Macro drivers of Energy and Climate Policy: an Agent-Based Perspective

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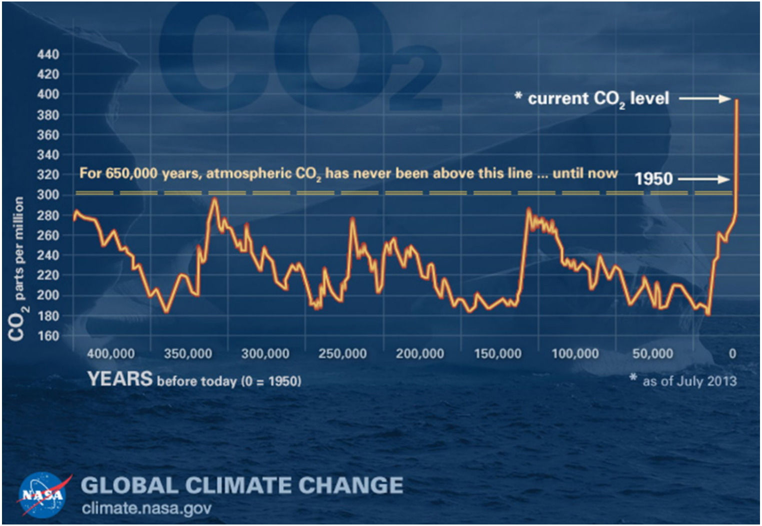
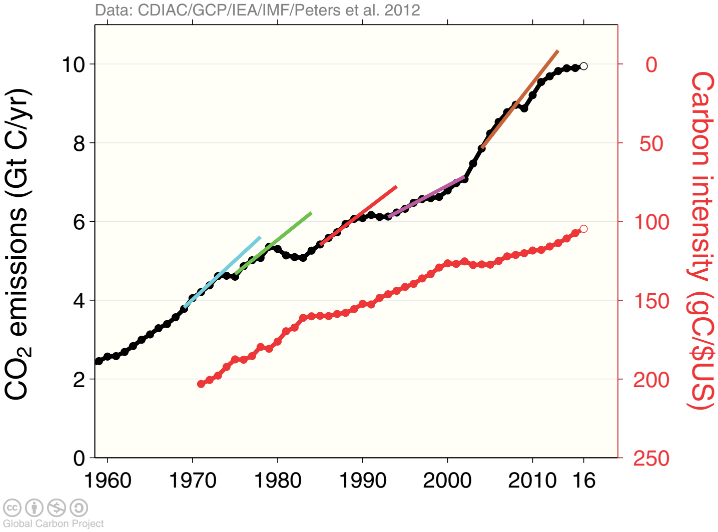
Energy Innovation Bootcamp - FSR - Fiesole

Motivation


440
420
400
380
360
340
320
300
280
260
240
220
200
180
160
CO_2 parts per million
* current CO_2 level
For 650,000 years, atmospheric CO_2 has never been above this line ... until now
1950
400,000
350,000
300,000
250,000
200,000
150,000
100,000
50,000
0
YEARS before today (0 = 1950)
* as of July 2013
GLOBAL CLIMATE CHANGE
climate.nasa.gov

Issue 1: emissions in the last half century

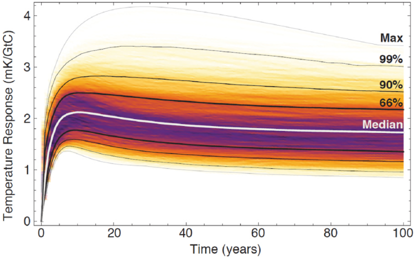
- Slowdowns as missed opportunities



Issue 2: emissions and temperature

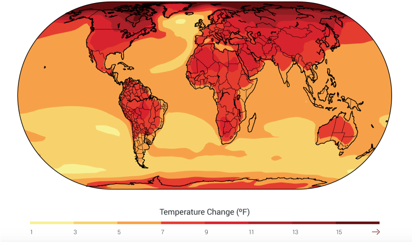
- Emissions bring about warming, unevenly in time and space

Temperature increase from unitary emission over time



(Ricke and Kaldeira, 2014)

Global temperature under RCP8.5 (business as usual)

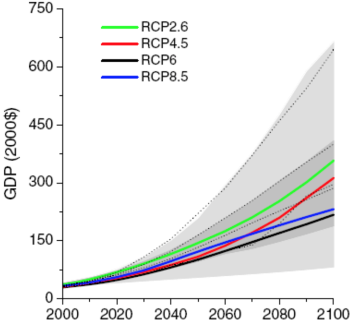


(NOAA NCDC, 2014)

Issue 3: impacts and policies

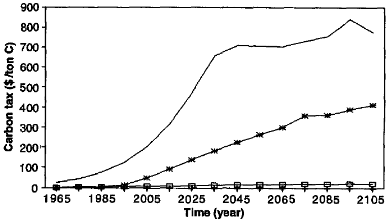
- Consequences and remedies to climate change are an open challenge

CGE models' projections



(IPCC, 2012)

DICE carbon tax



(Nordhaus, 1992)

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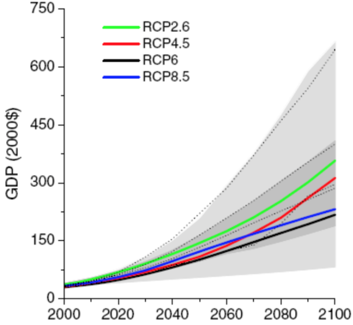

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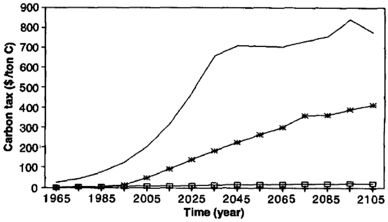

(Nordhaus, 1992)

Satisfactory?

How to contribute?

- **The role of technology in transition dynamics**

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- **The importance of heterogeneity (and interactions) in reacting to climate shocks**

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- **The role of technology in transition dynamics**
- **The importance of heterogeneity (and interactions) in reacting to climate shocks**
- **The double role of credit and finance**
- **Policy interactions and the role of institutions**

A Dystopian Schumpeter meeting Keynes model (DSK)

- Fist attempt to build an integrated assessment agent based model

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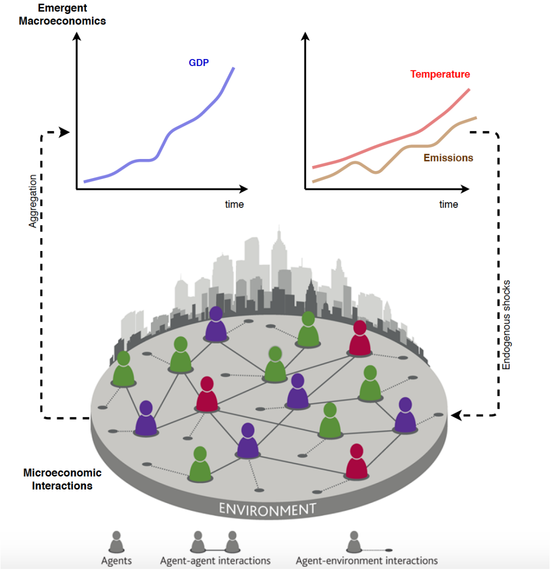
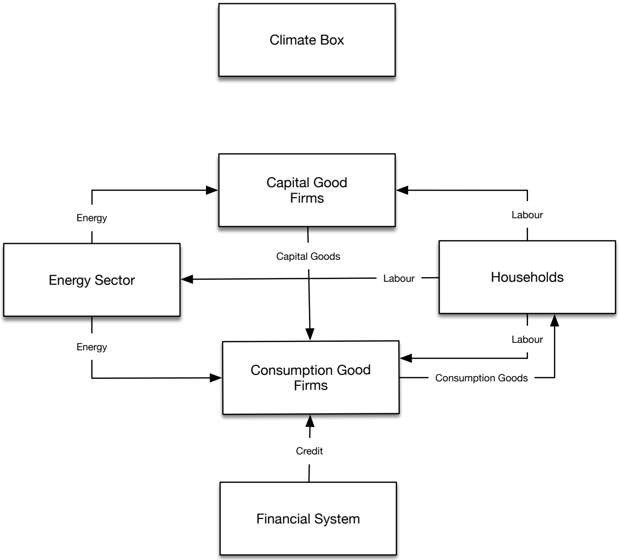
- Stochastic damage generating function

DSK - The Dystopian Schumpeter meeting Keynes model



DSK - The Structure of the Model



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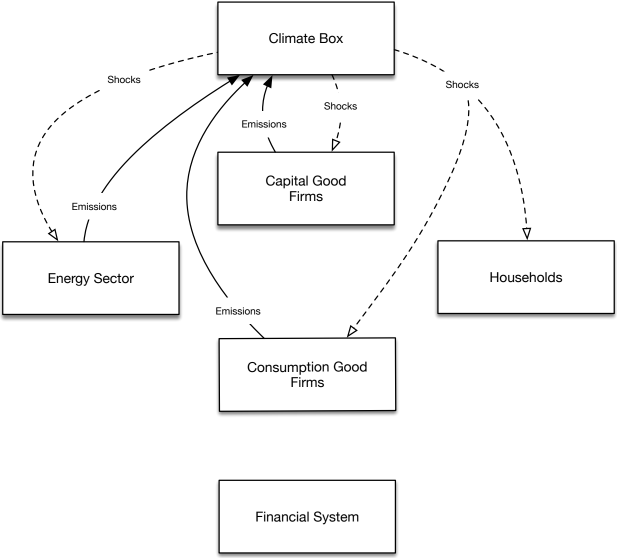

