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The public costs of climate-induced financial instability

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The public costs of climate-induced financial instability*

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Abstract

Recent evidence suggests that climate change will significantly affect macro-economic growth and several productive elements of modern economies, such as workers and land [Dell et al., 2009, Burke et al., 2015, Carleton and Hsiang, 2016]. Although historical records indicate that economic shocks lead to financial instability, few studies have focused on the impacts of climate change on the financial system [Dietz et al., 2016, Dafermos et al., 2018]. This paper evaluates a global economy where multiple banks provide credit to production activities exposed to climate damages. We use an agent based climate-macroeconomic model calibrated on stylized facts, future scenarios and climate impact functions [Nordhaus, 2017] affecting labour and capital. Results indicate that climate change will increase the frequency of banking crises (+26-148%). The public costs of rescuing insolvent banks will cause an additional burden of about 5-to-15% of GDP per year, and an increase of public debt to GDP by a factor of 2. We estimate that around 20% of such effects are caused by the deterioration of banks' balance-sheets. Macroprudential regulation attenuates bailout costs, but only moderately. Our results show that leaving out the financial system from climate-economy integrated assessment may lead to an underestimation of climate impacts, and that financial regulation can play a role in mitigating them.

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1 Introduction

Financial crises are known to cause and exacerbate economic downturns [Reinhart and Rogoff, 2009a, Jordà et al., 2013]. Recent evidences suggest that climate change is likely to bring about a variety of risks for banks and other financial institutions [Battiston et al., 2017, Dietz et al., 2016, Campiglio et al., 2018]. This paper studies the effects of climate-related damages to productive activities on the stability of the global banking system. We show that climate change will raise both the frequency of banking crises and the public costs that governments have to sustain to restore financial stability. The additional loss in economic growth due to the financial distress reaches 20% and the costs of banksfi bailouts increase linearly with the temperature. Macroprudential policy might have a sizable role in reducing the risk of climate-related financial crises.

Historical records suggest that financial crises are not rare events (Figure 1). On a global scale, the last 50 years have been characterized by a variety of crises, entailing an average cost of around 35% of the GDP of the country facing the event in terms of output lost and a fiscal burden for the government of 13% of country's GDP. Such crises reflect imperfections in the functioning of our economies, financial systems and - particularly - capital allocation mechanisms.

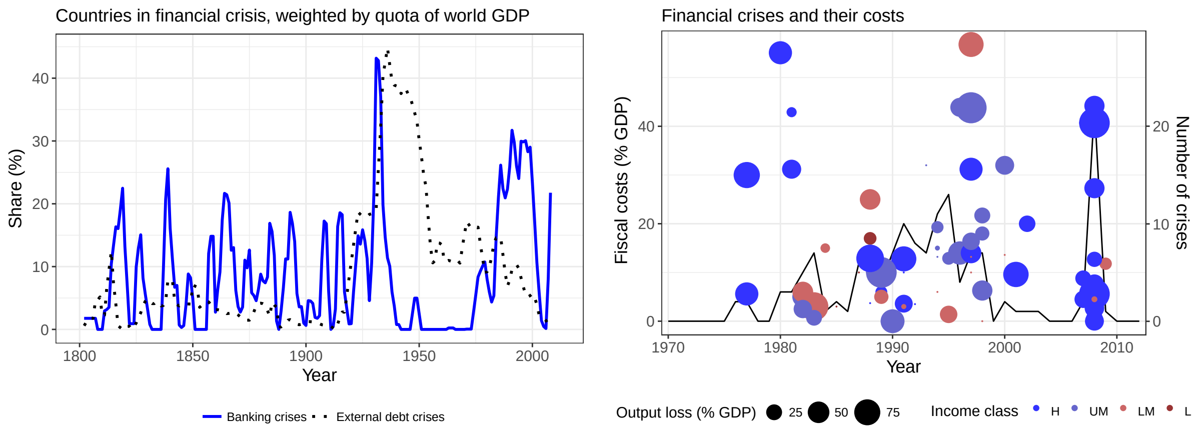

Figure 1: Long run share of countries in financial crisis according to Reinhart and Rogoff [2009b] data, weighted by share of world GDP (left; a three-year moving average is reported). Worldwide historical number of financial crises (line) and their costs (circles) in terms of lost output shares and fiscal spending governments have borne (right), according to the [Laeven and Valencia, 2012] data. Each episode is associated to its starting year. Output losses -red circles- are computed as the cumulative sum of the differences between actual and trend real GDP over the period [T, T+3], expressed as a percentage of trend real GDP, with T the starting year of the crisis. Fiscal costs are defined as the component of gross fiscal outlays related to the restructuring of the financial sector. Income classes are defined based on the World Bank 2018 classification; H stands for High income, UM for Upper Middle income, LM for Lower Middle income and L for Low income. Details in Section A of Supplementary Information.

