Warming the MATRIX: Uncertainty and heterogeneity in climate change impacts and policy targets in the Euro Area

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Macroeconomic Modelling Frontiers for Research and Policy in Central Banks
Frankfurt am Main, Nov 27-28, 2024

Outline

1. Economics of climate change: standard IAM
2. ABM-IAM: The MATRIX model
3. Results I: carbon cycle(s) and climate damage(s)
4. Results II: policies and abatement
5. Conclusions and future research agenda

Economics of climate change

Integrated Assessment Models (IAMs):

- Modelling tools for studying the joint evolution of climate-economic dynamics
- Combine climate and economic data to evalute:
    1. The impacts of climate change (social cost of carbon, SCC)
    2. Costs-benefit of various climate policies

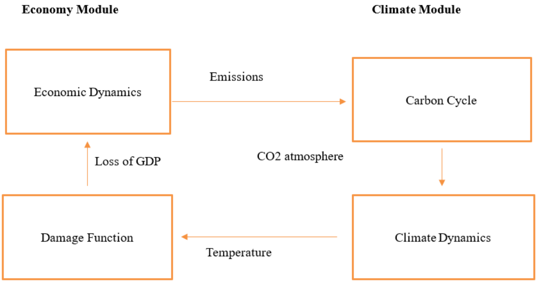


Figure: Nordhaus (1992), *The DICE model*

Climatic Change (2013) 117:585–597
DOI 10.1007/s10584-012-0572-8

Integrating tipping points into climate impact assessments

Timothy M. Lenton · Juan-Carlos Ciscar

Received: 30 September 2011 / Accepted: 1 August 2012 / Published online: 29 August 2012

Abstract There is currently a huge gulf between natural scientists' understanding of climate tipping points and economists' representations of climate catastrophes in integrated assessment models (IAMs). In particular, there are multiple potential tipping points and they are not all low-probability events; at least one has a significant probability of being passed this century under mid-range (2–4 °C) global warming, and they cannot all be ruled out at low (<2 °C) warming. In contrast, the dominant framing of climate catastrophes in IAMs, and in critiques of them, is that they are associated with high (> 4 °C) or very high (> 8 °C) global warming. This discrepancy could qualitatively alter the predictions of IAMs, including estimates of the social cost of carbon. To address this discrepancy and assess the economic impact of crossing different climate tipping points, we highlight a list of scientific points that should be considered, at least in a stylised form, in simplified IAMs. For nine different tipping events, the range of expected physical climate impacts is summarised and some suggestions are made for how they may translate into socio-economic impacts on particular sectors or regions. We also consider how passing climate tipping points could affect economic growth.

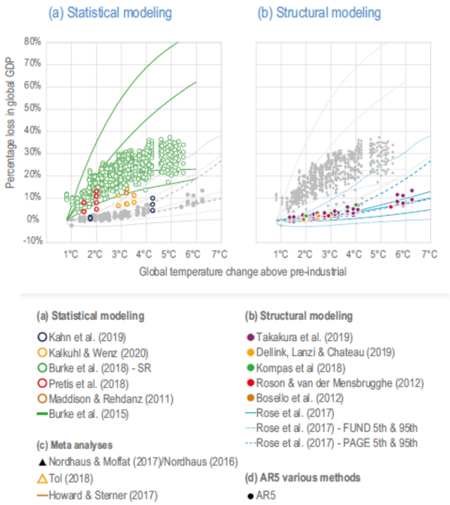
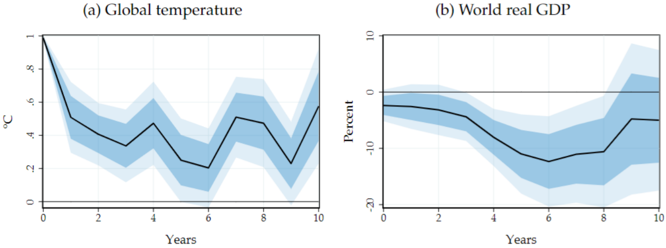


Figure: IPCC (2022)

Figure 3: The Effect of Global Temperature Shocks on World Output



Notes: Impulse responses of global mean temperature in panel (a) and world real GDP per capita in panel (b) to a global temperature shock, estimated based on (2). Solid line: point estimate. Dark and light shaded areas: 68 and 90% confidence bands.