What we do

- **Impact Assessment**
  We use both simulation and empirical data to identify the impacts of climate and weather dynamics on
  - economic output
  - public deficit
  - likelihood of crises/recessions

- **Policy Analysis**
  DSK can be used as a policy laboratory to test how to mitigate emissions and promote green growth
  - Command and control policies
  - Pricing policy (carbon taxes)
  - Fiscal instruments (energy taxes and R&D subsidy)
  - Mission Oriented / Entrepreneurial State policy
  - Climate-Finance policies

A Sneak Preview of the Results

Validation

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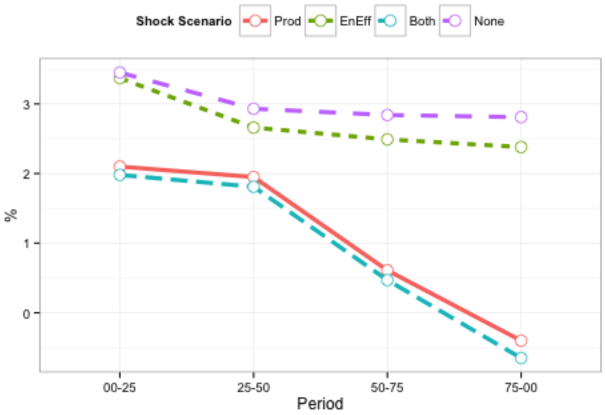
Policy analysis

- Timely and large-scale policies interventions are needed to foster the transition towards a green economy
- Such policies lead to win-win pathways characterized by higher GDP growth and lower unemployment in the long run (link to e.g. Green New Deal)
- Carbon price is not enough; regulation is helpful (e.g. for financial stability)

The Impacts of Climate: Growth

- **Large negative effect on growth, qualitative change of regime**

Average yearly growth rate of GDP



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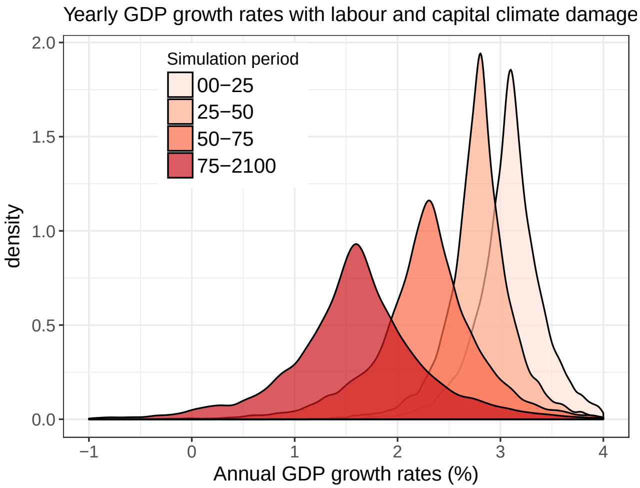
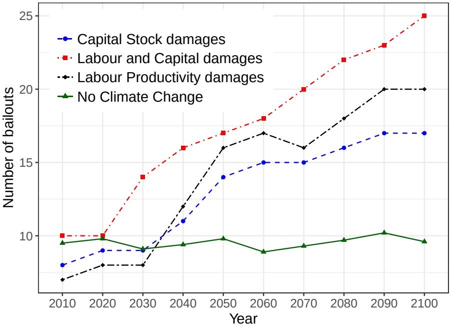


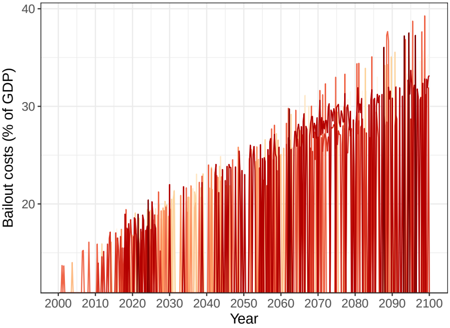
The Impact of Climate: the Banking System

- The differential effects across the impact scenarios magnify with time
- The number of bailouts sharply increases after 2060, when temperature anomaly reaches about 3 degrees
- Bailout costs can reach up to 40% of GDP

Average number of bailouts in each scenario

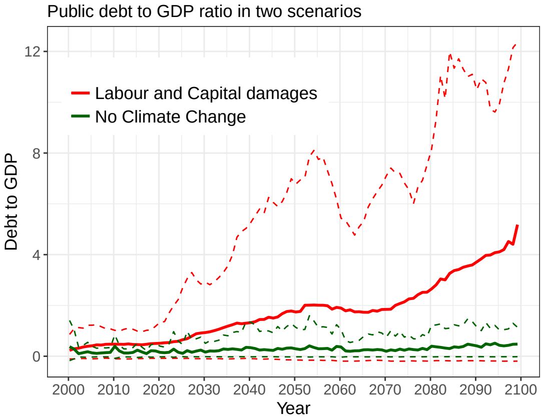


Public bailout costs in the labour and capital damages scenario



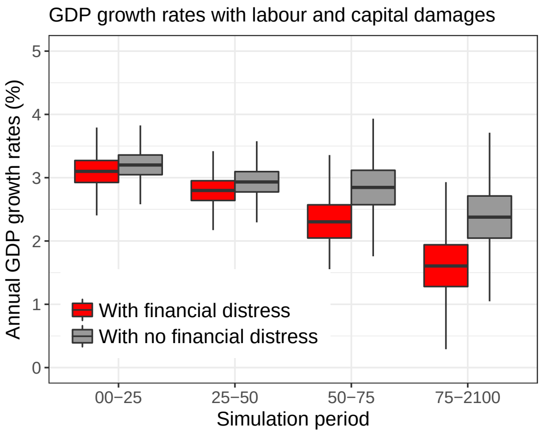
The Impacts of Climate: the Banking System

- Bailouts more than double the stock of public debt
- High variance of debt trajectory due to chancing likelihood of banks' insolvency



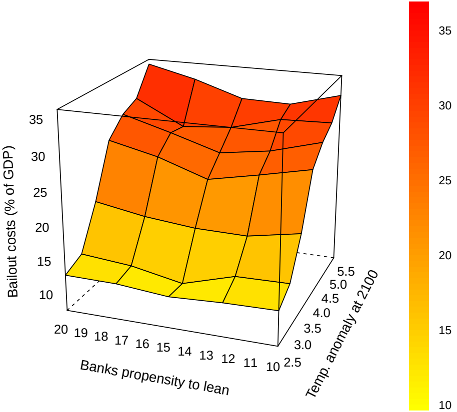
The Impacts of Climate: the Banking System

- Around 20% of real effects on GDP growth due to climate-induced worsening of banks' balance-sheet



Enriching climate policy: prudential regulation

- Banks' ability to lend may influence climate impacts on the financial system
- Climate impacts exacerbate the U-shaped relationship between credit availability and financial stability

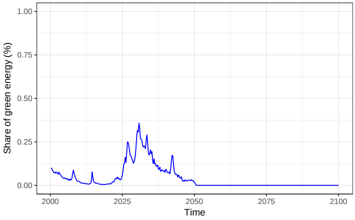


Policy: Transitions

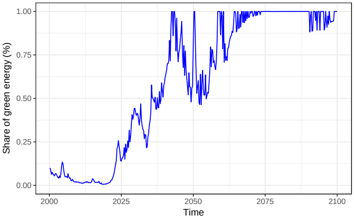
How likely is the transition towards a low carbon economy?

- **under BAU**
- **under different climate impacts**
- **under different energy policy**

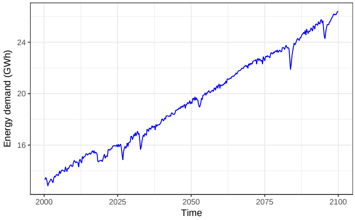
Transitions - Path Dependency and Lock-in



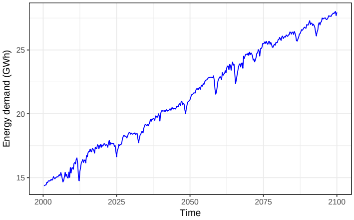
(a) Share of green - Lock in.



(b) Share of green - Transition.



(c) Energy demand - Lock in.



(d) Energy demand - Transition.

