Climate policy, physical and transition risks: evidence from a macro-financial agent-based model

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Outline

1. Introduction
2. The impact of climate change in a macro-financial agent-based model with feedback loops
3. Some considerations on climate policy and physical risks
4. Conclusions

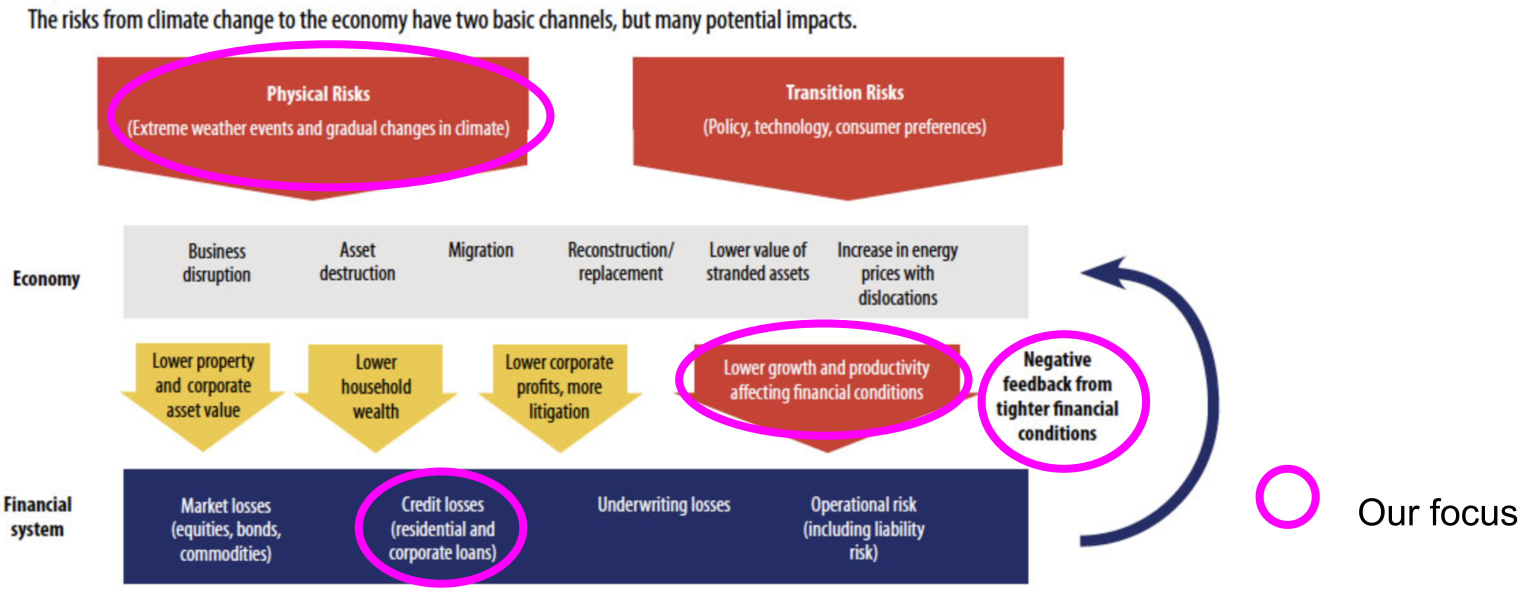
This talk largely draws on three papers

- Lamperti, F., Bosetti, V., Roventini, A., & Tavoni, M. (2019). The public costs of climate-induced financial instability. Nature Climate Change, 9(11), 829-833.
- Lamperti, F., Dosi, G., Napoletano, M., Roventini, A., & Sapio, A. (2020). Climate change and green transitions in an agent-based integrated assessment model. Technological Forecasting and Social Change, 153, 119806.
- Wieners C., Lamperti, F., Dosi, G. Buizza, R. and Roventini, A. (2022). Macroeconomic policies to stay below two degrees with sustainable growth. In preparation.

Financial stability and climate change

- **Can physical, transition and liability risks threat financial stability, price stability and growth?**
  (Carney 2015; Dafermos et al. 2018; Dietz et al. 2016; NGFS 2019; ECB/ESRB 2021; Monasterolo, 2021)

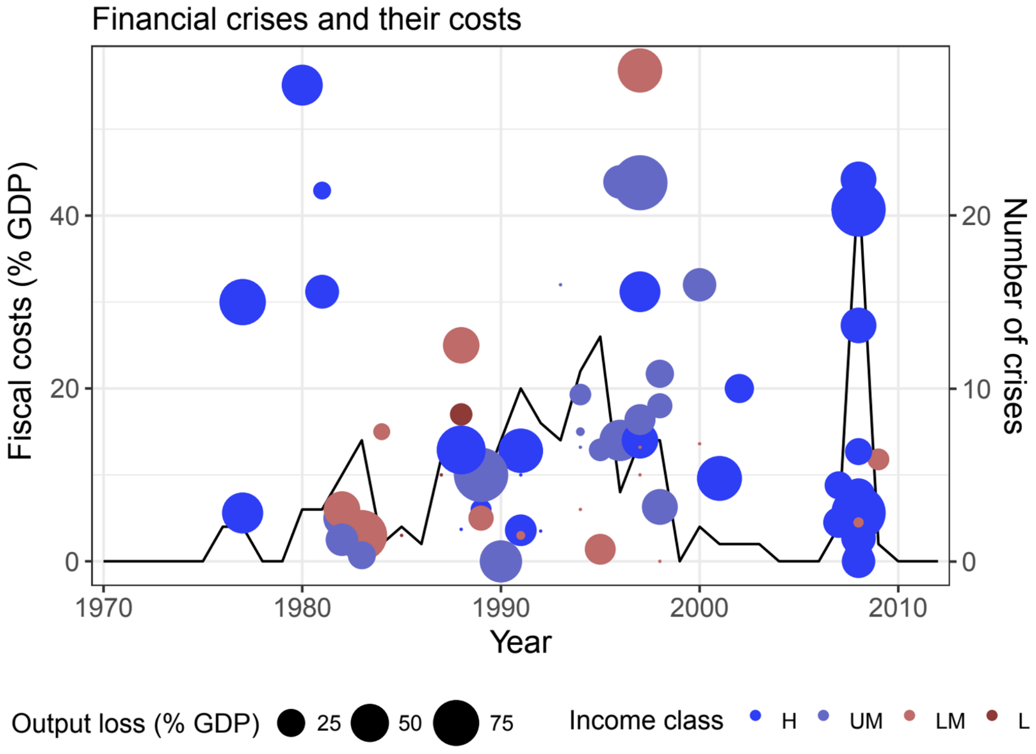
- **How can central banks and financial regulators react?**
  (Batten et al. 2016, Campiglio et al. 2018; Popoyan and D'Orazio 2019)



Source: IMF (2019)

Financial instability and real costs

- Historically, financial (banking) crises hadn't been infrequent events
- Large losses in terms of output lost (3y cum. loss wrt pre-crisis trend)
- Large fiscal costs (gross fiscal outlays related to the restructuring of the financial sector)
- We developed a growth model endogenously generating banking crises to study how climate change might eventually affect their frequency, size, impact



An agent-based perspective - I

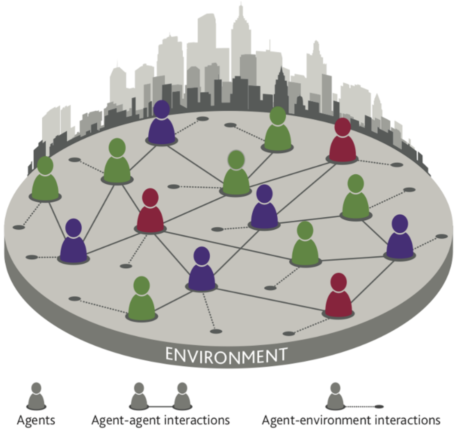
- ABMs are simulation models studying the evolution of complex systems

- Complex evolving system
  - micro: heterogeneity + interactions

    ↓
  - macro: emergent, evolving macro properties

- Key features of economic ABMs
  - Heuristics/satisficing behaviours
  - Local interactions/incomplete information
  - Learning/trial and error
  - Adaptive expectations

    ↓
  - General dis-equilibrium



Source: Haldane and Turrell (2018)

An agent based perspective - II

- ABMs widely used in natural (e.g. physics, biology) and social sciences (economics, marketing, finance, sociology, anthropology)

- Within the economics of climate change, ABMs have been developed to study a variety of issues (Balint et al, 2017; Farmer et al. 2015; Castro et al. 2021)
  - Resilience to natural disasters and shock propagation across time, space, sectors
  - Diffusion of low-carbon technologies
  - Heterogeneous risk perception and the investment in mitigation and adaptation
  - Heterogeneous beliefs and climate policy support
  - The consequences of asset stranding

Balint, T., Lamperti, F., Mandel, A., Napoletano, M., Roventini, A., & Sapio, A. (2017). Complexity and the economics of climate change: a survey and a look forward. *Ecological Economics*, *138*, 252-265.