Figure: Bilal and Kanzig (2024), The macroeconomic impact of climate change: global vs local tempereature, *NBER WP*

Main flaws of IAM

Key controversial points of IAM:

- Climate uncertainty
- Economic uncertainty
- Political uncertainty

Main flaws of IAM

Key controversial points of IAM:

- **Climate uncertainty**
  - Carbon cycle:
    - Inherent uncertainty in climate system concerning climate sensitivity and physical feedback mechanisms.
  - Climate damage function:
    - Aggregate form, arbitrary convex function linking ΔT to GDP losses;
    - Calibrated to give small damages for small temperature increases $\rightarrow$ rule out possibility of catastrophic climate outcome;
    - "*Most speculative element of the analysis*" (Pindyck, 2013).
- Economic uncertainty
- Political uncertainty

Main flaws of IAM

Key controversial points of IAM:

- Climate uncertainty
- **Economic uncertainty**
  - General equilibrium model based on intertemporal utility maximizing perfectly rational representative agent
  - No role for heterogeneity, financial sector, coordination failures e unemployment
  - Underestimate macro-financial risks associated with energy transition (ad es., supply chain disruption, stranded assets, defaults e inequalities)
- Political uncertainty

Main flaws of IAM

Key controversial points of IAM:

- Climate uncertainty
- Economic uncertainty
- **Political uncertainty**
  - Stringent climate actions requires public support which depends on:
    - Distribution of costs among individuals (Drews and van den Bergh, 2016);
    - Subjective preferences dependent on income and social influence (Konc et al., 2021);
    - Expectations on policy maker's commitment and ability to enforce (Campiglio et al., 2022).

Main flaws of IAM

Key controversial points of IAM:

- Climate uncertainty
- Economic uncertainty
- Political uncertainty

Key Implication: Insufficient treatment of uncertainties leads to:

- **Overestimating** likelihood of Net Zero targets
- **Underestimating** climate damages and mitigation costs

Rethinking climate-economic models

Environ Resource Econ (2015) 62:329–357
DOI 10.1007/s10640-015-9965-2

CrossMark

A Third Wave in the Economics of Climate Change

J. Doyne Farmer[1,2,3] · **Cameron Hepburn**[1,4,5] · **Penny Mealy**[1,4] · **Alexander Teytelboym**[1,4]

Accepted: 21 August 2015 / Published online: 1 October 2015

Abstract Modelling the economics of climate change is daunting. Many existing methodologies from social and physical sciences need to be deployed, and new modelling techniques and ideas still need to be developed. Existing bread-and-butter micro- and macroeconomic tools, such as the expected utility framework, market equilibrium concepts and representative agent assumptions, are far from adequate. Four key issues—along with several others—remain inadequately addressed by economic models of climate change, namely: (1) uncertainty, (2) aggregation, heterogeneity and distributional implications (3) technological change, and most of all, (4) realistic damage functions for the economic impact of the physical consequences of climate change. This paper assesses the main shortcomings of two generations of climate-energy-economic models and proposes that a new wave of models need to be developed to tackle these four challenges. This paper then examines two potential candidate approaches—dynamic stochastic general equilibrium (DSGE) models and agent-based models (ABM). The successful use of agent-based models in other areas, such as in modelling the financial

Research project at FEEM: the MATRIX model

Objective

To develop a new AB-SFC-IAM (MATRIX – *Multi-Agent model for Transition Risks*) to provide support for policy analysis on climate change mitigation and energy transition.

Outputs

- *'Enter the MATRIX: a Multi-Agent model for Transition Risks with application to energy shocks'*, Journal of Economic Dynamics and Control, 2023
- *'Energy shocks and macro-stabilization policies in the MATRIX model'*, Energy Policy, 2023
- *'Warming the MATRIX: Uncertainty and Heterogeneity in Climate Change Impacts and Policy Targets in the Euro Area'*, Energy Economics, 2024
- *'Beyond Green Preferences: Alternative Pathways to Net Zero Emissions in the MATRIX model'*, WP FEEM (UR)
- *'The Macro-Financial Risks of Taking the Green Pill: Energy Transition within the MATRIX model'*, ongoing

Related literature

- "Standard" IAMs: DICE (Nordhaus, 1994), RICE (Nordhaus and Yang, 1996), MERGE (Manne et al., 1995), FUND (Tol, 1997), WITCH (Bosetti et al., 2009) and related extensions.
- "Second wave" IAMs that address (climate) uncertainty and catastrophic outcomes: PAGE 09 (Hope, 2013), DICE variants (Dietz and Stern, 2015; Cai et al., 2015), often converging with DSGE methodologies (Traeger, 2014).
- "Third wave" Agent-Based IAMs (Farmer et al., 2015):
    - DSK models (Lamperti et al., 2018; Lamperti et al., 2020): K+S+Climate, later expanded to include a detailed financial sector;
    - EURACE model (Ponta et al., 2018): feed-in-tariff and renewable investment;
    - CPNS (Czupryna et al., 2020): multiple regions, different damages;
    - AB-IAM (Safarzýnska and van den Bergh, 2022): revisiting DICE's social cost of carbon and damage distribution as in Dennig et al. (2015).

