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Climate-Induced Economic Damages Can Lead to Private-Debt Tipping Points

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Abstract

Designing climate change policies requires considering the feedback loops between mitigation and adaptation, since more mitigation efforts today will trigger lower adaptation costs. In this framework, carbon taxes are often seen as promising tools but at the risk of financially overburdening the private sector, depriving it of important economic resources. However, analyzing the financial feasibility of mitigation-adaptation policies using conventional Integrated Assessment Models (IAM) is limited, as they do not simultaneously endogenize economic growth, emissions, and damages. Here, we present IDEE (Integrated Dynamic Environment-Economic), a new IAM based on the coupling of an Earth Model of Intermediate Complexity and a non-linear macroeconomic model in continuous time. Then, we analyze the simultaneous effects of carbon taxes and public spending, both on climate and on the world economy. We show that, above a warming about $+2.3^{\circ}\text{C}$, damages drastically foster the need for additional investments in productive capital—an adaptation necessity—that potentially leads private firms to a debt overhang and a worldwide cascade of defaults. This suggests that the Paris Agreement target should not only be motivated by the climatic non-linearities and tipping points arising beyond the $+2^{\circ}\text{C}$ threshold, but also by the emergence of private-debt tipping points. We also show that, provided public subsidies are high enough, a tax of USD 300 per tCO_2 by 2030 enables reaching net-zero emissions in 2050, preventing firms from suffering global bankruptcy. We anticipate IDEE to be a starting point for a new class of IAMs that better represent the reciprocal feedback loops between the environment and the economy.

Keywords: environmental impact, transition risk, debt burden, climate policy, integrated assessment, macroeconomic dynamics, stock-flow consistency

1 Introduction

For the first time in history, the 196 countries gathered at Sharm el-Sheikh (Egypt) for the COP27 agreed to create a financial fund by 2023 to fight against “loss and damage,” i.e., irreversible damage caused by extreme weather events induced by climate change. This decision was fortunately materialized on the first day of COP28 in Dubai with a commitment of 400 million dollars, demonstrating that decision-makers are increasingly focused on the long term. However how much money should finally go into this fund? And who should pay?

Contrary to the physical and biophysical consequences of global warming that are well documented^[1, 2], its effects on the world economy are much less well understood, modeled, and simulated^[2, 3]. However, it is widely acknowledged that the financial stake of the cost of mitigation and adaptation is substantial: according to Markandy et al. (2018)^[4], economic losses and damages could reach USD₍₂₀₁₈₎ 580 billion per year by 2030 at the world level. On the other hand, the 2018 New Climate Economy Report^[5] estimates that USD₍₂₀₁₈₎ 90 trillion will be needed up to 2035 to fund clean infrastructures that would make it possible to reach net-zero emissions before 2070.

However, if the private sector continues for too long to rely on highly greenhouse gas-emitting infrastructures, does it not risk finding itself trapped between the significant costs of climate damages on one hand and the urgent need to “green” its capital on the other, all of this in a context of high indebtedness? Is the global economy able to bear such an additional private and public debt burden? Alluding to the market downturn preceding a crash highlighted by Minsky^[6], the Bank of England governor, Mark Carney put it as follows,^[7]

“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.”

We address these questions by designing a new integrated model resulting from the coupling of a Stock-Flow-Consistent (SFC)^[8], continuous-time macroeconomic dynamics^[9–11] with an Earth Model of Intermediate Complexity (EMIC),

LOVECLIM^[12]. The latter includes a physical representation of the atmosphere, ocean, sea-ice, and vegetation. The resulting model, called IDEE (Integrated Dynamic Environment-Economy), allows researchers to study the interplay between the non-linear, out-of-equilibrium dynamics of wages, underemployment, debts, collateral and default, together with a spatialized climate model. This article can be viewed as the display of such a dynamical coupling, illustrated by means of prospective scenarios about one of the most challenging imperatives currently faced by the world economy, that of funding a worldwide mitigation policy compatible with a sustainable adaptation strategy.

On the economic side, our starting point is the Lokta-Volterra dynamics first introduced in economics by Goodwin, Akerlof, and Stiglitz^[13–15], and later extended with corporate debt^[16]. In this framework, employment is the prey, and wages play the predatory role. As a result, solution paths exhibit endogenous business cycles, defined as alternations of economic phases of expansion and contraction, with multiple asymptotic steady states. In accordance with empirical data, we show that private debt matters^[17], and the share of wages within total output is endogenously time-varying^[18].

