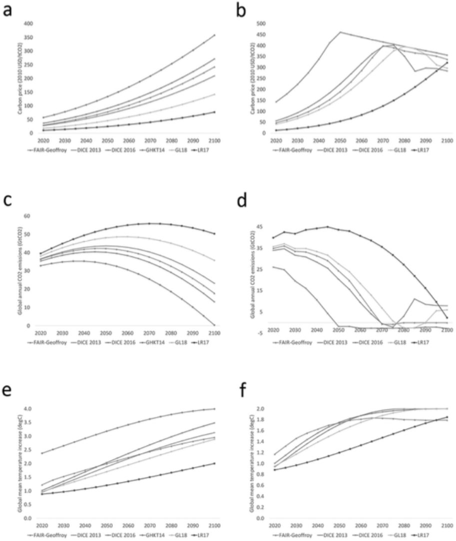
Economic policies

- What are the implications of these different climate models for economics ?

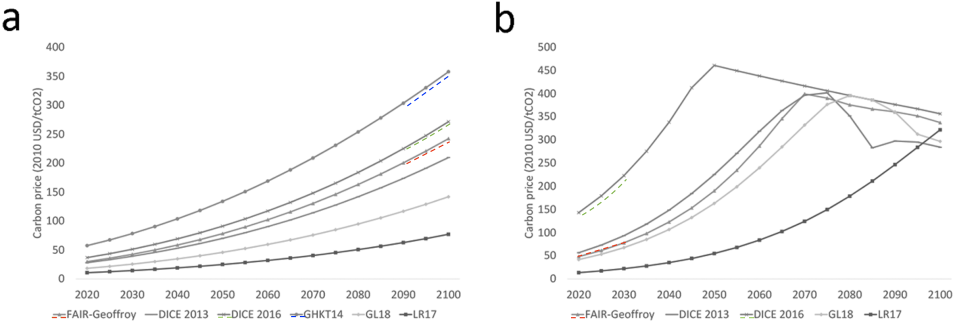
Economic policies

- What are the implications of these different climate models for economics ?
- Integrate different climate blocks into the standard IAM of Nordhaus DICE 2016 :
  - DICE 2016
  - DICE-GHKT14 (Golosov et al. (2014))
  - Other IAMs : DICE-DICE 2013, DICE-GL18 (Gerlagh Liski (2018)), DICE-LR17 (Lemoine Rudik (2017))
  - DICE-Joos-Geoffroy (Joos et al. (2013) carbon cycle + Geoffroy et al. (2013) warming model)
  - DICE-FAIR-Geoffroy (FAIR carbon cycle + Geoffroy et al. (2013) warming model)
- Two types of policies :
  - Welfare maximizing
  - Path to limit warming to $2°C$: minimum discounted abatement cost subject to constraint

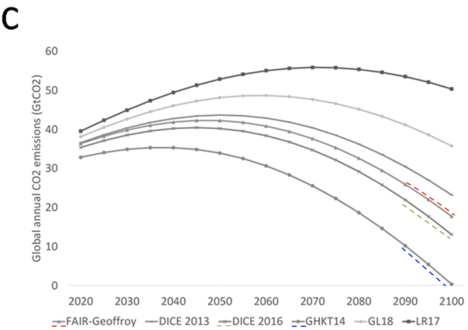


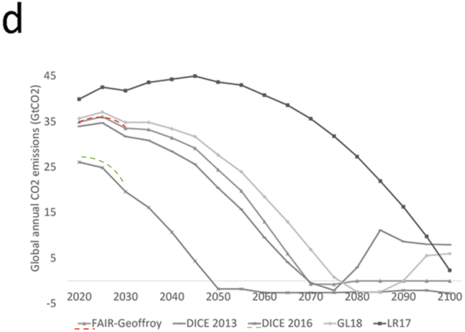
- Two types of policies :
  - Welfare maximizing
  - Limit warming to $2°C$
- Paths :
  - Carbon Price $2010US\$/tCO_2$
  - CO_2 Emissions $GtCO_2$
  - Temperature $°C$

Carbon price

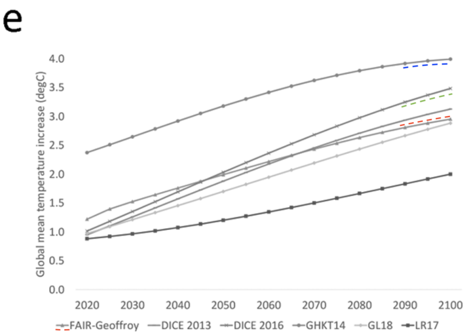


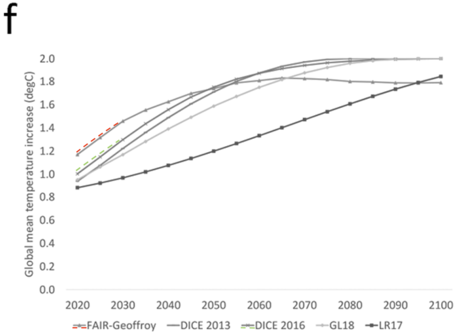
CO_2 emissions





Temperature emissions





Policy experiments (Table 4 and 5)

1 Excessive delay between CO_2 emission impulse and warming :

- Experiment :
  - Take DICE-Joos-Geoffroy model (closest to climate CMIP5 model)
  - ... with the same long-run response of temperature
  - ... but slowest short-run impulse as in IAMs :
    ▷ 56 or 112 instead of 11 years of peak warming
- Results :
  - Lower carbon price in both policy scenarios
  - Increase emissions (but ofc slow response of temperature by assumption)
  - More sensitivity on discount rates β
    (reason behind the Nordhaus vs. Stern debate)