Transitions - Path Dependency and Lock-in

	Carbon intensive lock in		Transition to green	
Likelihood	77%		23%	
	before 2025	after 2025	before 2075	after 2075
Likelihood	90%	10%	91%	9%
Output growth	3.16%	3.14%	3.27%	3.18%
	0.001	0.002	0.001	0.008
Unemployment	11.4%	12.1%	9.12%	10.0%
	0.016	0.020	0.019	0.012

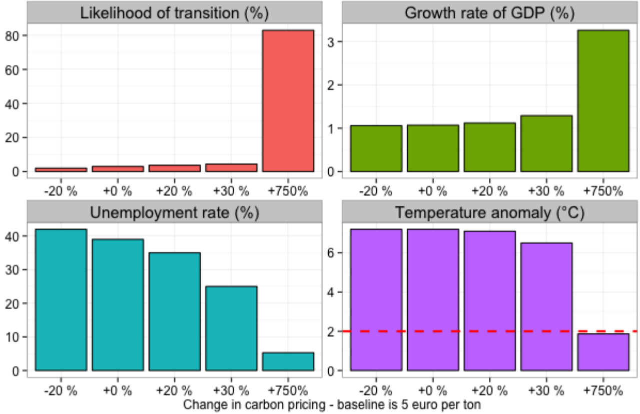
Transitions and Climate Shocks

- Climate shocks can increase or decrease the likelihood of a transition, depending on the impact channel
- Energy efficiency shocks do not cause large aggregate damage, but foster carbon lock-ins

Shock scenario:	Transition likelihood	GDP growth	Energy growth	Emissions at 2100
Aggregate output	18%	3.18%	3.09%	28.33
	(of which 83% before 2025)	(0.001)	(0.003)	(6.431)
Labour productivity	20%	1.30%	1.16%	25.70
	(of which 69% before 2025)	(0.002)	(0.003)	(4.921)
Energy efficiency	7%	3.12%	3.37%	40.64
	(of which 43% before 2025)	(0.001)	(0.003)	(3.872)

Carbon Tax (preliminary)

- Carbon price in EU averaged less than 18 euro per tCO_2e in 2018
- Assuming global pricing, we tested effectiveness of carbon tax



By way of conclusion: what future for Climate Policy?

- **Move beyond idea of carbon taxation alone**. Regulation and standards/feebates can produce similar results. Green R&D subsidies can foster the transition, reducing the size of the carbon tax. Carbon taxes are being proven of difficult political acceptability (e.g. yellow vests).

- **Green investments can be sustained by fiscal, innovation and monetary policy (synergies in policy objectives).** Mechanisms may include use of bonds (to reduce intergenerational inequity), highly progressive income taxation (to fund low-carbon investments while constrasting inequality), green quantitative easing (to channel banks' lending activities).

- **Low-carbon technological paradigms would benefit from a Mission Oriented approach**. Much of the transition comes from the trajectory of technological change; large and focused programs, sustained by public funds, could ease technological developemnt and diffusion.

- **Correct measurement of climate-risk exposure help credit allocation to green investments.** Recent attention on disclosure of climate-risks may improve credit allocation and risk analysis on the side of financial institutions, making green projects more attractive.

Thanks

Questions?

- Dosi G., G. Fagiolo, and A. Roventini (2010), “Schumpeter Meeting Keynes: A Policy-Friendly Model of Endogenous Growth and Business Cycle”, Journal of Economic Dynamics and Control, 34: 1748-1767
- Balint, T., F. Lamperti, A. Mandel, M. Napoletano, A. Roventini, A. Sapio (2017). “Complexity and the Economics of Climate Change: a Survey and a Look Forward", Ecological Economics, 138: 252?265
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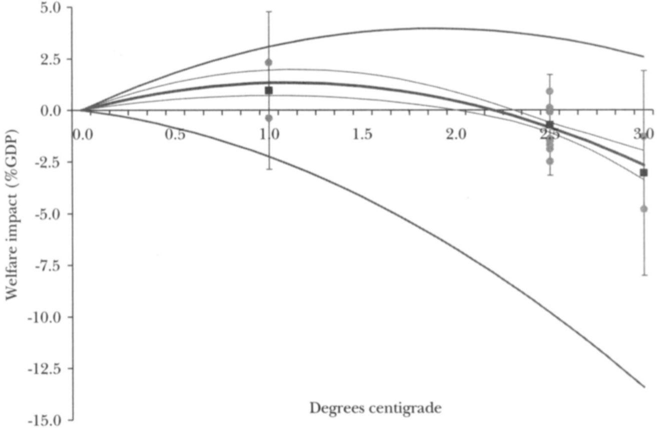
- Lamperti F., Bosetti V., Roventini A., Tavoni M. (2019). “The public costs of climate-induced financial instability”, Nature Climate Change, 9(11), 829-833.

Impacts of Global Warming on the Economy

- Integrated assessment models (e.g. Tol, 2009)



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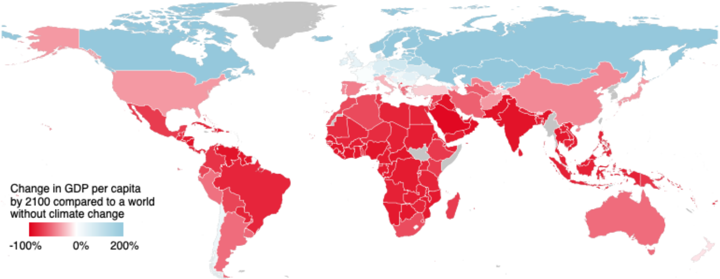
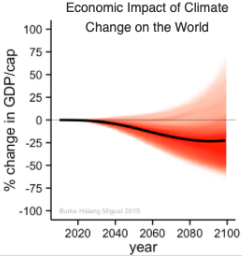
- Empirical approaches (e.g. Burke et al. 2015, Nature)





Likelihood climate change will reduce the World's GDP per capita by

- more than 0%: **71%**
- more than 10%: **63%**
- more than 20%: **51%**
- more than 50%: **12%**

Traditional Models of the Economy with Climate Change

- The majority of models in the literature are CGE based Integrated Assessment Models (IAMs)
  - DICE (Nordhaus, 1992, 2008; Nordhaus and Sztorc, 2013), FUND (Tol, 2002), PAGE (Hope, 2006), WiTCH (Bosetti et al., 2006; Emmerling et al., 2016)
  - Stern Review (Stern, 2007)
  - a plethora of ϵ-variations

- Issues about modeling
  - ad hoc **welfare functions**: time preferences and risk aversion
  - ad hoc **damage functions**
  - difficulty in dealing with low probability high-stake events (**natural disasters**)
  - **distributional issues** are mostly overlooked both in policy design and impact assessment
  - **high uncertainty** in the climate system

Policy implications

- **Strong emphasis on carbon taxation.** Vast majority of the IAM literature concentrates on the determination of the optimal price of carbon emissions (Nordhaus, 1992, 2014; Tol, 1997; Weyant, 2017; Nordhaus, 2017).

- **Carbon tax should be much higher than today levels.** Many studies estimate an optimal global tax between 20 and 50 USD per tCO_2 (today, growing at around 3% per year) to balance costs and benefits Nordhaus (2014); while, to stabilize climate at +1.5 °C, more than 100 USD per tCO_2 are required - on average - on some scenarios (Rogelj et al., 2018). Today, many large emitters (US, Russia and Brazil) do not price carbon at all, while EU's average price in 2018 was less than 18 USD.[1]

[1] https://carbonpricingdashboard.worldbank.org

Issues with carbon pricing

- **High carbon taxes create stranded assets.** Carbon taxes generates stranded assets in that they make unprofitable the use of assets (e.g. fossil-fuel reserves) that already exists in the balance-sheet of firms.
  - stranded assets might generate systemic financial risk Battiston et al. (2016)
  - high carbon taxation could reduce equity valuation of top fossil fuel corps by 40-60% (CTI, 2013)
  - exposures to stranded assets are of diffucult measurement (Monasterolo et al., 2017)

- **Carbon taxes might loose effectiveness through time.** Under multiple equilibria and endogenous technical change, carbon taxes might become ineffective in driving mitigation (Acemoglu et al., 2012; Lamperti et al., 2019)

- **Carbon taxes might have better policy alternatives.** Command and control instruments are more effective (Lamperti et al., 2019), feebates and mandates lead to the same result without creating stranded assets (Rozenberg et al., 2018).

Climate Change and Evolutionary Economics

- New generations of models grounded on evolutionary and complex-system approaches can jointly account for the salient features of climate change (Farmer et al., 2015; Stern, 2016; Balint et al., 2017)
  - deep Knightnian uncertainty
  - learning and innovation
  - structural change
  - path-dependency and lock-in
  - heterogenity and agents' interactions

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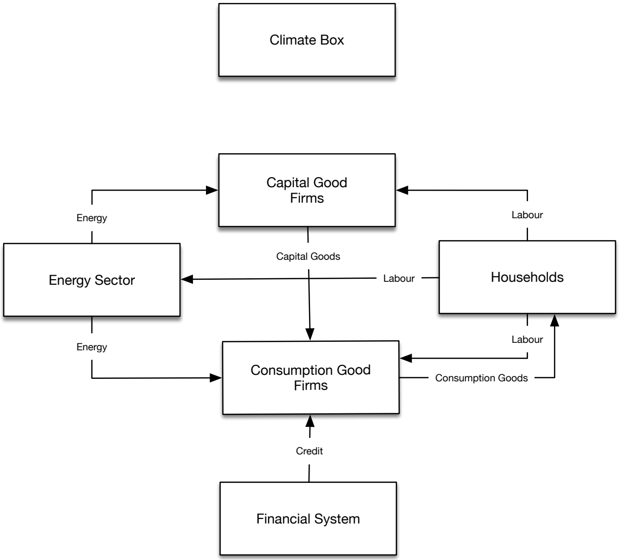
> *Agent Based Models (ABM) seek to provide more-realistic representations of socio-economics by simulating the economy through the interactions of a large number of different agents, on the basis of specific rules. ABMs are widely used in finance, but have yet to be seriously applied to climate change. These are promising developments.*
>
> Stern (2016)