An agent based perspective - II

- ABMs widely used in natural (e.g. physics, biology) and social sciences (economics, marketing, finance, sociology, anthropology)

Published: 24 February 2016

Economics: Current climate models are grossly misleading

Nicholas Stern

Nature **530**, 407–409 (2016) | Cite this article

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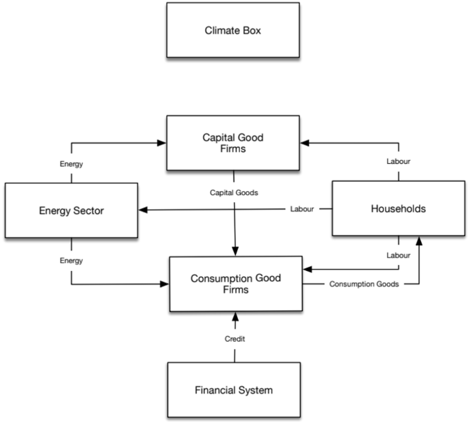
Relatively recent application to the macrofinance – climate nexus

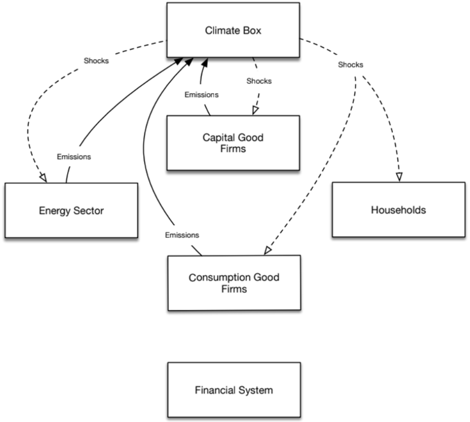
Balint, T., Lamperti, F., Mandel, A., Napoletano, M., Roventini, A., & Sapio, A. (2017). Complexity and the economics of climate change: a survey and a look forward. *Ecological Economics*, *138*, 252-265.

The “DSK” macro-financial agent-based IAM

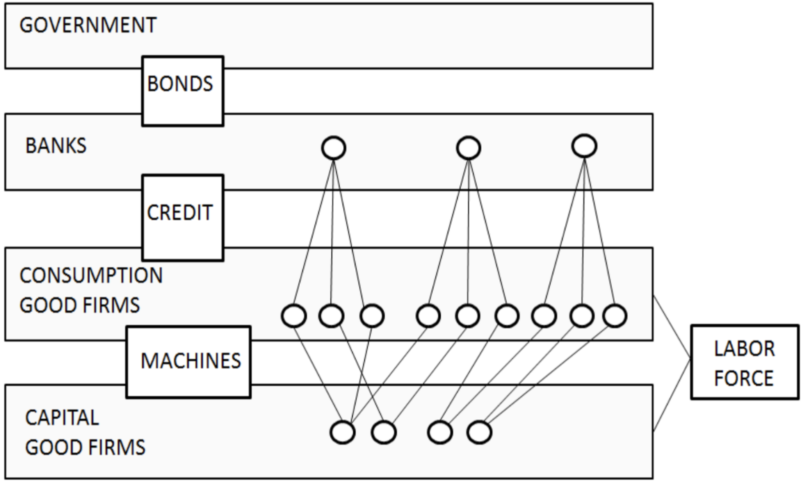
- A macro-financial model of endogenous growth and fluctuations endowed with a climate module and micro-level damage functions
- Heterogeneity in firms, banks, households, energy plants
- Firm-to-firm and firm-to-bank networks; competitive energy and labor markets
- Calibration on stylised facts and simulation along a RCP8.5+SSP5 future



(a) Economic flows.



(b) Climate-related flows.



Climate damages at the micro level

- A one-equation climate model
  - Given $[CE(t_{initial}), T(t_{initial})]$, we use $\frac{\Delta T}{\Delta CE} = \lambda_{CCR}$ to project temperature

- Firm-level climate damages

$$X_{i,\tau}(t) = X_i'(t)[1 - D_i(t)]$$

Post-shock level of the target variable

Targets:
- labour productivity
- capital stock

Micro-level shock

$$D_i(t) = \Omega(t) + \epsilon_i \text{ with } \epsilon_i \approx \text{i.i.d. N}(0, 0.01)$$

$$\Omega(t) = 1 - \frac{1}{1 + c_1 T(t) + c_2 T(t)^2}$$

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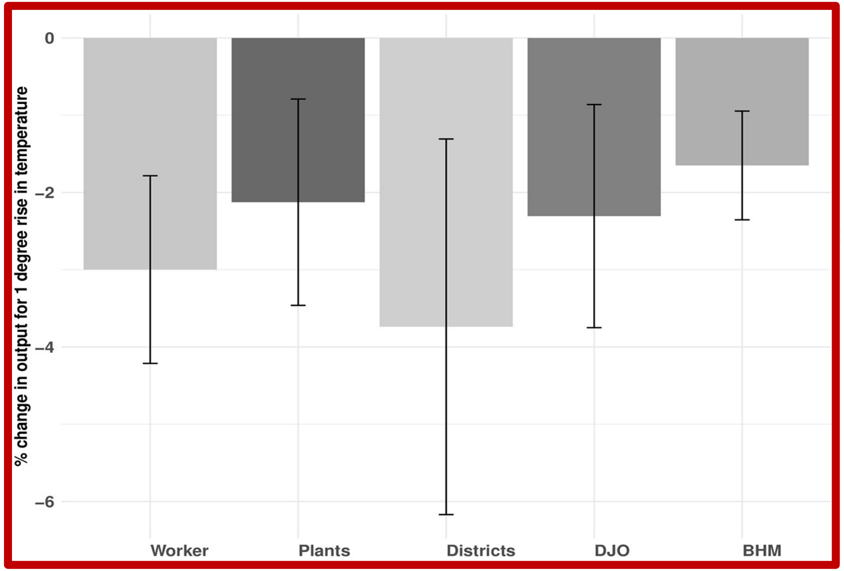