Evaluating the stress induced by climate risks on the financial system is crucial^[19]; see, e.g., a framework to couple IAMs with financial risk models in Battiston et al. (2021)^[20]. In our model, the financial sphere is modeled in a stylized manner since we only consider private firms’ debt and we do not incorporate any agent’s anticipation of climate policies, as done in the SFC model proposed in Dunz et al. (2021)^[21]. Nevertheless, our key result does not rely on the nitty-gritty of firm’s financing procedures (on the secondary financial markets, via capital increase or the banking system): it shows that, whatever being these procedures, the need to finance additional investment due to climate damages has a huge impact on the world economy.

Based on econometric tests, especially when back-tested on the U.S. economy over the past seven decades^[22], this simple non-linear dynamics has demonstrated its robustness as a foundational framework for advanced models that capture endogenous growth cycles^[23].

When coupled with \mathcal{I} LOVECLIM, economic growth is endogenously determined by the interplay between the bio- and the anthropospheres. In particular, economic and financial crisis cannot be excluded *ex hypothesi*. As a result, our computed temperature anomalies are broadly in line with IPCC’s WG I^[1]; and our assessment of climate is consistent with those reported by WG II^[2]. Moreover, our sustainability bifurcation scenarios are in agreement with WG III^[24], but add to the latter the economic downside of following the “business as usual” scenario, induced by the costs of mitigation and adaptation. Apart from the simultaneous endogenization of economic growth and climate, our out-of-equilibrium dynamics depart from more conventional IAMs insofar as we do not assume that households or firms have perfect foresight, nor that they solve inter-temporal expected benefit optimization programs to make decisions while having access to perfectly competitive markets^[25]. Rather, we assume that economic actors have imperfect foresight, unable to systematically make the best rational decisions ([Supplementary information](#)).

A first coupling analogous to the one introduced here was proposed by Bovari et al. (2018)^[9–11] with the climate feedback loop borrowed from the DICE model^[26]. Note that updated versions of the DICE model have been regularly proposed since. For example, in Hansel et al. (2020)^[27], the simple climate model is calibrated to replicate the temperature trajectories of the IPCC models. However, the model used relies solely on temperature and does not allow to incorporate other climate-related risks. Here, we address what the critics have formulated to the DICE’s simple back loop^[28] by replacing it with a comprehensive climate model (\mathcal{I} LOVECLIM). In addition, we add a few crucial novel ingredients such as endogenous technical progress, collateral and bankruptcy ([Methods](#)). As emphasized by Stern et al. (2022)^[29], the first two features have been largely ignored by older IAMs. The third point deserves comments.

Whenever current profits no longer suffice to finance corporate investment, firms borrow from the banking sector or financial markets. However, as with much lending in modern economies, corporate debt is secured by collateral, for which, here, we use as a proxy the current stock of capital, K , valued at its market price, p . A similar design has

been applied in the literature devoted to general equilibrium effects of financial instability^[30, 31]. As a consequence, aggregate corporate debt can never exceed pK —defining a kind of endogenous bankruptcy threshold. Indeed, whenever the face value of aggregate nominal debt exceeds the value of its aggregate collateral, it is certain that a cascade of bankruptcies will follow (see model details in [Supplementary information](#)).

2 IDEE: a dynamic coupling

The dynamic coupling between Earth’s climate and the world economy works as follows. Each year, \mathcal{I} LOVECLIM computes the yearly mean state of Earth’s climate, for a given level of atmospheric greenhouse gas (GHG) concentration. This climate state may induce economic damages in the world economy in terms of production, capital and growth effects. Consequently, not only is total production reduced because of the consequences of global warming, but installed capital is itself damaged, affecting future production potential.

In our economic model, the public sector, however, can impose a carbon tax in order to reward the firm’s mitigation efforts. It can also provide subsidies to virtuous companies using additional public expenditures. At the same time, the private sector can engage in both abatement and repairing activities in order to replace “dirty” and worn-out infrastructure with “clean” ones. Both types of investments for mitigation and adaptation pile up, and may require those firms whose current profit cannot absorb these additional costs to go into debt. This will increase the burden of corporate debt servicing, at a short-run interest rate assumed to be endogenously adjusted by some Central Bank according to inflation. At the same time, labor demand being dwindling because of the climate-driven output gap, households accrue less labor income; a more acute tension on the labor market may lead to money wage depression.

The resulting interaction between these various factors releases new GHG emissions, added to the atmosphere of \mathcal{I} LOVECLIM, and eventually leading to a new climatic state. Consequently, estimating the economic damages inflicted by climate change on global output and installed capital is crucial for IDEE’s dynamics.

Despite the difficulty of such estimations^[2, 3, 32, 33], the impact of climate on

an economy is usually quantified by damage functions^[26, 28, 34] which compile a wide range of events: biodiversity loss, ocean acidification, sea-level rise, ocean-circulation changes, glacier melting, growing scarcity of freshwater, droughts, and other extreme climatic events^[28, 34, 35].