The Dystopian Schumpeter meeting Keynes model



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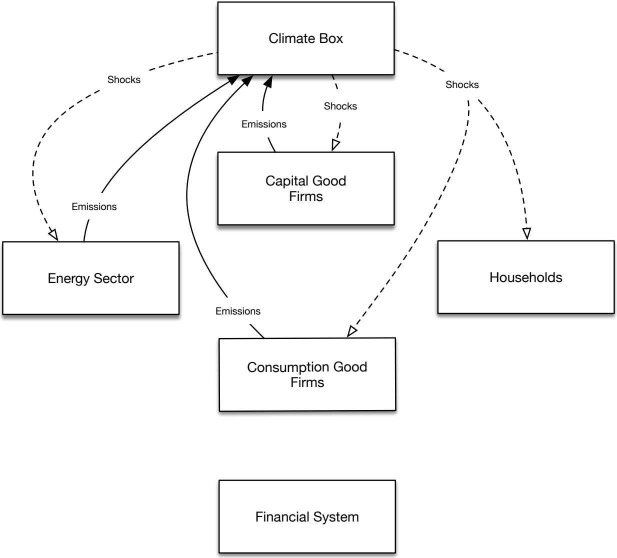

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Background Papers

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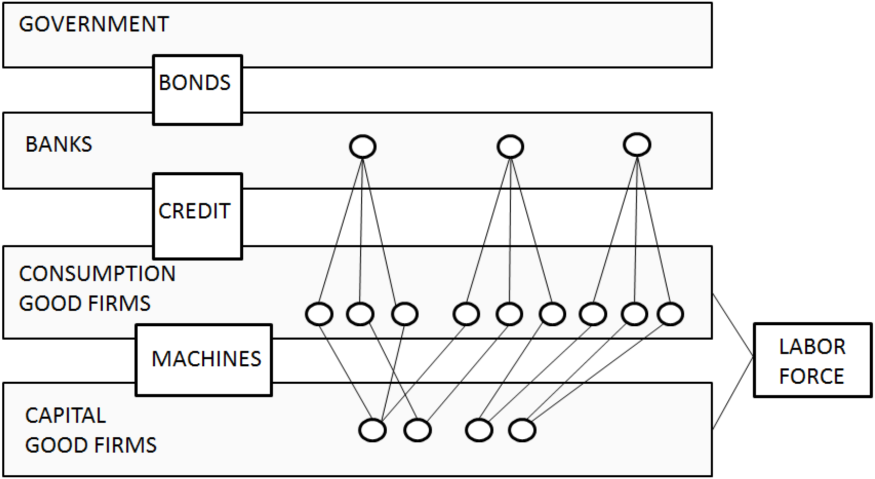
- Lamperti F., G. Dosi, M. Napoletano, A. Roventini, A. Sapio (2018). "And Then He Wasn't a She: Climate Change and Green Transitions in an Agent-Based Integrated Assessment Model", Sant'Anna LEM Working Paper Series 2018/24
- Lamperti F., Bosetti V., Roventini A., Tavoni M. (forthcoming). "The public costs of climate-induced financial instability", mimeo.

The Structure of the Economy

Close antecedents: Dosi et al. (2010, 2013, 2015)



Capital- and Consumption-Good Sectors

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  - labour productivity (L), Energy Efficiency (EE), Environmental Friendliness (EF)
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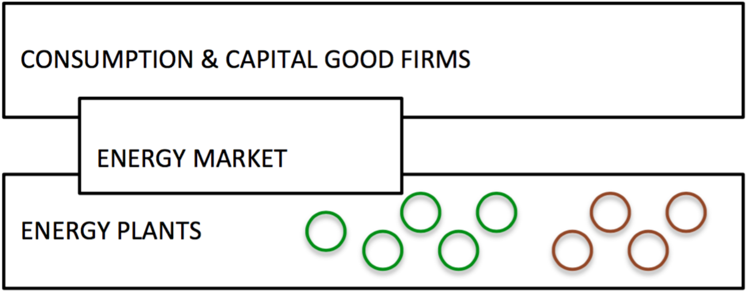
- Costs of production depends on labour, energy and (eventually) carbon taxes:

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

- Investment of consumption-good firms
  - expansionary investment driven by adaptive expectations (animal spiritis)
  - replacement investment driven by payback rule

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

Energy Structure



The Energy Sector

- 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)

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  - *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*: $IC_{de,\tau} = 0$

R&D and Innovation in the Energy Sector

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

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

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

The Banking Sector

- Credit demand:
  - consumption-good firms' desired production and investment
  - maximum credit demand is constrained by loan-to-value ratio
- Credit supply:
  - Basel capital adequacy, banks' maximum credit supply is a multiple of their equity
  - endogenous capital buffer, credit supply is reduced if the bank is fragile
- Credit allocation:
  - credit is allocated to firms on a pecking-order base
  - credit rationing endogenously arises

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- Credit allocation:
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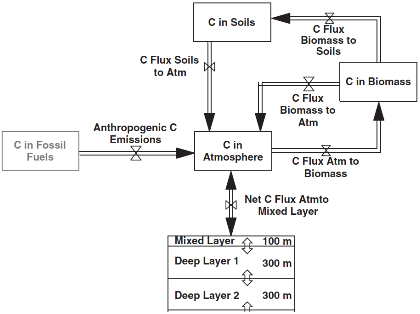
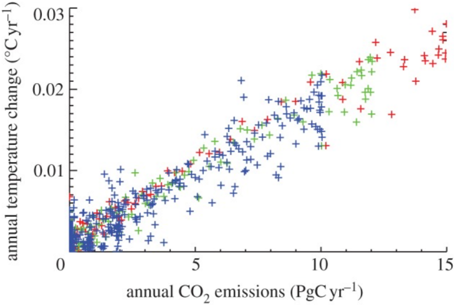
  - credit rationing endogenously arises
- Emergent banking crises:
  - firm bankruptcies affect banks' balance sheet
  - banks fails whenever their net worth become negative
  - the Government steps in and bails the failing bank out with a negative impact on the public budget and possible sovereign debt crises

The Climate Module

- C-ROADS (Sterman et al. 2012)



- 1-equation (Matthews et al. 2012)



Modelling Climate-Change Damages and Disasters

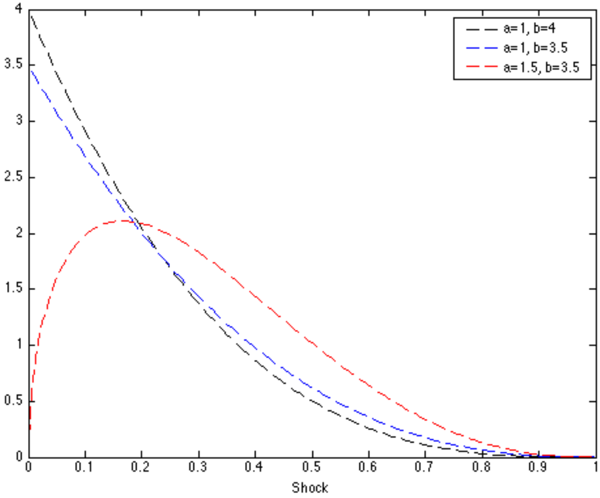
- Pindyck (2013): the choice of the **damage function** is the most speculative element of the analysis
  - aggregating everything in a loss of final output misses the heterogeneity, the aggregation and the long run effects of damages
  - extreme weather events generally overlooked

Damage Generating Function

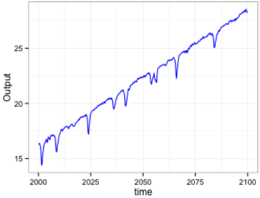
A parametric probability density function for dis-aggregated shocks that endogenously evolve according to the dynamics of the climate

- $f(s; a, b) = \frac{1}{B(a,b)} s^{a-1}(1-s)^{b-1}$
- (location) $a = a(t) = a_0[1 + \log[T_m(t)]]$
- (scale) $b = b(t) = b_0[1 - \log[T_m(t)]]$
- (shock realization) $X_i(t) = X_i'(t)[1 - \hat{s}_i(t)]$
- where X is the target of the shock

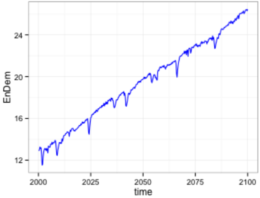
Damage Generating Function



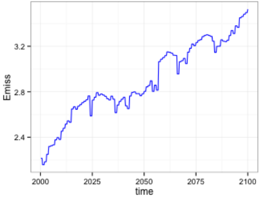
DSK Model Dynamics



(a) Output.

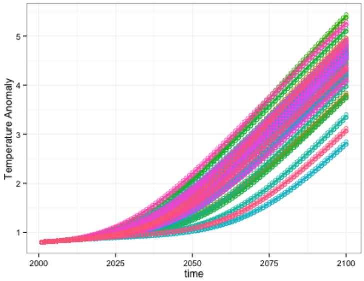


(b) Energy demand.