$$X_i'(t)[1 - D_i(t)]$$

Micro-level shock

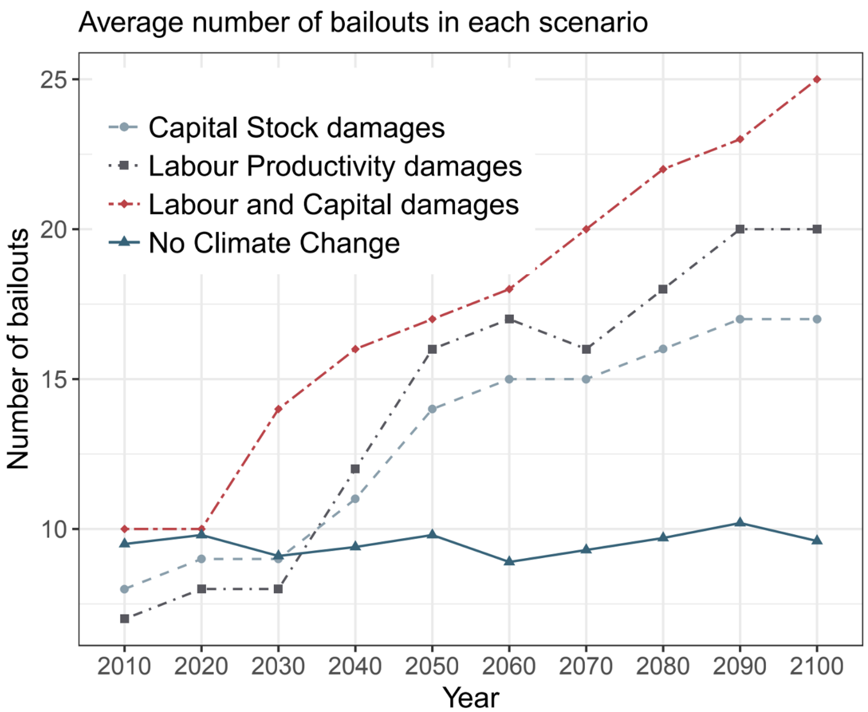
$$D_i(t) = \Omega(t) + \epsilon_i \text{ with } \epsilon_i \approx \text{i.i.d. N}(0, 0.01)$$

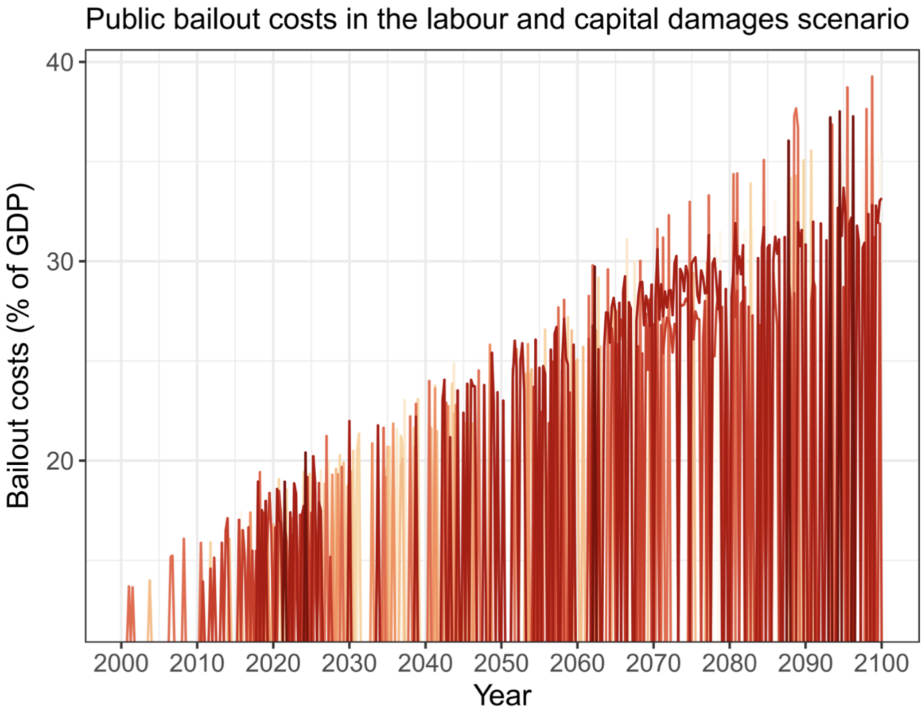
$$\Omega(t) = 1 - \frac{1}{1 + c_1 T(t) + c_2 T(t)^2}$$

Somanathan, E., Somanathan, R., Sudarshan, A., & Tewari, M. (2021). The impact of temperature on productivity and labor supply: Evidence from Indian manufacturing. *Journal of Political Economy*, *129*(6), 1797-1827.

Climate-induced financial instability

- Climate change increases frequency and size of banking crises
- Key channel: non-performing loans (→ credit losses)
- Non linear effect: contained climate change might even improve stability (via higher growth and investments)





The effects on growth and cycles

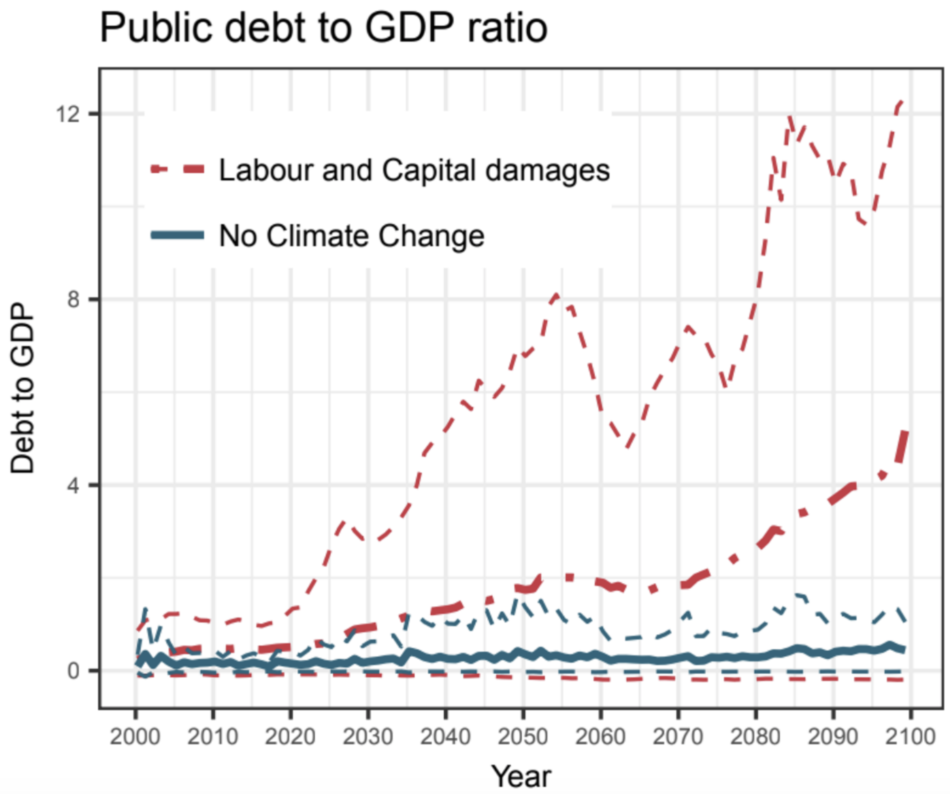
- Large and increasing impacts on growth
- Augmented growth volatility
- Qualitative change of regime in the second half of the simulation (2050-2100)

The effects on public debt

- If banking crises are solved through publicly financed bailouts, climate change raise the fiscal costs of crises' resolutions though increased deficit

- Reduced productivity growth and increased volatility lower aggregate demand (lower GDP)

- Debt/GDP ratio shows a slow-moving behaviour, but projected to increase by factor of 4 at 2100

