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Debt and damages: what are the chances of staying under the 2°C warming threshold?

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Abstract

In a stock-flow consistent macrodynamic model featuring two crucial endogenous destabilizing channels, namely debt accumulation and climate change, we perform a sensitivity analysis on four fundamental parameters of the climate and economic systems: the climate sensitivity, the inertia of the carbon cycle, the labor productivity growth, and the share of damages sustained by the capital stock. We find that we have a mere 0.36% chance of achieving the 2°C warming target of the Paris Agreement in a no policy scenario, while a carbon tax and a subsidy to mitigation efforts increase that probability to 5.64% and 25.6% respectively. We also investigate the trade-off between mitigating climate change damages and staying in a sustainable debt trajectory. While implementing effective climate policies comes at the cost of increasing the debt burden, the increasing risk of over-indebtedness seems to be limited even for very stringent policies.

Key words: Ecological macroeconomics, Stock-Flow Consistent Model, Climate change, Integrated assessment, Collapse, Debt.

JEL classification: C51, D72, E12, O13, Q51, Q54.

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ABSTRACT

In a stock-flow consistent macrodynamic model featuring two crucial endogenous destabilizing channels, namely debt accumulation and climate change, we perform a sensitivity analysis on four fundamental parameters of the climate and economic systems: the climate sensitivity, the inertia of the carbon cycle, the labor productivity growth, and the share of damages sustained by the capital stock. We find that we have a mere 0.36% chance of achieving the 2°C warming target of the Paris Agreement in a no policy scenario, while a carbon tax and a subsidy to mitigation efforts increase that probability to 5.64% and 25.6% respectively. We also investigate the trade-off between mitigating climate change damages and staying in a sustainable debt trajectory. While implementing effective climate policies comes at the cost of increasing the debt burden, the increasing risk of over-indebtedness seems to be limited even for very stringent policies.

1 Introduction

Since the recognition at the global level that the "burden-sharing" approach is an ethical and political dead-end for financing the transition to a sustainable development, the attention shifts to non-binding solutions that also embark the private sector. According to the New Climate Economy Report (New Climate Economy, 2014), US$ 90 trillion are needed at the world level over the next 15 years to fund clean infrastructures that would make it possible to reach zero net emissions and meet the ambitious targets of the Paris Agreement of December 2015. Even if not entirely additional —many infrastructures will have to be maintained and replaced in any case— such a level of commitment can only be met by joining public and private efforts, and is likely to generate massive amounts of debt, especially in a fast energy shift is to be performed soon. Fighting climate change is a race against time, there is consequently a trade-off to consider between financial and climatic stability. As aptly put by Bank of England Governor Mark Carney:

> A wholesale re-assessment of prospects, as climate-related risks are reevaluated, could destabilize markets, spark a pro-cyclical crystallization of losses and lead to a persistent tightening of financial conditions: a climate Minsky moment (Carney, 2016).

The economic literature is curiously scarce when it comes to modeling the interplay between the financial sphere, the real economy and the physical environment, which accounts for a strong perceived need for informative prospective studies.

The economic literature addresses this challenge in several complementary strands. The problem of the interacting climate and economy has long been covered by the integrated assessment modeling (IAM) literature, prominently featured in the successive IPCC reports (Stern, 2006; Stocker et al., 2013). In light of the struggles to turn the insights of these models into actions, recent contributions by top climate economists call for letting current models evolve (Revesz et al., 2014; Stern, 2016), and promising new avenues are being pursued with dynamic stochastic general equilibrium models and agent based models (Farmer et al., 2015). Another strand of the literature, ecological macroeconomics, emerges as a serious challenger to current IAM

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models. Rezai et al. (2013) presents how this growing body of literature may reconcile state-of-the-art macroeconomics with tenets of ecological economics on resource use and limits to growth (see also Jackson (2009) and Rezai and Stagl (2016)). Overall, these different strands of literature (also reviewed in New Climate Economy (2014)) aim at assessing the financing needs for a transition to a low-carbon economy. Besides several contributions in this special issue , however, few papers examine the financial costs of such transitions, or the systemic effects they entail (see e.g. Dafermos et al. (2017); Monasterolo and Raberto (2018) or Battiston et al. (2017)). This article —that is part of a broader research program— is part of this general effort of properly characterizing the determinants of and interactions between economic transitions, climate change and finance (Giraud and Grasselli, 2016; Giraud et al., 2017).

Another major problem arising in the IAM literature, highlighted by Nordhaus (2017) for instance, is how to tackle the high dimensionality of the interactions between the economy and the warming environment. Large uncertainties remain on key technical, physical and economic parameters, that prove to be powerful impediments to action (Fabert et al., 2014). In this paper, we reduce as much as possible the dimensionality of the problem by combining a compact macrodynamic framework with endogenous debt (Giraud et al., 2017) to a rather small climate module extensively used in the IAM literature.

Our contribution is to assess the extent to which simple policy levers can influence the climate and growth trajectories in a sensitivity and scenario analysis on key physical and economic parameters, by using a model where over-indebtedness and damages from climate change can lead to economic downturns. We test how different climate policies advocated by the Stern-Stiglitz Commission[1] allow to avoid overshooting two thresholds that we argue to be critical for the stability of our current economy and climate, namely a temperature anomaly above +2°C (as set in the Paris Agreement) and a global debt-to-output ratio above 2.7 (at which point the total private debt would exceed the value of the current stock of assets, arguably leading to systemic defaults). Both are associated to major potential destabilizing channels: damages to the capital stock from climate change and the ability of firms to invest in repairs and adaptation.

We find that we have a mere 0.36 % chance of achieving the 2°C warming target of the Paris Agreement in a no-policy, business-as-usual scenario. Introducing climate policies as recommended by the Stern-Stiglitz Commission allows to significantly increase that probability. Adding a growing carbon price trajectory increases to 5.64% the chances of staying under 2°C warming, and increasing the mitigation efforts by adding a 50% subsidy to investment in the backstop technology increases this probability to 25.6%. We also discuss the trade-off between the two principal objectives of a sustainable debt and a sustainable climate. Effective climate policies come indeed at the cost of increasing the probability of overshooting the debt-to-output threshold from 21.7% (business-as-usual scenario) to 23.6% (with a carbon tax) and 28.9% (with an additional subsidy to mitigation efforts).

The paper is organized as follows. Section 2 briefly introduces the modeling framework that is at the basis of our analysis. Section 3 discusses more extensively the introduction of climate and economic uncertainty within this framework in order to assess the recommendations of the Stern-Stiglitz commission on carbon price. Section 4 presents our results, and our main conclusions and areas for future research are outlined in a last section.

2 Model

This paper relies on the modeling framework developed in Giraud et al. (2017), a macroeconomic model of growth that combines the economic impact of climate change with the pivotal role of private debt. The model is briefly exposed in this section. We introduce an additional public policy tool (a subsidizing mechanism on the abatement cost performed by the public authorities to enhance the speed of the energy shift).

2.1 Macroeconomic model

The macroeconomic model, sketched in this section, belongs to the literature centered around Keen (1995).[2] One appeal of this framework lies in its ability to formalize long-term economic deflation and degrowth as a consequence of over-indebtedness.

Absent climate change, real output is assumed to be produced combining the available workforce, N, and the current physical capital stock, K, with a complementary factor technology

$$Y^0 := \min\left\{\frac{K}{\nu}, aN\right\}, \tag{1}$$

where ν and a respectively refer to the (constant) capital-to-output ratio and to the Harrod-neutral labor augmenting productivity. The dynamics of the global workforce is exogenous and calibrated to the prospective scenarios of the United Nations (2015), medium fertility, so that:

$$\beta(N) := \frac{\dot{N}}{N} = q\big(1 - \frac{N}{P^N}\big), \tag{2}$$

[1]"The Commission's objective is to identify indicative corridors of carbon prices which can be used to guide the design of carbon pricing instruments and other climate policies, regulations, and measures to incentivize bold climate action and stimulate learning and innovation to deliver on the ambition of the Paris Agreement and support the achievement of the Sustainable Development Goals." — Commission website.