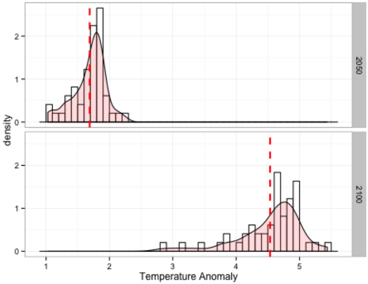


(c) Emissions.

Temperature Evolution in the DSK model



(a) Temperature projections.



(b) Distribution of temperature.

Model Dynamics (Business as Usual)

	MC average	MC median	MC st. dev.
Output growth	3.19%	3.19%	0.001
Likelihood of crises	12.1%	11.9%	0.076
Unemployment	12.0%	12.1%	0.022
Energy demand growth	2.15%	2.14%	0.002
Emissions growth	1.19%	1.17%	0.003
Volatility of output	0.268	0.270	0.022
Volatility of consumption	0.197	0.199	0.019
Volatility of investments	0.308	0.309	0.024
Volatility of energy demand	0.215	0.215	0.034
Share of emissions from energy sector	61.4%	61.0%	0.201
Share of green energy	29.9%	24.5%	0.285
Temperature at 2100	4.54	4.65	0.509

Impact Scenarios

- **We consider different kinds of micro-level shocks**
  - productivity shocks
  - energy efficiency shocks
  - capital stock shocks
  - different combination
  - inventories shocks (not reported here)
  - consumption shocks (not reported here)
  - labour force shocks (not reported here)

- The expected size of all shocks follows the damage function employed in the DICE2013R model (Nordhaus and Sztorc, 2013; Nordhaus, 2014):

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

- the aggregate macroeconomic impact is way larger (see next slides)

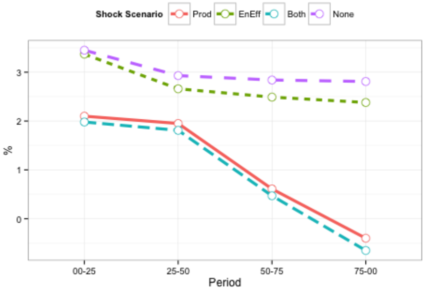
Aggregate Impact of Climate Shocks

- Climate impacts to labour productivity produce largest aggergate effects
- Capital shocks increase volatility rather than long term growth

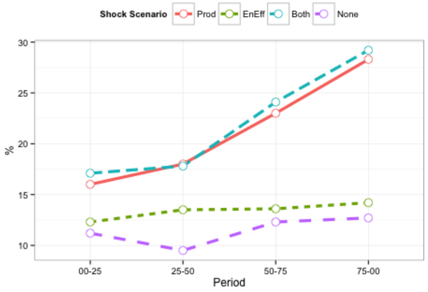
		Output growth	Likelihood of crises	Unemployment
Baseline (no Shocks)	MC average	3.19%	12.1%	12.0%
	MC median	3.19%	11.9%	12.1%
	MC st. dev.	0.001	0.076	0.022
Productivity Shocks	MC average	1.17%	25.6%	22.2%
	MC median	1.16%	27.2%	19.51%
	MC st. dev.	0.003	0.051	0.022
Energy Efficiency Shocks	MC average	3.02%	17.7%	13.8%
	MC median	3.04%	17.3%	13.7%
	MC st. dev.	0.001	0.034	0.015
Both	MC average	0.92%	26.8%	23.4%
	MC median	0.94%	29.4%	23.3%
	MC st. dev.	0.003	0.034	0.016

Tipping Points and Climate-Change Shocks (No Banks)

- Cumulative exposition to unmitgated climate can induce a stagnating (even negative) growth path
- Effects are much larger than in CGE-based literature



(a) Output growth.



(b) Unemployment.

Economic and Banking Impacts of Climate (Heter. Banks)

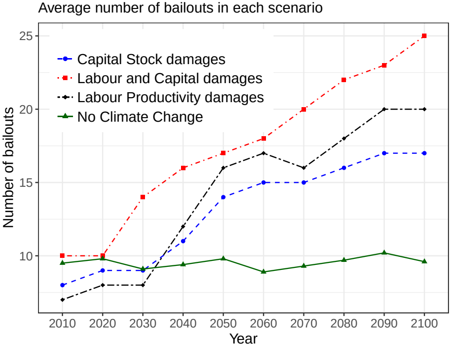
- Model calibrated on SSP 5, different impact scenarios

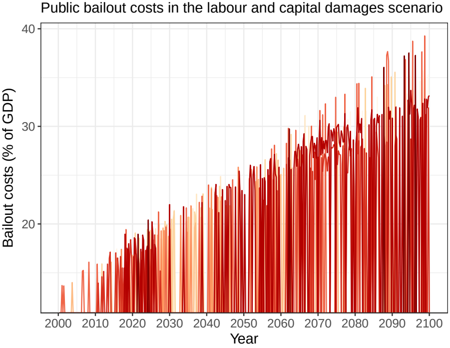
	No Climate Change Shocks	**Labour Productivity Damages**	**Capital Stock Damages**	**Labour and Capital Damages**
GDP growth (%)	3.4	2.2	2.9	2.0
	(0.002)	(0.004)	(0.004)	(0.003)
Firms' 10y Insolvency Likelihood (%)	15.2	32.4	38.8	47.1
	(0.031)	(0.047)	(0.050)	(0.052)
Banks' Equity to Total Asset ratio (%)	12.0	7.5	9.6	5.3
	(0.025)	(0.034)	(0.029)	(0.041)
Public Bailouts/10y	9.1	14.2	11.5	22.6
	(1.28)	(2.15)	(3.02)	(3.96)
Cost of Bailouts per year (% GDP)	10.3	15.7	14.6	25.0
	(0.013)	(0.027)	(0.029)	(0.031)
Average debt over GDP ratio	0.83	1.55	1.38	1.77
	(0.04)	(0.09)	(0.07)	(0.11)
Temperature Anomaly 2100	5.4[†]	5.0	5.2	4.8
	(0.312)	(0.461)	(0.411)	(0.470)
Cumulative emissions at 2100 (GtCO2-eq)	3061.4	2810.7	2961.2	2720.9
	(98.51)	(97.37)	(99.23)	(109.1)

Note: All values refer to averages from a Monte Carlo exercise of size 500; standard deviations in parenthesis. [†] indicates the temperature anomaly that would have realized in presence of climate change for the stock of emissions summarized in the lines below.

Climate Change Shocks and Bank Bailouts

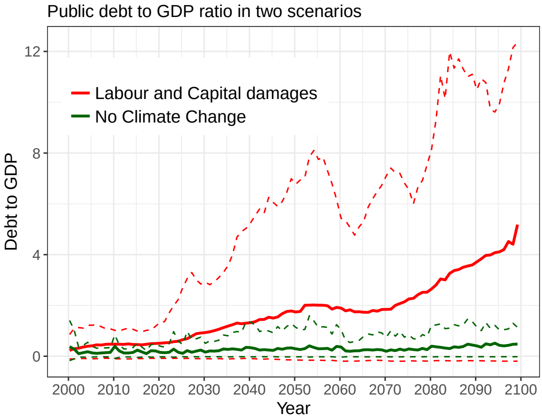
- The differential effects across the impact scenarios magnify with time
- The number of bailouts sharply increases after 2060, when temperature anomaly reaches about 3 degrees
- Bailout costs can reach up to 40% of GDP





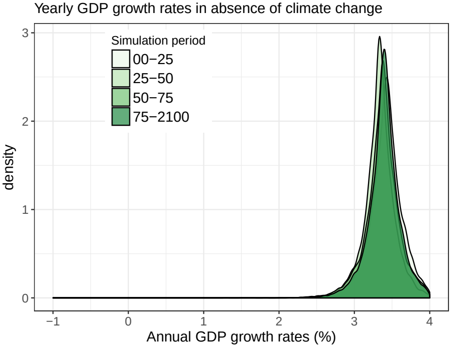
Climate Change Shocks, Banking Crises and Public Debt

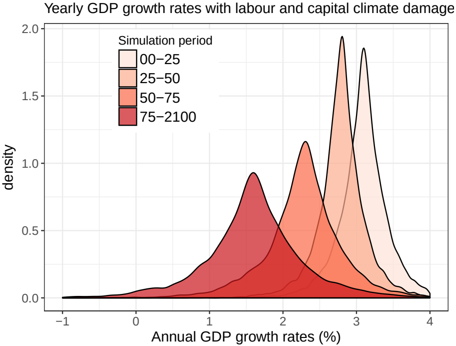
- Bailouts more than double the stock of public debt
- High variance of debt trajectory due to chancing likelihood of banks' insolvency



Impacts on Growth (Heter. Banks)