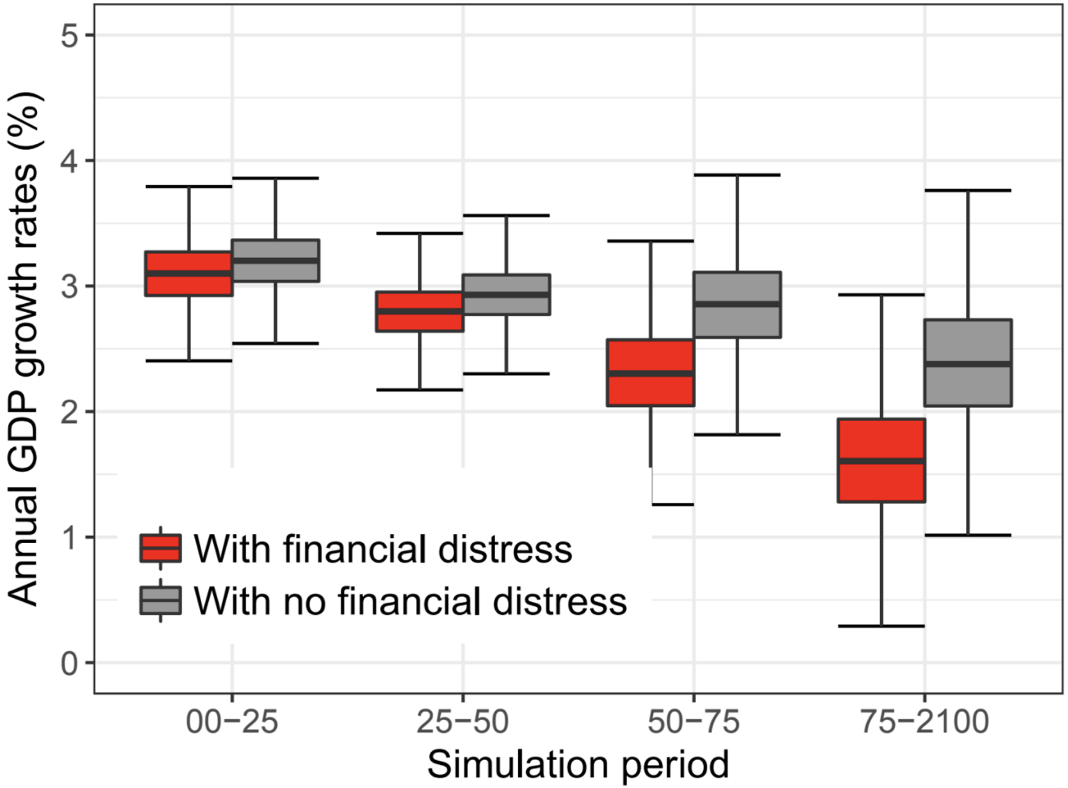


The feedback effect of “climate-induced financial distress”

- How much of the climate-induced effect on growth is attributable to “financial distress”?

- We develop a counterfactual scenario wherein loans from defaulting firms are immediately paid out by the government (i.e. credit supply channel is unaffected)

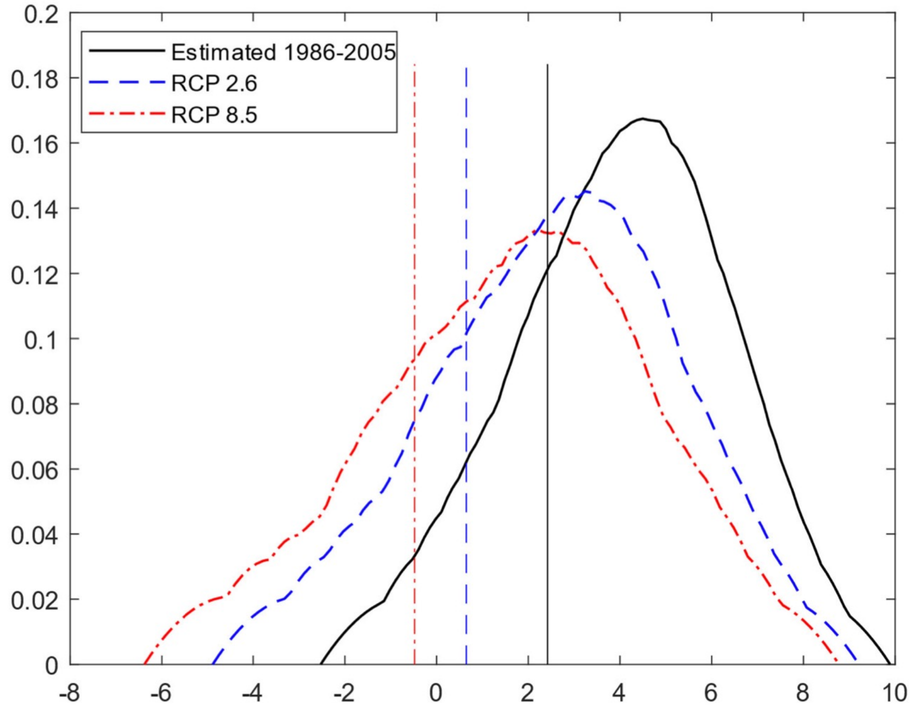
- We estimate that financial distress responsible for about 20% of GDP growth reduction



The empirical counterpart

- Growth-at-risk literature reveals similar projected patterns to simulated experiments
- Climate change may impact the entire distribution of economic activity over time
- Especially, the **left tail** of the growth rate distribution is affected: severe contractions in economic activity more likely

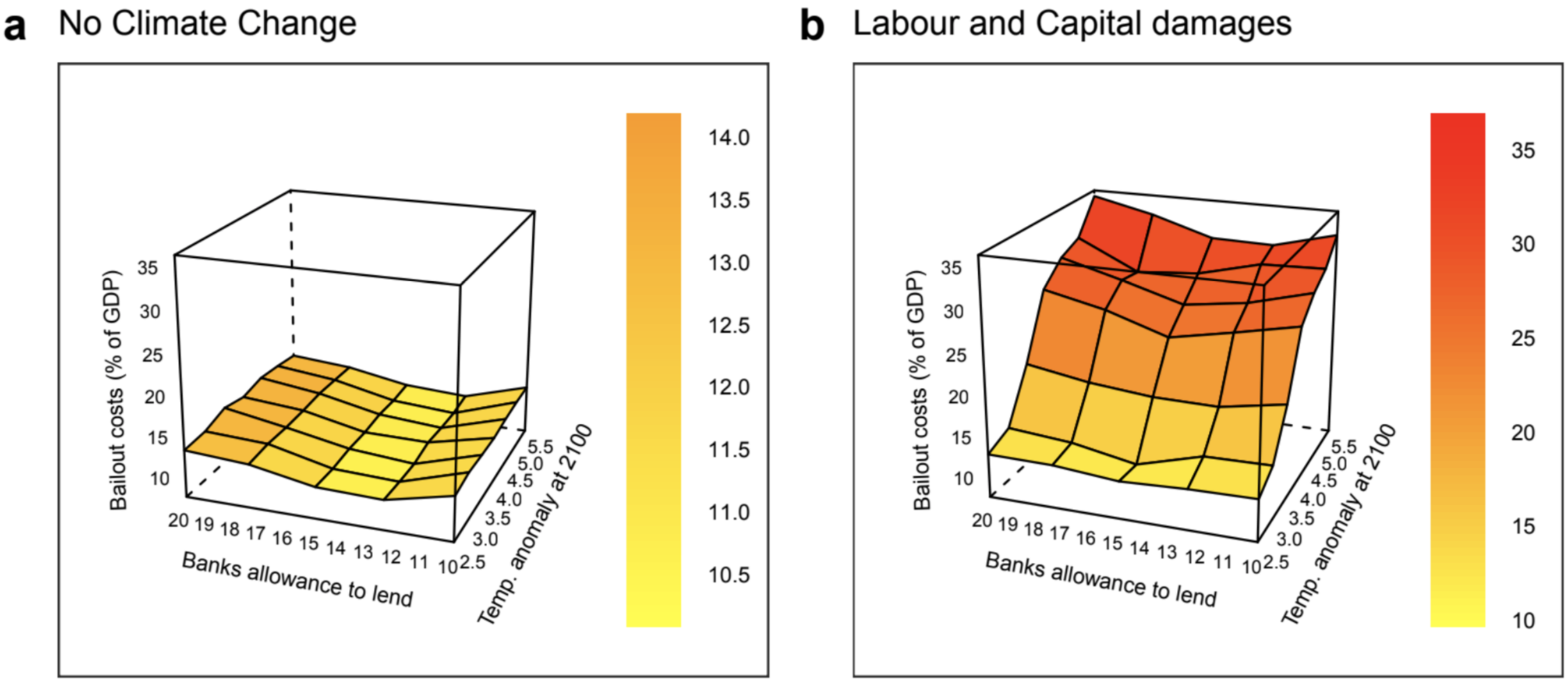
Effects of Alternative Representative Concentration Pathways on the Probability Distribution Function (PDF) of the Percent Change in Real GDP Per Capita in India



Kiley, M. T. (2021). *Growth at Risk From Climate Change* (No. 2021-054). Finance and Economics Discussion Series. Board of Governors of the Federal Reserve System (US).