[2]Such as Grasselli and Lima (2012),Grasselli et al. (2014), Nguyen-Huu and Costa-Lima (2014), Grasselli and Nguyen-Huu (2015) and Giraud and Grasselli (2016)*inter alia*.

where q represents the speed of the demographic transition and P^N the upper bound of the global workforce. The productive sector is assumed to follow a minimal rational behavior,

$$Y^0 = \frac{K}{\nu} = aL, \tag{3}$$

where L is the total employed labor. Thus, it defines the employment rate, $\lambda := L/N$. Production of commodities releases industrial emissions, E_{ind}, according to

$$E_{ind} := Y^0\sigma\big(1-n\big), \tag{4}$$

where, σ, stands for the exogenous emission intensity and, n, is the endogenous emission reduction rate of the productive sector. Indeed, a carbon tax, T_C, will be set on industrial emissions by the public authorities according to $T_C := p_C E_{ind}$, with, p_C, the real price of emissions.[3] To minimize the carbon burden, the productive sector might divert a fraction of its real production, A, to perform abatement activities. The public sector might partly subsidize this abatement at a rate s_A, such that a real transfer $S_f^c := s_a A Y^0$ is performed to the productive sector. Moreover, due to global warming —ultimately related to the accumulation of industrial emissions— a fraction, $\mathbf{D}^{\mathrm{Y}}$, of real output is lost. As a result, the production available on the commodity market will be

$$Y := (1-\mathbf{D}^{\mathrm{Y}})(1-A)Y^0. \tag{5}$$

The abatement technology, A, depends on the emission reduction rate chosen by the productive sector, n, the price of a back-stop technology, p_{BS}, —exogenously decreasing at some rate, $\delta_{p_{BS}}$— and the emission intensity of the economy, σ, according to

$$A := \frac{\sigma p_{BS}}{\theta} n^\theta, \tag{6}$$

where θ is a parameter controlling the convexity of this cost.

By setting the abatement reduction rate, n, the productive sector endogenously chooses the magnitude of the latter activities. The emission reduction rate, n, appears then to be the outcome of an arbitrage between the carbon price, p_C, the backstop technology price, p_{BS}, and the subsidizing rate by the public authorities, s_a:[4]

$$n = \min\left\{\left(\frac{p_c}{(1-s_a)p_{BS}}\right)^{\frac{1}{\theta-1}};1\right\}. \tag{7}$$

Introducing the unit nominal wage, w, the price of commodities, p, and the depreciation rate of capital, $\delta_{\mathbf{D}}$, the nominal profits of the productive sector writes:

$$\Pi := pY - wL - rD + pNS_f - p\delta_{\mathbf{D}}K, \tag{8}$$

where $NS_f := S_f^c - T_C$ is the net transfer to the public sector. The profit, Π, is partly distributed to shareholders according to

$$\Pi_d(\pi) := \Delta(\pi)pY + \mathcal{P}, \tag{9}$$

such that, $\Pi_r := \Pi - \Pi_d$, represents retained profits of the productive sector. $\mathcal{P}$ is an additional transfer to households that is not included in the price dynamics. The latter can be interpreted as resulting from activities that are not directly related to operational exercises. Nominal profits, Π, allows us to define the profit share, $\pi := \frac{\Pi}{pY}$, that captures the current profitability of the productive sector and thus drives investments according to Keen (1995),

$$I := \kappa(\pi)Y. \tag{10}$$

Next, the stock of capital obeys the standard rule of accumulation,

$$\dot{K} := I - \delta_{\mathbf{D}}K. \tag{11}$$

The nominal credit, $\dot{D}$, bridges the gap between the self-financing capabilities of the productive sector, i.e., the retained profits Π_r, and the current level of investment, I, according to

$$\dot{D} := pI + \Pi_d(\pi) - \Pi - p\delta_{\mathbf{D}}K. \tag{12}$$

Finally, the relationship between the real and nominal spheres is provided by a short-term Phillips curve set on nominal wages,

$$\frac{\dot{w}}{w} := \phi(\lambda). \tag{13}$$

and a relation capturing the dynamics of inflation

$$i := \frac{\dot{p}}{p} := \eta_p(mc-1), \tag{14}$$

According to Eq. 14, prices are set as a mark-up m over the average cost of production $c = \frac{pY-\Pi_r-\mathcal{P}}{pY}$ and relax subjected to some viscosity parameter η_p.

Table 1 displays balance sheets of the firms, the transactions of the economy and the flow of funds. The stock-flow consistency of the model can be readily checked. In particular, the accounting identity "investment = savings" holds by summing up the line savings in Table 1.[5]

[3] p_C refers to the real price per ton of CO_2-e.
[4] For the sake of clarity, the emission reduction rate, n, can be seen as the solution of a cost-minimization program between the abatement cost, AY, and the carbon tax, $p_C E_{ind}$.
[5] See Giraud et al. (2017) for further details.

	Households	Firms		Banks	Public Sector	Sum
Balance Sheet						
Capital stock		pK				pK
Deposits	M^h	M^c		$-M$		
Loans		$-L_c$		L_c		
Bonds	B				$-B$	
Equities	E	$-E^f$		$-E^b$		
Sum (net worth)	X^h	$X^f = 0$		$X^b = 0$	$-B$	X
Transactions		current	capital			
Consumption	$-pC$	pC				
Investment		pI	$-pI$			
Gov. Spend.		pG			$-pG$	
Acc. memo [GDP]		$[pY]$				
Wages	W	$-W$				
Capital depr.		$-(\delta + \mathbf{D}^{\mathrm{K}})pK$	$(\delta + \mathbf{D}^{\mathrm{K}})pK$			
Carbon taxes		$-pT_f$			pT_f	
Abatement subsidies		pS_f^C			$-pS_f^C$	
Int. on loans		$-r_c L_c$		$r_c L_c$		
Bank's dividends	Π_b			$-\Pi_b$		
Firm's dividends	Π_d	$-\Pi_d$				
Int. on deposits	$r_M M^h$	$r_M M^c$		$-r_M M$		
Int. on bonds	$r_B B$				$-r_B B$	
Column sum (balance)	S^h	$S^c = \Pi_r$	$-pI + (\delta + \mathbf{D}^{\mathrm{K}})pK$	S^b	S^g	
Flow of Funds						
Change in capital stock		$p\dot{K}$				$p\dot{K}$
Change in deposits	$\dot{M}^h$	$\dot{M}^c$		$-\dot{M}$		
Change in loans		$-\dot{L}_c$		$\dot{L}_c$		
Change in bills	$\dot{B}$				$-\dot{B}$	
Column sum (savings)	S^h	S^c		S^b	S^g	
Change in firm equity	$\dot{E}^f$	$-(S^f + \dot{p}K)$				
Change in bank equity	$\dot{E}^b$			$-S^b$		
Change in net worth	$S^h + \dot{E}$	0		0	S^g	$\dot{p}K + p\dot{K}$

Table 1: Balance sheet, transactions, and flow of funds in the economy

2.2 Climate module feedback-loop

The climate module is directly inspired by the DICE model of Nordhaus (2017), adapted here to our continuous framework. It describes the sequence of geo-physical processes linking the various sources of emissions —mainly industrial, E_{ind}— to the mean atmospheric temperature deviation with regards to the preindustrial era (hereafter temperature anomaly), T, through (i) the accumulation of carbon in a three-layer model, (ii) the resulting change of radiative forcing, and (iii) the dynamics of temperature in a two-layer model. The details of these equations are given in Appendix A.

For a given level of temperature anomaly level, we follow Nordhaus (2017) and adopt a damage function, $\mathbf{D}(\cdot)$, summarizing the total economic impacts of global warming on the economy

$$\mathbf{D} := 1 - \frac{1}{1 + \pi_1 T + \pi_2 T^2 + \pi_3 T^{\zeta_3}}. \tag{15}$$

However, as pointed out by Dietz and Stern (2015) and Dafermos et al. (2017), global warming may have an adverse impact not only on output but also on the factors of production themselves, such as the capital stock. Following Dietz and Stern (2015), we consequently distribute total damages between output, $\mathbf{D}^{\mathrm{Y}}$,

$$\mathbf{D}^{\mathrm{Y}} \quad := \quad 1 - \frac{1 - \mathbf{D}}{1 - \mathbf{D}^{\mathrm{K}}}, \tag{16}$$

and the stock of capital, $\mathbf{D}^{\mathrm{K}}$,

$$\mathbf{D}^{\mathrm{K}} \quad := \quad f_K \, \mathbf{D}, \tag{17}$$

where f_K represents the share of total damages, $\mathbf{D}$, allocated to the stock of capital.

It is worth mentioning that, throughout the simulations, we only use the damage function from Nordhaus (2014). This choice departs from Giraud et al. (2017) in testing only one damage function. The more severe specifications given by Weitzman (2011), or Dietz and Stern (2015) among others are left for further research.[6]

[6]However, the specification of Nordhaus (2014) is providing enough information for the purpose of the paper. Results given by other types of damage functions are very much likely to have similar consequences than the one found in Giraud et al. (2017).