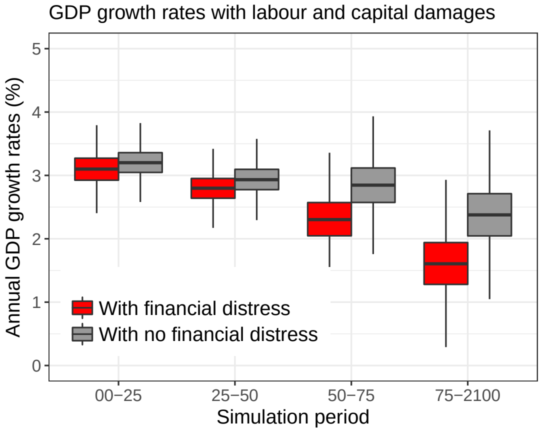
- Large and increasing impacts on GDP growth, not just ouput level
- Increased growth volatility





Impacts caused by banking stress

- Around 20% of real effects on GDP growth due to climate-induced worsening of banks' balance-sheet



Comparison of impact estimates

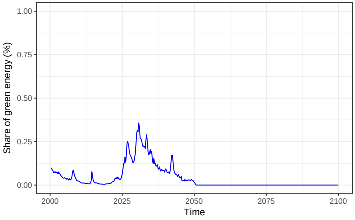
Study	Financial system	$\frac{GDP(2100)}{GDP^{*}(2100)}$
Nordhaus (2017)	N	0.94
Dietz et al. (2016)	Y	0.88
Lamperti et al. (damages to capital stock)	Y	0.62
Weitzman (2012)	N	0.35
Burke et al. (2015)	N	0.36
Lamperti et al. (damages to labour productivity)	Y	0.31
Lamperti et al. (damages to capital and labour)	Y	0.26
Dietz and Stern (2007)	N	0.22

Policy: Transitions

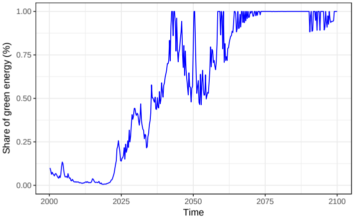
How likely is the transition towards a low carbon economy?

- **under BAU**
- **under different climate impacts**
- **under different energy policy**

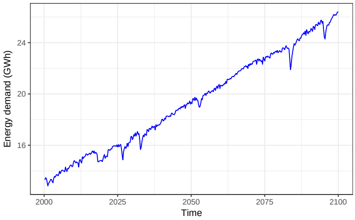
Transitions - Path Dependency and Lock-in



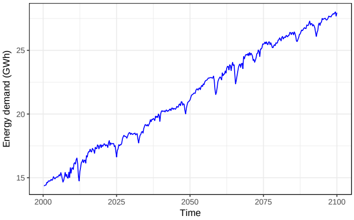
(a) Share of green - Lock in.



(b) Share of green - Transition.



(c) Energy demand - Lock in.



(d) Energy demand - Transition.

Transitions - Path Dependency and Lock-in

	Carbon intensive lock in		Transition to green	
Likelihood	77%		23%	
	before 2025	after 2025	before 2075	after 2075
Likelihood	90%	10%	91%	9%
Output growth	3.16%	3.14%	3.27%	3.18%
	0.001	0.002	0.001	0.008
Unemployment	11.4%	12.1%	9.12%	10.0%
	0.016	0.020	0.019	0.012

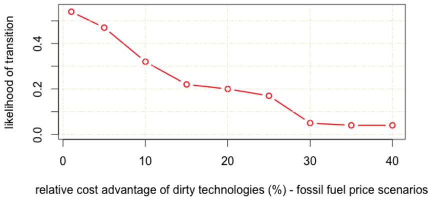
Transitions and Climate Shocks

- Climate shocks can increase or decrease the likelihood of a transition, depending on the impact channel
- Energy efficiency shocks do not cause large aggregate damage, but foster carbon lock-ins

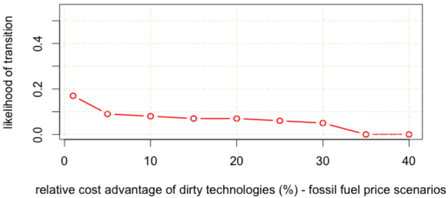
Shock scenario:	Transition likelihood	GDP growth	Energy growth	Emissions at 2100
Aggregate output	18%	3.18%	3.09%	28.33
	(of which 83% before 2025)	(0.001)	(0.003)	(6.431)
Labour productivity	20%	1.30%	1.16%	25.70
	(of which 69% before 2025)	(0.002)	(0.003)	(4.921)
Energy efficiency	7%	3.12%	3.37%	40.64
	(of which 43% before 2025)	(0.001)	(0.003)	(3.872)

Transitions and Price-Based Policy on Fossil Fuels

labor productivity shocks

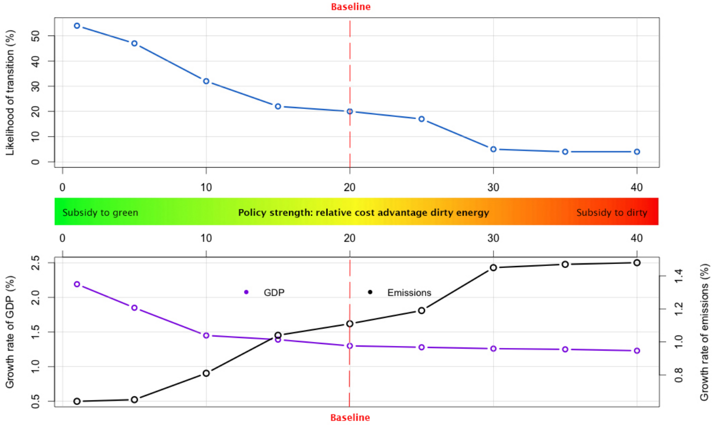


energy efficiency shock



Policy effectiveness in triggering the green transition changes according to the target of climate shocks

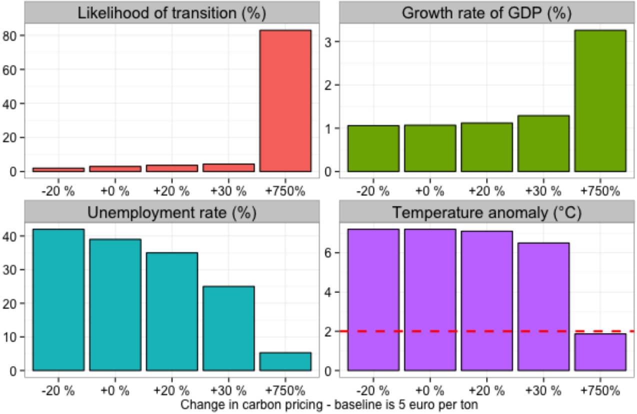
Transition and Macroeconomic Dynamics



- Climate change policies can lead to win-win pathways
- Large-scale and timely policy interventions are needed!

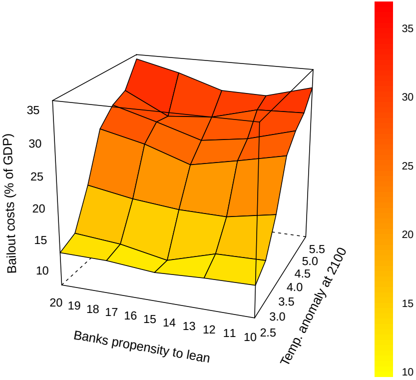
Carbon Tax (preliminary)

- Carbon price in EU averaged less than 18 euro per tCO_2e in 2018
- Assuming global pricing, we tested effectiveness of carbon tax



Macropru/Credit Climate Policy (preliminary)

- There is scope for climate macroprudential policy
- Modifying Basel II-type capital requirements, the economy (partially) adjusts to climate impacts



What future for Climate Policy?

- **Move beyond idea of carbon taxation alone**. Regulation and standards/feebates can produce similar results. Green R&D subsidies can foster the transition, reducing the size of the carbon tax. Carbon taxes are being proven of difficult political acceptability (e.g. yellow vests).

- **Green investments can be sustained by fiscal, innovation and monetary policy (synergies in policy objectives).** Mechanisms may include use of bonds (to reduce intergenerational inequity), highly progressive income taxation (to fund low-carbon investments while constrasting inequality), green quantitative easing (to channel banks' lending activities).

- **Low-carbon technological paradigms would benefit from a Mission Oriented approach**. Much of the transition comes from the trajectory of technological change; large and focused programs, sustained by public funds, might more likely to ease technological developemnt and diffusion.

- **Correct measurement of climate-risk exposure help credit allocation to green investments.** Recent attention on disclosure of climate-risks may improve credit allocation and risk analysis on the side of financial institutions, making green projects more attractive.

What we are doing/Our research agenda

1. **Improve empirical estimate of micro-level damages**. E.g. we are including impacts of extreme weather events (e.g. hurricanes, floods,...) that are usually left aside evaluation of climate damages. Inclusion in modelling building on Hallegatte (2014).

2. **Include agricultural sector**. Large part of impacts come from climate effects on crop yields, food production and food price. We are working on extending the model to account for such crucial sector.

3. **Test combinations of climate policy intiatatives**.
   - Command and control instruments in the energy sector
   - Credit-based policies
   - Green macroprudential requirements
   - High-income taxation
   - Public green investment banks (e.g. China)

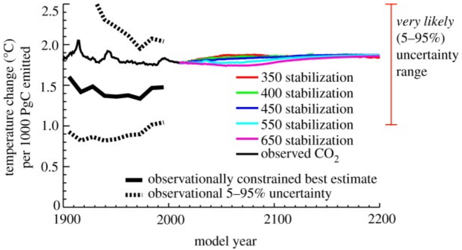
4. **Develop a modeling framework incorporating a Mission Oriented approach to climate change management**.