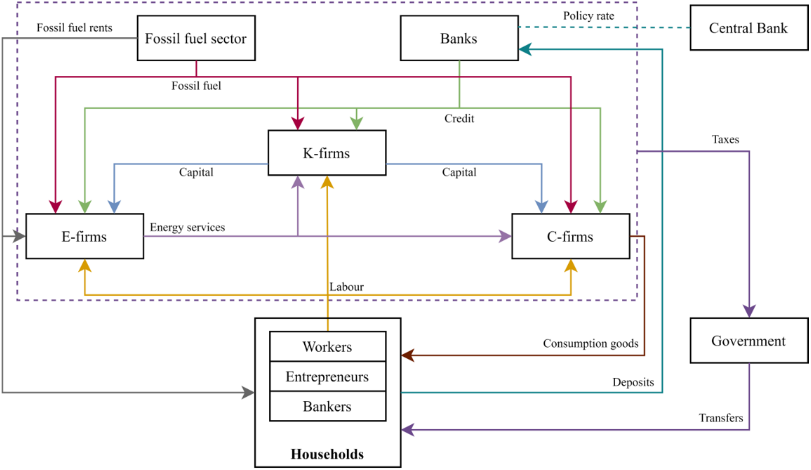
The MATRIX model

- The **MATRIX** model (*Multi-Agent model for Transition Risks*) is an **agent-based integrated assessment model** (AB-IAM) designed to simulate the impacts of energy and climate policies on the economic and climate dynamics
- AB-IAMs conceives the economy as a **complex system**, where aggregate (climate and economic) outcomes result from the interaction of heterogeneous agents in decentralized markets
- As such, AB-IAMs are seen as an complementary tool capable of capturing the role of **uncertainty** and **heterogeneity** in the ecological transition

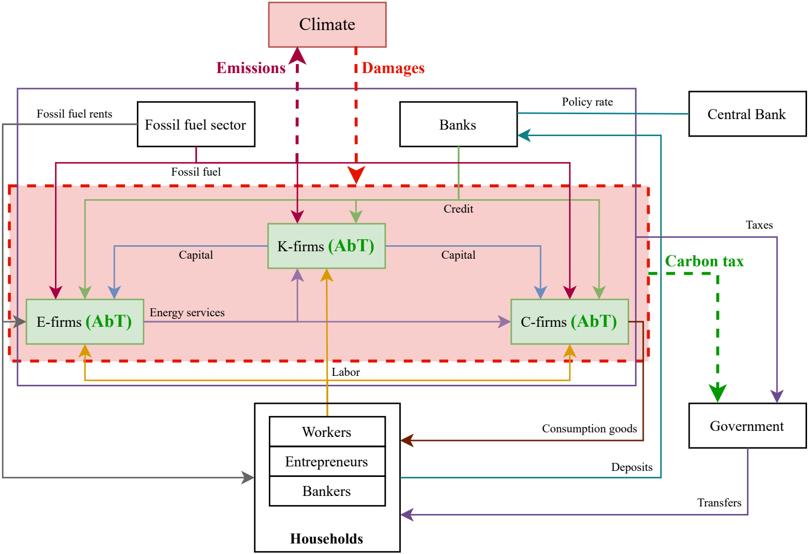
What we do

- We develop an extended version of the MATRIX model (Ciola et al., 2023; Turco et al., 2023) with a climate box $\rightarrow$ AB-IAM.
- The integrated-MATRIX model consists of:
  - Economic module: macroeconomic multi-sector multi-agent model calibrated on EA;
  - Climate module: carbon cycle + climate damage function.
- Goal:
  - Analyze the evolution of climate change and its macroeconomic effects using different climate boxes (carbon cycle & damage function) found in the literature (climate uncertainty);
  - Compare the effects of homogeneous vs heterogeneous climate shocks on the economy (socio-economic heterogeneity);
  - Conduct a set of climate policy experiments to reduce carbon emissions, focusing on the role of supply-side factors (carbon tax $\rightarrow$ incentive to invest in abatement technologies).