The recent research on climate damages emphasize that increased temperatures will have significant, non-linear effects on the global economy [Schlenker and Roberts, 2009, Hsiang, 2010, Burke et al., 2015, Carleton and Hsiang, 2016, Hsiang et al., 2017, Diffenbaugh and Burke, 2019, Martinich and Crimmins, 2019]. As a result of physical and economic losses, unmitigated climatic change could also affect the stability of the financial system. For example, the increase in climate-induced capital risks (due to heat waves, floods or storm surges) could have a negative effect on insurance companies, in turn affecting premiums. In case of uninsured risks, the deterioration of the balance sheets of affected households and firms could lead to losses for their lender banks. More in general, the inability to repay obligations - because of insolvency - generates what are usually referred to as non-performing loans (or bad debt) in the balance-sheet of banks and other financial institutions, with possible systemic implications that have been experienced at global scale during the 2008 financial crisis. Taxpayers are the final subject bearing the risks of instability. Hence, financial crises entail costs both to the economy, because of contractions in demand and in production, and to the public finances (fiscal costs), due to the rescuing interventions of the governments.

The literature on climate change impacts and finance is scant, yet rapidly developing. In a 2015 speech the governor of the Bank of England distinguished between climate-related *physical* and *liability*, and *transition risks* [Carney, 2015]. Some recent studies highlight the exposure of the global financial system to such risks [Dietz et al., 2016, Bansal et al., 2016, Battiston et al., 2017, Safarzyńska and van den Bergh, 2017, Dafermos et al., 2018, Trinks et al., 2018, Mercure et al., 2018], yet none of them examine the public costs of the ensuing instability and the role of the latter in amplifying the impact of climate on growth.[1] Based on these preliminary studies, attention is emerging on how central banks and financial regulation authorities could manage climate-related risks to financial stability [Campiglio et al., 2018, HLEG, 2017].

This paper contributes to the debate by analyzing the impacts of climate change on the global banking system, quantifying banking crises and the public costs of bailing out insolvent banks. We single out the potential underestimation of climate change damage estimates that neglect this element. We use a recently developed global agent-based integrated assessment model [Lamperti et al., 2018a,b] to simulate the behaviour of an economic system composed of heterogeneous households, firms, energy plants, banks and policy makers (a government and central bank) exposed to climate damages affecting the productivity of labour and the stock of capital owned by firms (see Methods). The model is calibrated on stylized facts and reproduce economic growth and emissions consistent with the Shared Socio-economic Pathways (SSP5 as central case; see Riahi et al., 2017 and sections D and F of Supplementary Information for details and results for SSP1). We consider four scenarios of climate damages. One, the baseline, with no climate change, and three scenarios where global warming affects the productivity of labour, that of capital, or both, respectively. Empirical studies have found that warming significantly reduces both operational and cognitive tasks of workers, thus lowering labour productivity [Seppanen et al., 2003, 2006, Somanathan et al., 2014, Adhvaryu et al., 2014, Kjellstrom et al., 2009]. Likewise, there is evidence that climate change can affect the stock and quality of capital directly - via crowding out - and indirectly - via extreme events [Batten et al., 2018]. As the magnitude of climate change impacts is extremely uncertain [Ricke et al., 2018], we perform an extensive sensitivity analysis around our central value based on estimates from Nordhaus [2017].

Damages impact the profitability of firms, which might go bankrupt creating non-performing loans (i.e. loans that won't be repaid) in the balance-sheets of banks. To prevent instability of the financial system, when a bank's equity goes negative, we test a bailing out policy such that the government immediately intervenes by providing fresh capital saving the insolvent bank (details are provided in the Section 4 and Section B of Supplementary Information).

[1]However, we notice that, with an aim similar to ours, Dafermos et al. [2018] find that climate damages to capital stocks seriously harm banks' leverage, with sizable effects on GDP growth.

2 Results

The employed model, described in Section 4, does not allow for analytical, closed-form solutions. This general feature of agent-based models forced us to perform Monte-Carlo analyses to wash away across-simulation variability and to present results as averages over 500 model runs, as standard in the literature [Fagiolo and Roventini, 2017, Balint et al., 2017].

Table 1 summarizes the behaviour of main macroeconomic, financial and climate indicators across the three impact scenarios and the baseline. Climate change has significant negative effects on economic growth, reducing the annual pace from 3.5% in the baseline, to 2.0-2.9%, depending on the climate impact scenario. Qualitatively, these evidences are confirmed when we target a SSP1 scenario (Section F of Supplementary Information).Impacts on the macro-economy are stronger when climate damages hit labour productivity, reflecting the prevalence of the labour share in most modern economies [OECD, 2018].[2] Above and beyond this effect, the accumulation of losses in the banking sector sharpens the impacts, as detailed below. Financial crises and banks' bailouts occur even in the absence of climate change: average fiscal costs in the baseline (10.3% of GDP) are comparable to historic values (see Figure 1).[3] However, the three impact scenarios significantly raise the number of banks' rescues the government must engage-in to preserve financial stability, with fiscal costs increasing by a factor ranging from 1.52 (95% CI: 1.04; 2.00) to 2.43 (95% CI: 1.86; 3.00) depending on the scenario.[4]

Table 1: Main macroeconomic and climate indicators in the baseline and impact scenarios.

