Coping with the Collapse: A Stock-Flow Consistent, Monetary Macro-dynamics of Global Warming

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Outlines

1. Introduction

2. The Keen (1995) Model

3. Macroeconomic model for climate change

4. Climate Module

5. Public Policy Module

6. Numerical Simulations

7. Further Work
Introduction

- *The Limits to Growth* was published (Meadows et al., 1972 and Meadows et al., 1974).
Introduction

Sustainable path or collapse?
Introduction

- Consistent with increasing capital costs and net energy (the decline of energy returned on energy invested, EROI).
- Growing scarcity of natural resources (energy, minerals, water...), while climate change plays little role, if any. (Caveat: Pollution).
- The question of whether global warming might *per se* induce a similar breakdown of the world economy (cf. COP 21).
We explicitly model the financial side of the world economy in order to assess the possible negative feedback of debt on the ability of the world economy to cope with the collapse.

Pivotal role of private debt.

Losses due to environmental damages force the global productive sector to invest a growing part of its wealth in restoring and maintaining capital.

The persistent level of debt may endanger the world economic engine itself as it is based on the promise of future wealth creation.
Introduction

Paper’s framework

- Depending upon the speed at which labor productivity increases compared to the severity of global warming, the shrink of investment induced by the burden of private debt may prevent the world economy from further adapting to the climate turmoil, leading ultimately to a collapse around the end of the twenty-first century.

- The global collapse captured in this paper can be interpreted as the result of a debt-deflation depression in the sense given to this concept by Irving Fisher (1933).

- That part of the world economy might be on the verge of falling into a liquidity trap is illustrated, today, by the two “lost decades” of Japan, of course, but also the recessionary state of the Southern part of the Eurozone, obstinately negative long-term interest rates on international financial markets and, last but not least, the brutal contraction of the world nominal GDP in 2015 (-6%, IMF (2016)).
These paradoxes may be viewed as signals of the translation of a secular decline induced by biophysical constraints into the financial sphere.
GEMMES

GEneral Monetary Multisectoral Macrodynamics for the Ecological Shifts
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7. Further Work
The Keen (1995) Model

Overview

1. Since the financial crisis of 2007-2009, the ideas of Hyman Minsky around the intrinsic instability of a monetary market economy have experienced a significant revival.


4. Investment financed by endogenous money creation.
The Keen (1995) Model
Private debt matters
The Keen (1995) Model

Stock and Flow consistent model

<table>
<thead>
<tr>
<th>Balance Sheet</th>
<th>Households</th>
<th>Firms</th>
<th>Banks</th>
<th>Government</th>
<th>Sum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capital stock</td>
<td>(K)</td>
<td></td>
<td></td>
<td>(K)</td>
<td></td>
</tr>
<tr>
<td>Loan</td>
<td>(-D)</td>
<td>(D)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sum (net worth)</td>
<td>(X^f)</td>
<td>(X^b)</td>
<td></td>
<td>(X)</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Transactions</th>
<th>current</th>
<th>capital</th>
</tr>
</thead>
<tbody>
<tr>
<td>Consumption</td>
<td>(-C)</td>
<td>(C)</td>
</tr>
<tr>
<td>Investment</td>
<td>(I)</td>
<td>(-I)</td>
</tr>
<tr>
<td>Government spend.</td>
<td>(G)</td>
<td>(-G)</td>
</tr>
<tr>
<td>Memo [GDP]</td>
<td>([GDP])</td>
<td></td>
</tr>
<tr>
<td>Wages</td>
<td>(W)</td>
<td>(-W)</td>
</tr>
<tr>
<td>Interests on debt</td>
<td>(-rD)</td>
<td>(rD)</td>
</tr>
<tr>
<td>Firms’ net profit</td>
<td>(-\Pi)</td>
<td>(\Pi)</td>
</tr>
<tr>
<td>Financial Balances</td>
<td>(-\dot{D})</td>
<td>(\Pi^b)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Flow of funds</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Investment</td>
<td>(I)</td>
<td>(I)</td>
</tr>
<tr>
<td>Change in Loans</td>
<td>(-\dot{D})</td>
<td>(\dot{D})</td>
</tr>
<tr>
<td>Column sum</td>
<td>(\Pi)</td>
<td>(\dot{D})</td>
</tr>
<tr>
<td>Change in Net worth</td>
<td>(\dot{X}^f = \Pi + (\dot{p} - \delta p)K)</td>
<td>(\dot{X}^b = \Pi^b)</td>
</tr>
</tbody>
</table>