3 Sensitivity analysis and policy scenario setups

This section presents our simulation strategy. We first introduce how we take uncertainty into account and how we perform our sensitivity analysis, before presenting our policy scenarios.

3.1 Economic and climate uncertainties

We perform a sensitivity analysis on four uncertain parameters: (i) the labor productivity, α, (ii) the climate sensitivity, S, (iii) the size of the intermediate reservoir, i.e biosphere and upper level of the oceans, C^{up}, and (iv) the repartition of climate change damages between capital stock and output, f_K. The latter one will be treated differently as discussed shortly.

The first three parameters have been extensively studied in the climate literature and in integrated assessment (climate-economy) models. Estimates for probability density functions (hereafter pdf) could thus be found. We approximate the pdfs from Nordhaus (2017) (see Fig. 1).[7]

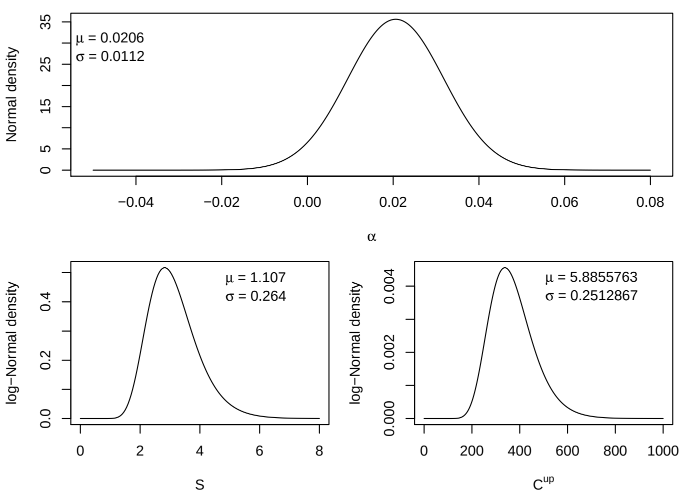

Figure 1: Probability density functions for the vector of parameters (α, S, C^{UP})

It is worth mentioning that Nordhaus (2017) considers two additional parameters in his sensitivity analysis: (i) the initial value of the decarbonization rate of the economy; and (ii) the coefficient of the damage function that drives its convexity (i.e., the coefficient of order 2). The consensus on the uncertainty is weaker for the initial value of the decarbonization rate of the economy. This parameter seems, *prima facie*, to have an impact of lesser magnitude than the parameters (S, C^{up}) on the climate module. Moreover, given our purpose in this paper —the assessment of the feasibility of the $+2°$C objective under specific carbon price trajectories— we focus on the certainty equivalent of Nordhaus's damage function since $+2°$C belongs to the range of temperature anomaly that have been empirically tested. Finally, the reduction of the dimensionality of the uncertainty allow us to perform a true Monte Carlo approach without approximations due to computational issues as chosen by Nordhaus (2017).

3.1.1 Productivity growth

As in Nordhaus (2017), over the period 2016-2100, the probability distribution adopted by the labor productivity growth is a Gaussian distribution with a mean (hereafter μ) of 2.06% and a standard deviation (hereafter σ) of 1.12%. In other words, $\alpha \sim \mathcal{N}(0.0206, 0.0112)$. Those estimates are based on a survey of experts by a team at Yale university led by Peter Christensen. This panel of experts characterized uncertainty on global output for the periods 2010-2050 and 2010-2100.

3.1.2 Equilibrium temperature sensitivity

There is an intrinsic uncertainty on the long term temperature anomaly whenever the CO_2 concentration in the atmosphere is doubling. We consider the same distribution as in Nordhaus (2017), that is a $\log$-Gaussian distribution with $\mu = 1.107$ and $\sigma = 0.264$. In other words, $S \sim \log - \mathcal{N}(1.107, 0.264)$. Those estimates are from Gillingham et al. (2015). The distribution is the posterior of a Bayesian procedure that gathers previous studies as prior and observational data to compute the likelihood. Moreover, as validated by the climate-economy literature, this parameter captures in a synthetic way the complex interactions usually modeled in complete ocean-atmosphere models.

3.1.3 Carbon cycle

Many parameters of the carbon cycle are uncertain, although the most important one is certainly the size to the intermediate reservoir (biosphere and upper level of the oceans). Changes may have a substantial impact on the absorption property of the CO_2 into the carbon cycle. To take into account the uncertainty for this parameter, we find the parameters of a log-Gaussian distribution that are the closest to the quantile reported in Nordhaus (2017). In other words, $C^{up} \sim \log - \mathcal{N}(5.8855763, 0.2512867)$. This uncertainty aims at mimicking the results from Friedlingstein et al. (2014) in the difference of concentration in 2100 using the RCP8.5 CO_2 emissions.

[7] We assumed the distributions to be independent, as in Nordhaus's paper, since we virtually have no information on the dependence structure between the parameters.

3.1.4 Allocation of damages to the capital stock

We consider the impact of a fourth parameter governing the share of damages sustained by the capital stock, f_K (presented in Eq. 17). In our model, climate change may damage the output either directly, or indirectly by damaging the capital stock. A sensitivity analysis of this parameter is motivated by the potential contagion effect of this channel of damages into the financial environment of this paper's model. Given the radical nature of uncertainty on the specification of the damage functions in general and on damages to production factors in particular, we explore this crucial channel by testing a discrete array of values. Nordhaus and Boyer (2000) and Dietz and Stern (2015) give some point estimates of this parameter around $1/3$. We consequently test three different values: $f_K = 0, 1/3, 1/2$. We take $f_K = 0$ as a reference point —e.g., no damages on capital, for compatibility with earlier work such as Nordhaus (2017). The central value implies that the capital stock sustains a third of the damages (in consumption-equivalent terms). We consider an additional value of 50% damages sustained by the capital stock as an extreme case study.

3.2 Public policy scenarios

Our paper proceeds by comparing two different public policy scenarios: a scenario with a carbon tax calibrated from the Stern-Stiglitz Commission (Stiglitz and Stern, 2017), and a combination of the same carbon tax *plus* a subsidy for the backstop technology. The two scenarios are discussed against a no-policy baseline where, as performed in Nordhaus (2017), the public intervention is limited to a weak carbon tax compatible with the calibration of the model at the initial period, and then growing at a constant 2% rate per year.

The main recommendation by the Stern-Stiglitz Commission is a corridor of carbon price levels consistent with achieving the Paris temperature target and the Sustainable Development Goals: from at least US\$40-80/tCO_2 by 2020 to US\$50-100/tCO_2 by 2030.[8]

For our simulation purposes, we will focus on the upper bound of the price corridor (hereafter High p_C). This choice allows us to explore the maximal potential of the carbon price recommendation made by the Stern-Stiglitz commission. Note, however, that our simulations run from 2016 to 2100 while the recommendation lies in the time range 2020-30. We assume some linear interpolations of the price of carbon for the out-of-recommendation time range.

Moreover, the Commission also concluded on the necessity to adopt context-relevant policy packages to overcome the various barriers and failures associated with carbon prices. Building on that recommendation, we consider another policy instrument, namely a subsidy on mitigation technologies. As presented in Eq. 7, the endogenous setting of the mitigation rate, n, by the productive sector as a result of a cost minimization will be speed up by the fact that the real cost of abatement activities, AY^0, is partly subsidized. In other words, the government intervention could be summarized as a proportional diminution of the real abatement cost (from p_{BS} to $(1 - s_a)p_{BS}$).

In summary, the three scenarios investigated in this paper are the following ones:

1. The **"No policy"** scenario is based on a Monte Carlo simulation of the model with a weak public intervention.[9]

2. The **"Carbon tax"** scenario is based on a Monte Carlo simulation of the model without further public intervention than the carbon price trajectory at High p_C.

3. The **"Carbon tax and subsidy"** scenario is the scenario 2 counterpart with public subsidies on abatement cost to the extent of 50%.

4 Results

In this section, we present the major results of our sensitivity analysis. We first discuss the trajectories of the main output of the model, before quantifying the probability of overshooting critical temperature and debt thresholds. A last subsection discusses the trade-off between these two thresholds.

4.1 Trajectories and narratives

Fig. 2 shows the outcome of the Monte Carlo simulations for all the scenarios with $f_K = 33\%$.[10] The blue, orange, and red shades respectively represent the $[0.05; 0.95]$ probability interval in the **No policy**, **Carbon tax**, and **Carbon tax and subsidy** scenario. The solid lines associated to a scenario display the median values of each Monte Carlo exercise. The black dotted/dashed lines in the *debt-to-output ratio* and *temperature anomaly* quadrants represent the two thresholds discussed in the next subsection.