The MATRIX model



The MATRIX model



The MATRIX model: economic module

1. **Household sector:** (i) workers, (ii) entrepreneurs and (iii) bankers:
   - Receive income, consume and save + owners recapitalize defaulted firms/banks.
2. **Corporate sector:** (i) energy, (ii) capital-goods and (iii) final-goods firms:
   - Opt input demand via cost minimization (CES) given desired production and prices;
   - Desired production and prices adaptively revised based on excess supply/demand;
   - If financially constrained, firms maximize attainable production given liquidity constraints;
3. **Fossil fuel sector:**
   - Supplies fossil fuel with infinite elasticity;
   - Fossil rents redistributed to energy firms and households.
4. **Banking sector:**
   - Banks collect deposits, supply credit to firms and buy public bonds;
   - If firms default, banks record NPLs resulting in equity loss.
5. **Public sector:**
   - Government sets budget (tax + transfer) via intertemporal debt sustainability rule;
   - Central bank sets interest rate via Taylor rule.

Firms' behaviour: input demands

- Given the desired quantity $Q_{c,t+1}$ and expected input prices $\mathbb{E}_t[P_{j,t+1}]$, C-firms set their inputs demand:

$$\min_{\Delta X_{j,f,t+1}} \mathbb{E}_{f,t}[DC_{f,t+1}] = \sum_{j=1}^{n} \mathbb{E}_{f,t}[P_{j,t+1}]\Delta X_{j,f,t+1}$$

subject to the CES production function

$$Q_{j,t+1} = [\sum_{i=1}^{I} A_j(X_{i,j,t+1})^{\rho_j}]^{\frac{1}{\rho_j}}$$

$$X_{j,f,t+1} = \Delta X_{j,f,t+1} + (1-\delta_j)X_{j,f,t}$$

- where $\Delta X_{j,f,t+1}$, δ_j, $A_{j,f,t}$ are the additional input demand, depreciation rate and factor share of input j, while $\rho_f = \frac{\sigma_f - 1}{\sigma_f}$ is the elasticity substitution parameter.

Firms' behaviour: price and quantity

- Firms set desired prices and quantities through an evolutionary Algorithm with Strategic Complementarities
- Each firm f observes a target competitor T with probability:

$$\Pr_{f,T,t} = \frac{\exp(-\omega \Delta^{T}_{f,t})}{\sum_z \exp(-\omega \Delta^{T}_{f,t})}$$

where $\Delta^{T}_{f,t} = |y^*_{f,t} - y^*_{T,t}|$ is a measure of the distance between the firm f and T, while ω is the intensity of choice;

Firms' behaviour: price and quantity

- The firm f updates its desired quantity and price $\{Q_{f,t+1}; P_{f,t+1}\}$ according to the following rule:

$$Q_{f,t+1} = \begin{cases} \zeta^q Q_{f,t} + (1-\zeta^q) Q_{T,t} & \text{if } \pi_{T,t} \geq \pi_{f,t} \\ \zeta^q Q_{f,t} + (1-\zeta^q)(1+U) Q^O_{f,t} & \text{otherwise} \end{cases}$$

$$P_{f,t+1} = \begin{cases} \zeta^p P_{f,t} + (1-\zeta^p) P_{T,t} & \text{if } \pi_{T,t} \geq \pi_{f,t} \\ \zeta^p P_{f,t} + (1-\zeta^p)(1+U) P^O_{f,t} & \text{otherwise} \end{cases}$$

where $\{P_{T,t}, Q_{T,t}\}$ and $\{P^O_{f,t}, Q^O_{f,t}\}$ are the target price and quantity under different cases, while ζ^p and ζ^q are parameters governing the speed of adjustment towards target price and quantity.

Firms' behaviour: CES and exogenous growth

- Exogenous growth process: Harrod-neutral technical progress.
- Given the CES production function:

$$Q_{f,t} = \left[\sum_{j=1}^{J} A_{j,f,t} \left(X_{j,f,t} \right)^{\frac{\sigma_f - 1}{\sigma_f}} \right]^{\frac{\sigma_f}{\sigma_f - 1}},$$

- The factor shares evolve as follows:

$$A_{j,f,t} = A_{j,f,t-1} \left(1 + \zeta^{\text{growth}} \right)^{\frac{\sigma_f - 1}{\sigma_f}},$$

- where j identifies labor and fossil fuels, and ζ^{growth} is the exogenous growth rate.

Households' behaviour: consumption budget

- Households' income (before tax and subsidy):

$$Y_{h,t} = \begin{cases} W_t N_{w,t} & \text{if employed worker} \\ \text{DIV}_{f,t-1} - \text{REC}_{f,t-1} & \text{if entrepreneur} \\ \text{DIV}_{b,t-1} - \text{REC}_{b,t-1} & \text{if banker} \\ 0 & \text{otherwise} \end{cases}$$

- Each consumer computes her nominal permanent income (Assenza et al., 2015):

$$\bar{Y}_{h,t} = \beta \bar{Y}_{h,t-1} + (1 - \beta) Y_{h,t}$$

- and sets the consumption budget:

$$C_{h,t} = \bar{Y}_{h,t} + \chi D_{h,t}$$

- where χ is the MPC out of financial wealth.