Many estimation studies do not account for catastrophic events, abrupt changes, or irreversible processes such as the occurrence of tipping points^[1, 2]. Work attempting to incorporate these issues shows that their economic impact can be significant^[36–39]. Here, for simplicity, we focus only on two damage functions that depend solely upon the average global temperature. The most optimistic one (O) assesses that a $+6^{\circ}\text{C}$ temperature anomaly would lead to a 10% loss of the world real GDP^[26]. By contrast, the most pessimistic function (P) implies a loss of 50% of the world’s real output for a global warming around $+4^{\circ}\text{C}$ ^[28] (and 90% for $+6^{\circ}\text{C}$).

These damage functions were proposed about a decade ago and have been widely criticized and updated (see, e.g., the function proposed in Howard and Sterner (2017)^[40] and used with DICE^[27], which lies between O and P). For instance, the calculation of damages requires a discount factor but the scientific justification for this factor remains challenging^[41]. Damage functions rely on GDP, a disputed metric for addressing the mitigation and adaptation challenges of future societies^[42], and the used here are global and do not represent regional variabilities. However, these damage functions are still in use today and allow for the embedding of the economy into its biophysical environment, paying attention to the additional costs associated with global warming^[3], rather than considering the economy as a stand-alone system.

Our contention in considering only these two extreme damage functions here is that more realistic ones will most probably be located somewhere in between. Our results can therefore be viewed as a sensitivity analysis with respect to the choice of a damage function, based on two extreme points.

3 Notion of a private-debt tipping point

To quantify the effect of global warming on the world economy, we first run our model with the

climate change effect—i.e., with climate-induced economic damages—and compare the outcome with a reference scenario where damages are not taken into account. Note that we do not consider any carbon policy at this stage.

In the absence of climate change effects, and provided the world economy follows a business-as-usual path, its trajectory is given by the green curves in Fig. 1. Until 2100, the GHG emissions (in CO_2e) induced by this damage-free scenario evolve slightly below that of the SSPs 4-6.0^[43] (Fig. 1(a)) – a reasonable baseline narrative given current emission trends^[24]. It leads to a temperature anomaly of about $+3.5^{\circ}\text{C}$ in 2100 (Fig. 1(c)), with nearly a fourfold increase of the world real GDP in comparison with 2015 (Fig. 1(g)). The employment rate (resp. the labor wage share) remains stable (Fig. 1(d)), cycling between 70% and 75% (resp. 55% and 65%). The private debt-to-capital ratio starts at about 50% in 2015 and caps out below 70% throughout (Fig. 1(e)). Annual inflation (Fig. 1(h)) safely oscillates between $+1\%$ and $+5\%$, while the short-run interest rate never exceeds 6% (Fig. 1(i)).

Introducing economic damages drastically changes the picture, depending upon the damage function considered: the optimistic blue (O damages) and the pessimistic red (P damages) curves in Fig. 1 respectively. With O damages, the world output (here also GDP or world production) almost quadruples by 2090 in comparison with 2015 (Fig. 1(g)). The temperature anomaly is close to $+3.25^{\circ}\text{C}$ (Fig. 1(c)), and GDP (resp. capital) losses are below -2% (resp. -1%) (Fig. 1(b)), but the output gap between this blue trajectory and the green damage-free one is about -14% (Fig. 1(g)). By way of comparison, it was of -3.1% in 2020 because of the COVID pandemic^[44]. And yet the last decade of this century is the period when economic outputs start to irreversibly drop out from the damage-free scenario: real growth, employment rate, wage share, inflation, interest rate, emissions. At the turn of the century, real GDP stagnates and, eventually, experiences forced degrowth around 2140 (Fig. 1(g)). Strikingly enough, direct output (resp. capital) losses are then just evolving in about -2.5% (resp. -1%) (Fig. 1(b)). By comparison, we find these losses to represent 0.3% of world GDP in 2030, in line with Markandya et al. (2018)^[4]. Therefore, an apparently mild level of direct losses may suffice to