The role of macroprudential instruments

- Bailout costs increase almost linearly with temperature
- Capital adequacy ratios (inverse of “banks allowance to lend”) can partially offset the fiscal costs of financial instability
- Policy effectiveness increases with temperature → scope for a “climate-based capital buffer”?



What about other impact channels? An additional example

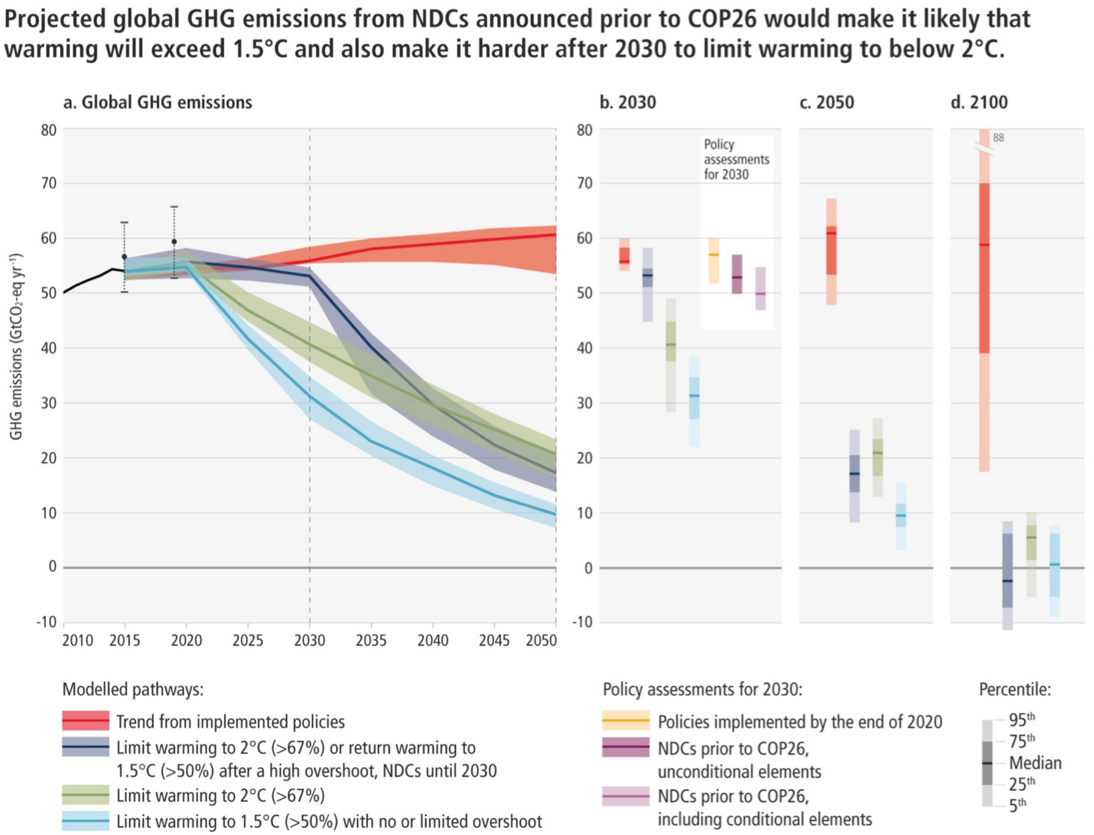
- Can climate change affect the low carbon transition via physical risks?
- DSK has been used to investigate the likelihood of a low carbon transition under different “impact scenarios”
- The level of energy demand positively affect the speed of path-dependent technological change
- Reduced labour productivity exert large effect on output and energy demand growth, which facilitate the transition
- Energy efficiency shocks leave growth unaffected while increase energy demand, which foster the pace of technological change in the incumbent (fossil-fuel) technology and reduce the odds of the low carbon transition
- Should climate policy strength reflect the distribution of physical risks?

Shock scenario:	Transition likelihood	Output growth	Energy growth	Emissions at 2100
Aggregate output	18% (of which 83% before 2025)	3.18% (0.001)	3.09% (0.003)	28.33 (6.431)
Labour productivity	20%* (of which 69% before 2025)	1.51%* (0.002)	1.16%* (0.003)	25.70* (4.921)
Energy efficiency	7%* (of which 43% before 2025)	3.02% (0.003)	3.37%* (0.003)	40.64* (3.872)

Note: all values refer to the average computed from a Monte Carlo of size 200. Standard errors are reported below each coefficient in parenthesis. * indicates a statistically significant (0.05 level) difference with respect to the *Aggregate output* scenario; tests for transition likelihoods are carried out via bootstrapping.

Policy risks

- Current policies likely ineffective/insufficient
- Which policies should be implemented?
- We tested ensembles of
  - Price-based policies
  - Regulations



Policy risks

Counterfactual policy evaluation

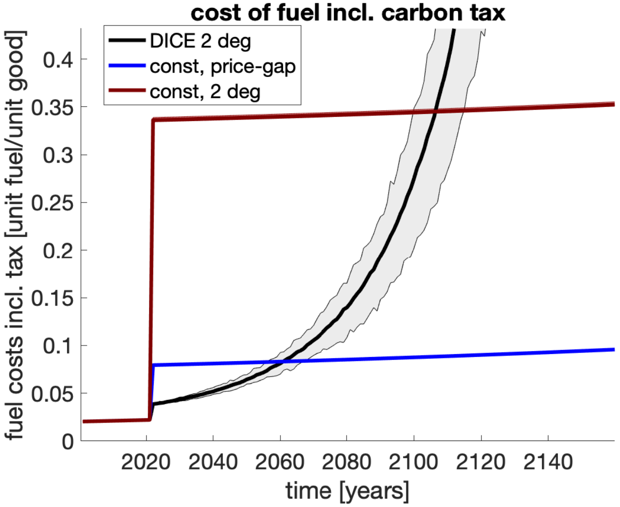
Label	Policy instrument	Description
	Carbon Taxation	
Taxcrit	Constant carbon tax	Sufficiently high tax to induce full energy transition by 2100
Tax2d	Constant carbon tax	Sufficiently high tax to keep warming below 2°C
Tax2dh	Constant carbon tax	As Tax2d, with full rebate of revenues on households
Tax2df	Constant carbon tax	As Tax2d, with full rebate of revenues on firms
TaxDICE2d	Increasing carbon tax	Exponentially increasing tax; same rate as the optimal policy of the DICE model constrained to below 2°C warming
TaxDICEopt	Increasing carbon tax	Exponentially increasing tax; same rate as the optimal policy of the (unconstrained) DICE model
TaxDICEhigh	Increasing carbon tax	As TaxDICE2d, but with initial value corresponding to Taxcrit
	Green Subsidies	
Csub	Lump-sum transfer	Subsidy for the construction of green plants in the power sector
RnD	Lump-sum transfer	Subsidy for green R&D in the power sector
	Command and Control	
Elreg	Mandatory regulation with fine	Ban on fossil-fuel use in the capital good sector, with T_{Elreg} years grace period
Ban	Mandatory regulation with fine	Ban on the construction of brown electricity plants, with T_{Ban} years grace period

