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

Financial stability and climate change


- 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

An agent based perspective - II

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Within the economics of climate change, ABMs have been developed to study a variety of issues:

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Relatively recent application to the macrofinance – climate nexus

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
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

$$X_{i,T}(t) = X'_i(t)[1 - D_i(t)]$$

Post-shock level of the target variable

Micro-level shock

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

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

Targets:
  ● labour productivity
  ● capital stock
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

\[
X'_i(t)[1 - D_i(t)]
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Micro-level shock

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

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

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.

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?

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

*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

Projected global GHG emissions from NDCs announced prior to COP26 would make it likely that warming will exceed 1.5°C and also make it harder after 2030 to limit warming to below 2°C.
Counterfactual policy evaluation

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

**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 2°**: carbon tax which in Nordhaus’ DICE2016 model is the optimal to stay below 2° warming.

**Const, gap**: constant tax, just sufficient to trigger the transition in the power sector

**Const, 2°**: constant tax, just sufficient to stay <2°
Regulation policies and subsidies

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

i) Likelihood bankruptcy cons. good firms

Alternative policy mix

e) Cost green construction + R&D subsidy

f) Cost refinancing electricity firm

i) Profit electricity firm
### Overall comparison

<table>
<thead>
<tr>
<th>Policy</th>
<th>Decarbonization speed</th>
<th>Climate mitigation</th>
<th>Transition frictions</th>
<th>Sustainable growth</th>
<th>Policy cost</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Power sector</td>
<td>Industry sector</td>
<td>Peak warming</td>
<td>Business failures</td>
<td>Unemployment crises</td>
</tr>
<tr>
<td>Taxcrit</td>
<td>Carbon tax</td>
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<tr>
<td>ET2</td>
<td>Regulation + tax</td>
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<td></td>
<td></td>
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<tr>
<td>RT2</td>
<td>Subsidy + tax</td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>BE</td>
<td>Only regulation</td>
<td></td>
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<tr>
<td>CE</td>
<td>Regulation + subsidy</td>
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<tr>
<td>BCE</td>
<td>Regulation + subsidy</td>
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<td>BCER</td>
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</tr>
<tr>
<td>BCET</td>
<td>Regulation + subsidy + tax</td>
<td></td>
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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:
  \[ c_i(t) = \frac{w(t)}{A_i^{\ell}} + \frac{c_{en}(t)}{A_i^{EE}} + t_{CO2}Em_i \]

• R&D:
  • R&D investment ($RD$) is a fraction of firm sales ($S$):
    \[ RD_i(t) = \nu S_i(t - 1) \quad \nu > 0 \]
  • capital-good firms allocate R&D funds between innovation ($IN$) and imitation ($IM$):
    \[ IN_i(t) = \xi RD_i(t) \quad IM_i(t) = (1 - \xi) RD_i(t) \quad \xi \in [0, 1] \]
• 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 $IN_i(t)$:
     \[ \theta_1(t) = 1 - e^{-o_1IN_i(t)} \quad o_1 > 0 \]
  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 $IM_i(t)$:
     \[ \theta_2(t) = 1 - e^{-o_2IM_i(t)} \quad o_2 > 0 \]
  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 \( p_i + c_i^1 \cdot b \)
    • \( p_i \): 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 \( p_i + c_i^1 \cdot b \) 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:

\[
\frac{p_{\text{new}}}{\left[ \frac{w(t)}{A_{i,\tau}} + \frac{c^{en}(t)}{A_{i,\tau}^{EE}} \right] - c_{j}^{\text{new}}} \leq b
\]

- also machine older than \(\Lambda\) 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:
    \[ \text{Deb}_j(t) \leq \kappa S_j(t-1), \quad \kappa \geq 1 \]

• 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
• 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*: \(c_{de}(t) = \frac{p_f(t)}{A_{de,\tau}}\) 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:

\[ RD_{ge}(t) = \xi S_{ge}(t - 1) \quad \quad \quad RD_{de}(t) = \xi S_{de}(t - 1) \]

• 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:

\[
\begin{align*}
  p_e(t) &= \mu_e & D_e(t) &\leq K_{ge}(t) \\
  p_e(t) &= \overline{c}_{de}(\tau, t) + \mu_e & D_e(t) &> K_{ge}(t),
\end{align*}
\]

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:

\[ \overline{IC}_{ge} \leq bc_{de} \]

where \( b \) is a discount factor, \( \overline{IC}_{ge} = \min_{\tau} IC_{ge}^\tau \), and \( c_{de} = \min_{\tau} c_{de}^\tau \).
- **Supply:**
  - imperfect competition: prices \((p_j)\) \(\Rightarrow\) variable mark-up \((m_{ij})\) on unit cost of production \((c_j)\)
    \[
p_j(t) = (1 + m_{ij}(t))c_j(t);
    \]
    \[
m_{ij}(t) = m_{ij}(t - 1) \left(1 + \alpha \frac{f_j(t - 1) - f_j(t - 2)}{f_j(t - 2)}\right);
    \]
    \(\alpha > 0; \quad f_j: \) 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:

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

*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:

\[
\Pi_{k,t}^b = \sum_{cl=1}^{C_{l_k}} r_{deb,cl,t} L_{cl,t} + r_{res,t} Cash_{k,t} + r_{B,t} Bonds_{k,t} - r_{D} Dep_{k,t} - BD_{k,t}
\]

  • 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

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

• 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)