

AIEE Energy Symposium
Current and Future Challenges to Energy Security

COPING WITH THE COLLAPSE
A Stock-Flow Consistent, Monetary Macro-dynamics of Global Warming

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Gaël Giraud Florent Mc Isaac Emmanuel Bovari Ekaterina Zatsepina



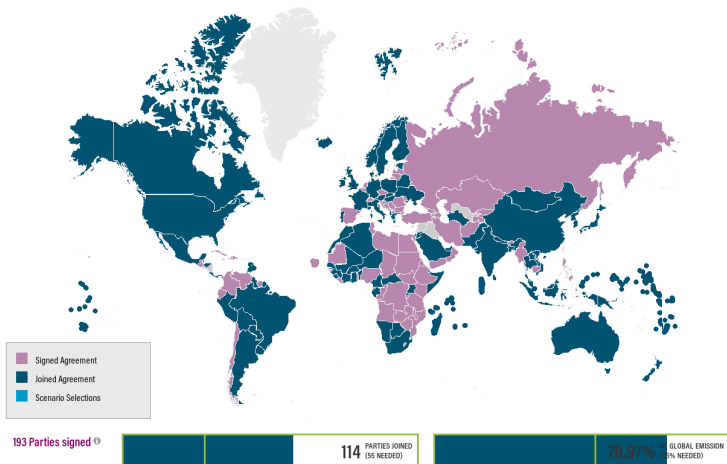
University of Paris 1 Panthéon Sorbonne
Chair Energy and Prosperity
Centre d'Économie de la Sorbonne
Agence Française de Développement

■ Summary

- 1** Introduction
- 2 Context
- 3 Structure of the model
- 4 Impact of climate change
- 5 Climate prospective
- 6 Conclusions

■ Introduction

Climate change as a milestone for the XXIst century



■ Introduction

The 2008 crisis: a revival of Minsky's theory of financial instability

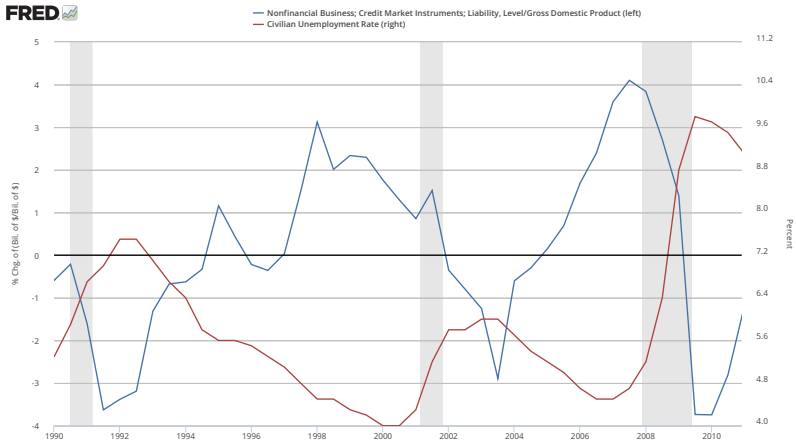


Figure: Time series of the private debt ratio and employment rate in the United States over the period 1990-2010.

■ Introduction

Key research highlights

1. Combine two sources of global instabilities (climate and finance) in a minimal and rational framework to provide prospective analysis insight on the climate-economy interactions
2. Identify the instability factors and their transmission channels (in particular the pivotal role of private debt)
3. Provide public policy guidance for the implementation of the emblematic objective of the Paris Agreement to contain global warming below 1.5°C

■ Summary

1 Introduction

2 Context

- The Keen model (1995)^[9]
- The DICE model (2013)^[11]

3 Structure of the model

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■ Context – The Keen model (1995)^[9]

Theoretical elements

- Minimum (bounded) rationality
- Endogenous business cycles as in the Goodwin model (1967)^[6]
- Mathematical formalization of Minsky's moment
 - Lotka-Volterra relationship linking the employment rate to the wage share
 - Dynamics of the private debt of firms
- Phenomenological empirical approach to ground aggregated behavior:
 - Short-term Phillips curve (Mankiw (2010)^[10], Krugman (2014))
 - Investment function
- Dualism of long-term equilibria:
 - A desirable steady-state equilibrium
 - A bad attractor leading to a breakdown

■ Context – The Keen model (1995)^[9]

Convergence to the locally asymptotically stable steady-state equilibrium

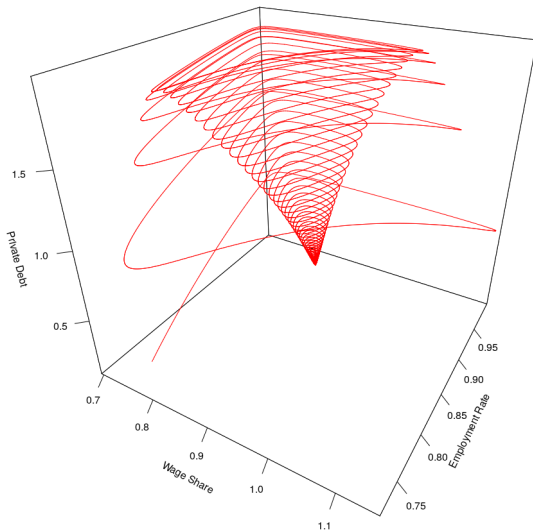


Figure: Phase diagram in the Keen model (1995)^[9].