Table: Stock-Flow Table
The Keen (1995) Model

The model

$\lambda$: the employment rate.

$$\lambda := \frac{L}{N}.$$  

$L$: the labor force, and $N$: the total population.

$$\frac{\dot{N}}{N} = \beta.$$  

$a$: the labor productivity.

$$\frac{\dot{a}}{a} = \alpha.$$  

$w$: the wage per worker, $W = wL$: the total wage, $\omega$: the wage share ad $Y$: the production.

$$\omega = \frac{W}{Y} = \frac{wL}{aL} = \frac{w}{a}$$
The Keen (1995) Model

The model

\[ \dot{K} = I - \delta K. \]

\( K \): the stock of capital.

The Leontief production function

\[
Y = \min \left( \frac{K}{\nu}, aL \right) \\
= \frac{K}{\nu} = aL.
\]
The Keen (1995) Model

The model

\[ \dot{D} = I - \Pi. \]

with \( \Pi := Y - W - rD \): the real profit of the firm, and \( r \): the interest rate.

\( \pi \): the profit-to-production ratio.

\[ \pi = \frac{\Pi}{Y}. \]

\( d \): the debt-production ratio.

\[ d = \frac{D}{Y}. \]
The Keen (1995) Model
Aggregate behaviours

The Short-term Phillips Curve (Mankiw, 2010).

\[
\frac{\dot{w}}{w} = \phi(\lambda).
\]

The Investment Function: it evolves positively with the profit share.

\[
\frac{I}{Y} = \kappa(\pi).
\]
The Keen (1995) Model

The three-dimensional system

One can retrieve the following set of equations:

\[
\begin{align*}
\dot{\omega} & = \omega \left[ \phi(\lambda) - \alpha \right] \\
\dot{\lambda} & = \lambda \left[ \frac{\kappa(\pi)}{\nu} - \delta - \alpha - \beta \right] \\
\dot{d} & = d \left[ r - \frac{\kappa(\pi)}{\nu} + \delta \right] + \kappa(\pi) - (1 - \omega)
\end{align*}
\]
The Keen (1995) Model

Aggregate behaviours

- Phenomenological approach: $\phi(.)$ and $\kappa(.)$ are empirically estimated.
- Sonnenschein-Mantel-Debreu (1975): anything can happen.
- Agent-based model.
Three long run equilibria exist:
- An unstable equilibrium at \((0, 0, d_0)\)
- A **good** equilibrium locally stable
- A **bad** equilibrium locally stable
Simulations - good equilibrium with finite debt

Fig. 4 Employment, wages, debt and output as functions of time converging to a stable equilibrium with finite debt in the Keen model
Simulations - bad equilibrium with infinite debt

Fig. 5 Employment, wages, debt and output as functions of time converging to a stable equilibrium with infinite debt in the Keen model
Basin of Attraction
The Keen (1995) Model

Possible outcome induced by climate change

- Depending upon the basin of attraction where the state of the economy is driven by climate damages, the ultimate breakdown may occur as the inescapable consequence of the business as usual trajectory.
Outlines

1 Introduction

2 The Keen (1995) Model

3 Macroeconomic model for climate change

4 Climate Module

5 Public Policy Module

6 Numerical Simulations

7 Further Work
Macroeconomic model for climate change

Modelling:
- The macroeconomics is borrowed from Keen (1995).
  - Stock-Flow consistent.
  - Phenomenological functions.
- The climate feed-back loop is in line with Nordhaus’ DICE model (2013).