Banks' behaviour: interest rates and credit supply

- The policy rate i_t^{cb} is set by the Central Bank following a Taylor rule:

$$i_t^{cb} = \rho^{cb} \cdot i_{t-1}^{cb} + (1-\rho^{cb}) \cdot \max[0, r^* + \bar{g}^P + \lambda^u(\bar{u} - u_t) + \lambda^p(g_t^P - \bar{g}^P)]$$

where r^* is the natural rate, u_t and g_t^P are the current unemployment and inflation rates, and $\bar{u}$ and $\bar{g}^P$ are the policy targets.

- Interest rate on loans:

$$i_{f,b,t} = i_t^{cb} + \varrho^B \left[1 - \frac{E_{b,t}}{\max(E_{z,t})}\right] + \rho^B \left(\frac{L_{f,t}}{E_{f,t} + L_{f,t}}\right) + \iota^B \left(\frac{NPL_t}{L_t}\right)$$

- Constraints on credit supply:

$$L_{b,t}^{\max} \leq \frac{E_{b,t}}{\gamma^B} \quad \text{and} \quad L_{f,t} \leq \kappa^B E_{b,t}$$

where γ^B is the capital adequacy ratio, and κ^B is the maximum exposure to a single counterpart.

Government's behaviour: fiscal rules

- The government supports the economy by making transfers, TRA_t, to households, funded by tax revenues, TAX_t, or new issuances of public debt, B_t:

$$B_t = (1 + i^{cb}_{t-1})B_{t-1} + TRA_t - TAX_t$$

- Fiscal sustainability rule: the government sets the primary balance, f_{t+1}, such that the debt-to-GDP, b_t, smoothly converges to a target ratio b^* at a rate ρ^g, namely:

$$\begin{cases} b_{t+1} = \frac{1+i^{cb}_t}{1+g_t} b_t - f_{t+1} \\ b_{t+1} = b_t + \rho^g (b^* - b_t) \end{cases} \Rightarrow -f_{t+1} = \rho^g b^* + (1-\rho^g)\left(\frac{g_t - i^{cb}_t}{1+g_t}\right) b_t$$

- Given the planned primary balance and a constant ratio of social transfers over GDP, the tax rate is determined accordingly.

Calibration and validation: economic module

- The model includes approximately 60 structural parameters;
- Given the large number of parameters, we divide them into two groups and set their values following two different approaches:
  - **Calibration**: assign the values to the parameters based on micro- or macroeconomic evidence for the EA:
    - Households: discount factor;
    - Firms: number, factor shares, depreciation rates;
    - Credit market: regulatory requirements, Taylor rule;
  - **Validation**: set the value of the remaining parameters to reproduce empirical regularities of the European economy.

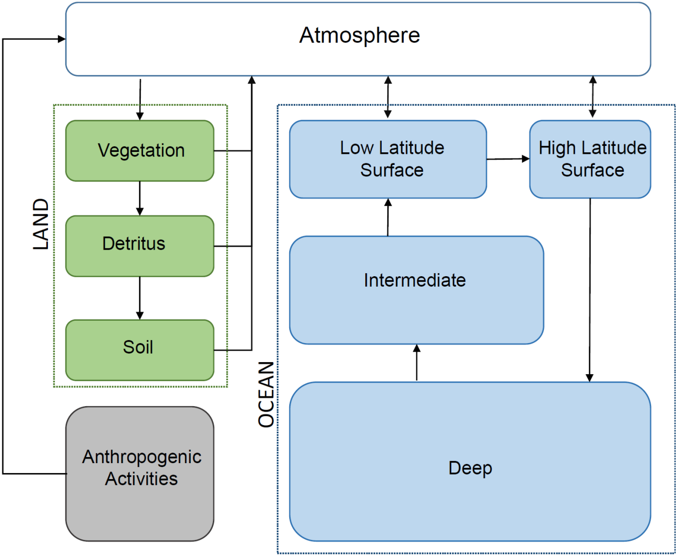
Climate box I: carbon cycle

- **Euro Area (EA):**
  - Firms contribute to climate change by generating emissions through fossil fuel consumption:
    - At time t=2020, emissions are regionalized and rescaled to match EA GHG;
    - Emission intensity by sector calibrated using data on fossil fuel consumption and final emissions for NACE sectors (re-mapped into E, K, and C).
- **Rest of the World (RoW):**
  - Following the *STIRPAT* literature (Dietz and Rosa, 1994, 1997), we bootstrap future emissions using a Vector Autoregressive model estimated on the log differences of global population, GDP per capita, and emissions per unit of GDP (1960-2020).