In the **No policy** scenario (blue shade of Fig. 2), the output grows close to the balanced growth path —the draw of α in the Monte Carlo procedure— following the exogenous labor productivity growth. The mean growth of the median GDP is 2.38% over the whole period and 2.1% for the period 2050-2100. Moreover, with a negligible carbon price

[8] See footenote 1 on page 2. See also Stiglitz and Stern (2017). No indication on the measure (real versus current) of the monetary unit is explicitly given. Some of the figures report in the report are in 2005US\$. We will therefore assume that the latter is the monetary unit.

[9] Again, for the sake of precision, this scenario is inspired by the Baseline case of Nordhaus (2017) with an exponential real carbon price path at a 2% annual growth rate.

[10] The counterpart cases $f_K \in \{0\%, 50\%\}$ present only slight changes in their trajectories, and will be discussed in the next subsection.

the backstop technology barely takes any market share and growth is mostly fueled by fossil energy. In 2100, the median of the temperature anomaly is estimated to be 3.96°C, almost double the Paris Agreement's objective, and presents no sign of curbing downward.

This global behavior of the GDP is similar in the **Carbon Tax** scenario (resp. **Carbon tax and subsidy** scenario). The median real GDP, the solid orange line (resp. solid red line) is 1.22% lower in 2050 (resp. 5.19%) compared to the **No policy** scenario. In 2100 the order is, however, reversed: the real GDP in **Carbon Tax** (resp. **Carbon tax and subsidy**) gains 1.53% (resp. 2.73%) compared to **No policy**. Indeed, as more involved public policies are implemented, the energy shift occurs earlier resulting in: (i) a fall of profits due to the carbon tax in **Carbon tax** and **Carbon tax and subsidy**; and (ii) a rise in abatement activities, due to subsidy in **Carbon tax and subsidy**, that diverts output from sales. As a result, real investment in physical capacities falls and the economy slows down. However, once the energy shift is performed, the resulting temperature anomaly is smaller compared to **No policy**, implying lower damages and a higher output.

Turning to industrial CO_2 emissions, one can see a clear and significant difference between the public policy scenarios. In all simulations of the $[0.05; 0.95]$ probability interval, emissions reach zero by 2064 in the **Carbon tax and subsidy** scenario, with a much lower deviation. Under the **Carbon Tax** scenario, the median emissions stay above zero until 2100, reaching 7.6 GtC. This implies that a carbon price at the upper bound of the corridor as given by the Stern-Stiglitz commission is not enough to achieve the Paris objective in the median case, our simulations indicate a median temperature anomaly just below 3°C in 2100. As discussed in the Commission's report, a carbon price alone does not lead *per se* firms to be carbon neutral by 2100, other policies are required. In our **Carbon tax and subsidy** scenario, firms are also subject to a subsidy, and become carbon neutral by 2064. Even then, the median temperature anomaly is 2.37°C in 2100.

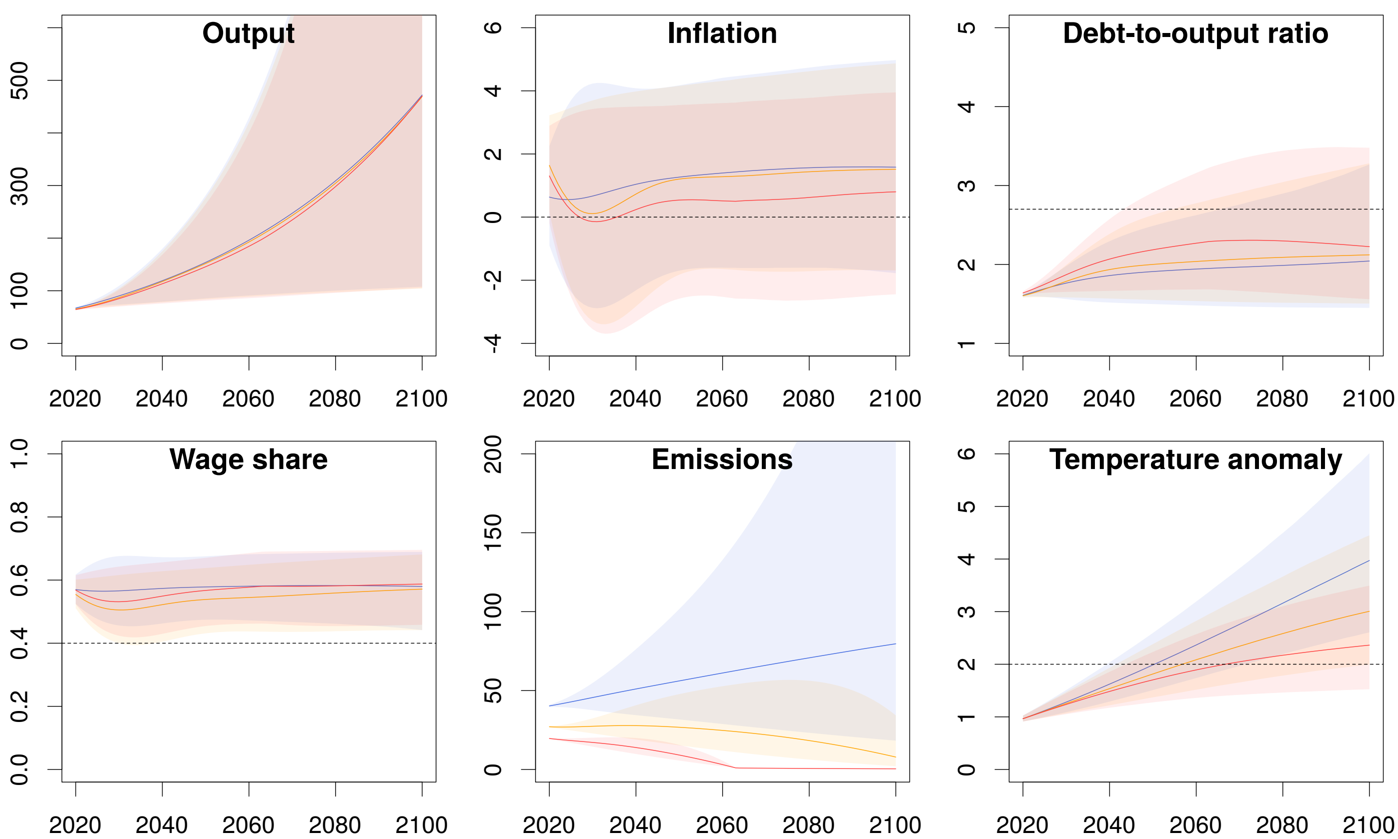

Figure 2: $[0.05; 0.95]$ probability interval of the **No policy**, **Carbon tax**, and **Carbon tax and subsidy** scenarios with a damage-to-capital ratio of 33% respectively in blue, orange and red shades (medians in solid lines)

The debt-to-output ratio dynamics reveals a clear trade-off between indebtedness and temperature anomaly: introducing a climate policy increases the debt-to-output ratio (Fig. 2). The rationale is the following: whenever public intervention is higher, the higher carbon price will inflate the unitary cost of production. Moreover, as the backstop technology takes a higher market share, a larger share of output is diverted to finance abatement efforts. The GDP is depressed in the short run, inducing a lower employment rate, and through Eq. 13 a lower wage share. This makes the probability distribution of the **Carbon tax** scenario more platykurtic, and explains the reduced inflation around the 2030s.

Moreover, the higher retained profits will generate additional investment through Eq. 10, and thus additional indebtedness. Together with a lower inflation, this brings a higher debt-to-output ratio for the **Carbon tax** scenario compared to the **No policy** scenario. Table 2 illustrates this mechanism. For $k = 1/3$, the 95% level of the probability distribution of the debt-to-output ratio reaches the 2.7 threshold in 2063 for **No policy** while this date is no later than 2053 for the **Carbon Tax** scenario. This mechanism is enhanced in the **Carbon tax and subsidy** scenario: the 95% quantile of the debt-to-output ratio is reached already in 2044.