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

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

The number of bailouts induced by climate impacts magnify over time (Figure 2, top-left panel), with the largest increase taking place between 2030 and 2060, when temperature

[2]Such macro-economic impacts are larger than what usually reported in the literature [Nordhaus, 2014, Auffhammer, 2018], as they emerge from shocks to individual interacting agents that are not fully absorbed by markets through price-adjustment mechanisms (Lamperti et al., 2018a,b; see section F of Supplementary Information for a sensitivity analysis on the size of damages).

[3]Based on the definitions adopted in this paper (see Section 1), we qualitatively associate an insolvent bank's public bailout in our simplified model encompassing 10 asymmetric financial institutions with a financial crisis. This is also coherent with Reinhart and Rogoff [2009b].

[4]Such effects are driven by the stock of bad debt accumulating in the financial system as a consequence of cascades of firms' bankruptcies induced by climate damages [Lamperti et al., 2018a].

anomaly reaches about 3 degrees Celsius - consistently with a SSP5 scenario - and the corresponding average damage to firms exceeds 2%.[5] Under labour and capital damages, banks' bailouts increase faster than in all other scenarios and, at the end of the century, they become more than twice as frequent as in the baseline (average of 25.0 vs. 9.8 in the last decade of simulation), imposing costs to the government reaching 40% of GDP per episode (Figure 2, top-right panel). Such costs negatively affect the public budgets and, over time, translate in an increasing stock of government debt (Figure 2, bottom panel). By the end of the century, the expected debt to GDP ratio is slightly above 400%, which should be compared to the 85% of the scenario with no climate change. Note also that bailouts are less frequent in two climate impact scenarios vis-á-vis the baseline during the first couple of simulation decades (Figure 2, top-right panel). This suggests beneficial effects of mild climate change (Carleton and Hsiang, 2016, Burke et al., 2015; Section F of Supplementary Information document a non-linear relation between bailouts and GDP losses across scenarios). In a SSP1 future the impacts are less severe yet sizable: firms' insolvency and bailouts' frequency increase by +33% and +9% respectively (as opposed to a baseline without warming), and public debt to GDP averages 250% at 2100 (see Section F of Supplementary Information).

Crises in the banking system exacerbates the downturns in the real sector through credit crunches, i.e. periods of substantially reduced credit inflow blocking the investments of firms [Bernanke et al., 1991, Brunnermeier, 2009]. The combination of such events and the direct damages that climate change exerts to economic agents in our impact scenarios (see Section 4) produce large detrimental effects on the long run performance of the economy (Figure 3). While in absence of climate change the yearly growth rates of output are almost identical over the century, when firms suffer labour and capital damages in an SSP5 world the economy gradually shifts towards regimes of progressively weaker paces of developments and larger volatility, with average growth rates corresponding to 91% (95% CI: 67%; 119%), 84% (95% CI: 65%; 108%), 68% (95% CI: 34%; 103%) and 48% (95% CI: 33%; 91%) than those in the baseline for the first, second, third and fourth century quarters, respectively. In a SSP 1 future, we show that output growth rate contracts by 9% (with respect to a scenario without warming; Section F of Supplementary Information). Damages to labour productivity cut firms' operative margins, depress wages and the aggregate demand, with dynamically adverse effects on technical change and the Schumpeterian engine of growth. Differently, capital stock losses amplify fluctuations in the business cycle, exacerbating the reliance of firms on external financing [Lamperti et al., 2018a]. Finally, the ability of the banking sector to alleviate the direct implications of climate impacts on firms, weakens due to the cumulated effects of nonperforming loans. Section F of Supplementary Information offers a comparison of the economic damages emerging in the present study with respect to previous findings.

To establish the contribution of climate-induced financial distress to such a shrinkage of economic performances we run an additional simulation experiment comparing the actual bailout mechanism with an alternative regime. In the latter, the government absorbs any non-performing loan, thus fully preserving banks' equity and lending capacity.[6] Such experiment is run on our preferred impact scenario (Labour and Capital Damages) and results are

[5] To put numbers into perspective, during the Great Recession (2007-2013) most developed countries experienced average losses in output of 2.66% per year, a loss of capital intensity of 0.40% per year and a loss in productivity of 1.30% per year Oulton [2018]. Using an oversimplification, for the average firm, imposing a 2% damage in a given period is vaguely similar to experiencing one year of the recent crisis.

[6] In particular, in the scenario without financial distress, the Government provides liquidity for an amount equivalent to the non-performing loan. As we only want to precisely assess the contribution of climate-induced financial distress on the performance of the economy, we do not consider the cost of this bailout rule for the public budget.