■ Context – The Keen model (1995)^[9]

Viability analysis through the basin of attraction

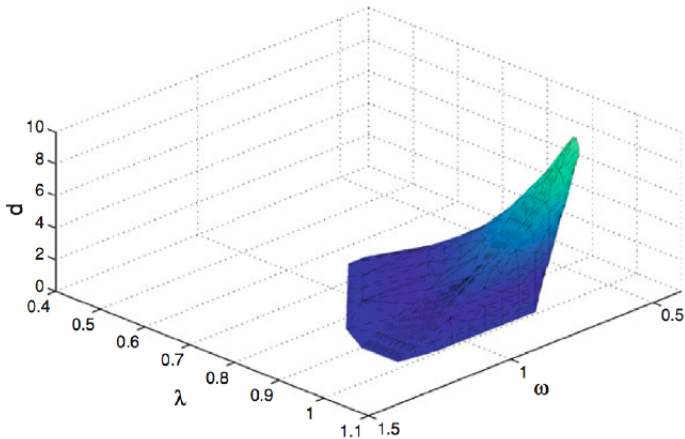


Figure: Basin of attraction of the desirable steady-state in the Keen model. Source: Grasselli *et al.* (2012)^[7]

■ Context – The Keen model (1995)^[9]

Stock-Flow consistency “à la” Godley-Lavoie (2012)^[5]

	Households	Firms	Banks	Sum
Balance Sheet				
Deposits	M		-M	
Capital		K		K
Debt		-D	D	
Net Wealth	X^h	X^f	X^b	X
Transactions				
		current	capital	
Consumption	-C	C		
Investment		I	-I	
Accounting Memo [PIB]		[Y]		
Wages	W	-W		
Interests on Debt		-rD	rD	
Net Profits		- π		
Financial Balance			- \dot{D}	π^b
Flow of Funds				
Gross Fixed Capital Formation		I		I
Change in Loans		$-\dot{D}$	\dot{D}	
Column Sum		π	\dot{D}	I
Change in Net Wealth		$\dot{X}^f = \pi - \delta K$	$\dot{X}^b = \pi^b$	\dot{X}

Table: Balance sheet, transactions, and flow of funds in the world economy.

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Context – The DICE model (2013)^[11]

A seminal model of IAMs

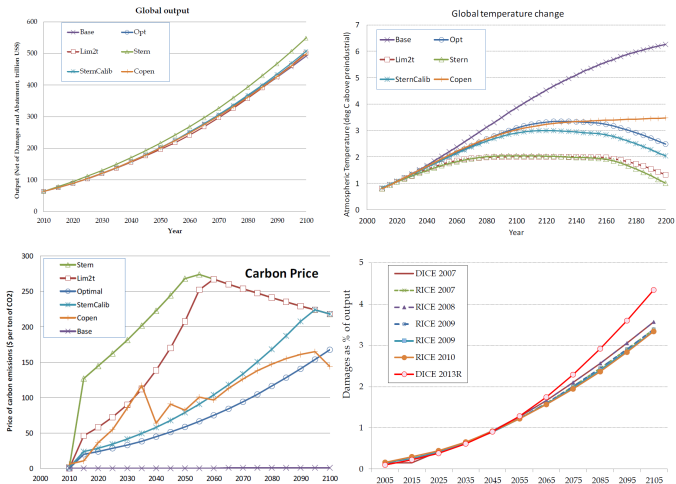


Figure: Trajectories from the model Dynamic Integrated Climate Economy (DICE). Source: Nordhaus (2013)^[11].

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■ Structure of the model

Key modeling highlights

Taking advantage of two prominent models:

- The macrodynamic model of Keen (1995)^[9] refined with:
 - Price system under imperfect competition (Grasselli *et al.* (2014)^[8])
 - Sigmoid pattern of the global workforce (UN population scenarios (2015)^[1])
 - Dividends payments of firms to households

- The DICE model of Nordhaus (2013)^[11] refined with:
 - More convex damage functions (Weitzman (2011)^[13], Dietz *et al.* (2015)^[3])
 - Allocation of environmental damage between:
 1. Output
 2. Capital accumulation (Dietz *et al.* (2015)^[3])
 3. Labor productivity (Burke *et al.* (2015)^[2])

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■ Structure of the model – The macroeconomic framework

Framework

- Closed economy
- Continuous time
- No public sector
- Three agents: households, firms and banks

■ Structure of the model – The macroeconomic framework

Main variables considered

- Real output: Y
- Global workforce: N
- Employed workforce: L
- Unitary wage: w
- Private debt stock: D
- Short-term interest rate: r
- Price index level: p
- Capital stock: K
- Dividend payment: D_i
- The net result of firms: $\Pi = pY - wL - rD$

■ Structure of the model – The macroeconomic framework

The reduced variables

- The profit share: $\pi := \frac{\Pi}{pY}$
- The employment rate: $\lambda := \frac{L}{N}$
- The private debt ratio: $d := \frac{D}{pY}$
- The global workforce: N