Experiment : positive carbon cycle feedback (Table 4 and 5)

2 IAMs do not include weakening of carbon sinks : CO_2 is removing/decaying too fast

- Experiment :
  - Compare DICE-Joos-Geoffroy model (closest to climate CMIP5 model) but without feedback
  - ... vs. DICE-FAIR-Geoffroy model : includes these feedbacks
- Results :
  - Higher carbon price in both policy scenarios with feedbacks ($2.7, i.e. $10-15\%$ higher in 2020)
  - But have larger effects in the long run when CO_2 concentration will be higher ($83 i.e. 23% by 2100)
  - Reduce emission budget and optimal emissions

Conclusion

- Standard IAMs are getting the climate wrong :
  - Temperature inertia is too long, and rise too much in the long run
  - Carbon cycles vary widely in IAMs, in DICE it decays too slowly
  - Absence of positive carbon feedbacks : carbon sinks weaken.
- Matters for policy prescriptions :
  - Change/increase the price of carbon
  - Pitfalls can be easily fixed :
    - Recalibration of the carbon cycle as in FAIR (Millar et al 2017)
    - Replace the temperature models as in CMIP5 (Geoffroy et al 2013)
    - Or simply specify temperature as a linear function of cumulative emissions (TCRE), c.f. first slide

$$T_t = 1^\circ C + \int_0^t E_s ds \Big|_{TtC} \times 1.7^\circ C$$

  - Need to talk about uncertainty too...

DICE model 2016

- Climate block
  - Emissions :

$$E_t = \sigma_t(1 - \mu_t)Y_t + E_{\text{land}\,t}$$

  - Carbon cycle : 3 boxes j (Atm., Up Ocean, Low Ocean)

$$M_{j,t} = \sum_i \phi_{i,j} M_{i,t-1} + \phi_{0,j} E_t$$

$$\boldsymbol{M}_t = A\boldsymbol{M}_{t-1} + bE_t$$

  - Radiative forcing :

$$F(t) = \eta \left\{\log_2 \left[M_{a,t}/M_{a,1750}\right]\right\} + F_{ex}(t).$$

  - Warming temperature : 2 boxes (a = Atm, l = Low Ocean)

$$T_{a,t} = T_{a,t-1} + \xi_1 \left\{F_t - \xi_2 T_{a,t-1} - \xi_3 \left[T_{a,t-1} - T_{l,t-1}\right]\right\}$$
$$T_{l,t} = T_{l,t-1} + \xi_4 \left[T_{a,t-1} - T_{l,t-1}\right]$$

DICE model 2016

- Economic block
  - Welfare

$$W = \sum_{t=1}^{T\max} R(t)V[c(t), L(t)] = \sum_{t=1}^{T\max} \left(\tfrac{1}{1+\rho}\right)^t U(c_t)L_t$$

  - Output net of damages (Y_t Cobb Douglas)

$$Q_t = \Omega_t(1 - \Lambda_t)Y_t$$

  - Damages :

$$\Omega_t = \frac{D_t}{1 + D_t} \qquad D_t = \varphi_1 T_{a,t} + \varphi_2 T_{a,t}^2$$

  - Social cost of carbon :

$$\mathrm{SCC}(t) \equiv \frac{\partial W}{\partial E(t)} / \frac{\partial W}{\partial C(t)} \equiv \partial C(t)/\partial E(t)$$

Welfare-Maximizing Paths with variants of the DICE Model

Table 4. Welfare-Maximizing Paths with Variants of the DICE Model

Model	Carbon-Cycle Feedback	Temp. Model	Carbon Price (USD/tCO_2) 2020	Carbon Price 2050	Carbon Price 2100	CO_2 Emissions ($GtCO_2$) 2020	CO_2 Emissions 2050	CO_2 Emissions 2100	Warming (°C) 2020	Warming 2050	Warming 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	.98	1.81	2.93
4. Delay 112	No	Long delay	17.88	42.17	122.98	38.19	48.91	39.68	.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

Note. Comparing DICE-Joos-Geoffroy to Delay 56 and Delay 112 shows that an excessive warming delay results in lower carbon prices, higher CO_2 emissions, but lower temperatures. Comparing DICE-FAIR-Geoffroy (with positive carbon cycle feedbacks) to DICE-Joos-Geoffroy (no feedbacks) shows that positive feedbacks result in higher carbon prices, particularly in the long run, and in lower emissions and temperatures.

Cost-Minimizing Paths with variants of the DICE Model

Table 5. 2°C Cost-Minimizing Paths in Variants of the DICE Model

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	47.98	189.91	337.33	34.88	24.38	.00	1.17	1.74	1.79
2. DICE-Joos-Geoffroy	No	Short delay	41.62	167.56	337.34	35.65	27.05	.00	1.20	1.84	1.89
3. Delay 56	No	Long delay	39.41	159.58	318.24	35.93	28.03	2.79	.97	1.66	2.00
4. Delay 112	No	Long delay	35.83	140.72	357.64	36.40	30.44	−2.79	.91	1.43	1.96
5. 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

Note. Comparing DICE-Joos-Geoffroy to Delay 56 and Delay 112 shows that an excessive warming delay results in lower carbon prices and higher emissions in 2020 and 2050, but lower temperatures. Comparing DICE-FAIR-Geoffroy (with positive carbon cycle feedbacks) to DICE-Joos-Geoffroy (no feedbacks) shows that positive feedbacks result in higher carbon prices in 2020 and 2050, and in lower emissions and temperatures.