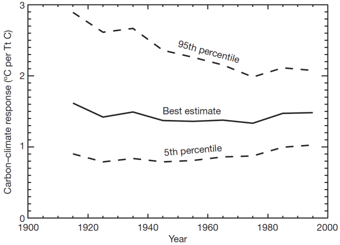
Clim-NET: a simple model of growth, supply chain and climate damages propagation

- Small model to explore role of heterogeneity and interactions for climate change impacts in an economy
- Builds on 3 literatures:
  - evolutionary competition of firms/industries
  - network origins of aggergate flucutuations
  - simple integreated assessment modeling (e.g. DICE)
- Agents are firms or industries and are embedded in a production supply chain
- They also compete to satisfy final demand and gain market shares
- Production involves emissions, which contribute to climate change

The carbon-climate relationship

In search for the simplest yet credible approach



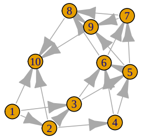


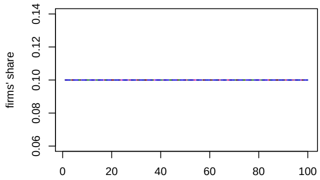
Matthews et al (2012, Philos Trans A) on the left; Matthews et al (2009, Nature) on the right

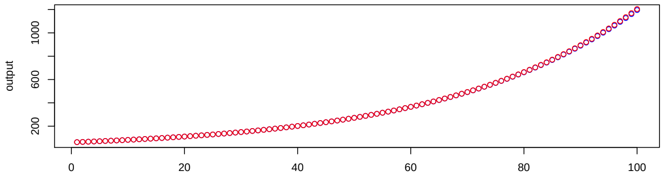
Preferred estimate: 1.8°C per 1000 GtC; 95% CI: [1°C-2.1°C]

Clim-net simulation: homogenous damages

Economic structure and GDP

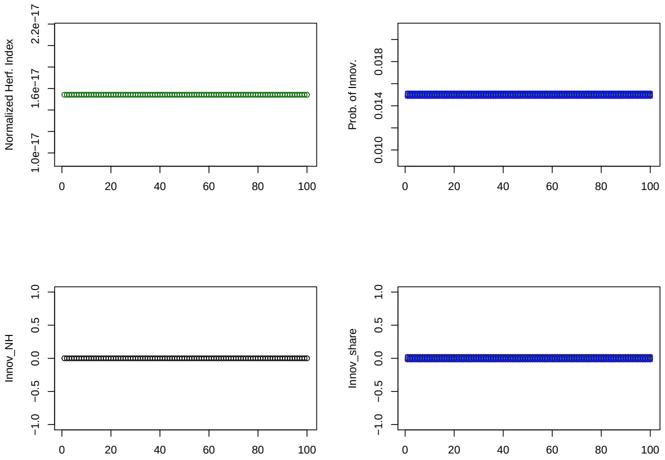






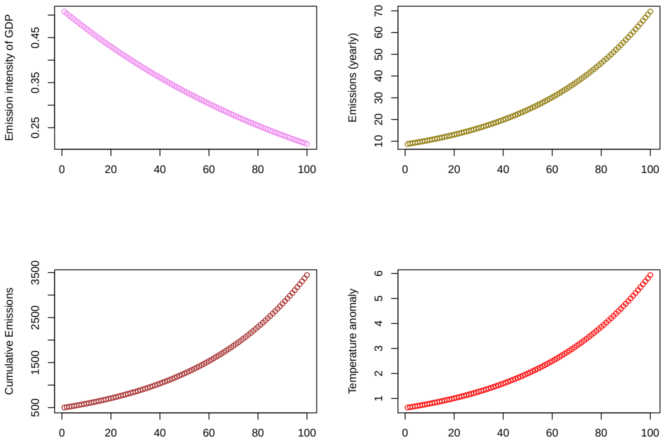
Clim-net simulation: homogenous damages

Technical change and industry



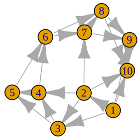
Clim-net simulation: homogenous damages

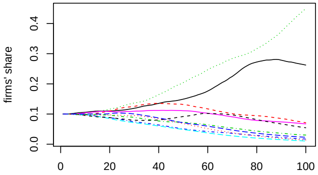
Climate variables

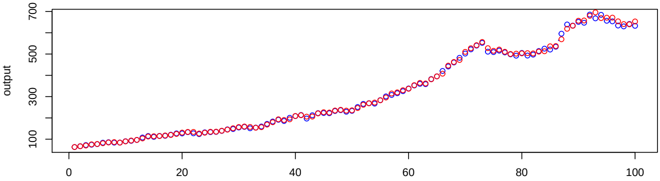


Clim-net simulation: heterogenous damages

Economic structure and GDP

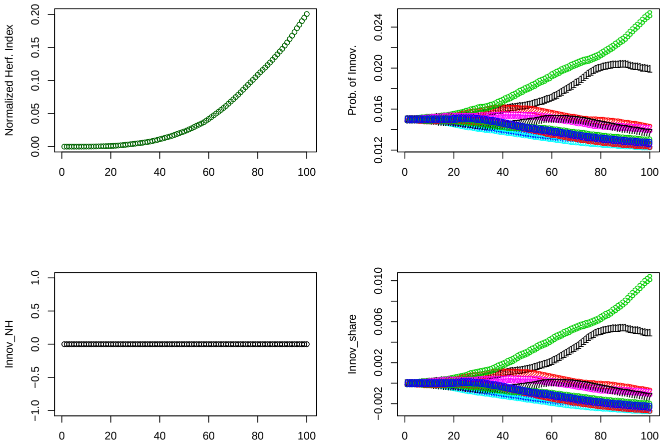






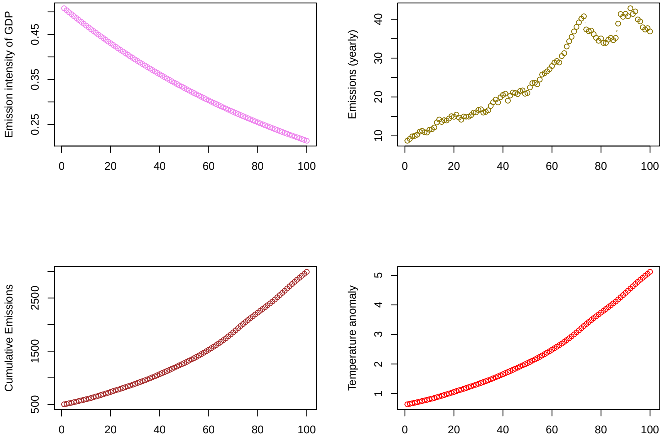
Clim-net simulation: heterogenous damages

Technical change and industry



Clim-net simulation: heterogenous damages

Climate variables



To do

Preliminary result

GDP growth with heterogeneous damages is - on average - 0.88 of GDP growth with representative economy

- Test different mitigation/SPSS scenarios
- Test different network stuctures
  - Watts Strogatz
  - Small words
  - Core-periphery structures
  - ...
- Test different damage functions and entry-exit conditions
- Sensitivity analysis of key parameters

AGRI-lowe

We model a **Spatial economy** on a $x \cdot y$ wide cell grid, 2 types of lands: i) **forestry**; ii) **arable lands**.

- Ecology of N farmers (entry & exit allowed) spread over available arable land (possibly owning more than 1 cell);
- **Two Layers Agents**: Some activities carried out at the farmer level, some at the cell/farm level.
- Each cell is endowed with an intrinsic (initial) soil productivity.
- we do not include livestock;
- **Exogenous demand**

To explore model features, we randomize initial soil fertility and each farmer initially owns only one farm/cell.

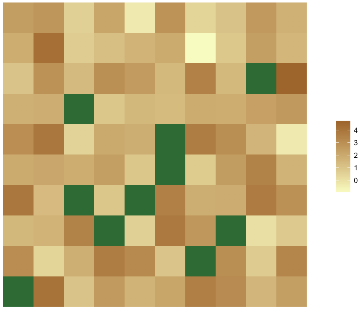


Figure: Spatial structure of the model: soil productivity (θ) inizialization. Green cells are non-arable land

Study of Adoption of Technology/Behaviour

The choice of the production style/management is carried out at the farmer level and depends on (i) **productivity**, (ii) **neighborhood composition**, (iii) **level of knowledge**, (iv) **risk attitute**.

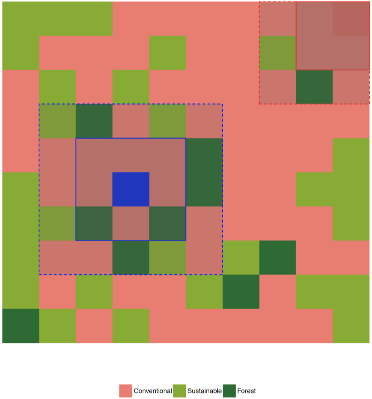


Figure: Observed neighborhoods from

If $a : \{c, s\}$, each farmer look around the cell he owns with a ray q, defining the sets of farms C and S.