Scenario	**Variable**	$\mathbf{f_K = 33\%}$		
No policy	*Quantile*	5	50	95
	$d > 2.7$	-	-	2063
	$T > 2°C$	2072	2051	2040
Carbon tax	*Quantile*	5	50	95
	$d > 2.7$	-	-	2053
	$T > 2°C$	-	2057	2042
Carbon tax and subsidies	*Quantile*	5	50	95
	$d > 2.7$	-	-	2044
	$T > 2°C$	-	2067	2044

Table 2: Dates at which thresholds are reached

4.2 Staying under the temperature and debt thresholds

The debt-to-output ratio and temperature anomaly trajectories in Fig. 2 suggest that only part of the runs allow to stay safely below two specific thresholds: (i) a 2°C temperature anomaly and (ii) a 2.7 debt-to-output ratio. Those two important thresholds are informative on the dynamics of a possible collapse by shedding light on two important channels: the changes in the mean surface temperature and the total aggregate private debt. In this section, we compute the probability distribution of the temperature anomaly and private debt-to-output ratio in order to provide insights about the probability to respect these thresholds.

Our climate change module captures some of the uncertainties on the physical response of the Earth system to GHG emissions in an aggregated way (namely on the climate temperature sensitivity and the inertia of the upper carbon reservoirs). Climate change is, however, multifactorial and features many specific feedback loops. Indeed, the Paris Agreement set a threshold at 2°C on the temperature anomaly based on our current knowledge of climate change gathered by the IPCC. The Agreement considers that above this 2°C threshold, climate change has a risk of reaching tipping points, leading to severe and possibly uncontrolled damages to our economy and environment.[11]

Our simulation framework allows to take another important threshold of the economic sphere into account, informative about the financial channels of possible breakdowns of the economy. When taking private debt into account, one can explore how the service of this debt can hinder the investment capacities of firms, making it more difficult to invest in adaptation and in repairs of climate change damages. There is a threshold at the firm level when liabilities exceed the total capital stock, at which point a rational choice would be to default. At the aggregate level, one can also consider this point to be a threshold informing on the overall private debt burden. Using the Penn World Table (Feenstra et al., 2015), we can calibrate the global average capital-to-GDP ratio at 2.7. Above this threshold, it is rational to globally default, bringing us in uncharted economic territory.

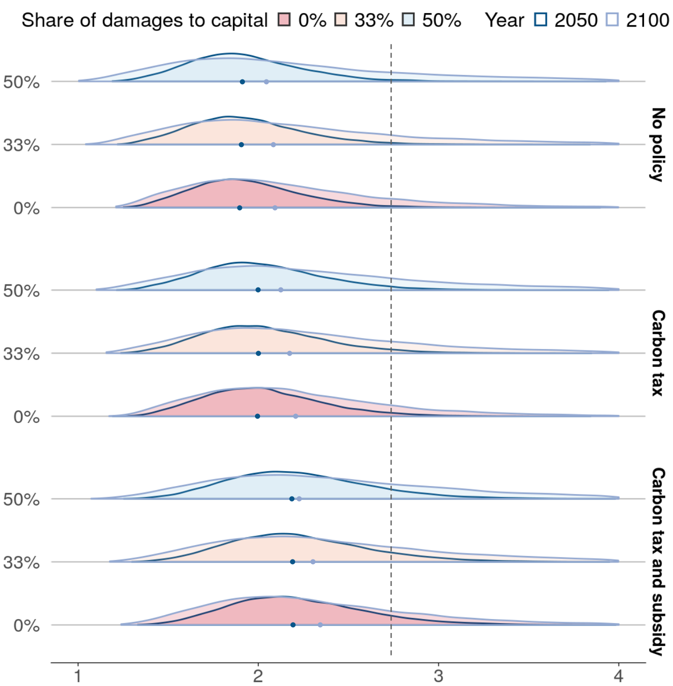

Figure 3: Probability density function of the private debt-to-output ratio in 2050 and 2100.
The median values are identified by a point, and the dashed vertical line indicates the critical debt-to-output threshold.

We compute the probability distribution of the debt-to-output ratio (Fig. 3) and the temperature anomaly (Fig. 4) for the simulation outcomes of all the parameters combinations in the three policy scenarios in 2050 and 2100. In

[11] See for instance Lenton et al. (2008), Stern (2013) or Carney (2015) for a more extensive discussion about these issues.

Figs. 3 and 4, the X-axis represents respectively the debt-to-output ratio and the temperature anomaly. The three policy scenarios are vertically stacked, representing for each scenario the three different damages-to-capital ratios considered ($f_K \in \{0\%, 33\%, 50\%\}$). For all the policy scenario and each damages-to-capital ratio value, two distributions are represented. The dark-blue contoured distribution represents the frequency of all the outcomes in 2050, and the lighter contoured one the frequency in 2100. The vertical dashed lines represent respectively the critical thresholds of 2.7 debt-to-output ratio and 2°C temperature anomaly. The area under the probability density function on the right of the thresholds, or survival function values at the thresholds, can be interpreted as a probability of exceeding it, given our model structure and our knowledge of the parameter distributions.[12]

In Fig. 3 we see the effects of the increasing allocation of damages to capital on the debt-to-output ratio for each scenario, and the effects of changing the policy mix from one scenario to the other. Increasing the damage-to-capital ratio has a positive effect on the debt-to-output ratio in 2050: it shifts the whole distribution to the right, leading to a higher debt-to-output ratio level at the threshold. The effect is clearly visible on the median values in 2100, and follows a clear intuition. When the capital stock bears a greater share of the damages, the necessary repairs and replacement of capital destruction increase the overall debt burden. The effect is even stronger in 2100, and is at play in all the policy scenarios, as can be seen in Table 3, which summarizes the survival function values for the debt-to-output ratio at the point 2.7.

$\mathbb{P}(d > 2.7)$ in %	$f_K = 0\%$	$f_K = 33\%$	$f_K = 50\%$
No policy	15.1	21.7	24.9
Carbon tax	16.6	23.6	26.2
C. tax and subsidy	22.7	28.9	32.0

Table 3: Value of the survival function for the debt-to-output ratio at the point 2.7

Increasing the stringency of the climate policy mix (from no policy to a tax and a tax plus subsidy) also shifts the distribution to the right, and makes the effects of changes in f_K even larger. This highlights the trade-off faced by public authorities in balancing financial stability and climate change, as will be discussed below.

Fig. 4 displays the effects of the share of damages sustained by the capital stock on the temperature anomaly. As can be expected, the effect appears to be much weaker than on the debt-to-output ratio. Changes in the capital stock only marginally affect emissions —through the growth engine— and hence temperature anomaly.

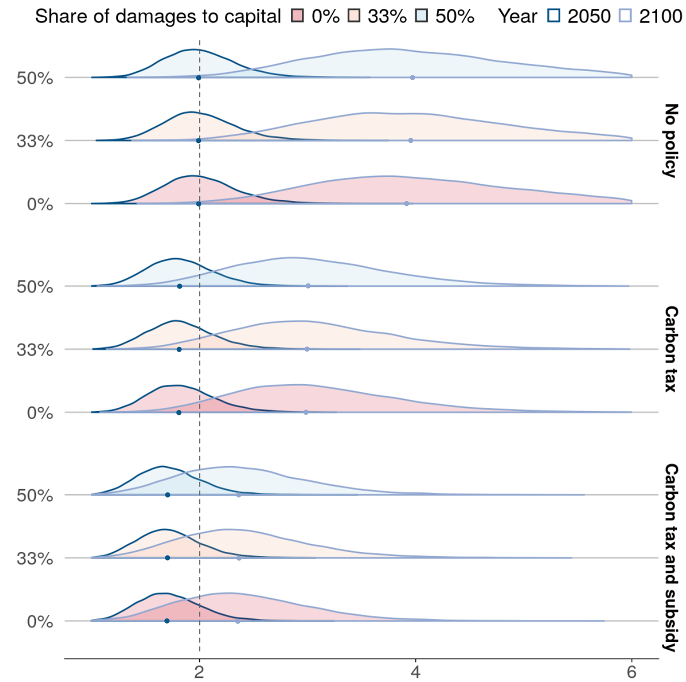

Figure 4: Probability density function of the temperature anomaly in 2050 and 2100.
The median values are identified by a point, and the dashed vertical line indicates the critical debt-to-output threshold.

The impact of public policies is, however, prominent between scenarios, especially in the long run. The more stringent **Carbon tax and subsidy** scenario has predictably a larger influence, as it triggers more abatement efforts and curbs emissions faster. Table 4 shows that from the **No policy** to the **Carbon tax and subsidy** cases, the median decrease of temperature anomaly is close to -1.6° C.