Climate box I: carbon cycle

- **Global emissions (EA + RoW) enter the carbon cycle:**
  - TCRE (Dietz and Venmans, 2019): simple linear relationship btw GHG and T;
  - DICE (Nordhaus, 1993): atmosphere + ocean (2 boxes);
  - WITCH (Emmerling et al., 2016): variant of DICE;
  - C-ROADS (Sterman et al., 2012): atmosphere + land (3 boxes) + ocean (3 boxes);
  - HECTOR (Hartin et al., 2015): atmosphere + land (3 boxes) + ocean (4 boxes).

Example of a carbon cycle: Hector



Calibration of the climate part

- Initial emission intensities e_{f,t^*} at time t^*:

$$e_{f,t^*} = \frac{\varepsilon_{f,t^*} E_{t^*}}{\sum_{f=1}^{N^F} \varepsilon_{f,t^*} O_{f,t^*}}$$

where:

  - ε_{f,t^*}: real-world relative values
  - E_{t^*}: EA CO_2 emissions in 2019 ($\approx$ 2.90 $GtCO_2$)
  - O_{f,t^*}: observed consumption of fossil fuels

- Implicit carbon tax $\tau_t^{CA^*}$:

$$\tau_t^{CA^*} = \frac{P_t^O}{e_{f^*,t^*}} \tau_t^{CA} = \frac{P_t^O O_{f^*,t^*}}{E_{f^*,t^*}} \tau_t^{CA} = \psi_{f^*,t}^{OE} \tau_t^{CA}$$

where $\psi_{f^*,t}^{OE} = 90$ euro per ton of CO_2

Climate box II: damage functions

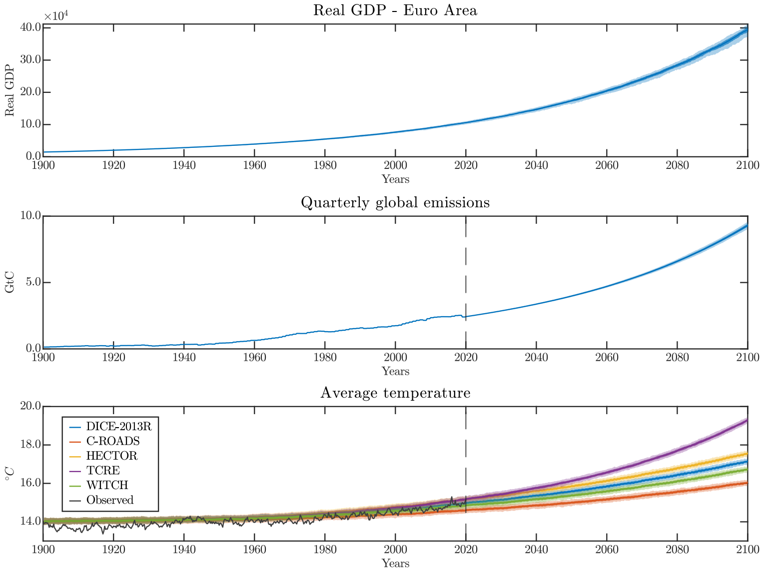
Temperatures increases cause micro-economic shocks. We test four different types of climate damage functions:

Name	Average damage	Source
DICE 1991	$CD_t = 0.0133 \left(\frac{\Delta T_t}{3}\right)^2$	Nordhaus (1993b)
RICE 1999	$CD_t = 1 - \frac{1}{1 + 0.001\Delta T_t + 0.049\Delta {T_t}^2}$	Nordhaus and Boyer (2000)
DICE 2013	$CD_t = 1 - \frac{1}{1 + 0.00267\Delta {T_t}^2}$	Nordhaus and Sztorc (2013)
DSK 2018	$CD_t = \frac{a_{b,t}}{a_{b,t} + b_{d,t}}$ with $a_{b,t} = \log(1 + \Delta T_t)$ and $b_{d,t} = 100\frac{\sigma^T_{t*}}{\sigma^T_t}$	Lamperti et al. (2018)

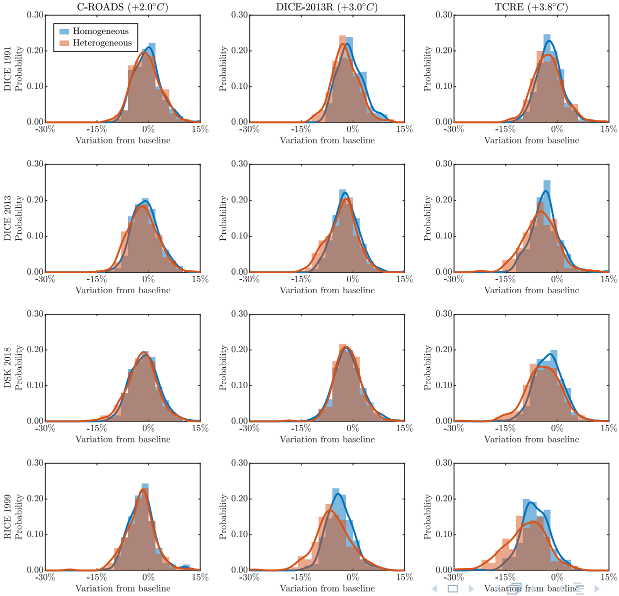
Two types of shocks:

- *Homogeneous*: all firms experience the same economic loss CD_t
- *Heterogeneous*: each firm has a probability CD_t of suffering a 100% reduction in production.

Climate box: GDP, emissions and temperature



Climate damages:GDP, emissions and temperature



Climate box II: economic effects of climate change

- Heterogeneous shocks amplify the effects of climate change on real GDP (+50% compared to homogeneous shocks):
  - *Homogeneous shocks*: all firms are evenly hit by the shock, hence they cut production and optimal input demand in a coordinated manner;
  - *Heterogeneous shocks*: firms are unevenly hit by the shock, giving rise to coordination failures and supply chain distortions.

	C-ROADS (+2.0°C)			DICE-2013R (+3.0°C)			TCRE (+3.8°C)		
	Expected	Realized		Expected	Realized		Expected	Realized	
		Homog.	Heterog.		Homog.	Heterog.		Homog.	Heterog.
DICE 1991	−0.6%	−0.3%	−0.7%	−1.4%	−0.8%	−2.2%	−2.3%	−2.2%	−2.7%
DICE 2013	−1.0%	−0.9%	−1.6%	−2.4%	−2.1%	−3.3%	−3.9%	−3.6%	−5.1%
DSK 2018	−1.3%	−1.2%	−1.8%	−1.8%	−1.4%	−2.7%	−2.9%	−2.6%	−4.1%
RICE 1999	−1.7%	−2.0%	−2.4%	−4.0%	−3.8%	−5.8%	−6.6%	−6.4%	−9.1%

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DICE 1991	−0.6%	−0.3%	−0.7%	−1.4%	−0.8%	−2.2%	−2.3%	−2.2%	−2.7%
DICE 2013	−1.0%	−0.9%	−1.6%	−2.4%	−2.1%	−3.3%	−3.9%	−3.6%	−5.1%
DSK 2018	−1.3%	−1.2%	−1.8%	−1.8%	−1.4%	−2.7%	−2.9%	−2.6%	−4.1%
RICE 1999	−1.7%	−2.0%	−2.4%	−4.0%	−3.8%	−5.8%	−6.6%	−6.4%	−9.1%

Climate box II: economic effects of climate change

- Coordination failures and additional defaults exacerbate heterogeneous climate shocks → reduction in economic activity and increase in the unemployment rate.
- Depressive effects on aggregate demand, nominal (and real) wages and prices, akin to a supply-induced demand shock.

GDP deflator

	C-ROADS (+2.0°C)		DICE-2013R (+3.0°C)		TCRE (+3.8°C)	
	Homog.	Heterog.	Homog.	Heterog.	Homog.	Heterog.
DICE 1991	0.8%	0.6%	1.7%	0.7%	3.8%	−0.3%
DICE 2013	1.7%	0.4%	3.7%	−0.4%	5.8%	−1.1%
DSK 2018	1.9%	0.2%	2.3%	0.0%	3.8%	−0.5%
RICE 1999	3.2%	0.4%	5.5%	0.0%	10.3%	−1.6%

Real wage

	C-ROADS (+2.0°C)		DICE-2013R (+3.0°C)		TCRE (+3.8°C)	
	Homog.	Heterog.	Homog.	Heterog.	Homog.	Heterog.
DICE 1991	−0.6%	−1.3%	−1.2%	−2.9%	−2.1%	−4.6%
DICE 2013	−1.0%	−2.2%	−2.2%	−5.4%	−3.7%	−8.0%
DSK 2018	−1.4%	−3.3%	−1.9%	−4.9%	−2.9%	−7.3%
RICE 1999	−1.6%	−3.7%	−4.0%	−9.1%	−6.4%	−13%

Cumulative unemployment rate

	C-ROADS (+2.0°C)		DICE-2013R (+3.0°C)		TCRE (+3.8°C)	
	Homog.	Heterog.	Homog.	Heterog.	Homog.	Heterog.
DICE 1991	1.2%	4.9%	3%	12.5%	3.7%	22.3%
DICE 2013	2.1%	10.1%	4.8%	26.7%	8.8%	40.3%
DSK 2018	3.9%	14.9%	5.3%	23.2%	8.1%	35.9%
RICE 1999	2.3%	17.0%	10.6%	44.4%	16.2%	66.7%