■ Structure of the model – The macroeconomic framework

The main macroeconomic relations

- The production: $Y := \frac{K}{\nu}$
- The capital accumulation: $\dot{K} := I - \delta K$
- The private debt accumulation: $\dot{D} := \rho I + \Delta(\pi) p Y - \Pi$
- Short-term Phillips curve: $\frac{\dot{w}}{w} := \Phi(\lambda) + \gamma i$
- Price dynamics: $i := \frac{\dot{p}}{p} := \eta_p(m\omega - 1) + i_{LT}$
- The global workforce dynamics: $\frac{\dot{N}}{N} := q \left(1 - \frac{N}{P} \right)$
- The labor productivity: $a := (1 - \mathbf{D}) \frac{Y}{L}$

■ Structure of the model – The macroeconomic framework

Differential system

- A 4-dimensional system of differential equations:

$$\left\{ \begin{array}{l} \dot{\omega} = \omega \left[\Phi(\lambda) - (1 - \gamma)i(\omega) - \frac{\dot{a}}{a} \right] \\ \dot{\lambda} = \lambda \left[\frac{\dot{Y}}{Y} - \frac{\dot{a}}{a} - \frac{\dot{N}}{N} \right] \\ \dot{d} = d \left[r - \left(\frac{\dot{Y}}{Y} + i(\omega) \right) \right] + \kappa(\pi) + \Delta(\pi) - (1 - \omega) \\ \dot{N} = qN \left(1 - \frac{N}{PN} \right) \end{array} \right.$$

- Where intervene the following variables of interest:

$$\pi = 1 - \omega - rd$$

$$\frac{\dot{Y}}{Y} = \frac{\kappa(\pi)}{\nu} - \delta$$

$$i(\omega) = \eta_p(m\omega - 1) + c$$

■ Structure of the model – The macroeconomic framework

Convergence toward a steady-state without climate change

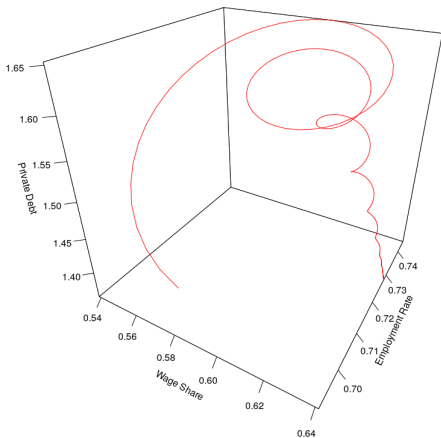


Figure: Phase diagram in the absence of climate change (calibrated model).

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■ Structure of the model – The climate module

Physical process overview

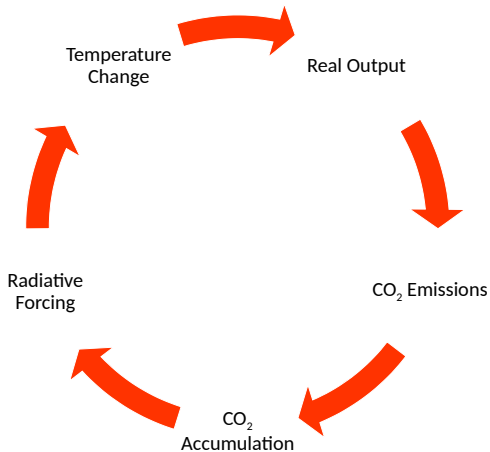


Figure: Climate-economy interactions diagram.

■ Structure of the model – The climate module

CO₂ emissions

Global CO₂ emissions are the sum of two contributions: $E := E_{ind} + E_{land}$

- Endogenous industrial emissions:

$$E_{ind} := Y\sigma(1 - n)$$

- Proportional to real output Y
 - Emission intensity of the economy: σ
 - Emissions reduction rate: n
- Exogenous emissions linked to land-use change E_{land}

■ Structure of the model – The climate module

CO₂ accumulation (1/2)

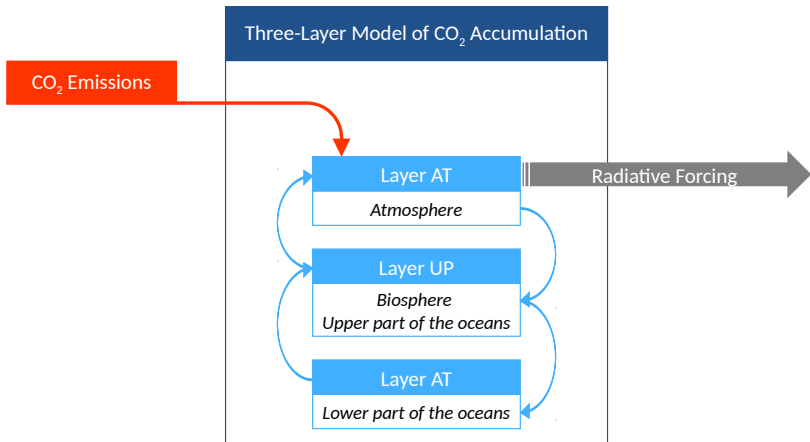


Figure: CO₂ accumulation in a three-layer model.