Estimation
- Calibration of the climate and public policy modules in line with Nordhaus’ DICE model (2013).
- Macroeconomic module estimation in progress: panel analysis to benefit wider volatility.
Macroeconomic model for climate change

Production, capital and debt accumulation

The real output

\[ Y = (1 - D) \frac{K}{\nu}. \]

The investment function with abatement cost

\[ I = (\kappa(\pi) - \mu G) Y. \]

Population grows according to a UN scenario,

\[ \frac{\dot{N}}{N} = q(1 - \frac{N}{M}). \]
Macroeconomic model for climate change

Monetary economy

The wage dynamic evolves according to a short-term Phillips curve

\[ \frac{\dot{w}}{w} = \Phi(\lambda) + \gamma i. \]

The price dynamics,

\[ i = \frac{\dot{p}}{p}, \]

\[ = \eta_p(\omega - 1) + i_{LT}. \]
As an example, for deterministic exponential scenario, climate change positively impact the share of wages

\[
\frac{\dot{\omega}}{\omega} = \frac{\dot{w}}{w} - \frac{\dot{a}}{a} + \frac{\dot{D}}{1 - D} - i \\
= \phi(\lambda) - \alpha + \frac{\dot{D}}{1 - D} - (1 - \gamma)i.
\]
## Macroeconomic model for climate change

<table>
<thead>
<tr>
<th></th>
<th>Households</th>
<th>Firms</th>
<th>Banks</th>
<th>Sum</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Balance Sheet</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Capital stock</td>
<td></td>
<td>$+p_t K_t$</td>
<td></td>
<td>$+p_t K_t$</td>
</tr>
<tr>
<td>Loan</td>
<td></td>
<td>$-D_t$</td>
<td>$+D_t$</td>
<td></td>
</tr>
<tr>
<td>Sum (net worth)</td>
<td>$X^f_t$</td>
<td>$X^b_t$</td>
<td>$X_t$</td>
<td></td>
</tr>
<tr>
<td><strong>Transactions</strong></td>
<td></td>
<td>current</td>
<td>capital</td>
<td></td>
</tr>
<tr>
<td>Consumption</td>
<td>$-p_tC_t$</td>
<td>$+p_tC_t$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Investment</td>
<td>$+p_tI_t$</td>
<td></td>
<td>$-p_tI_t$</td>
<td></td>
</tr>
<tr>
<td>Accounting memo [GDP]</td>
<td></td>
<td>$[p_t Y_t(1 - D_t)]$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wages</td>
<td>$+W_t$</td>
<td>$-W_t$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Interests on debt</td>
<td>$-rD_t$</td>
<td>$+rD_t$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Firms’ net profit</td>
<td>$-\Pi_t$</td>
<td></td>
<td>$+\Pi_t$</td>
<td></td>
</tr>
<tr>
<td>Dividends</td>
<td>$+D_i_t$</td>
<td></td>
<td>$-D_i_t$</td>
<td></td>
</tr>
<tr>
<td>Financial Balances</td>
<td></td>
<td>$-\hat{D}_t$</td>
<td>$+\Pi^b_t$</td>
<td></td>
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<tr>
<td><strong>Flow of funds</strong></td>
<td></td>
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<tr>
<td>GFCF</td>
<td></td>
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<td>$+p_tI_t$</td>
</tr>
<tr>
<td>Change in Loans</td>
<td>$-\hat{D}_t$</td>
<td></td>
<td>$+\hat{D}_t$</td>
<td></td>
</tr>
<tr>
<td>Column sum</td>
<td>$\Pi_t - D_i_t$</td>
<td>$D_t$</td>
<td>$p_tI_t$</td>
<td></td>
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<tr>
<td>Change in Net worth</td>
<td>$\dot{X}^f_t = \Pi_t - D_i_t + (\dot{p}_t - \delta p_t)K_t$</td>
<td>$\dot{X}^b_t = \Pi^b_t$</td>
<td>$\dot{X}_t$</td>
<td></td>
</tr>
</tbody>
</table>

**Table:** Balance sheet, transactions, and flow of funds for a three-sector economy.
Macroeconomic model for climate change

**Productivity**

- The Business as usual Scenario
  \[ \frac{\dot{a}}{a} = \alpha \]

- The Burke et al. (2015) Scenario
  \[ \frac{\dot{a}}{a} = \alpha_1 T\alpha + \alpha_2 T^2\alpha \]