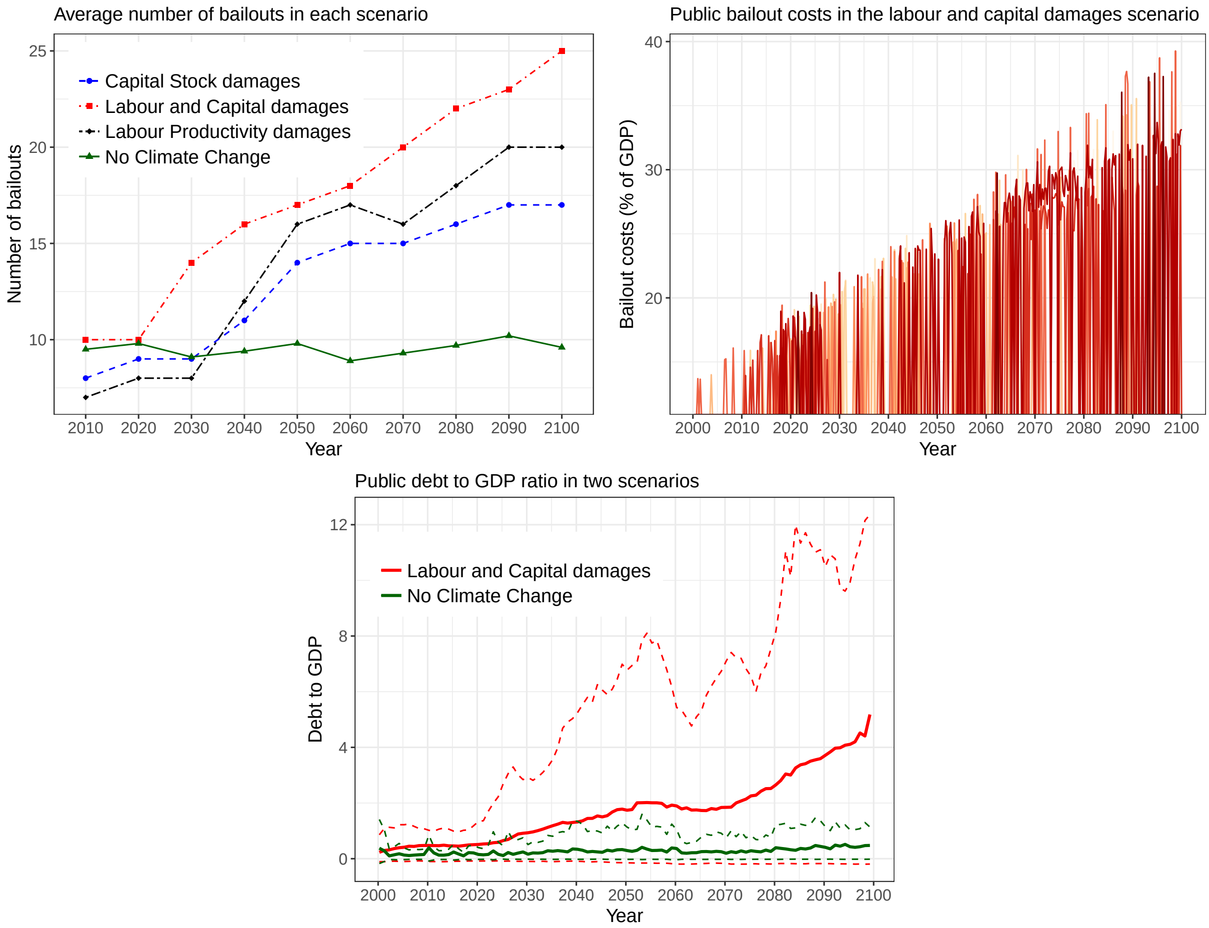

Figure 2: Ten years average number of bailouts (out of 500 simulations) in the three scenarios and in the baseline (top-left); bailout costs as share of GDP in the Labour and Capital Damages scenario, each line represents a model run (top-right); public debt behaviour in the Labour and Capital Damages scenario and in the No Climate Change scenario, solid lines are yearly averages (out of 500 simulations) and dashed lines are 90% confidence intervals.

reported in Figure 3 (bottom panel). We estimate that around 20% (95% CI: 5%; 43%) of growth rates reduction observed in the top-right panel of Figure 3 is attributable to financial distress (Section F of Supplementary Information reports an effect of 14% for SSP1).

We find that public costs of climate-induced bailouts increase approximately linearly with temperature anomaly (Figure 4). In the scenario with both labour and capital damages (panel B) such burden for the public budget moves from an yearly estimate of 17.5% (95% CI: 8%; 24%) of GDP under +2.5 degrees Celsius in year 2100 to 31.0% (95% CI: 19%; 48%) for a temperature of about 5 degrees Celsius in the same year. These values correspond to increments of 7.14 and 20.64 percentage points with respect to the bailout costs in the baseline scenario without climate change.

Finally, we test whether macroprudential regulation relying on Basel-type capital requirements can be used to mitigate the costs of banking bailout. An U-shaped relation emerges between the banks' allowance to loan and the costs from financial distress. Tight capital requirements reduce the availability of loans, forcing firms to rely more on their highly volatile net profits. At the opposite side, large credit supply allows firms to over-finance unsuccessful investments [Dosi et al., 2013], eventually leading to losses and bankruptcies. Climate change is found to exacerbate such relationship, with "the U" becoming steeper as the temperature rises.