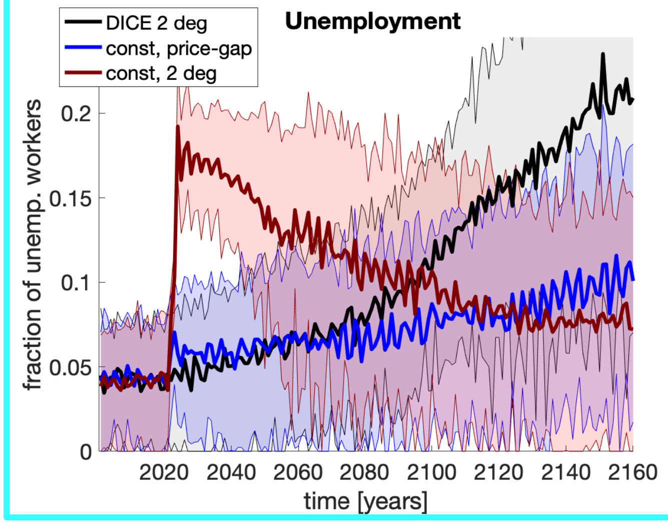
Simulation protocol

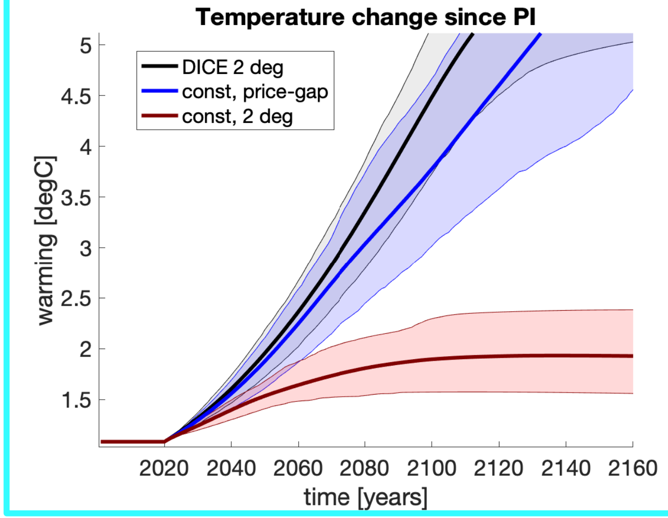
1. Calibration of the business-as-usual «benchmark» scenario (no policy) and validation (stylyzed facts replication)
2. Definition of policy implementation rules
3. Simulation experiments: 100 independent replicas for each experiment
4. Comparison of across-replicas averages + characterization of uncertainty

The fallacy of carbon taxation

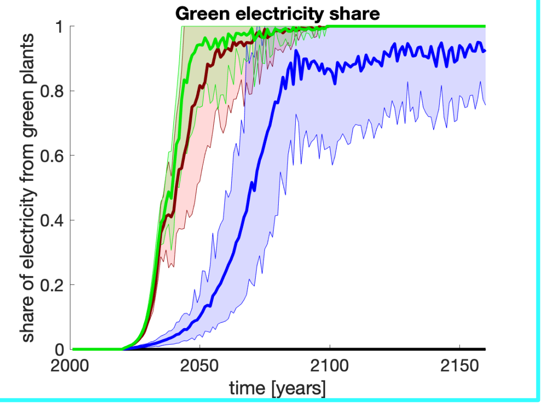
DICE 2º: carbon tax which in Nordhaus' DICE2016 model is the optimal to stay below 2º warming.
Const, gap: constant tax, just sufficient to trigger the transition in the power sector
Const, 2º: constant tax, just sufficient to stay <2º

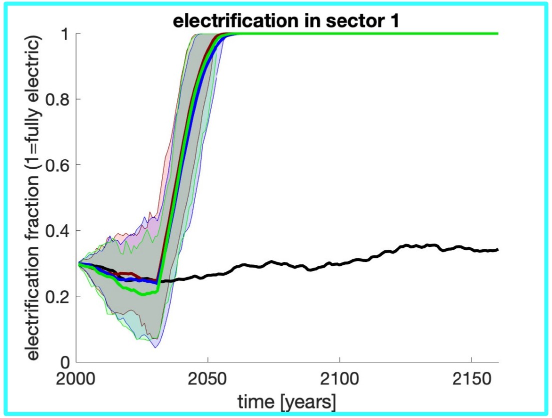


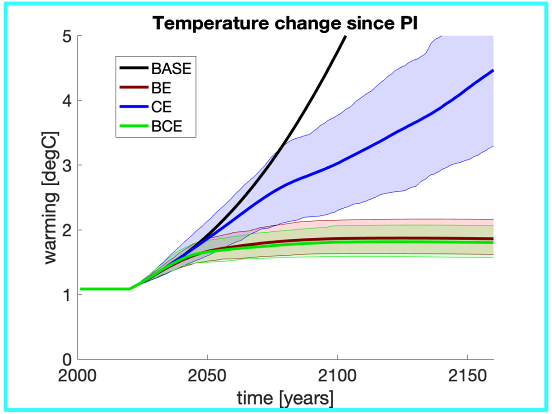




Regulation policies and subsidies







Combine electrification regulation (forcing heavy industry to electrify), with measures to get green electricity:

-- banning brown plant construction (BE), with 20 years grace period

-- subsidising green plant construction (CE), by an amount that is $S = \max(\, C_g - \frac{1}{3} C_b, 0\,)$

-- or both of them (BCE)

(base = no policy at all)

Non-tax instruments can bring about 2º.

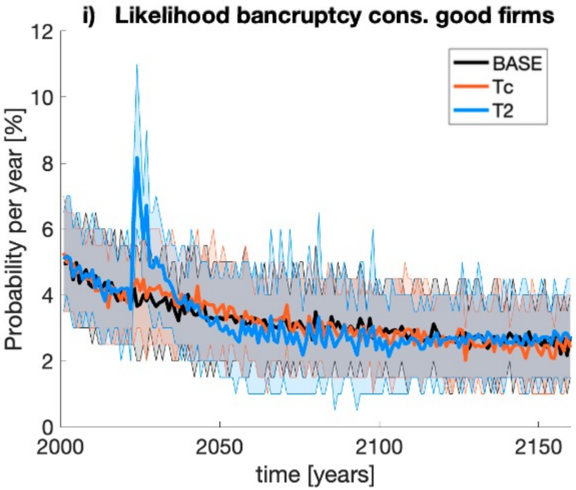
Slight *reduction* in unemployment due to workers being needed to construct green plants (while no adverse impact of tax).

Lower impact on economy basically due to state taking most of the cost; while tax puts cost on firms.

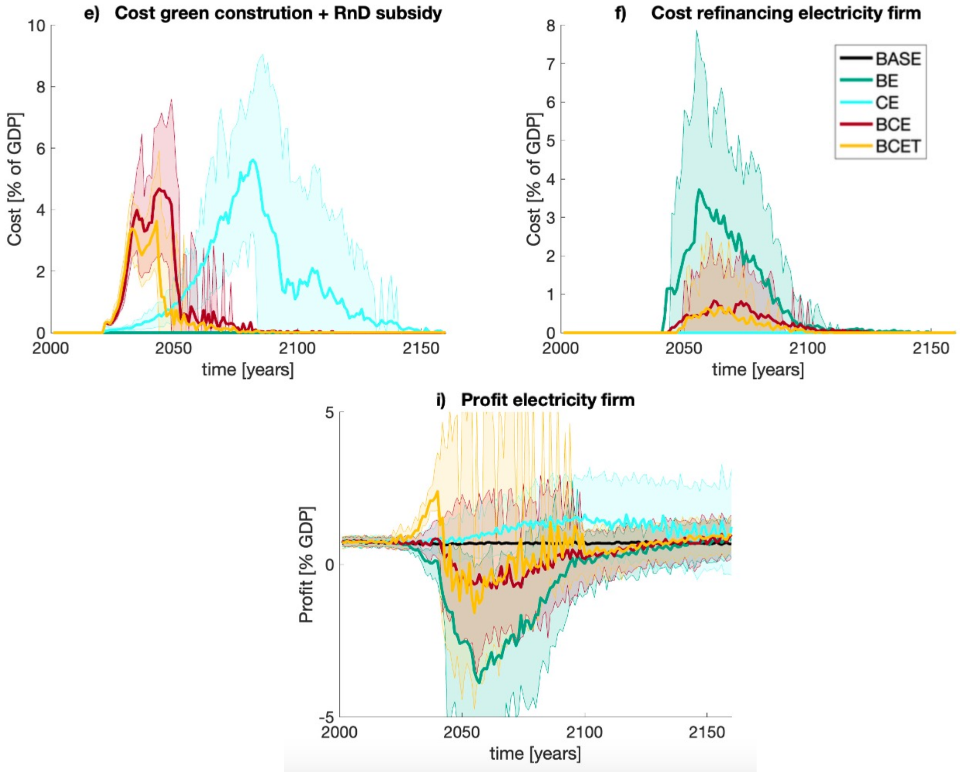
This might adversely affect public finances