■ Structure of the model – The climate module

CO₂ accumulation (2/2)

Modeling through the following system:

$$\begin{pmatrix} \dot{CO}_2^{AT} \\ \dot{CO}_2^{UP} \\ \dot{CO}_2^{LO} \end{pmatrix} := \begin{pmatrix} E \\ 0 \\ 0 \end{pmatrix} + \begin{pmatrix} -\phi_{12} & \phi_{12} \frac{CO_2^{AT_{init}}}{CO_2^{UP_{init}}} & 0 \\ \phi_{12} & -\phi_{12} \frac{CO_2^{AT_{init}}}{CO_2^{UP_{init}}} - \phi_{23} & \phi_{23} \frac{CO_2^{UP_{init}}}{CO_2^{LO_{init}}} \\ 0 & \phi_{23} & -\phi_{23} \frac{CO_2^{UP_{init}}}{CO_2^{LO_{init}}} \end{pmatrix} \begin{pmatrix} CO_2^{AT} \\ CO_2^{UP} \\ CO_2^{LO} \end{pmatrix}$$

■ Structure of the model – The climate module

Radiative forcing

Radiative forcing is the sum of two contributions: $F := F_{ind} + F_{exo}$

- CO₂ accumulation in the atmospheric layer:

$$F_{ind} := \frac{F_{2 \times CO_2}}{\log(2)} \log \left(\frac{CO_2^{AT}}{CO_2^{AT_{init}}} \right)$$

- Exogenous radiative forcing F_{exo} to model residual factors (dynamics calibrated on the IPCCs' *RCPs* (2013)^[12])

■ Structure of the model – The climate module

Temperature change (1/2)

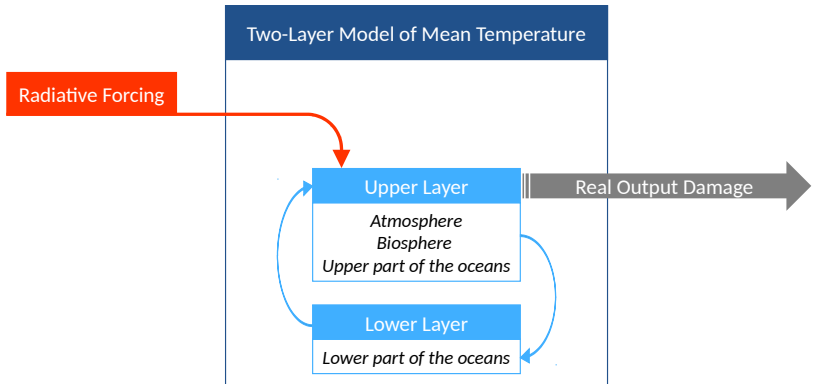


Figure: Dynamics of temperature.

■ Structure of the model – The climate module

Temperature change (2/2)

Temperature's evolution is inspired by Geoffroy *et al.* (2013)^[4]:

- *Energy Balanced*
- A two-layer model:
 - Atmosphere, biosphere, ocean upper level (temperature anomaly):

$$C\dot{T} = F - \rho T - \gamma^*(T - T_0)$$

- Deep ocean (temperature anomaly T_0):

$$C_0\dot{T}_0 = \gamma^*(T - T_0)$$

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■ Structure of the model – Climate damages and mitigation

Environmental damages due to global warming

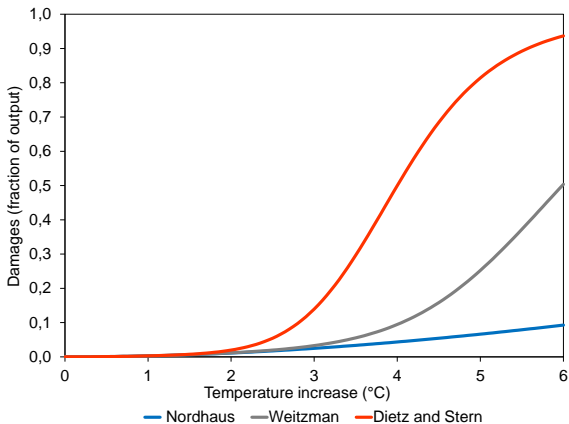


Figure: Comparison of the shape of covered damage functions.

■ Structure of the model – Climate damages and mitigation

Allocation of environmental damages between output flows and capital stock

■ Allocation of damages according to:

- Damages on capital stock:

$$\mathbf{D}^K := f_K \mathbf{D}$$

- Damages on output flows:

$$\mathbf{D}^Y := 1 - \frac{1 - \mathbf{D}}{1 - \mathbf{D}^K}$$

■ Introduction of damages in the macroeconomic model:

- Capital accumulation:

$$K := I - (\delta + \mathbf{D}^K)K$$

- Production function:

$$Y := (1 - \mathbf{D}^Y) \frac{K}{\nu}$$

■ Structure of the model – Climate damages and mitigation

Environmental damages on labor productivity

- Alternate definition of the damage function introduced by Burke *et al.* (2015)^[2] as a quadratic alteration of the labor productivity.
- Endogenous labor productivity growth:

$$\frac{\dot{a}}{a} := \alpha_1 T_a + \alpha_2 T_a^2$$

■ Structure of the model – Climate damages and mitigation

Mitigation effort

- Impulsed by the emission reduction rate n sets by public authorities, inspired by Nordhaus (2013)^[11] :
 - Exogenous trajectories of the carbon price p_C
 - Exogenous de-growth trajectories of the backstop technology p_{NC}
 - Arbitrage relationship:

$$n := \min \left\{ \left(\frac{p_C}{p_{NC}} \right)^{\frac{1}{\theta_2 - 1}} ; 1 \right\}$$