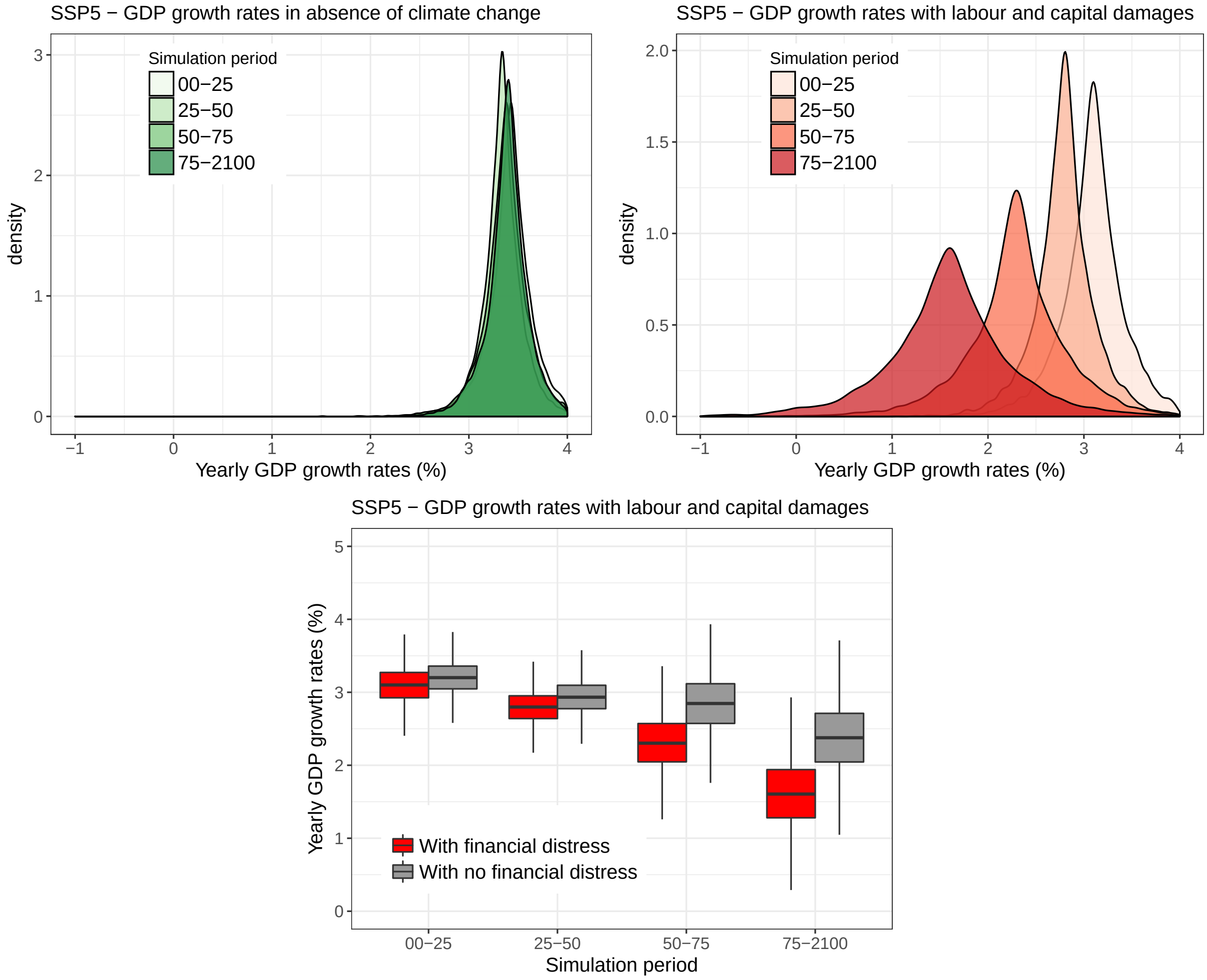

Figure 3: Kernel densities of yearly growth rates of global GDP pooled per 25-years periods in the baseline scenario with No Climate Change (top-left) and in the scenario with Labour and Capital Damages (top-right); bottom Figure shows the box-plots of yearly growth rates in the Labour and Capital Damages scenario in presence and absence of financial distress. Yearly growth rates are computed for each model run, clustered according to each 25-years long period; a Gaussian kernel density plot is than provided for each cluster. The boxplots whiskers contains the 95% of observations.

Results underline a pivotal role of macro-prudential regulation in climate risk management. As Figure 4 (panel B) indicates, our analysis suggests that climate-dependent capital requirements can counterbalance eventual excessive or reluctant credit provision, accounting for the impacts of climate damages on firms' solvency [Campiglio, 2016, Campiglio et al., 2018]. Supplementary Information (Section F) shows that a countercyclical capital buffer (as proposed in the Basel III framework; BIS, 2011) could help address climate physical risks, even though it proves to be ineffective when damages surge. Nonetheless, even if such macroprudential regulation is in place, the impacts of climate change on financial crises remain dominant.