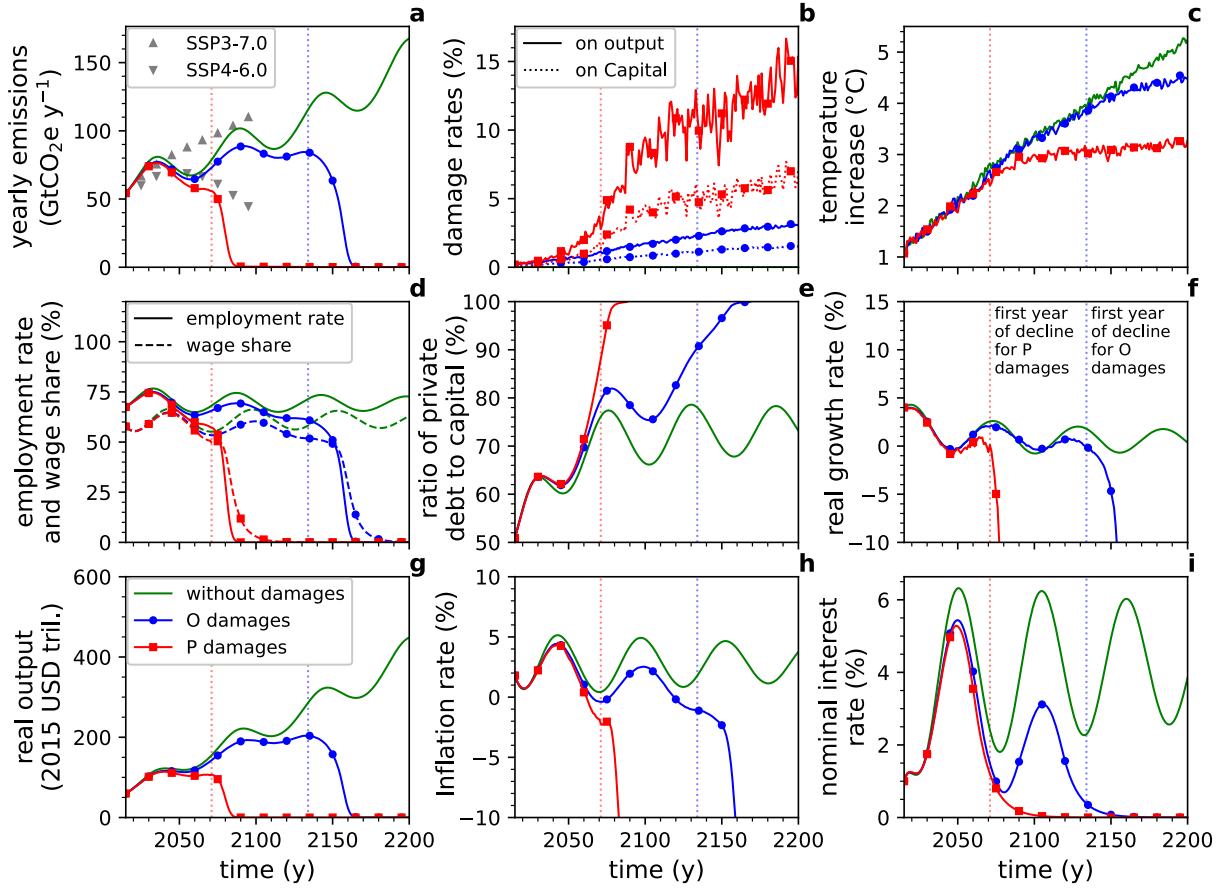


Fig. 1 Business-as-usual scenarios with and without climate-induced economic damages. The green curves correspond to our damage-free business-as-usual scenario. The blue (resp. red) scenario is with the optimistic (o) (resp. pessimistic (p)) damage function. The vertical dotted lines give the years corresponding to the private-debt tipping points: 2068 for P-like damages (red dotted lines) and 2134 for O damages (blue dotted lines).

trigger economic contraction. Eventually, the year where private debt reaches its maximum, signaling a worldwide cascade of defaults in the private sector, is attained in about 2160, at a time when all variables are already plummeting.

The P damages lead to a qualitatively analogous pattern with 80 years in advance: A doubling of GDP until the end of the 2020s is followed by a plateau and, eventually, forced degrowth in the last quarter of the 21st century (Fig. 1(g)). Employment starts to decline in 2040 (Fig. 1(d)). Inflation becomes negative in about 2060 (Fig. 1(h)), and the short-run interest rate quickly shrinks to its zero floor (Fig. 1(i)). As output begins to dwindle, there is a massive shift of income from wages to profit: in 2090, the profit share reaches approximately 75% since the wage share is only about 25% (Fig. 1(d)). This loss of

bargaining power from the hands of employees who struggle to find a job, however, does not succeed in alleviating the debt burden of firms. Corporate debts reach their collateral ceiling in about 2080, accompanied by massive defaults and plummeting employment (Fig. 1(e)). Note that for both types of economic damage, the decrease in economic activities implies a free fall of GHG emissions. For P damages, the free fall of GHG emissions after 2080 (Fig. 1(a)) leads to a temperature anomaly culminating at about $+3^{\circ}\text{C}$ in 2100, inducing “only” a $\sim 15\%$ (resp. 5%) loss of real GDP (resp. capital) at the end of the century (Fig. 1(b)).