■ Structure of the model – Climate damages and mitigation

Abatement cost of carbon

- The implementation of mitigation effort impose a burden on the economy modeled through the abatement cost of carbon: $G := \theta_1 \sigma p_{BS} n^{\theta_2}$
- This cost is partly born by firms:
 - The effective Gross Capital Fixed Formation: $I^{ef} := (\kappa(\pi) - \mu G) Y$
 - The accumulation of capital:

$$\begin{aligned}\dot{K} &:= I^{ef} - \delta K \\ &= \kappa(\pi) Y - \left(\delta + \mathbf{D}^K + \frac{\mu}{\nu} G \right) K\end{aligned}$$

- The dynamics of private debt:

$$D := \rho l + \Delta(\pi) \rho Y - \Pi$$

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■ Structure of the model – Wrap-up: stock-flow consistent table

Stock-flow consistency à la (Godley et Lavoie (2012))^[5]

	Households		Firms		Banks	Sum
Balance Sheet						
Deposits	+ M				- M	
Capital stock			pK			pK
Loan			$-D$		D	
Sum (net worth)	X^h		X^f		X^b	X
Transactions						
Consumption	$-pC$	current	pC	capital		
Investment			pI	$-pI$		
Accounting memo [GDP]			$[pY(1 - \mathbf{D}^Y)]$			
Wages	W		$-W$			
Interests on debt			$-rD$		rD	
Firms' net profit			$-\Pi$		Π	
Dividends	D_i				$-D_i$	
Financial Balances	S^h				$-D$	Π^b
Flow of funds						
Deposits	$+M$				$-M$	
Gross Fixed Capital Formation			pI			pI
Change in loans			$-D$		D	
Column sum	S^h		$\Pi - D_i$		D	pI
Change in net worth	S^h		$\dot{X}^f = \Pi - D_i + (\dot{p} - (\delta + \mathbf{D}^K + \frac{\mu}{V} G))pK$		$\dot{X}^b = \Pi^b$	\dot{X}

Table: Balance sheet, transactions, and flow of funds in the world economy.

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■ Impact of climate change – Mathematical analysis

Properties of the global long-term equilibria

1. The energy shift is performed (no more emissions or abatement cost)
2. The climate and economic modules are decoupled and can be studied separately
3. The climate module admits a unique equilibrium characterized by:
 - (i) The quantity of CO_2 is the sum of the preindustrial one *plus* total emissions
 - (ii) The relative preindustrial quantities of CO_2 in each layer are respected
 - (iii) The mean atmospheric deviation is constant and strictly positive
 - (iv) The radiative forcing is constant and strictly positive
4. The macroeconomic module admits at least 2 equilibria

■ Impact of climate change – Mathematical analysis

Shape of the steady-state macroeconomic equilibrium

- Assuming constant prices, the steady-state equilibrium is defined by:

$$\left\{ \begin{array}{l} \pi_1 = \kappa^{-1} \left(\frac{\nu (g_{aeq} + \delta + \mathbf{D}^K_{eq})}{1 - \mathbf{D}^Y_{eq}} \right) \\ \omega_1 = 1 - \pi_1 - rd_1 \\ = 1 - \left(1 - \frac{r}{g_{aeq}} \right) \pi_1 - r \frac{\kappa(\pi_1) + \Delta(\pi_1)}{g_{aeq}} \\ \lambda_1 = \Phi^{-1}(g_{aeq}) \\ d_1 = \frac{\kappa(\pi_1) + \Delta(\pi_1) - \pi_1}{g_{aeq}} \\ N_1 = P \\ g_{aeq} = \frac{\dot{a}}{a} (T = T^{eq}) \end{array} \right.$$

- At the desirable steady-state, the income distribution is shifted at the expense of households:
 - Converse forces on the profit share reasonably pushed forward
 - Increased debt ratio by cutting wages *in case of “over-optimism”*
 - Unfavorable for wage share

■ Impact of climate change – Mathematical analysis

Stability of the macroeconomic equilibria

- Assuming a constant dividend and considering damages on output:
 - A necessary condition for the stability of the steady state equilibrium is:

$$\pi_1 > \frac{\nu(\delta + \mathbf{D}^K_{eq})}{1 - \mathbf{D}^Y_{eq}}$$

- A necessary condition for the stability of the breakdown attractor is:

$$r > \frac{\kappa_0}{\nu}(1 - \mathbf{D}^Y_{eq}) - (\delta + \mathbf{D}^K_{eq})$$

- The local stability conditions are twisted by climate in favor of the breakdown attractor
- Global warming tends to drive the economy out of the desirable steady-state basin of attraction

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■ Impact of climate change – Numerical analysis

Temperature paths of the steady-state (1/3)