Section F of Supplementary Information provides a series of robustness tests for our results. This battery of exercises confirms (i) the role of the banking system in amplifying damages; (i) the relevance of setting adequate capital requirements, following both phases of the business cycle and (iii) the inadequacy of contractionary fiscal policy in restoring financial stability.

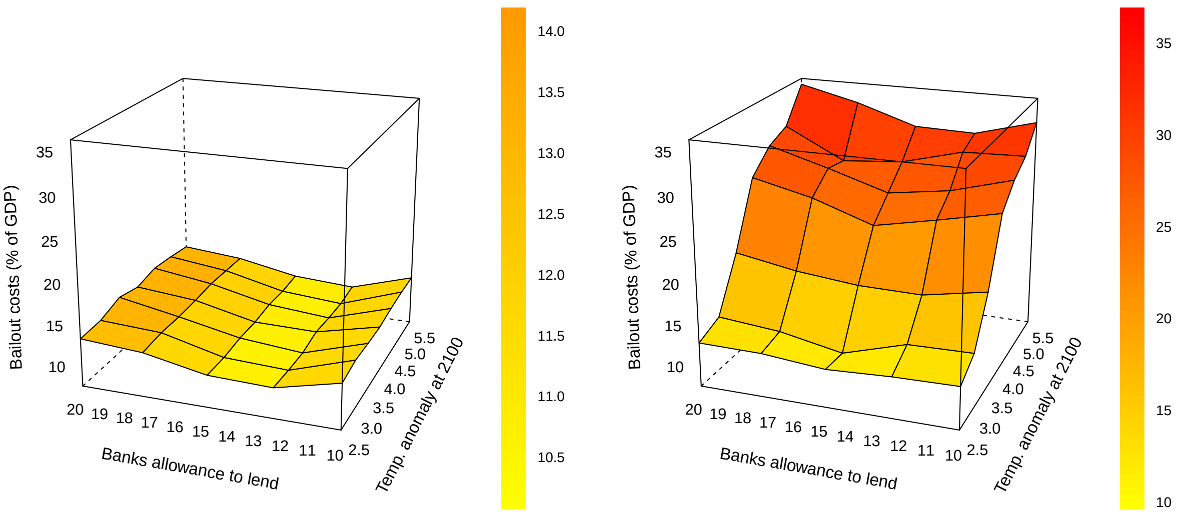

Figure 4: Public costs of bank bailouts in the baseline scenario with absence of climate change damages (left) and in the scenario with both labour and capital damages (right). We started from the baseline configuration and let vary the parameter τ_{CAR} (see the Methods section) to obtain a multiplier $1/\tau_{CAR}$ (i.e. banks allowance to lend) as indicated in the Figure. Then, we sample 100 times the parameters controlling the growth rate of the economy within a $\pm 10\%$ range with respect to the baseline (see Supplementary Information, Section E). For each of such combinations we perform a Monte Carlo exercise of 100 runs. Points in the graphs represent the average yearly cost of bailout in the cluster of runs whose 2100 temperature anomaly falls in the represented interval.

3 Conclusions

The public costs of climate-induced banking instability are found to be significant, corresponding to an yearly average of 30% of GDP in a SSP 5+RCP 8.5 future (against 10.3% in the scenario with no climate change). Such a result should be tentatively compared with an historical average, which were doubtfully affected by climate change, of 3.5 financial crises per year at world level, producing fiscal costs averaging 12% of the GDP of the affected country [Laeven and Valencia, 2012]. Even though it is admittedly difficult to match model results with the reality, the systematic comparison of our impact scenarios with the baseline configuration robustly shows that climate damages affecting the micro-economic behaviour of firms and workers cause a significant amount of additional non-performing loans, threatening solvency of financial institutions. This requires an extraordinary support of the government to absorb losses.

While our findings might tend to overestimate bailout costs because of a baseline with relatively many crises, they also completely neglect (i) any secondary systemic effects of banks' equity deterioration, such that financial institutions exposed towards troubled banks may suffer losses in the market value of their assets, potentially triggering contagion phenomena [Kiyotaki and Moore, 2002, Roukny et al., 2013, Chinazzi and Fagiolo, 2015] (ii) as well as firms' equity holding by banks .[7] A third reason of potential underestimation comes from the missing link between the energy industry and the banking system.