These findings contrast with a stream of the economic literature which tends to conclude that “societal optimisation” entails accepting an increase in temperature of around $+3.5^{\circ}\text{C}$ to

+4°C^[45]. The main difference between the previous approach and ours is that we explicitly model the corporate debt dynamics, and we do not assume perfect foresight. Indeed, rational expectations would enable firms to realize that they are financing too many high-emission GHG infrastructures that continuously exacerbates the pressure of climate damages. They would then commit earlier to transiting towards carbon-neutral technologies. Here, there is no intertemporal optimization of welfare, as agents envisage the future based on current observations. Consequently, even a minor loss of output directly induced by global warming may provoke a catastrophic outcome in the long-run because of the inability of the corporate sector to cope with the resulting burden of debt—at least absent any public support—and the need to simultaneously repair their infrastructures. Thus, it is the interplay between the costs of mitigation and adaptation which turns the debt dynamics into the key variable of our prospective projections.

From a dynamical system viewpoint, the economy converges in the long run to two possible equilibrium points: the first corresponding to an economic disaster, the other to a stabilized economy (see details in Section 8.4 of [Methods](#) and Figs. 4 and 5 in [Extended data](#)). As already pointed out in a simpler setting by Bovari et al. (2018)^[9], the phenomenon underpinning these results is the following: global warming pulls the state of the economy away from a “desirable” long-run equilibrium, with business cycles and a functioning economy, toward a catastrophic debt-deflationary long-run steady state (see [Methods](#) and [Supplementary information](#)). This geometric insight suggests the definition of a “financial threshold” as being the combination of macroeconomic characteristics such that, when crossed, the economy is irremediably trapped on a trajectory toward this catastrophic long-run equilibrium. On one hand, the need to repair damages caused by global warming incentivizes firms to invest more. This additional cost can only be financed either by taking on more debt or by raising consumption prices. In both cases, however, an upper-bound is given by the households’ ability to save money. Indeed, SFC imposes that firms’ debt be equal to households’ saving. Therefore, to restore households’ saving, inflation must be compensated by a raise in workers’ wages, adding even more pressure on firms’ production costs. In the following,

we call this threshold the private-debt tipping point (see computation details in [Methods](#)). In the dynamics of our model, it is the frontier beyond which, absent public intervention, the world corporate sector will enter a recessive debt-spiral ultimately leading to a cascade of defaults.

Note that this is a global private-debt tipping point. Thus, for damages reasonably within the range of the two damage functions, it necessarily implies that a significant portion of the global economy will reach its own local tipping point in the preceding decades. By analogy, the world conventional peak oil has been reached around 2008, but the U.S. had already crossed their own conventional peak of extraction in 1970^[46].

The private-debt tipping point is given by the vertical dotted lines in Fig. 1. It is crossed in about 2134 for the O scenario, and in 2068 for the P scenario. The corresponding temperature anomaly is respectively +3.8°C (Fig. 1(i)) in the O trajectory, and +2.3°C (Fig. 1(i)) in the P scenario.

In the Paris Agreement of 2015, there is a commitment (Article 2) to limit warming to “well below +2°C above preindustrial levels.” The usual rationale for this international commitment is the presence of strong non-linearities in climatic phenomena beyond the +2°C threshold, potentially leading to extreme climate risks^[47]. Our results suggest a new type of justification: the presence of private-debt tipping points not far away from the +2°C cap. Indeed, these private-debt tipping point will most probably be lower than +3.8°C. And it might be as close as +2.3°C, if we were to discover that climatic tipping points (e.g., massive deforestation of the Amazon rainforest, permafrost thawing, ice-sheet melting^[47]) force us to revise upward the severity of the O damage function.

4 Temperatures of potential decline

Among the climate effects already mentioned, Mora et al. (2017)^[48] showed that high temperature and humidity combinations—named “deadly heatwaves”—may exceed human thermoregulatory capacity. Empirical data suggest the existence of a *lethal temperature threshold*^[48], which depends on relative humidity. Clearly, the increase in lethal heatwaves intensity and duration will