Policy: carbon tax & abatement investment

- **Carbon tax** τ_t^{CA} adjusts adaptively:

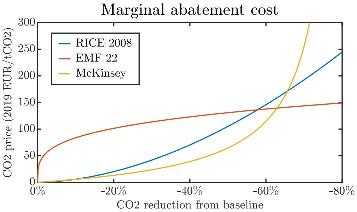
$$\tau_t^{CA} = \begin{cases} \tau_{t-1}^{CA} + \epsilon^{CA} & \text{if } E_{t-1} \geq \overline{E}^{CA}, \\ \tau_{t-1}^{CA} - \epsilon^{CA} & \text{otherwise.} \end{cases}$$

  $\overline{E}^{CA}$: emission reduction target (low: -25%, medium: -50%, high: -75%)

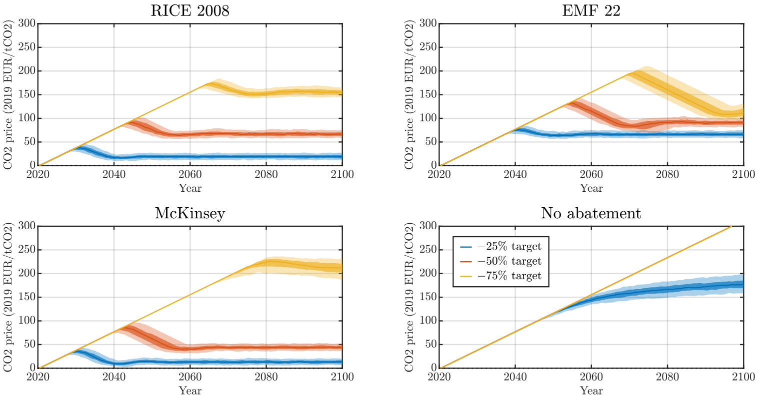
- It incentivizes the **Abatement Technology (AbT)**:
  - *Marginal Abatement Cost (MAC) curve*: Technological steps with increasing costs and abatement potential (Foramitti et al., 2021)
  - Abatement choice: Cost-effective (MAC $<$ carbon price) or Profit-driven (adopt if competitor more profitable)

- Final fuel price reflects carbon tax and abatement cost

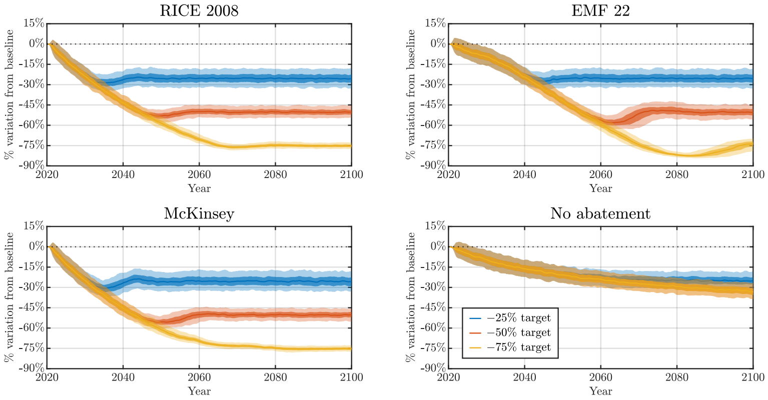
Policy: abatement cost functions



Policy: price of CO2 emissions by emission target



Policy: variation of emissions by emissions target



Conclusions

- We develop and calibrate an integrated-assessment version of the MATRIX model. We assess the evolution of climate change and its macroeconomic effects by comparing different types of carbon box in the existing literature:
  - By 2100, supply-side climate damages will produce a significant contraction in aggregate production and real wages (btw -2% and -7%)
  - Heterogeneous shocks amplifies its effects – assumption of **homogeneous shocks** may **underestimate** the effects of climate change on aggregate output
- We conduct a set of climate policy experiments to assess the economic impact of a low-carbon transition using a carbon tax (and allowing for abatement investment):
  - High initial costs **postpone** the adoption of less polluting production techniques

Future Research Directions

Technical Improvements

- Incorporate endogenous technological change
- Expand energy sources beyond fossil fuels
  - Include renewable energy options
  - Model transition dynamics between sources

Policy Analysis Extensions

- Evaluate broader climate policy instruments
- Analyze different revenue recycling schemes
- Examine distributional impacts across:
  - Income groups
  - Sectors
  - Regions

Thanks for your attention!