- The Kaldor-Verdoorn (2002) Scenario
  \[ \frac{\dot{a}}{a} = \alpha + \eta g \]

- The Gordon (2014) Scenario - productivity growth is 1.3%
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Climate Module

**CO₂ Emissions**

Global emissions are the sum of industrial and land-use emissions

\[ E := E_{ind} + E_{land}, \]

where industrial emissions depend on output,

\[ E_{ind} := Y \sigma (1 - n), \]

with,

\[
\frac{\dot{\sigma}}{\sigma} = -g_{\sigma}
\]

\[
\frac{g_{\sigma}}{g_{\sigma}} = \delta_{g_{\sigma}} \text{ with } \delta_{g_{\sigma}} < 0
\]

and the land-use emissions,

\[
\frac{\dot{E}_{land}}{E_{land}} = \delta_{E} \text{ with } \delta_{E} < 0
\]
Climate Module

CO₂ Accumulation

The CO₂ evolves according to a three-layer model, the atmosphere (AT), the upper ocean (UP) and the lower ocean (LO),

\[
\begin{pmatrix}
\dot{C}O_2^{AT} \\
\dot{C}O_2^{UP} \\
\dot{C}O_2^{LO}
\end{pmatrix} = \begin{pmatrix} E \\ 0 \\ 0 \end{pmatrix} + \begin{pmatrix}
-\phi_{12} & \phi_{12} \frac{C_{ATeq}}{C_{UPeq}} & 0 \\
\phi_{12} & -\phi_{12} \frac{C_{ATeq}}{C_{UPeq}} - \phi_{23} & \frac{C_{UPeq}}{C_{LOeq}} \\
0 & \phi_{23} \frac{C_{UPeq}}{C_{LOeq}} & -\phi_{23} \frac{C_{UPeq}}{C_{LOeq}}
\end{pmatrix} \begin{pmatrix}
C_{O2}^{AT} \\
C_{O2}^{UP} \\
C_{O2}^{LO}
\end{pmatrix}.
\]
Radiative forcing is the sum of the radiative forcing due to CO$_2$ and other gases,

\[ F := F_{\text{ind}} + F_{\text{exo}}, \]

with,

\[ F_{\text{ind}}(t) = \frac{F_2 \times \text{CO}_2}{\log(2)} \log \left( \frac{C_{\text{CO}_2(t)}}{C_{\text{CO}_2(t_0)}} \right), \]

\[ \dot{F}_{\text{exo}} = \delta F_{\text{exo}} F_{\text{exo}} \left( 1 - \frac{F_{\text{exo}}}{F_{\text{exo}}^{\text{max}}} \right). \]
The temperature dynamics is a two-layer model, with $T$ being the mean atmospheric temperature deviation with respect to its value in 1900 and $T_0$ represents the deep-ocean temperature deviation.

\[
\begin{align*}
C \dot{T} &= F - (RF)T - \gamma^* (T - T_0) \\
C_0 \dot{T}_0 &= \gamma^* (T - T_0)
\end{align*}
\]
Climate Module

Damage Function (1/2)

The Nordhaus’s Damage function (2013),

\[
D = 1 - \frac{1}{1 + \pi_1 T + \pi_2 T^2}
\]

The Weitzman’s (2010) and Dietz-Stern’s (2015) Damage functions,

\[
D = 1 - \frac{1}{1 + \pi_1 T + \pi_2 T^2 + \pi_3 T^{6.754}}
\]

In Weitzman (2010), \(\pi_3\) is calibrated so that \(D = 50\%\) whenever \(T = 6\).