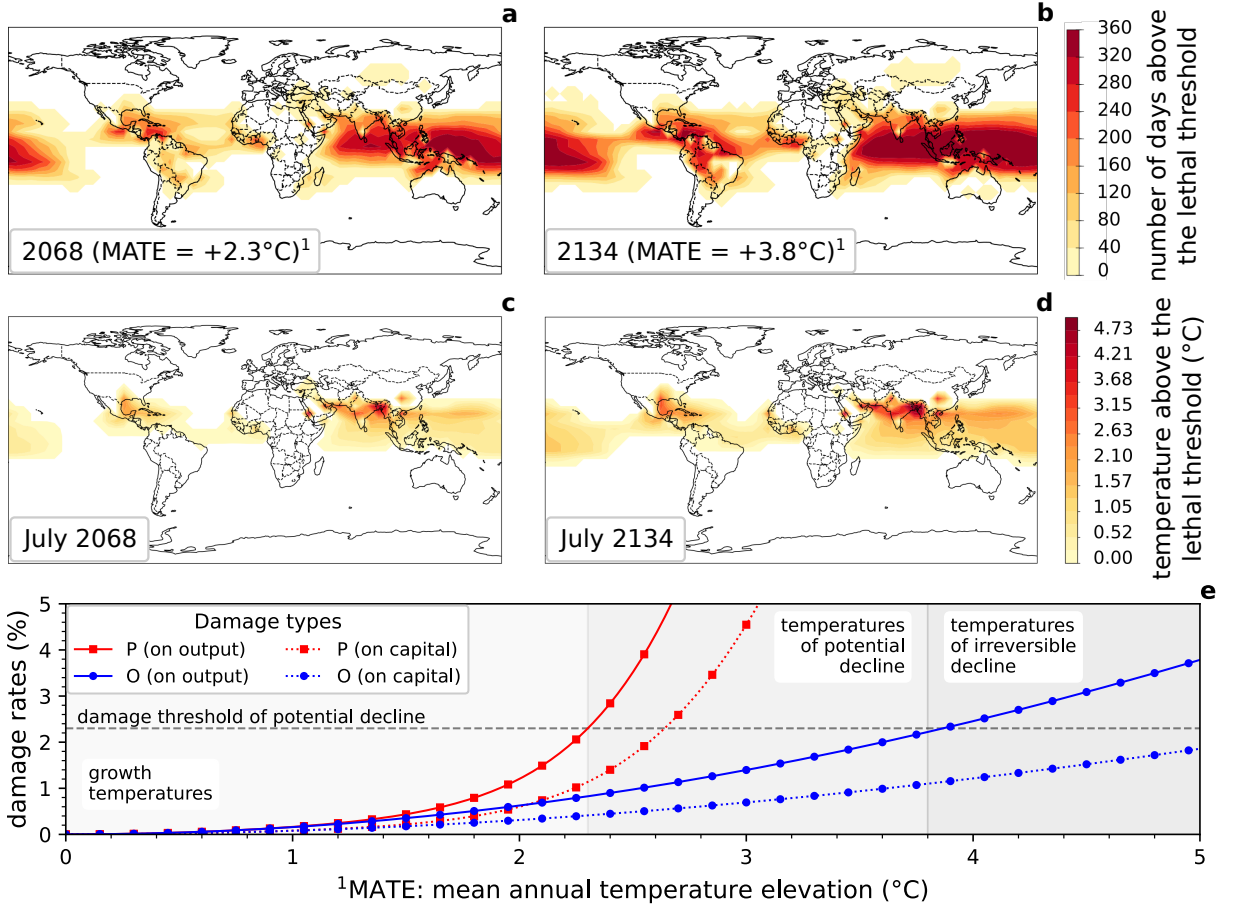


Fig. 2 Deadly heatwaves and damage functions. **a,b** Maps represent the number of days spent above the lethal threshold as defined by Mora et al. (2017)^[48] in 2068 and 2134, which correspond to the years of the private-debt tipping points for the red and green trajectories of Fig. 1. **c,d** Maps represent the average relative surface air temperature above the lethal threshold for July of the same previous years. **e** The optimistic (O) and the pessimistic (P) damage functions depending on the annual mean global surface air temperature anomaly, computed considering a reference period defined from 1850 to 1900.

strongly affect populations. Since relative humidity and surface air temperature are endogenous dynamical variables in IDEE, it is possible to map the frequency with which the lethal threshold might be exceeded in the next decades.

In Figs. 2(a)-(d), the climatic conditions computed by IDEE are shown for the year 2068 (reps. 2134), corresponding to the private-debt tipping point with P (reps. O) damages for a mean annual temperature elevation (MATE) of about +2.3°C (reps. +3.8°C). They highlight frequent (Figs. 2(a,b)) and intense (Figs. 2(c,d)) deadly heatwave events, especially around the tropical belt. Our maps (see computation details in [Methods](#)) are in line with previous studies^[48–50].

Dramatic living conditions are observed in several highly populated regions, like India and the archipelago of Southeast Asia: some of these regions are exposed to atmospheric conditions above the lethal threshold during an average of 200 days per annum (Figs. 2(a,b)), and exhibit a mean temperature increase about +3.15°C above the lethal threshold during summer by 2068 (Figs. 2(c,d)). Moreover, leading economies are also concerned, though to a lesser degree, like the USA (80 days in the Southeast (Fig. 2(b)) with temperature +2.10°C above the lethal threshold (Fig. 2(d)), China (80 days in the South (Fig. 2(b)) with an average of +1.57°C above the threshold (Fig. 2(d)).