° C	$f_K = 0\%$	$f_K = 33\%$	$f_K = 50\%$
No policy	3.97	3.96	3.92
Carbon tax	3.01	3.00	2.98
C. tax and subsidy	2.36	2.37	2.35

Table 4: Median value of temperature anomaly distribution in 2100 reported in Fig. 4

Again, we compute in Table 5 the probabilities of exceeding the temperature anomaly threshold of 2°C by measuring values of the survival functions at the threshold. From the most pessimist to the most optimistic scenario, we gain 25 probability points for achieving the 2°C target. In our central **No policy** scenario (with $f_K = 33\%$), there is less than 1% chance of achieving the 2°C target, while it grows to above 5% in our **Carbon tax** scenario and above 25% in our **Carbon tax and subsidy** scenario.

[12] The expression "survival function" may not seem appropriate as it stands for the part of the probability related to a collapse in the context of the paper. However, in this context, survival function, or reliability function, has to be understood in its meaning in probability theory. That is, if $f(x)$ is the survival function of the probability variable X at the point x, then $f(x) = \mathbb{P}(X > x)$.

These figures are comparable to the ones recently presented in Nature Climate Change by Raftery et al. (2017) using a very different methodology. They make a projection based on Kaya's identity at the country level. GDP and CO_2 emissions are forecasted in a probabilistic way to compute the chances of staying below the 2°C threshold. They also find a 5% chance of meeting the Paris Agreement. Contrary to this article, however, they do not propose any theory or causal factor to disentangle the different channels at play, nor do they estimate the effect of global climate policy mixes. Their findings are consistent with our **Carbon tax** scenario, implying that a minimal public intervention in favor of abatement efforts are required to achieve this result. We find that increasing the stringency of the policy mix by adding a subsidy to the abatement technology allows to raise the probability of achieving the target of Paris Agreement to 25%.

$\mathbb{P}(T > 2°C)$ in %	$f_K = 0\%$	$f_K = 33\%$	$f_K = 50\%$
No policy	99.5	99.6	99.4
Carbon tax	94.8	94.4	94.2
C. tax and subsidy	74.3	74.4	73.8

Table 5: Value of the survival function for the temperature anomaly at the point 2°C

A comparison between scenarios in Fig. 3 and 4 shows that there is a trade-off between fighting the climate and financial instabilities. More effective climate policy mixes can be put in place, but at the cost of increasing the private debt in the long run. The underlying economic mechanism can be described as a kind of rebound effect, stressing the cost of public interventions. On one hand, the carbon tax and the subsidy from the public sector provide stronger incentives to perform the energy shift, and thus are effective in mitigating global warming. On the other hand, the additional source of funds for the productive sector boosts its profitability and thus investment, favoring a larger indebtedness. These results are in line with the recommendations of the Stern-Stiglitz Commission (Stiglitz and Stern, 2017), calling for a wider involvement of public actors, notably in terms of co-financing.

Comparing different values for f_K in Fig. 3 and 4 and Tab. 3, 4 and 5 highlights the potential role of targeted adaptation efforts, or the detrimental effect of not doing so. If targeted action can reduce the share of damages sustained by the capital stock (say from $1/3$ to 0) has little effect on the temperature anomaly, it can reduce significantly the burden of the debt and the chance of overshooting the debt-to-output threshold by more than 6 percentage points. On the contrary, implementing action that would increase the exposure of the stock of capital to damages from climate change (say from $1/3$ to $1/2$) by e.g. destroying carbon sinks or natural buffer zones, accelerating erosion, etc., would increase the chance of overshooting the debt-to-output threshold by approximately 3 percentage points.

4.3 Parameter spaces

The Monte Carlo analysis allows us to investigate in more details the physical and economic determinants of overshooting the thresholds. In this section, we explore the parameter values for productivity growth, climate sensitivity and inertia of the climate reservoirs that allow to stay below the thresholds.

We know from Giraud et al. (2017) that employment policy, debt relief and income distribution are effective ways to lever on the drivers of the collapse by moving the starting point of the economy inside the so-called basin of attraction ensuring the economy is in a sustainable path. While the three parameters considered here are not levers for public action *per se*, we can use our results to discuss three additional types of public intervention that can influence the shape of the basins.

The second line of Fig. 5 shows the set of initial conditions drawn from our Monte Carlo simulations that allow the economy to remain below the 2°C threshold in 2100. The range of colors from green to pink indicates the level of the debt-to-output ratio for the same initial values. It appears that the 2°C threshold is only feasible for extremely favorable combinations of low growth and high resilience from the climate —that is a low climate sensitivity and a somewhat low inertia of the carbon cycle.

For the **No policy** scenario, the set of initial conditions —almost negligible ($\approx 0.50\%$ of draws)— is clearly restricted in a very favorable region for the climate model that has negative labor productivity growth along with low climate sensitivity, suggesting that without climate policies, only paths of low growth (even negative) might be compatible with the 2 °objective.

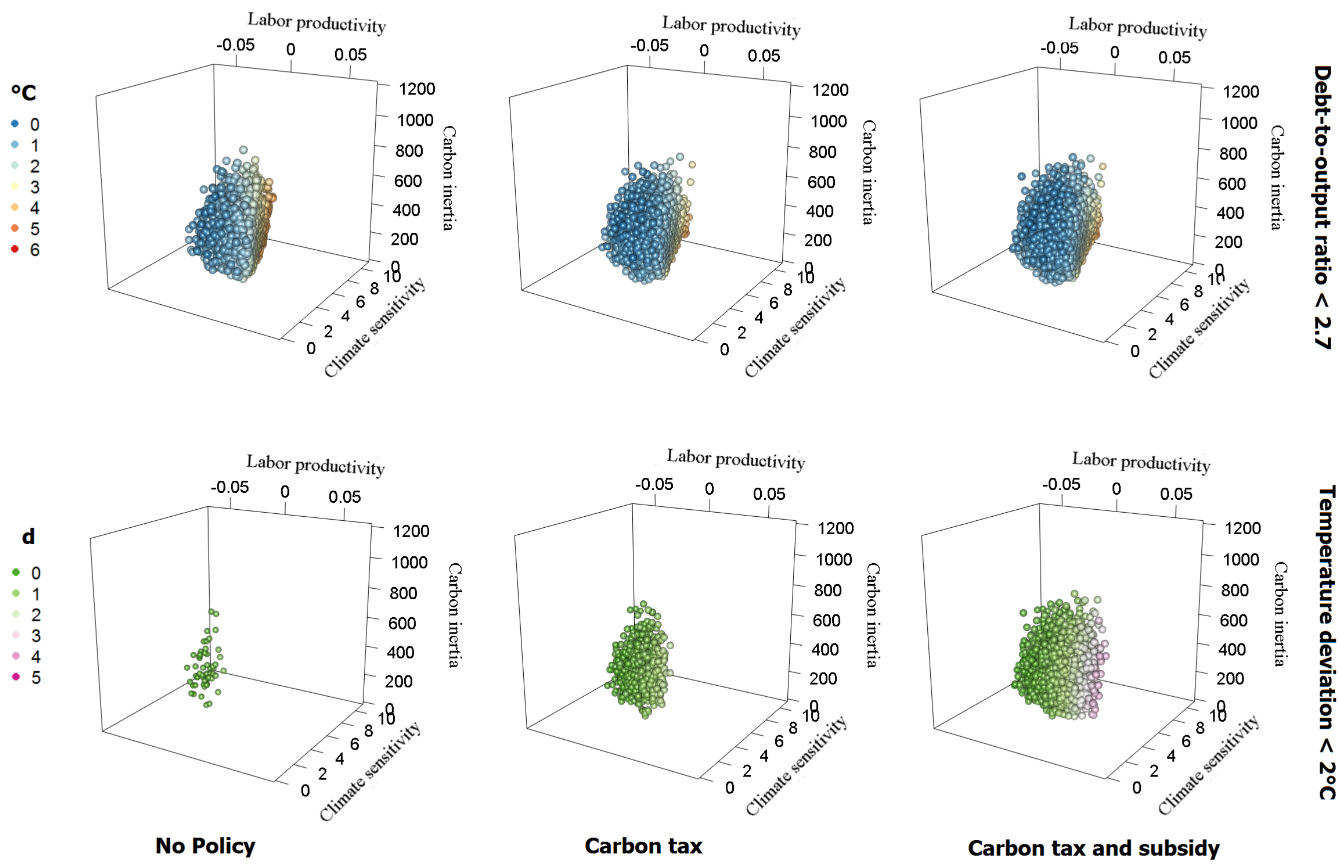

Figure 5: Set of points (α, S, C^{up}) from the Monte Carlo simulation of all scenarios with $k = 1/3$.
The upper line displays the set of initial conditions from simulations with a debt-to-output ratio below 2.7 in 2100 (the color of the points indicates the temperature anomaly of each simulation in 2100, with a colorscale on the left). The lower line displays the set of initial conditions from simulations with a temperature anomaly below 2°C in 2100 (the color of the points indicates the debt-to-output ratio level of each simulation in 2100, with a colorscale on the left).