In Dietz-Stern (2015), \(\pi_3\) is calibrated so that \(D = 50\%\) whenever \(T = 4\).
Figure: Comparison of the proposed Damage functions as percentage of output.
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The abatement cost

\[ G := \theta_1 n^{\theta_2} \]

with \( \theta_1 \) and \( \theta_2 \) borrowed from Nordhaus (2013). \( n \), the reduction rate of emissions implied by the abatement cost evolves according to,

\[ n = \min \left\{ \left( \frac{p_c}{p_{BS}} \right)^{\frac{1}{\theta_2 - 1}} ; 1 \right\}. \]

Prices are exogenously given so that,

\[ \frac{p_{BS}}{p_{BS}} = \delta_{p_{BS}}, \text{ with } \delta_{p_{BS}} < 0 \]

\[ \frac{p_C}{p_C} = \delta_{p_C}, \text{ with } \delta_{p_C} > 0 \]
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## Numerical Simulations

### Scenarios - Baseline Calibration

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Y_{\text{init}}$</td>
<td>64.4565</td>
</tr>
<tr>
<td>$N_{\text{init}}$</td>
<td>4.5510</td>
</tr>
<tr>
<td>$\omega_{\text{init}}$</td>
<td>0.5849</td>
</tr>
<tr>
<td>$\lambda_{\text{init}}$</td>
<td>0.6910</td>
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<tr>
<td>$d_{\text{init}}$</td>
<td>1.4393</td>
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<tr>
<td>$\rho_{\text{init}}$</td>
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<tr>
<td>$\eta_p$</td>
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<td><strong>markup</strong></td>
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<td>Monetary illusion</td>
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<tr>
<td>$\delta$</td>
<td>0.0625</td>
</tr>
<tr>
<td>$\nu$</td>
<td>2.8956</td>
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<tr>
<td>$r$</td>
<td>0.0303</td>
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<tr>
<td>dfi</td>
<td>0.1672</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>0.0226</td>
</tr>
</tbody>
</table>
Numerical Simulations

The BAU Scenario

Figure: Trajectories of the main simulation outputs in the BAU case.
Numerical Simulations

The BAU Scenario

Figure: Trajectories of the main simulation outputs in the BAU case.
### Numerical Simulations

#### The BAU Scenario

<table>
<thead>
<tr>
<th>Wage Share</th>
<th>Employment Rate</th>
<th>Debt to Nominal GDP Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.54</td>
<td>0.68</td>
<td>1.26</td>
</tr>
<tr>
<td>0.57</td>
<td>0.7</td>
<td>1.35</td>
</tr>
<tr>
<td>0.6</td>
<td>0.72</td>
<td>1.44</td>
</tr>
<tr>
<td>0.63</td>
<td>0.74</td>
<td>1.53</td>
</tr>
<tr>
<td>0.63</td>
<td>0.74</td>
<td>1.62</td>
</tr>
</tbody>
</table>

**Figure:** Trajectories of the main simulation outputs in the BAU case.
## Numerical Simulations

*The BAU Scenario - Values*

<table>
<thead>
<tr>
<th>Metric</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>GDP Real Growth 2100 (wrt 2010)</td>
<td>1053%</td>
</tr>
<tr>
<td>t CO₂ per capita (2050)</td>
<td>7.72</td>
</tr>
<tr>
<td>Temperature change in 2100</td>
<td>+3.94 °C</td>
</tr>
<tr>
<td>CO₂ concentration 2100</td>
<td>968.98 ppm</td>
</tr>
</tbody>
</table>

*Table:* Key values of the world economy by 2100 — the exogenous case.
Numerical Simulations

The Kaldor-Verdoorn Scenario

Figure: Trajectories of the main simulation outputs in the Kaldor-Verdoorn case.
Numerical Simulations

The Kaldor-Verdoorn Scenario

Figure: Trajectories of the main simulation outputs in the Kaldor-Verdoorn case.
Numerical Simulations
The Kaldor-Verdoorn Scenario - Values

GDP Real Growth 2100 (wrt 2010)  
$t CO_2$ per capita (2050)  
Temperature change in 2100  
$CO_2$ concentration 2100  

53%  
3.17  
$+2.63 ^\circ C$  
521.09 ppm

Table: Key values of the world economy by 2100 — the Kaldor-Verdoorn case.
Numerical Simulations

The Burke et al. (2015) Scenario

**Figure:** Trajectories of the main simulation outputs in the Burke et al. (2015) case.
Figure: Trajectories of the main simulation outputs in the Burke et al. (2015) case.
Numerical Simulations
The Burke et al. (2015) Scenario - Values

Table: Key values of the world economy by 2100 — The Burke et al. (2015) case.