Our results suggest a central role for macro-prudential policies in managing climate-

[7]Recent evidence suggests that secondary effects might be as large as (or even greater) than direct effects of bad debt on bank's balance-sheets [Battiston et al., 2016].

induced financial risks, which might be integrated in a more comprehensive set of adaptation and mitigation interventions. The emerging evidence of a U-shaped relationship between costs of restructuring in the banking sector and its lending propensity points to the existence of an optimal level of capital adequacy requirements, balancing the needs of fueling investments and increasing resilience. Deviations from such policy are found to exacerbate bailout costs as temperatures rise. In sums, the findings of this paper evidence that climate damages reverberate to the financial system, inducing feedback loops that sharpen macroeconomic damages vis-à-vis a system where allocation of capital is assumed to be frictionless. Hence, we suggest that integrated assessment models of climate change [Weyant, 2017] should start including a financial system and financial regulation authorities. Both direct and indirect effects (i.e. linked to contagion phenomena) on the financial system need to be considered, as well as macroprudential regulations mitigating this potential vicious cycle.

4 Methods

The present paper makes use of a novel development of the DSK model [Lamperti et al., 2018a] to evaluate the impacts of climate change on the financial system, intended as a stylized yet realistic banking sector. The DSK model is an agent-based simulation laboratory representing a global economy and its relationship with changes in mean surface temperature. In particular, the model is composed of heterogeneous and interacting firms, devoted to the production of either capital or consumption goods and receiving inputs from an energy sector, a financial system and a variety of households. Firms compete to serve both demand of capital and consumption goods; in case of failure, a novel firm with average characteristics of the firm pool enters the relevant market. Anthropogenic emissions arise from production of goods and, especially, energy, while there is no formal representation of land use and transportation. Cumulative emission are linked to temperature increases through a single equation model calibrated on recent estimates of the carbon-climate response [Matthews et al., 2012]. Economic growth is driven by endogenous technical change, which ameliorates the set of technologies available both to firms and energy plants. The major modelling innovation this paper brings about is the inclusion into the DSK model of a financial system made up of multiple heterogeneous banks. The role of the banking sector has historically shown to be pivotal in modern economies, with both positive and negative effects. Primarily, banks collect deposits from households and provide credit to firms fueling their investments and, hence, spurring economic growth. On the other side, when banks enter financial troubles incurring in equity losses, they freeze funding opportunities for the real economy and slow down productivity growth. In our model, we account for both these two features through imperfect capital markets. The banking sector, based on Dosi et al. [2015], encompasses B commercial banks that gather deposits from households/workers and provide credit to firms, plus a single central bank running monetary policy and buying government bonds when needed. Banks are heterogeneous in their number of clients, balance-sheet structure and lending conditions. Imperfect information prevents firms from screening all existing banks in search for optimal lending rates, the bank-firm networks is assumed to be fixed and reflecting the empirical distribution of bank size. The crucial decision for a financial institution regards the amount of credit to provide to its clients. We assume that the supply of credit is a multiple of a bank's net worth (i.e. equity):

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

where TC indicates total credit supplied by bank b at time t, NW denotes the value of the bank's equity and TA the value of total assets. Credit supply is thus impacted by changes in the banks' balance-sheet, which is itself affected by bank profits net of loan losses. Further, the policy parameter τ_{CAR} indicates capital adequacy requirements, while β is a behavioural parameter measuring banks' sensitivity to financial fragility of their balance-sheet. These two parameters contribute determining the lending ability of a bank to the real economy: on one side, capital adequacy requirements inspired by Basel-framework rules constrain banks' credit supply; on the other side, there is supportive evidence that banks maintain a buffer over the mandatory level of capital, whose magnitude is strategically altered over the business cycle according to their financial fragility [BIS, 1999, Bikker and Metzemakers, 2005], which is proxied by the ratio of "bad debt" (BD, indicating the amount of non-performing loans) and total assets of bank b. Indeed, the larger the stock of bad debt created by insolvent firms in a given period, the higher its financial fragility and the lower the amount of credit a bank will supply to the economy. This is the major link between climate change impacts, banking crises and macro-economic dynamics: if climate damages lead firms to bankruptcy, the loss transmits to the financial system, where banks exposed to defaulted businesses suffer reductions in their equity value. Such an effect provides a feedback to the real economy in terms of lower credit supply and, if large enough, it might also threat the very solvency of banks.[8] In our setup banks do not exchange assets (e.g. overnight loans) and, therefore, contagion effects due to interbank exposure are absent, potentially leading to an underestimation of the true societal costs of climate impacts to the financial sector. Crucially, to estimate the public cost of banks' instability, we assume that insolvent banks are bailed out by the government, which re-capitalizes their equity in the period ahead preventing the default. In particular, the government is providing fresh capital amounting to a fraction of the smallest incumbent equity, provided that it satisfies the Basel type capital adequacy requirements (bank's equity to total loans ratio larger than a given threshold, which equals 8% in our simulations). In such a context, heterogeneity is crucial, as banks with diverse capital structures are differentially vulnerable to (climate-induced) shocks and differentially impact the macro-economy in case of failure [Jimnez et al., 2017], while also possibly triggering bankruptcy cascades. In that respect, our modelling choice allows for a genuine and realistic representation of heterogeneity and interactions amongst ecologies of individuals. Agent based models have been increasingly advocated as adequate tools to study complex and intricate set of relationships, especially in climate change economics [Mercure et al., 2016, Stern, 2016, Balint et al., 2017], macroeconomics [Fagiolo and Roventini, 2017] and finance [Bonabeau, 2002, Farmer and Foley, 2009], where top-down aggregate modelling might hide effects that bottom-up approaches allow disentangling. The model is validated through stylized fact replication both at micro-economic level (firm size distribution, heterogeneity in productivity, lumpy investment behaviour,...) and at macro-economic one (persistent fluctuations in output, identification of cyclical, leading and lagging indicators, distribution of banking crises,...). A detailed description of the