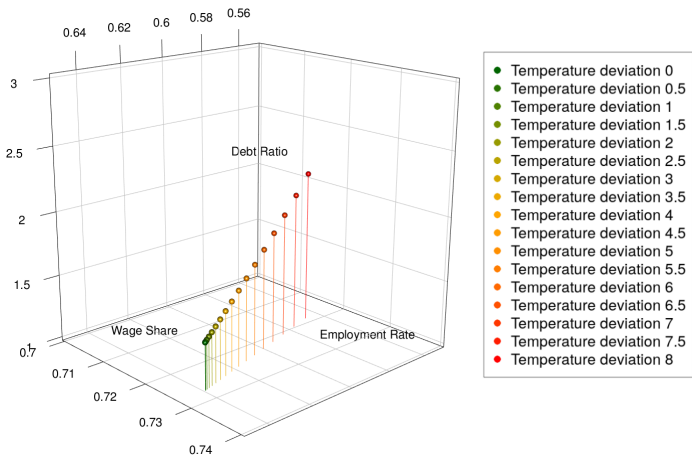


Figure: Bifurcation graph of the steady-state – Damage on output.

■ Impact of climate change – Numerical analysis

Temperature paths of the steady-state (2/3)

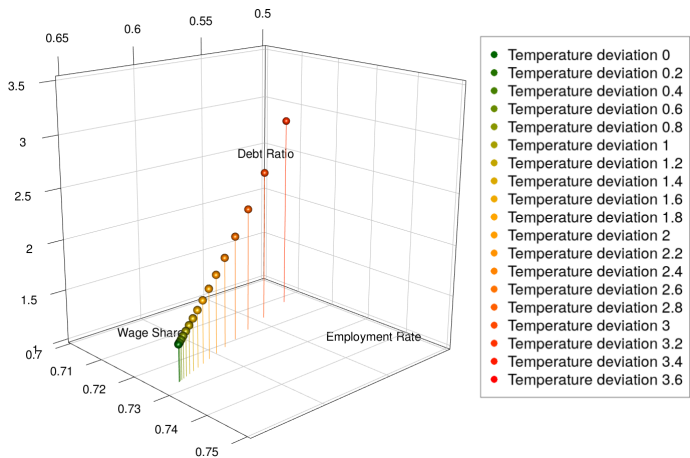


Figure: Bifurcation graph of the steady-state – Damage on output and capital.

■ Impact of climate change – Numerical analysis

Temperature paths of the steady-state (2/3)

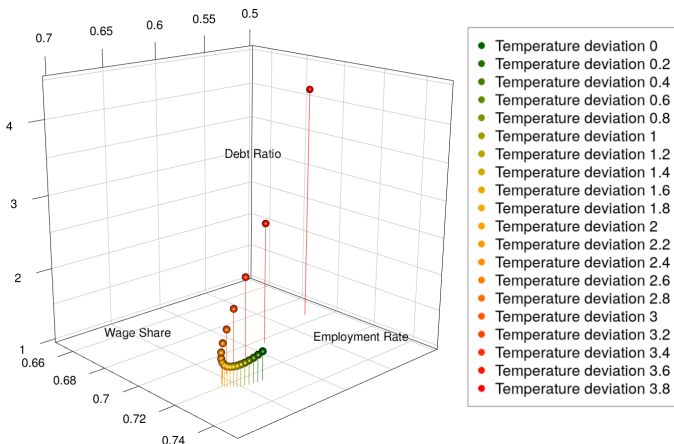


Figure: Bifurcation graph of the steady-state – Damage on capital and labor productivity.

■ Impact of climate change – Numerical analysis

Basin of attraction of the steady-state (1/3)

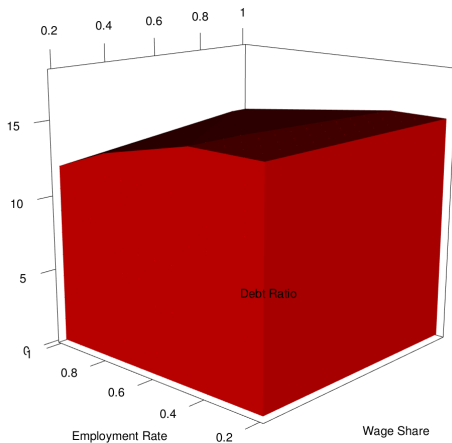


Figure: Basin of attraction without climate change.

■ Impact of climate change – Numerical analysis

Basin of attraction of the steady-state (2/3)

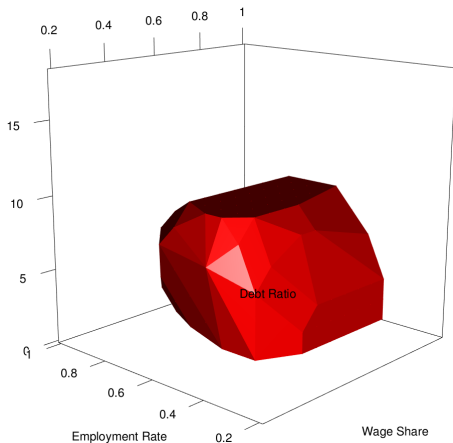


Figure: Basin of attraction with damages on output and capital.