More stringent climate policies significantly increase the set of favorable parameter combinations, enlarging the basin of attraction of favorable trajectories. Indeed, the scenario **Carbon tax and subsidies** allows positive labor productivity growth together with values for the climate sensitivity and the carbon inertia that are at their pdf's median. However, as visible in the pink shade of the dots, these additional points in the set come together with a higher debt-to-output ratio (sometimes higher than the 2.7 threshold) highlighting the trade-off faced by the public authorities discussed earlier.

$\mathbb{P}(\{T > 2°C\} \cup \{d > 2.7\})$	$f_K = 0\%$	$f_K = 33\%$	$f_K = 50\%$
No policy	99.5	99.7	99.4
Carbon tax	94.8	94.4	94.2
C. tax and subsidy	78.2	79.3	78.6

Table 6: Value of the survival function for the joint temperature anomaly and debt-to-output ratio at the point (2°C,2.7)

The first line of Fig. 5 shows the set of initial conditions drawn from our Monte Carlo simulations that allow the economy to remain below the 2.7 debt-to-output threshold in 2100. The range of colors from blue to red indicates the level of the temperature anomaly in 2100 for the same initial values. As discussed above, climate policies have a much smaller effect on the basin of attraction of favorable debt-to-output trajectories compared to their effect on favorable temperature anomaly trajectories. While climate policies do increase the level of indebtedness, the mass of simulations going above the 2.7 debt-to-output threshold when adding a climate policy is much smaller (some percentage points, visible in Tab. 3). However, we can note that, throughout the scenarios, the color of each point tends to change from red towards blue. This means that climate policies help meet both thresholds: the temperature anomaly and the debt-to-output ratio. Table 6 gives the probabilities of overshooting at least one of the two thresholds. It appears that while over-indebtedness starts to be a problem for very stringent climate policies, reducing the probability of meeting the two targets together from 25.6% to 20.7% in the central case, it does not affect much sustainable trajectories with a carbon tax only.

5 Conclusion

We perform a sensitivity analysis of the model presented by Giraud et al. (2017). This model combines two sources of instability: (i) global warming and (ii) private over-indebtedness, in a rather low-dimensional stock-flow consistent, integrated ecological macroeconomic model. In this article, we allow three fundamental parameters of the climate and economic systems to follow a pdf taken from Nordhaus (2017): the climate sensitivity, the inertia of the carbon cycle, and the labor productivity growth. We also let another techno-climatic parameter vary: the share of damages sustained by the capital stock (instead of only considering damages to output). We then test how different climate policies allow to avoid overshooting two thresholds that we argue to be critical for the stability of our current economy and climate, namely a temperature anomaly above the +2°C target set in the Paris Agreement and a global debt-to-output ratio above 2.7, a value calibrated at the level of the current stock of assets. Above, the value of the total private debt would exceed the principal, arguably leading to systemic defaults. Both are associated to major potential destabilizing channels: damages to the capital stock from climate change and the ability of firms to invest in repairs and adaptation.

We find that we have a mere 0.36 % chance of achieving the 2°C warming target of the Paris Agreement in a no-policy scenario. Introducing climate policies, as advocated in a recent report by the High Level Commission on Carbon Prices at the Pricing Leadership Coalition (Stiglitz and Stern, 2017), allows to increase that probability to 5.64%. We highlight the role of additional climate policies beyond a carbon price, as well as the potential of targeted adaptation aiming at reducing the share of damages sustained by production factors (instead of considering that all damages from climate change occurs *via* changes in the output). Increasing mitigation efforts by adding a 50% subsidy to investment in the backstop technology increases the probability of meeting the 2°C target to 25.6%. On the other hand, increasing adaptation efforts would have little effect on the temperature anomaly, but would reduce the burden of the debt and hence the chances of global instability: reducing the share of damages sustained by the stock of capital from 50% to zero reduces the probability of exceeding the 2.7 debt-to-output threshold from 24.9% to 15.1% (in the no-policy scenario) or 26.2% to 16.6% (with a carbon tax).

We also shed light on the trade-off between the two principal objectives of a sustainable debt and a sustainable climate. Effective climate policies come at the cost of increasing the probability of overshooting the 2.7 debt-to-output ratio threshold from 21.7% (**No policy** scenario) to 23.6% (with a **Carbon tax**). Subsidizing mitigation efforts further increases the chances to 28.9%. Yet, considering the two thresholds together, it appears that over-indebtedness only becomes a problem for very stringent climate policies.

Several important limitations should be kept in mind when interpreting our results. First, we present an aggregate model of the global economy and of the finance sector. Geographical and sectoral disaggregation is a prerequisite for a complete understanding of the debt and damage interaction channels. More details in the energy and finance sectors are also key as they are highly condensed in the paper, especially when one seeks to understand the role of an energy vector (green electricity) possibly having a role in all sectors. In this paper, we are concerned with the aggregate effect, a useful first step in the analysis of this complex problem, but extensions and disaggregation are on the research agenda. Technological aspects have also been shown to play important roles. R&D, knowledge effects, and the nature of the backstop would all deserve a closer look in a stock-flow consistent macrodynamic framework. Another interesting avenue of research is also the role of different types of money, such as central money VS commercial money in a post-Keynesian framework (Aglietta et al., 2015).

Nevertheless, our work allows a better interpretation of the dynamics often overlooked in IAMs and policy advice such as in the Stern-Stiglitz Commission report (Stiglitz and Stern, 2017). In particular, we highlight the role of monetary channels and debt, as well as their interactions with climate change damages, and do not presuppose a balanced growth path. This allows a finer look at possible climate policy mixes, the trade-off they imply at the global level, and the possible balance between mitigation and adaptation efforts. Further work will be required to deepen the understanding of these channels and the interactions of sectors and regions in the global energy shift.

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Appendices

A Equations of the climate module

The climate module is directly inspired from the DICE model of Nordhaus (2017) adapted to our continuous framework. More precisions about these equations can be found on Giraud et al. (2017)

Total emissions E are expressed in CO_2-e units and result from two sources: (i) industrial emissions E_{ind} defined in Eq. 4 and (ii) exogenous land-use emissions E_{land} with the dynamics $\dot{E}_{land} := \delta_{E_{land}} E_{land}$, with $\delta_{E_{land}}$ a parameter, such that $E := E_{ind} + E_{land}$.

The emission intensity σ also obeys an exogenous dynamics given by $\dot{\sigma} := g_\sigma \sigma$ and $\dot{g_\sigma} := \delta_{g_\sigma}$ with $\delta_{g_\sigma} g_\sigma$ a parameter.

The carbon cycle is described through a three-layer model describing the interactions between (i) the atmosphere layer AT where emissions are released and (ii) the biosphere-upper ocean layer UP as well as the lower ocean layer LO acting as carbon sinks. Thus, the concentration in CO_2-e ${CO_2}^i, i \in \{AT, UP, LO\}$ evolves according to the following system:

$$\begin{pmatrix} \dot{CO_2}^{AT} \\ \dot{CO_2}^{UP} \\ \dot{CO_2}^{LO} \end{pmatrix} := \begin{pmatrix} E \\ 0 \\ 0 \end{pmatrix} + \Phi \begin{pmatrix} CO_2^{AT} \\ CO_2^{UP} \\ CO_2^{LO} \end{pmatrix} \quad \text{with} \quad \Phi := \begin{pmatrix} -\phi_{12} & \phi_{12}\frac{C^{AT}}{C^{UP}} & 0 \\ \phi_{12} & -\phi_{12}\frac{C^{AT}}{C^{UP}} - \phi_{23} & \phi_{23}\frac{C^{UP}}{C^{LO}} \\ 0 & \phi_{23} & -\phi_{23}\frac{C^{UP}}{C^{LO}} \end{pmatrix},$$

where C^i corresponds to the CO_2-e pre-industrial concentration in the corresponding layer, $i \in \{AT, UP, LO\}$, and ϕ_{ij} stands for the diffusions coefficients between layers, $i \in \{AT, UP, LO\}$ and $j \in \{AT, UP, LO\}$.

The resulting radiative forcing in the atmospheric layer —resulting from a change in the energy balance of this layer— is the sum of two terms: (i) the industrial forcing $F_{ind} := \frac{F_{2\times CO_2}}{\log(2)} \log\left(\frac{CO_2^{AT}}{C^{AT}}\right)$ where $F_{2\times CO_2}$ is the radiative forcing resulting from a doubling of the pre-industrial atmospheric concentration in CO_2-e, and (ii) an exogenous radiative forcing defined by $\dot{F}_{exo}$ which is linearly growing from its initial value to a plateau in 2100 as in Nordhaus (2017).