[8] The fact that the amount of capital lent to firms shrinks during downturns and financial crises, eventually leading to credit crunches, is a well established empirical regularity, and the recent financial crisis was not an exception [Bernanke, 1983, Lown and Morgan, 2006, Jimnez et al., 2017]. However, we remark other channels leading to financial instability might exist [Campiglio et al., 2018].

stylized facts replicated by the model is contained in Supplementary Information (Section D), while the model itself is fully described in Section B of Supplementary Information.

The model does not allow for analytical, closed-form solutions. This stems from the non-linearities that characterize agents' decision rules and their interaction patterns, and forces to run computer simulations to analyze the properties of the stochastic processes governing the co-evolution of micro- and macro-variables.[9] In what follows, we therefore perform Monte-Carlo analyses to wash away across-simulation variability and present results as averages over 500 model runs, as standard in the literature.

The DSK model is calibrated on a coupled SSP 5-RCP 8.5 scenario [van Vuuren et al., 2014] characterized by high growth [O'Neill et al., 2014], sustained energy demand [Riahi et al., 2017] and soaring emission concentrations until the end of the century [Riahi et al., 2011]. The choice of such a scenario is justified by two reasons. On the one side, the willingness to isolate the effects of climate-induced financial instability in a context where climate change bites and damages are substantial, in a way to evaluate the aggregate effects of mechanisms (default chains) that might be opaque under milder conditions. On the other, we deliberately target a worst-case scenario with the aim of characterizing the financial costs of inaction, i.e. providing a first estimate of the public costs of banking fragility associated to climate change under business as usual. The economy-climate linkage is voluntarily simple and makes use of the well documented approximately linear relationship translating cumulative emissions in temperature increases [Matthews et al., 2009, Allen et al., 2009], with the preferred specification assuming global mean surface temperature to rise by 1.8 degrees Celsius for each emitted 1000 GtC [Matthews et al., 2012]. Economic losses due to temperature changes are modelled at the level of firms, which might suffer damages either to their labour or capital production factors [Dietz et al., 2016], while the average climate-induced shock follows the quadratic damage function employed in the DICE 2016R model [Nordhaus, 2017]:

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

where T indicates the mean surface temperature anomaly and $c_1 = 0$, $c_2 = 0.0022$. Such a configuration implies a 0.236% loss per degree Celsius squared; this leads to a damage of 2.1% at +3 °C, and 8.5% at a global temperature rise of 6 °C. The relevant difference with respect to the standard use of such damage functions [e.g. Nordhaus, 1992, 2014] and, Nordhaus [2017] particularly, is that we do not assume $\Omega(t)$ to affect the global output (i.e. GDP). Rather, employing a model with multiple agents instead of an aggregate economic sector, we consider microeconomic damages, $D_i(t) = \Omega(t) + \epsilon_i$ with $\epsilon_i \approx$ i.i.d. $\mathrm{N}(0, 0.01)$, hitting each firm. To exemplify, in a scenario where climate change only affects capital stocks [e.g. Dietz et al., 2016], each firm receives - on average - a loss of capital amounting to 0.236% for each °C of temperature increase. The term ϵ_i is used to capture the fact that different firms (e.g. at different locations) tend to suffer a different damage [Hsiang et al., 2017, Ricke et al., 2018].

Then, we design three impact scenarios: (i) climate damages target the productivity of labour, (ii) climate damages target the availability of physical capital and (iii) climate damages target both labour productivity and capital stock, with the relative impact weighted according to global labour and capital shares of GDP [Dietz et al., 2016]. To the contrary, the baseline configuration of the model runs in absence of climate change and, hence, climate damages. The only difference between the baseline and the three impact scenarios is the presence of

[9] For more information about macroeconomic agent-based models, see Fagiolo and Roventini [2017]. Balint et al. [2017] provides a survey of complexity models in climate change economics.

climate change. Supplementary Information (Section D) offers additional details on the calibration procedure and scenario design. Additionally, to isolate the effect of climate-induced financial distress on the real economy we run a counter-factual numerical experiment (Figure 3, bottom panel) where we assume that the government exchange the non-performing loans created by firms' bankruptcies with liquidity to impede a deterioration of banks' net worth (equities). The simulation data that support the findings of this study and the code for the analysis are available from the corresponding author upon reasonable request. The data used to produce Figure 1 are publicly available Laeven and Valencia [2012].

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Authors' contributions

All authors have contributed to the design of the simulation experiments, to the analysis of the results and to the writing of the paper. FL has also run all the simulations.

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