■ Impact of climate change – Numerical analysis

Basin of attraction of the steady-state (3/3)

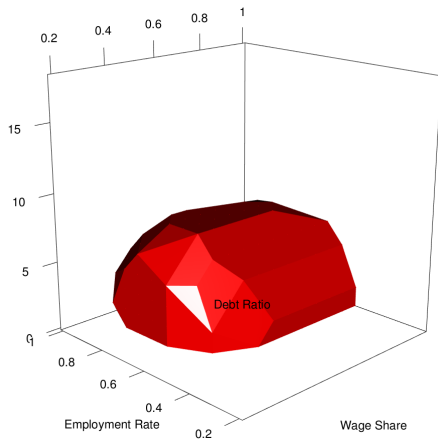


Figure: Basin of attraction with damages on capital and labor productivity.

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■ Climate prospective – Scope of analysis

Simulations calibration

- Identification thanks to the stock-flow consistency property
- Macroeconomic module:
 - Build a database at World level
World Bank, Penn, Bureau of Economic Analysis, United Nations
 - Estimation and calibration of the phenomenological functions
 - Main economic variables:

Parameters	Y_{2010}	N_{2010}	ω_{2010}	λ_{2010}	d_{2010}	ρ_{2010}
value	64.4565	4.5510	0.5849	0.6910	1.4393	1

- Climate module: calibrated on DICE (2013)^[11]
- Damage function and endogenous labor productivity growth: literature

■ Climate prospective – Scope of analysis

Design of the prospective scenarios

- Prospective analysis through 5 classes of scenarios:
 - **Baseline**: absent climate change
 - **Nordhaus**: Nordhaus-type damage on output
 - **Stern**: allocation of Weitzman-type damage between output and capital
 - **Burke**: Weitzman-type damage on capital and Burke-type damage on labor productivity
 - **Burke Extreme**: Dietz-type damage on capital and Burke-type damage on labor productivity

- Public policy insight to cope with potential collapse through the appropriate carbon-price instrument:
 1. Run of the scenarios with a low-constraining carbon-price path
 2. Analysis of carbon-price instrument deployment trade-offs compatible with the realization of the +1.5°C limitation of global warming in 2100 of the Paris Agreement
 3. Proposal of minimal carbon-price path for public policy implementation

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Climate prospective – Low mitigation constraint

An imperious need for public involvement (1/3)

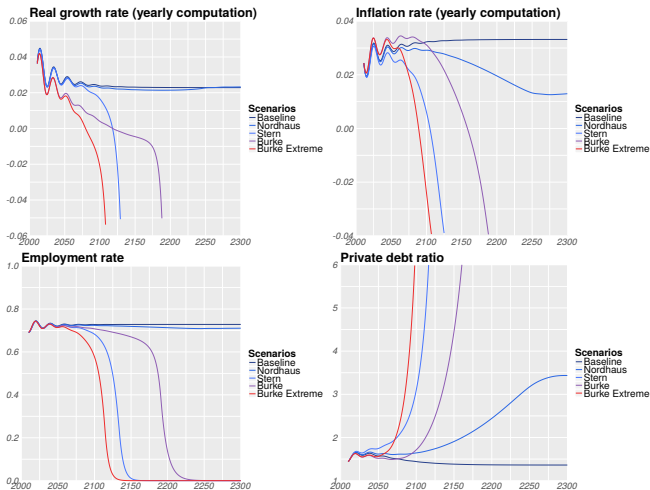


Figure: Trajectories of the main macroeconomic and climate variables absent strong mitigation constraints.

■ Climate prospective – Low mitigation constraint

An imperious need for public involvement (2/3)

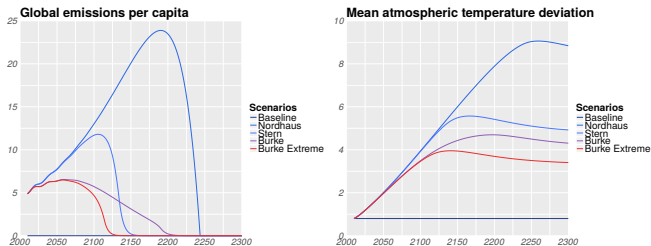
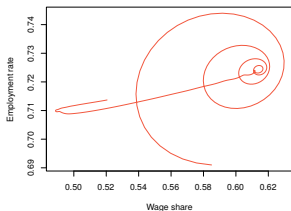


Figure: Trajectories of the main macroeconomic and climate variables absent strong mitigation constraints.

■ Climate prospective – Low mitigation constraint

An imperious need for public involvement (3/3)

Phase diagram - Nordhaus Scenario - Horizon 2010 to 2500



Phase diagram - Stern Scenario - Horizon 2010 to 2500

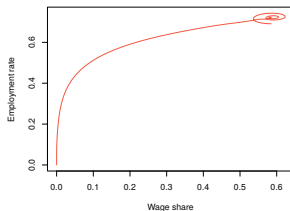


Figure: Phase diagrams in a long term horizon.