Technical Change I

- **Capital-good firms search for better machines and for more efficient production techniques**
  - $A_{i,k}(t)$: feature of machine manufactured by firm i
  - $B_{i,k}(t)$: feature of production technique of firm i
  - $A_{i,k}(t)$ and $B_{i,k}(t)$ determine the technology of firm i at time t

- **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*):

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

Technical Change II

- **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 Market

- **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

Investment

- **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:
    - an incumbent machine is scrapped if

$$\frac{p^*}{c(\tau)-c^*} \leqslant b, \qquad b > 0$$

    - $c(\tau)$ unit labor cost of an incumbent machine;
    - p^*, c^* price and unit labor cost of new machines
  - also machine older than Λ periods are replaced

Financial Structure

- **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 (*Deb*) of consumption-good firms is limited by their gross cash flows (= sales *S*):

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

Banks credit provision

Banks are different in terms of their fundamentals, as well as their supply of credit, which is a function of their equity (NW_b). In that, Basel-type capital adequacy requirements constrain credit supply but, on the other hand, banks maintain a buffer over the mandatory level of capital, whose magnitude is strategically altered over the business cycle according to their financial fragility (BIS, 1999; Bikker and Metzemakers, 2005). In particular, following Adrian and Shin (2010), we proxy banks' fragility with the accumulated bad debt to assets ratio. Therefore, given the parameter $\tau_b \in [0, 1]$ fixed by the regulatory authority (the central bank in our case), the higher the bad-debt-to-asset ratio, the lower the credit the bank provides to its clients:

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

where TC_b indicates total credit supplied, BD_b the stock of bad-debt and TA_b the amount of total assets. $\beta > 0$ is a parameter which measures the sensitivity of banks to their financial fragility.

Consumption-Good Markets

- **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)

Consumption-Good Markets

- **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 Bankruptcies and Banking Crisis

- **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

Energy Sector

Profits of the energy monopolist at the end of period t are equal to

$$\Pi_e(t) = S_e(t) - PC_e(t) - EI_e(t) - RD_e(t)$$

where

- $S_e(t)$ are revenues
- $PC_e(t) = \sum_{\tau \in IM} g_{de}(\tau, t) c_{de}(\tau, t) A^{\tau}_{de}$ are production costs
- $EI_e(t) = K^d_e(t) - K_e(t)$ are expansion investments
- $RD_e(t)$ are R&D expenditures

To obtain **revenues**, the energy producer adds a fixed mark-up $\mu_e \geq 0$ on the average cost of the more expensive infra-marginal plant. Hence the selling price reads

$$p_e(t) = \mu_e$$

if $D_e(t) \leq K_{ge}(t)$, and

$$p_e(t) = \overline{c}_{de}(\tau, t) + \mu_e$$

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

The **expansion investment** is made up of new green capacity is added whenever the cheapest vintage of green plants must be 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 $\underline{c}_{de} = \min_\tau c^\tau_{de}$.

Validation

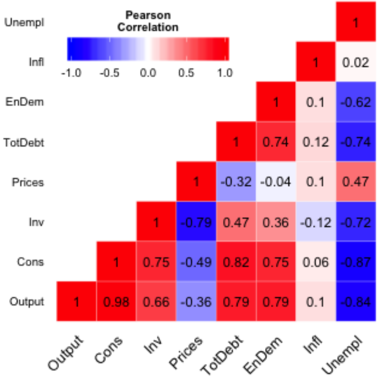
Can the model replicate major empirical stylized facts of growth/business cycles?

Should we care about business cycles frequency in a long run model of climate change?

Until recently, the usual thinking among macroeconomists has been that short-term weather fluctuations don't matter much for economic activity. Construction hiring may be stronger than usual in a March when the weather is unseasonably mild, but there will be payback in April and May. If heavy rains discourage people from shopping in August, they will just spend more in September. But recent [events] prompted a rethink of this view. Extreme weather certainly throws a ringer into key short-term macroeconomic statistics. It can add or subtract 100,000 jobs to monthly US employment, the single most-watched economic statistic in the world, and generally thought to be one of the most accurate. The impact of El Niño related weather events [...] can be especially large because of their global reach. (Rogoff, 2016)

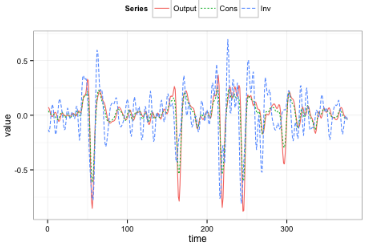
Business Cycle Properties

Contemporaneous cross-correlations.

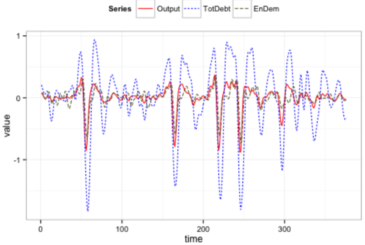


Business Cycle Properties

Dynamics of filtered macroeconomic series



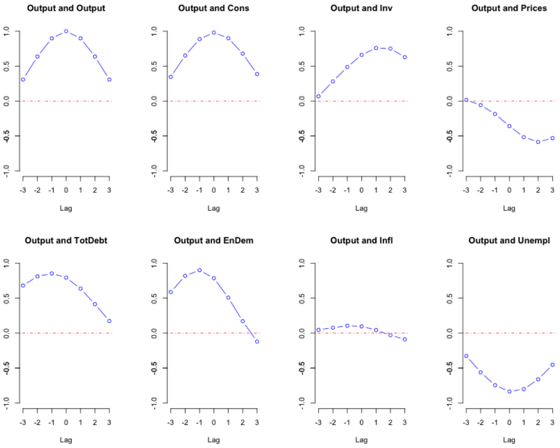
(a) Output, Consumption and Investments.



(b) Output, Total private debt, Energy demand.

Business cycle properties

Auto-cross correlations between output and main macroeconomic aggregates.



Long-Run Empirical Regularities

Cointegrating relationships among output, energy demand and emissions

	Test statistic	5%-threshold	MC st. dev.	Runs passing test
		Engle-Granger Procedure		
Output-EnDem	-6.668	-2.58	2.557	96%
Emissions-Output	-3.877	-2.58	3.099	60%
Emissions-EnDem	-6.809	-2.58	3.410	90%
		Phillips-Ouliaris Procedure		
Output-EnDem	274.999	55.19	117.441	100%
Emissions-Output	134.381	55.19	130.312	100%
Emissions-EnDem	258.777	55.19	133.838	100%
		Johansen Procedure (three-variate VAR)		
r<=2	9.344	12.25	4.220	57% (null rejected)
r<=1	40.156	25.32	12.837	90% (null rejected)
r=0	98.003	42.44	17.962	100% (null rejected)

Micro and Macro Regularities: a Recap

Stylized facts	Empirical studies (among others)
Macroeconomic stylized facts	
SF1 Endogenous self-sustained growth	Burns and Mitchell (1946); Kuznets and Murphy (1966)
with persistent fluctuations	Zarnowitz (1985); Stock and Watson (1999)
SF2 Fat-tailed GDP growth-rate distribution	Fagiolo et al. (2008); Castaldi and Dosi (2009)
	Lamperti and Mattei (2016)
SF3 Recession duration exponentially distributed	Ausloos et al. (2004); Wright (2005)
SF4 Relative volatility of GDP, consumption, investments and debt	Stock and Watson (1999); Napoletano et al. (2006)
SF5 Cross-correlations of macro variables	Stock and Watson (1999); Napoletano et al. (2006)
SF6 Pro-cyclical aggregate R&D investment	Wälde and Woitek (2004)
SF7 Cross-correlations of credit-related variables	Lown and Morgan (2006); Leary (2009)
SF8 Cross-correlation between firm debt and loan losses	Foos et al. (2010); Mendoza and Terrones (2012)
SF9 Pro-cyclical energy demand	Moosa (2000)
SF10 Syncronization of emissions dynamics and business cycles	Peters et al. (2012); Doda (2014)
SF11 Co-integration of output, energy demand and emissions	Triacca (2001); Ozturk (2010); Attanasio et al. (2012)
SF12 Banking crises duration is right skewed	Reinhart and Rogoff (2009)
SF13 Fiscal costs from recessions is fat tailed	Laeven and Valencia (2012)
Microeconomic stylized facts	
SF14 Firm (log) size distribution is right-skewed	Dosi (2007)
SF15 Fat-tailed firm growth-rate distribution	Bottazzi and Secchi (2003, 2006)
SF16 Productivity heterogeneity across firms	Bartelsman and Doms (2000); Dosi (2007)
SF17 Persistent productivity differential across firms	Bartelsman and Doms (2000); Dosi (2007)
SF18 Lumpy investment rates at firm-level	Doms and Dunne (1998)
SF19 Persistent energy and carbon efficiency heterogeneity across firms	DeCanio and Watkins (1998); Petrick et al. (2013)
SF20 Firm bankruptcies are counter-cyclical	Jaimovich and Floetotto (2008)
SF21 Firm bad-debt distribution fits a power-law	Di Guilmi et al. (2004)

Climate Impacts

What are the aggregate effects of climate change affecting economic actors?

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