On transition frictions

Carbon Taxation



Alternative policy mix



Overall comparison

	Policy	Decarbonization speed: *Power sector*	Decarbonization speed: *Industry sector*	Climate mitigation: *Peak warming*	Transition frictions: *Business failures*	Transition frictions: *Unemployment crises*	Sustainable growth: *Job creation during the transition*	Sustainable growth: *Long run growth*	Policy cost: *Impact on deficit*
Taxcrit	Carbon tax	Green	Red	Red	Orange	Orange	Red	Red	Green
Tax2d	Carbon tax	Green	Green	Green	Red	Red	Red	Green	Green
Tax2dh	Carbon tax	Green	Green	Green	Orange	Red	Orange	Green	Green
Tax2df	Carbon tax	Green	Green	Green	Orange	Red	Red	Green	Green
TaxDICE2d	Carbon tax	Orange	Orange	Red	Orange	Red	Red	Red	Green
ET2	Regulation + tax	Green	Green	Green	Red	Red	Red	Green	Green
RT2	Susbidy + tax	Green	Orange	Green	Red	Red	Orange	Green	Green
BE	Only regulation	Green	Green	Green	Green	Green	Green	Green	Red
CE	Regulation + subsidy	Orange	Green	Orange	Green	Green	Green	Orange	Red
BCE	Regulation + subsidy	Green	Green	Green	Green	Green	Green	Green	Red
BCER	Regulation + subsidy	Green	Green	Green	Green	Green	Green	Green	Red
BCET	Regulation + subsidy + tax	Green	Green	Green	Green	Orange	Green	Green	Green

Conclusions

- Agent based models can offer a novel and complementary perspective to the analysis of the economic consequences of climate change
- By leveraging on a model with heterogeneous micro-level climate damages we find evidence of climate induced threats to economic and financial stability
- Financial distress in the banking sector exacerbates the macroeconomic costs of climate change through the credit channel
- Prudential regulation targeting climate risks can alleviate impacts, but complementary mitigation measures are required
- Policy (transition) risk may be extremely dangerous to economic stability, but almost only if comes through too aggressive price-based policies → need of policy packages (carbon tax can be used as a signal, providing revenues)

Appendix

- **Capital-good firms search for better and greener machines and for more efficient production techniques**
  - $A_{i,k}(t)$ and $B_{i,k}(t)$ determine the technology of firm i at time t
  - $A_{i,k}(t)$: productivity of machine in the consumption-good sector
  - $B_{i,k}(t)$: productivity of production technique of capital-good firm i
  - machines also characterized by energy efficiency (EE) and environmental friendliness (EF)
  - technical change occurs along all the three dimensions

- **Production depends on labour, energy and carbon taxes:**

  $c_i(t) = \frac{w(t)}{A^L_{i,\tau}} + \frac{c^{en}(t)}{A^{EE}_{i,\tau}} + t_{CO2} Em_i$

- **R&D:**
  - R&D investment (RD) is a fraction of firm sales (S):

$$RD_i(t) = \upsilon S_i(t-1) \qquad \upsilon > 0$$

  - capital-good firms allocate R&D funds between innovation (IN) and imitation (IM):

$$IN_i(t) = \xi RD_i(t) \qquad IM_i(t) = (1-\xi) RD_i(t) \qquad \xi \epsilon [0,1]$$

- **Innovation and imitation: two steps procedure**
- **Innovation:**
  1) firm successfully innovates or not through a draw from a Bernoulli($\theta_1(t)$), where $\theta_1(t)$ depends on $IN_i(t)$:
  $$\theta_1(t) = 1 - e^{-o_1 IN_i(t)} \qquad o_1 > 0$$
  2) search space: the new technology is obtained multiplying the current technology by $(1 + x_i(t))$, where $x_i(t) \sim Beta$ over the support (x_0, x_1) with $x_0 < 0, x_1 > 0$
- **Imitation**
  1) firm successfully imitates or not through a draw from a Bernoulli($\theta_2(t)$), where $\theta_2(t)$ depends on $IM_i(t)$:
  $$\theta_2(t) = 1 - e^{-o_2 IM_i(t)} \qquad o_2 > 0$$
  2) firms are more likely to imitate competitors with similar technologies (Euclidean distance)

- **Capital-good firms:**
  - if they successfully innovate and/or imitate, they choose to manufacture the machine with the lowest $p_i + c_i^1 b$
    - p_i: machine price;
    - c_i^1: unit labor cost of production entailed by machine in consumption-good sector;
    - b: payback period parameter
  - fix prices applying a mark-up on unit cost of production
  - send a "brochure" with the price and the productivity of their machines to both their historical and some potential new customers

- **Consumption-good firms:**
  - choose as supplier the capital-good firm producing the machine with the lowest $p_i + c_i^1 b$ according to the information contained in the "brochures"
  - send their orders to their supplier according to their investment decisions

- **Expansion investment**
  - demand expectations (D^e) determine the desired level of production (Q^d) and the desired capital stock (K^d)
  - firm invests (EI) if the desired capital stock is higher than the current capital stock (K):

$$EI = K^d - K$$

- **Replacement investment**
  - payback period routine:

$$\frac{p^{new}}{\left[\frac{w(t)}{A^L_{i,\tau}} + \frac{c^{en}(t)}{A^{EE}_{i,\tau}}\right] - c^{new}_j} \leq b$$

  - also machine older than Λ periods are replaced

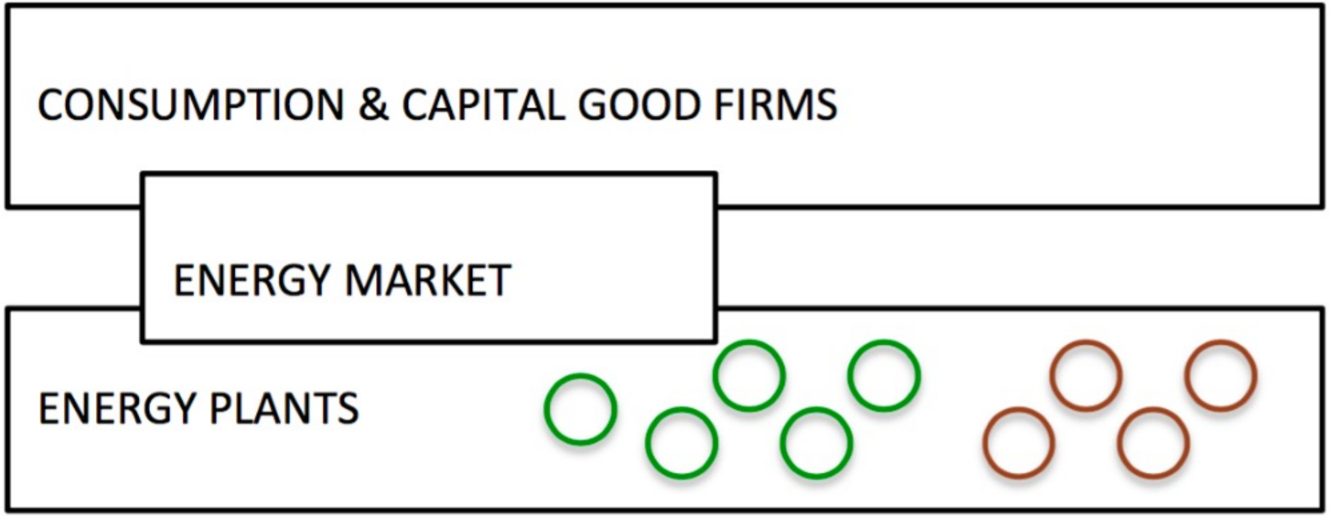
- **Production and investment decisions of consumption-good firms may be constrained by their financial balances**
    - consumption-good firms first rely on their stock of liquid assets and then on more expensive external funds provided by the banking sector
    - credit ceiling: the stock of debt of consumption-good firms is limited by their gross cash flows:

$$Deb_j(t) \leqslant \kappa S_j(t-1), \quad \kappa \geqslant 1$$

- **Banks:**
    - they provide credit according to Basel II macroprudential framework:

$$TC_b(t) = \frac{NW_b(t-1)}{\tau\left(1 + \beta \frac{BD_b(t-1)}{TA_b(t-1)}\right)},$$