When these types of damage are sufficiently high, our simulations suggest that the economy systematically reaches a private-debt tipping point. We call this endogenously determined level of damages the *damage threshold of potential decline* (see [Methods](#)). It is represented by the horizontal dashed black line in Fig. 2(e). Together with the effects already mentioned, Fig. 2 leads us to pay attention to the set of MATE from $+2.3^{\circ}\text{C}$ to 3.8°C that we call temperatures of potential decline ([Methods](#)). To maintain a sustainable trajectory, both for the environment and the world economy, GHG emissions must therefore be reduced to maintain global warming below the $+2.3^{\circ}\text{C}$ ceiling—which strengthens the Paris Agreements^[51]. Otherwise, as the MATE enters the area of temperatures of potential decline, it means that, depending upon the severity of damages, the MATE may overreach the damage threshold of potential decline. In which case, the private sector would presumably reach its private-debt tipping point (Fig. 1). Of course, each step of this narrative is surrounded by uncertainties that we have carefully pinpointed. The bottom line, however, is that running the risk that the MATE rises into the temperatures of potential decline is a bet on the severity of future climate damages. If the latter turn out to be harsh enough, the world private sector would then be inescapably led to bankruptcy.

5 The key role of public subsidies

To limit global warming below the temperatures of potential decline, companies must move from high-emitting capital to carbon-neutral infrastructures. This low-carbon transition will be complete when the GHG emissions balance is net-zero. To stay below the threshold of $+1.5^{\circ}\text{C}$, the IPCC recommendations expect a drop of about -43% in 2030 and -84% in 2050^[24]. Many studies have argued that public interventions should focus on getting the price of carbon emissions correct, and plead for a price (reflecting the “social cost of carbon”) around USD₍₂₀₀₇₎ 50 per tCO₂e by 2030 (assuming a 3% discount rate)^[52].

We now consider a dynamic price of carbon in IDEE, and assume that tax receipts are used by the public sector to support households. Beyond

providing incentives for firms to go green, the carbon tax therefore amounts to transferring part of corporate profits to households^[53].

The idealized narrative of the low-carbon transition in IDEE follows the strategy proposed by Bovari et al. (2020)^[11, 25] (see details in [Supplementary information](#)). Given the carbon price set by public authorities (Fig. 3(a)), firms face a trade-off between paying a carbon tax (Fig. 3(f)), proportional to their emissions (Figs. 3(c,d)), and affording the cost of “greening” their production technology. This decarbonization effort made by firms is measured by the abatement rate (Fig. 3(e)), that is, the fraction of productive capacity that is temporarily diverted from production to perform abatement activities. The higher the abatement rate, the faster the transition occurs. As for the public sector, it is involved in the sustainability transition via public subsidies targeting the private sector. The dynamic carbon price curves we consider exhibit two phases: first, they increase up to the price of the cheapest green technology (exogenously given); then they decline at the same speed of the best-in-class green technology. As a result, our carbon price trajectories are in good agreement with previous studies^[54, 55].

Note that because the public sector is not considered productive here, it can only give support through public subsidies. These latter lead to a decrease of the burden on the private sector; especially, they increase the abatement rate (Fig. 3(e)), allowing it to reach 10% of GDP, twice the maximum of those computed by previous studies^[53]. The high level of public subsidies found here (Section 6) may motivate the study of nationalizations of strategic sectors. We leave this question to future research.

The trajectories obtained by IDEE highlight the key role of public subsidies in supporting the low-carbon transition of the private sector. Indeed, our simulations show that if these public subsidies remain relatively “low,” i.e., do not exceed 35% of the abatement cost (blue curves in Fig. 3), the private-debt tipping point is systematically reached before 2100, for both damage functions (Figs. 3(i)-(n))). It means that if the transition costs are mainly shifted on the private sector while the public sector is weakly involved, then the private-debt tipping point is reached sooner than in business-as-usual scenarios. This result highlights the crucial role that must be played by