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Climate prospective – Deployment of carbon-price instrument

Stability vs Indebtedness trade-offs

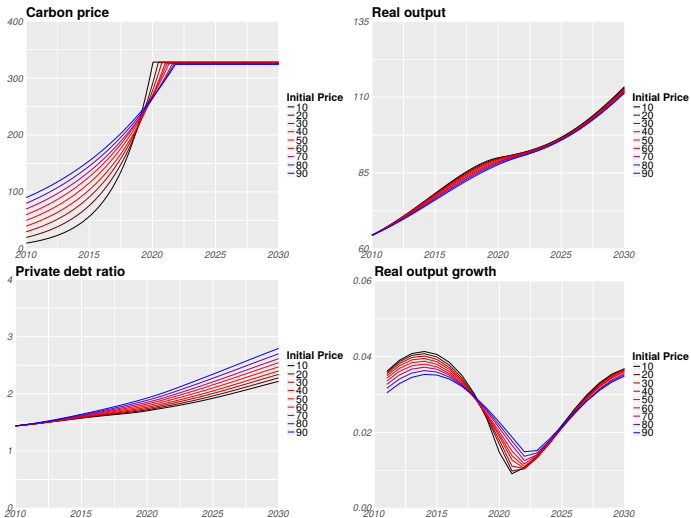


Figure: Minimal carbon-price path implementation.

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■ Climate prospective – Minimal prospective paths

Realizing the Paris Agreement objective – Initial carbon-price of 10 (1/2)



Figure: Trajectories of the main macroeconomic and climate variables with minimal mitigation constraint.

■ Climate prospective – Minimal prospective paths

Realizing the Paris Agreement objective – Initial carbon-price of 10 (2/2)

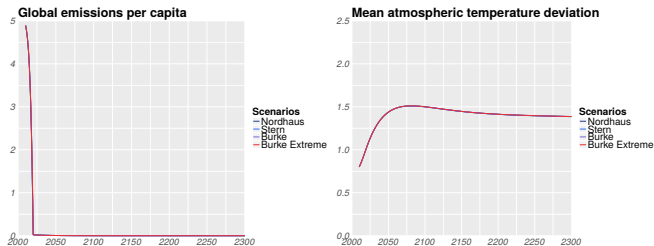


Figure: Trajectories of the main macroeconomic and climate variables with minimal mitigation constraint.

Climate prospective – Minimal prospective paths

Realizing the +2° C-global warming limitation objective – Initial carbon-price of 10 (1/2)

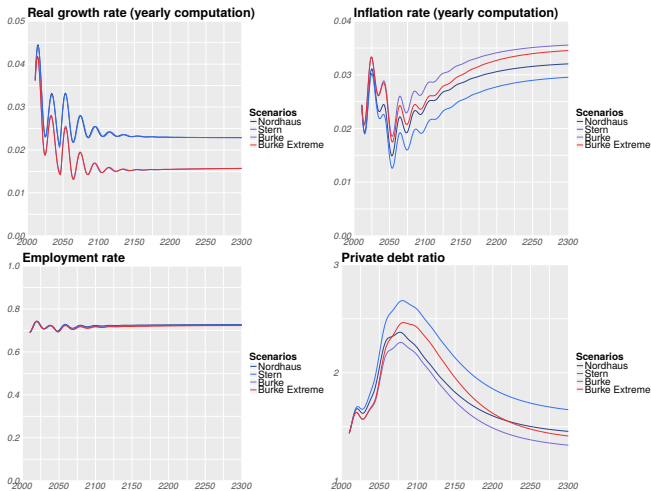


Figure: Trajectories of the main macroeconomic and climate variables with minimal mitigation constraint.

■ Climate prospective – Minimal prospective paths

Realizing the +2° C-global warming limitation objective – Initial carbon-price of 10 (2/2)

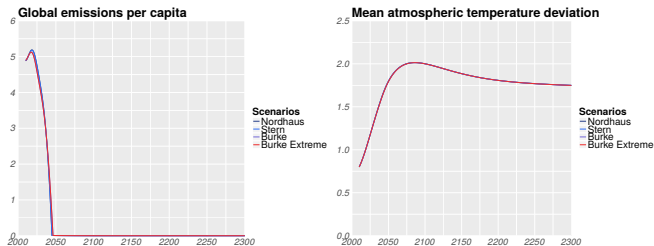


Figure: Trajectories of the main macroeconomic and climate variables with minimal mitigation constraint.

■ Summary

- 1 Introduction
- 2 Context
- 3 Structure of the model
- 4 Impact of climate change
- 5 Climate prospective
- 6 Conclusions**

■ Conclusions

Main results

- Development of a climate feedback framework in a stock-flow consistent macroeconomic monetary model producing a wide range of outcomes
- Identification of the influence of climate change as a channel of financial instability
- Key role of the temperature anomaly in the stability of the economy
- Inaction will most likely lead to a global collapse of the financial/socio-economic system
- Trade-off between climate and financial instability in the rhythm of implementation of a carbon price path
- Involvement of firms more than ever necessary to perform this energy shift, as about 70% of the required investment to perform the energy shift shall come from the private sector

■ Conclusions

Limitations and further research

- Refine economic modeling:
 - Substitution between capital and labor
 - Clarify public policy intervention (including tax incidence)
 - Clarify the energy shift process through investment and technology
 - Make explicit the demand side (consumption, public authorities)

- Add limitations on non-renewable energy and materials

- Build the spacial dimension of the energy shift

Thank you for your attention.

■ Summary

7 Bibliography

■ Bibliography

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