<table>
<thead>
<tr>
<th>Metric</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>GDP Real Growth 2100 (wrt 2010)</td>
<td>397%</td>
</tr>
<tr>
<td>t CO₂ per capita (2050)</td>
<td>6.29</td>
</tr>
<tr>
<td>Temperature change in 2100</td>
<td>+3.48 °C</td>
</tr>
<tr>
<td>CO₂ concentration 2100</td>
<td>744.49 ppm</td>
</tr>
</tbody>
</table>
**Numerical Simulations**

*The Weitzman Scenario*

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**Figure:** Trajectories of the main simulation outputs in the Weitzman case.
Numerical Simulations

The Weitzman Scenario

Figure: Trajectories of the main simulation outputs in the Weitzman case.
Numerical Simulations

The Weitzman Scenario - Values

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>GDP Real Growth 2100 (wrt 2010)</td>
<td>987%</td>
</tr>
<tr>
<td>t CO$_2$ per capita (2050)</td>
<td>7.72</td>
</tr>
<tr>
<td>Temperature change in 2100</td>
<td>+3.93 °C</td>
</tr>
<tr>
<td>CO$_2$ concentration 2100</td>
<td>958.17 ppm</td>
</tr>
</tbody>
</table>

Table: Key values of the world economy by 2100 — the Weitzman case.
Numerical Simulations
The Dietz-Stern Scenario

Figure: Trajectories of the main simulation outputs in the Dietz-Stern case.
Numerical Simulations

The Dietz-Stern Scenario

Figure: Trajectories of the main simulation outputs in the Dietz-Stern case.
Numerical Simulations
The Dietz-Stern Scenario - Values

GDP Real Growth 2100 (wrt 2010) 495%
t CO₂ per capita (2050) 7.72
Temperature change in 2100 +3.84 °C
CO₂ concentration 2100 860.53 ppm

Table: Key values of the world economy by 2100 — the Dietz-Stern case.
Numerical Simulations

The Combined Burke et al. and Dietz-Stern Scenario

Figure: Trajectories of the main simulation outputs in the Combined Burke et al. and Dietz-Stern case.
Numerical Simulations

The Combined Burke et al. and Dietz-Stern Scenario

**Figure:** Phase portrait in the Combined Burke *et al.* and Dietz-Stern case
Numerical Simulations

The Combined Burke et al. and Dietz-Stern - Values

GDP Real Growth 2100 (wrt 2010) 265%
t CO₂ per capita (2050) 6.23
Temperature change in 2100 +3.41 °C
CO₂ concentration 2100 708.98 ppm

Table: Key values of the world economy by 2100 — The Combined Burke et al. and Dietz-Stern case.
Numerical Simulations

The Combined Burke et al. and Dietz-Stern - Demographic

Figure: Trajectories of the main simulation outputs in the Combined Burke et al. and Dietz-Stern - Demographic.
**Numerical Simulations**

The Combined Burke-Dietz Scenario - Demographic

**Figure:** Trajectories of the main simulation outputs in the Combined Burke *et al.* and Dietz-Stern - Demographic.
Numerical Simulations

The Combined Burke et al. and Dietz-Stern - Demographic - Values

GDP Real Growth 2100 (wrt 2010) 244%
t CO₂ per capita (2050) 5.21
Temperature change in 2100 +3.20 °C
CO₂ concentration 2100 660.37 ppm

Table: Key values of the world economy by 2100 — the Combined Burke et al. and Dietz-Stern - Demographic.
we find the initial condition in 2010 that the growth rate that match with the 2015 and 2055 values (2005 $US 12 and 29 t/CO2 respectively)
Numerical Simulations

The Combined Burke et al. and Dietz-Stern - Carbon Price

Figure: Trajectories of the main simulation outputs in the Combined Burke et al. and Dietz-Stern - Carbon Price.
Numerical Simulations
The Combined Burke et al. and Dietz-Stern - Carbon Price

Figure: Trajectories of the main simulation outputs in the Combined Burke et al. and Dietz-Stern - Carbon Price.
### Numerical Simulations