Finally, the dynamics of temperature is given by a two-layer model describing the interactions between (i) the atmosphere and upper ocean, with a mean temperature deviation of T with regards to the pre-industrial situation, and (ii) the lower ocean with a mean temperature deviation of T_0 with regards to the pre-industrial situation, according to:

$$\begin{aligned} C\dot{T} &:= F - \rho T - \gamma^*(T - T_0), \\ C_0\dot{T}_0 &:= \gamma^*(T - T_0), \end{aligned}$$

where ρ is the radiative feedback parameter, γ^* is the heat exchange coefficient between the two layers, C is the heat capacity of the atmosphere, land surface, and upper ocean layer, and C_0 is the heat capacity of the deep ocean layer. It is worth mentioning that this system defines the equilibrium climate sensibility (ECS) by $T = F/\rho$ in this framework).

B Calibration of the Model

The calibration of the model is directly borrowed from Giraud et al. (2017). The parameters objects to the prospective analysis performed in this paper —namely: (i) the growth rate of labor productivity α; (ii) the preindustrial CO_2 capacity of the biosphere and upper ocean reservoir of the carbon cycle, $CO2_{UP}$; (iii) the allocation of damages between output and capital, f_K; (iv) the equilibrium climate sensitivity, S; (v) the subsidy of the public to abatement activities, s_A; and (vi) the trajectory of the carbon price— are not displayed in this table.

Symbol	Description	Value	Remarks and sources
C	Heat capacity of the atmosphere, biosphere and upper ocean	1/.098	DICE model, Nordhaus (2017), adjusted for a continuous framework
C_0	Heat capacity of the deeper ocean	3.52	DICE model, Nordhaus (2017), adjusted for a continuous framework
$C_{AT_{pind}}$	CO_2-e preindustrial concentration in the atmosphere layer	588 Gt C	DICE model, Nordhaus (2017)
$C_{LO_{pind}}$	CO_2-e preindustrial concentration in the deeper ocean layer	1,720 Gt C	DICE model, Nordhaus (2017)
div_0	Constant of the dividend function, $\Delta(\cdot)$	-0.078	Empirically calibrated, macroeconomic database, more details available upon request
div_π	Slope of the dividend function, $\Delta(\cdot)$	.473	Empirically calibrated, macroeconomic database, more details available upon request
$div_{\min}$	Minimum of the dividend function,$\Delta(\cdot)$	0	Selected among a range of reasonable values
$div_{\max}$	Maximum of the dividend function, $\Delta(\cdot)$	0.3	Selected among a range of reasonable values
$F_{2\times CO_2}$	Change in the radiative forcing resulting from a doubling of CO_2-e concentration w.r.t. to the pre-industrial period	3.681 W/m^2	DICE model, Nordhaus (2017)
F_{exo}^{start}	Initial value of the exogenous radiative forcing	0.7 W/m^2	DICE model, Nordhaus (2017)
F_{exo}^{end}	Final value of the exogenous radiative forcing	0.7 W/m^2 (after 2100)	DICE model, Nordhaus (2017)
P^N	Upper limit of the workforce dynamics in billions	7.056	Empirically calibrated, macroeconomic database, more details available upon request
P_G^N	Upper limit of the total population dynamics in billions	12	Empirically calibrated, macroeconomic database, more details available upon request
q	Speed of growth of the workforce dynamics	0.0305	Empirically calibrated, macroeconomic database, more details available upon request
q_G	Speed of growth of the total population dynamics	0.027	Empirically calibrated, macroeconomic database, more details available upon request
r	Short-term interest rate of the economy	0.02	Selected among a range of reasonable values
T_{preind}	Preindustrial temperature	13.74°C	NASA (2016)NASA (2016)
δ	Depreciation rate of capital	0.04	Inklaar and Timmer (2013)
$\delta_{E_{Land}}$	Growth rate of land use change CO_2-e emissions	-0.022	DICE model, Nordhaus (2017), adjusted for a continuous framework
δ_{g_σ}	Variation rate of the growth of emission intensity	- 0.001	DICE model, Nordhaus (2017), adjusted for a continuous framework
$\delta_{p_{BS}}$	Exogenous growth rate of the back-stop technology price	- 0.005	DICE model, Nordhaus (2017), adjusted for a continuous framework
ζ_3	Damage function parameter	6.754	DICE model, Nordhaus (2017)
η	Relaxation parameter of the inflation	0.5	Selected among a range of reasonable values
θ	Parameter of the abatement cost function	2.6	DICE model, Nordhaus (2017)
κ_0	Constant of the investment function, $\kappa(.)$	0.0318	Empirically estimated, macroeconomic database, more details available upon request
κ_1	Slope of the investment function, $\kappa(.)$	0.575	Empirically estimated, macroeconomic database, more details available upon request
μ	Mark-up of prices over the average cost	1.3	Selected among a range of reasonable values
ν	Constant capital-to-output ratio	2.7	Inklaar and Timmer (2013)
π_1	Damage function parameter	0 /°C	DICE model, Nordhaus (2017), adjusted for a continuous framework
π_2	Damage function parameter	0.00236/°C^2	DICE model, Nordhaus (2017)
π_3	Damage function parameter in the Weitzman case	0.00000507/°C$^{\zeta_3}$	Weitzman (2011) and Dietz and Stern (2015)
ϕ_0	Constant of short-term Phillips curve, $\phi(.)$	-.292	Empirically estimated, macroeconomic database, more details available upon request
ϕ_1	Slope of the short-term Phillips curve, $\phi(.)$	.469	Empirically estimated, macroeconomic database, more details available upon request
Φ_{12}	Transfer coefficient for carbon from the atmosphere to the upper ocean/biosphere	0.024	DICE model, Nordhaus (2017), adjusted for a continuous framework
Φ_{23}	Transfer coefficient for carbon from the upper ocean/biosphere to the lower ocean	0.001	DICE model, Nordhaus (2017), adjusted for a continuous framework
$C_{\mathcal{P}}$	Constant share of the nominal capital for $\mathcal{P}$	0.08	Empirically estimated, macroeconomic database, more details available upon request

The mentioned macroeconomic database gathers data from the World Bank, Penn University, the U.S. Bureau of Economic Analysis, and the United Nations.

C Initial values of the Model

Symbol	Description	Value	Remarks/sources
CO_2^{AT}	CO_2-e concentration in the atmosphere layer	851 Gt C	DICE model, Nordhaus (2017)
CO_2^{UP}	CO_2-e concentration in the biosphere and upper ocean layer	460 Gt C	DICE model, Nordhaus (2017)
CO_2^{LO}	CO_2-e concentration in the deeper ocean layer	1,740 Gt C	DICE model, Nordhaus (2017)
d	Private debt ratio of the economy	1.53	Empirically calibrated, macroeconomic database
E_{ind}	Industrial CO_2-e emissions	35.85 Gt CO_2-e	DICE model, Nordhaus (2017)
E_{land}	Exogenous land use change CO_2-e emissions	2.6 Gt CO_2-e	DICE model, Nordhaus (2017)
F_{exo}	Exogenous radiative forcing	0.5 W/m^2	DICE model, Nordhaus (2017)
g_σ	Growth rate of the emission intensity of the economy	- 0.0152	DICE model, Nordhaus (2017)
p	Composite good price level	1	Normalization constant
p_{BS}	Backstop price level	547.22	DICE model, Nordhaus (2017), compound 1-year ahead
n	Emissions reduction rate	0.03	DICE model, Nordhaus (2017)
N	Workforce of the economy in billions	4.83	Empirically calibrated, macroeconomic database
NG	Total population in billions	7.35	Empirically calibrated, macroeconomic database
T	Temperature in the atmosphere, biosphere and upper ocean layer	0.85 °C	DICE model, Nordhaus (2017)
T_0	Temperature in the deeper ocean layer	0.0068 °C	DICE model, Nordhaus (2017)
Y	Gross domestic product (at factor prices) in trillions USD	59.74	Empirically calibrated, macroeconomic database
λ	Employment rate of the economy	0.675	Empirically calibrated, macroeconomic database
ω	Wage share of the economy	0.578	Empirically calibrated, macroeconomic database

The mentioned macroeconomic database gathers data from the World Bank, Penn University, the U.S. Bureau of Economic Analysis, and the United Nations.

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