    - credit is allocated to firms on a pecking-order base according to their ratio between turnover and stock of liquid assets
    - credit rationing endogenously arise


CONSUMPTION & CAPITAL GOOD FIRMS
ENERGY MARKET
ENERGY PLANTS

- A vertically integrated monopolist employing *green* and *dirty* plants
- Plants are heterogeneous in terms of cost structures, thermal efficiencies and environmental friendliness
- Unit production cost of energy
  - *green*: $c_{ge}(t) = 0$
  - *dirty*: $c_{de}(t) = \frac{p_f(t)}{A^{TE}_{de,\tau}}$ where $p_f(t)$ is the price of fossil fuels (exogenous)
- Total energy production cost depends on the mix of active plants
- Energy price is fixed adding a mark-up on the inframarginal unit' cost
- The energy sector invest to expand production capacity
  - *green*: $IC_{ge,\tau} > 0$
  - *dirty*: $IC_{de,\tau} = 0$

- The energy firm invest a fraction of its past green and dirty revenues in R&D:

$$RD_{ge}(t) = \xi S_{ge}(t-1) \qquad RD_{de}(t) = \xi S_{de}(t-1)$$

- Innovations:
    - reducing the fixed cost of green plant investment
    - increasing the thermal efficiency of dirty plants OR reducing their emissions

- The energy producer adds a fixed mark-up $\mu_e \geq 0$ on the average cost of the more expensive infra-marginal plant:

$$p_e(t) = \mu_e \qquad D_e(t) \leq K_{ge}(t)$$

$$p_e(t) = \overline{c}_{de}(\tau, t) + \mu_e \qquad D_e(t) > K_{ge}(t),$$

where $\overline{c}_{de}(\tau, t) = \max_{\tau \in IM} c_{de}(\tau, t)$.

- Expansion investment is made up of new green capacity whenever the cheapest vintage of green plants is below the discounted production cost of the cheapest dirty plant:

$$\underline{IC}_{ge} \leq b\underline{c}_{de}$$

where b is a discount factor, $\underline{IC}_{ge} = \min_\tau IC^\tau_{ge}$, and $\underline{c}_{de} = \min_\tau c^\tau_{de}$.

- **Supply:**
  - imperfect competition: prices (p_j) $\Rightarrow$ variable mark-up (mi_j) on unit cost of production (c_j)

$$p_j(t) = (1 + mi_j(t))c_j(t);$$

$$mi_j(t) = mi_j(t-1)\left(1 + \alpha \frac{f_j(t-1) - f_j(t-2)}{f_j(t-2)}\right);$$

    $\alpha > 0$; f_j: market share of firm j
  - firms first produce and then try to sell their production (inventories)

- **Market dynamics:**
  - market shares evolve according to a “quasi” replicator dynamics:

$$f_j(t) = f_j(t-1)\left(1 + \chi \frac{E_j(t) - \overline{E}(t)}{\overline{E}(t)}\right); \quad \chi \geqslant 0$$

    E_j: competitiveness of firm j; $\overline{E}$: avg. competitiveness of consumption-good industry;
  - firm competitiveness depends on price and unfilled demand (l_j):

$$E_j(t) = -\omega_1 p_j(t) - \omega_2 l_j(t), \quad \omega_{1,2} > 0$$

- **Firm failure:**
  - zero market share or negative stock of liquid assets
  - in that case, firm exits and defaults on its loans

- **Bank failure:**
  - firm's default (BD) has a negative effect on banks' profits:

$$\Pi^{b}_{k,t} = \sum_{cl=1}^{Cl_k} r_{deb,cl,t} L_{cl,t} + r_{res,t} Cash_{k,t} + r_{B,t} Bonds_{k,t} - r_D Dep_{k,t} - BD_{k,t}$$

  - banks fail whenever their net worth becomes negative

- **Full bail-out rule**
  - the Government always steps in and save the failing bank
  - bank bail-out has a negative impact on public budget

- Exogenous labor supply

- Wage dynamics determined by avg. productivity, inflation and unemployment

$$\frac{\Delta w(t)}{w(t-1)} = \pi^T + \psi_1 * (\pi_t - \pi^T) + \psi_2 * \frac{\Delta \overline{AB}(t)}{\overline{AB}(t-1)} - \psi_3 * \frac{\Delta U(t)}{U(t-1)}$$

- Involuntary unemployment $+$ possibility of labor rationing

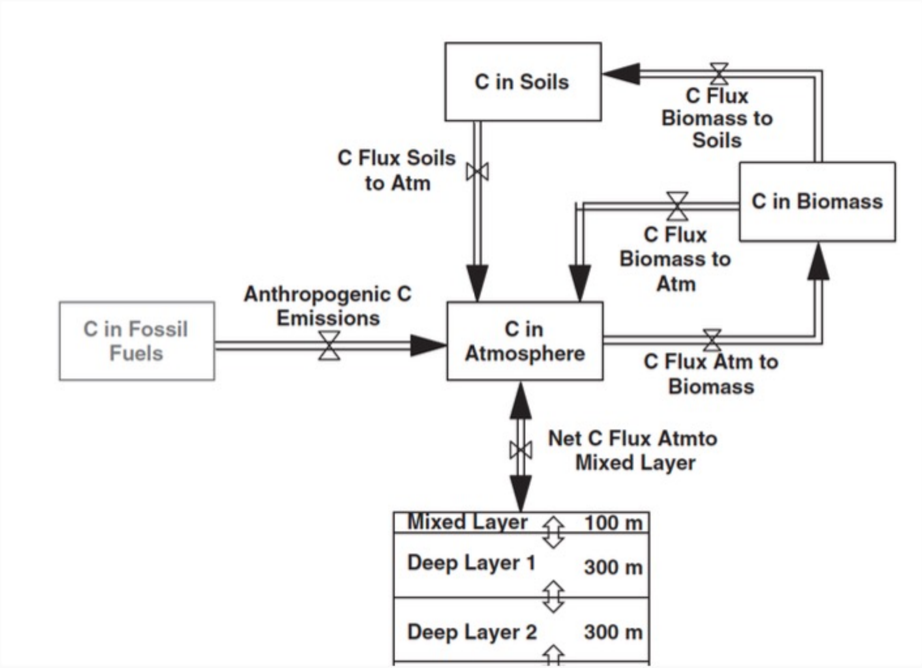
- **Fiscal policy and the public budget:**
    - constant tax and unemployment-subsidy rate
    - the public deficit in each period is:

$$Def_t = -Tax_t + G_t + r_{B,t} Debt_t$$

- **Monetary policy:**
    - fixed interest rate
    - Taylor rule

- **Employment, consumption, investment, inventories and GDP are obtained by aggregating micro quantities**

- C-ROADS (Sterman et al. 2012)



- 1-equation (Matthews et al. 2012)