The Combined Burke et al. and Dietz-Stern - Carbon Price- Values

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
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<tbody>
<tr>
<td>GDP Real Growth 2100 (wrt 2010)</td>
<td>3.17%</td>
</tr>
<tr>
<td>t CO(_2) per capita (2050)</td>
<td>5.54</td>
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<tr>
<td>Temperature change in 2100</td>
<td>+3.22 °C</td>
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<tr>
<td>CO(_2) concentration 2100</td>
<td>643.77 ppm</td>
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</table>

**Table:** Key values of the world economy by 2100 — the Combined Burke *et al.* and Dietz-Stern- Carbon Price.
Numerical Simulations

The Combined Burke et al. and Dietz-Stern - Carbon Price - Sensitivity of

Figure: Trajectories of the main simulation outputs in the Combined Burke-Dietz Scenario - Carbon Price case.
Numerical Simulations
The Combined Burke et al. and Dietz-Stern - Carbon Price- Values

GDP Real Growth 2100 (wrt 2010) $-9.1\%$
$t \text{CO}_2$ per capita (2050) $5.00$
Temperature change in 2100 $+4.4552^\circ \text{C}$
$\text{CO}_2$ concentration 2100 $549.78 \text{ ppm}$

Table: Key values of the world economy by 2100 — the Combined Burke et al. and Dietz-Stern - Carbon Price.
Numerical Simulations

Price of Carbon 2

we find the initial condition in 2010 that the growth rate that match with the 2015 and 2055 values (2005 $US 74 and 306 t/CO2 respectively)
Numerical Simulations

The Combined Burke et al. and Dietz-Stern - Carbon Price 2 - Sensitivity of 6 case.

Figure: Trajectories of the main simulation outputs in the Combined Burke et al. and Dietz-Stern - Carbon Price 2 - Sensitivity of 6 case.
### Numerical Simulations

The Combined Burke et al. and Dietz-Stern - Carbon Price- Values

<table>
<thead>
<tr>
<th>Metric</th>
<th>Value</th>
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<tbody>
<tr>
<td>GDP Real Growth 2100 (wrt 2010)</td>
<td>272%</td>
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<td>t CO₂ per capita (2050)</td>
<td>0.49</td>
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<td>Temperature change in 2100</td>
<td>+3.2293°C</td>
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<tr>
<td>CO₂ concentration 2100</td>
<td>397.98 ppm</td>
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</table>

**Table:** Key values of the world economy by 2100 — the Combined Burke *et al.* and Dietz-Stern - Carbon Price.
Numerical Simulations

Objective 1.5

According to the 2015 climate meeting, held in Paris, the universal agreement’s main goal is to stay, in this century, within the +2 C of temperature anomaly and to drive efforts to limit even further to +1.5C above pre-industrial levels.
Numerical Simulations

Objective + 1.5° C

<table>
<thead>
<tr>
<th></th>
<th>Sensitivity of 1.5</th>
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<th>Sensitivity of 2.9</th>
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<tr>
<td></td>
<td>Init price of 15</td>
<td>Init price of 80</td>
<td>Init price of 15</td>
<td>Init price of 80</td>
</tr>
<tr>
<td>Price in 2015</td>
<td>18.58</td>
<td>86.27</td>
<td>65.50</td>
<td>144.32</td>
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<tr>
<td>Price in 2020</td>
<td>23.00</td>
<td>93.04</td>
<td>286.02</td>
<td>260.35</td>
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<tr>
<td>Price in 2050</td>
<td>82.93</td>
<td>146.35</td>
<td>xxx</td>
<td>xxx</td>
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</table>

**Table:** Price in order to prevent the temperature anomaly to reach the + 1.5° ceiling in 2100, prices are in 2005 US$/t CO₂.
Outlines

1. Introduction
2. The Keen (1995) Model
3. Macroeconomic model for climate change
4. Climate Module
5. Public Policy Module
6. Numerical Simulations
7. Further Work
Further Work

To model non-renewable energy, natural resource scarcity.
To introduce the public sector.
To refine the statistical framework.
To distinguish the agricultural from the industrial production.
To precise the determination of the damage functions.
Thank you for your attention.