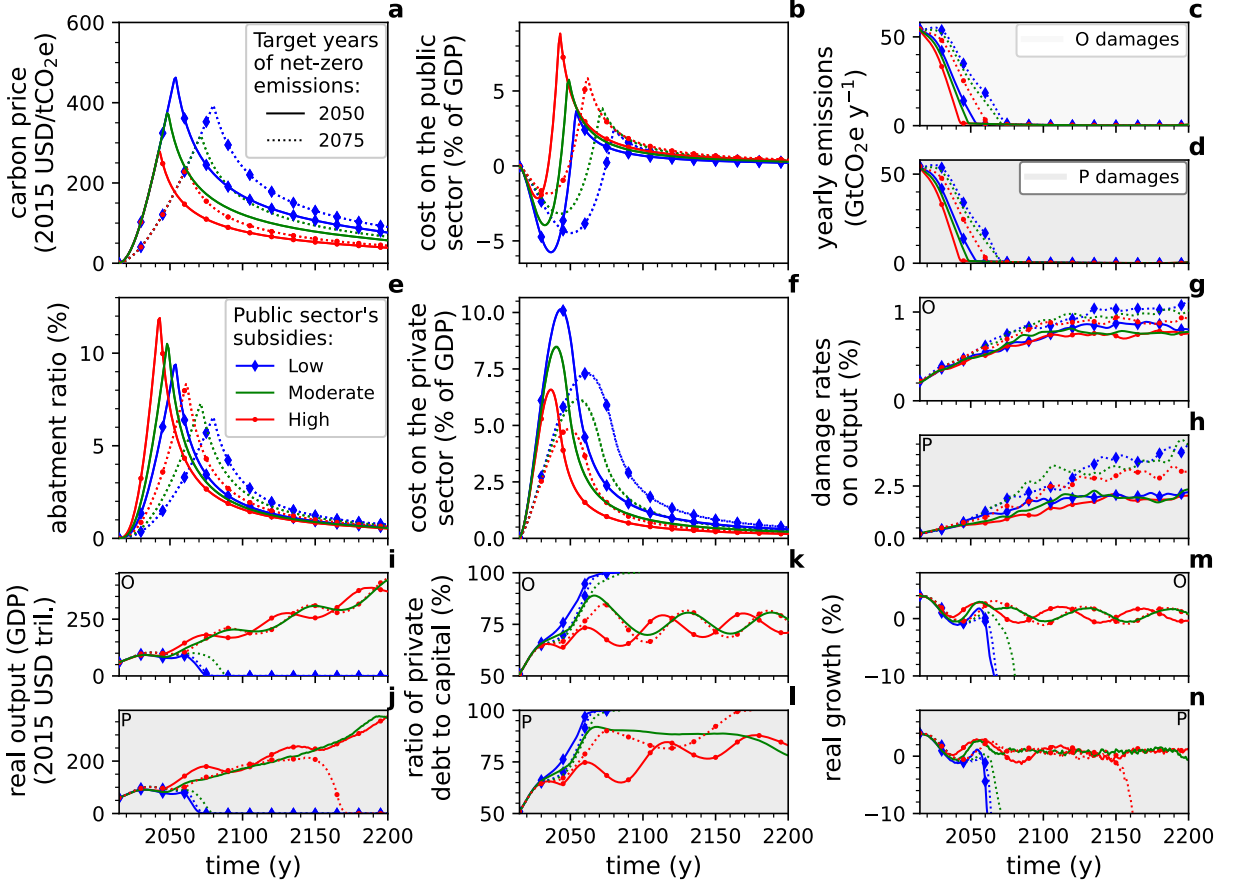


Fig. 3 Time evolution of the main IDEE's variables with different levels of public policy. The solid (resp. dashed) curves correspond to two types of carbon prices aiming at net-zero emissions before the year 2050 (resp. 2075). The blue, green, and red curves correspond to the three levels of public sector involvement: 35%, 50%, and 65%, respectively, of abatement costs. The trajectories on blue **c,g,i,k,m** (resp. red **d,h,j,l,n**) backgrounds have been computed with the optimistic (O) (resp. pessimistic (P)) damage function.

the public sector to complete the green transition. By contrast, if public subsidies are high (65% of the abatement cost, green curves in Fig. 3), then the private-debt tipping point is avoided in most cases. One exception is as follows: with pessimistic types of damage and high public subsidies, the path which enables to reach net carbon neutrality by 2062 eventually crosses the private-debt tipping point in about 2170 (dashed red line in Fig. 3(j)).

Note that we do not consider that the public sector already subsidizes fossil fuel activities to a large extent, and it would be necessary to consider both the subsidies of green activities as we propose here, and also the end of fossil fuel subsidies. SFC models have recently shown that a gradual phase-out of the latter contributes to improving macroeconomic performance, reducing

inequalities, and helps the public sector find fiscal space to support stable green policies^[56, 57]. Our results suggest that the low-carbon transition cannot be handled only by the private sector. Furthermore, they strongly support advocacy for active public aid to the mitigation efforts of firms, echoing, e.g., the New Climate Economy Report, which recommends tripling public investment^[5].

6 To speed or not to speed?

In his 1991 article^[58], Nordhaus asked the question: “To slow or not to slow?” Our results unambiguously suggest the following answer: the quicker, the less costly, confirming the viewpoint defended by Stern (2015)^[28].

Table 1 shows the transition costs in the different scenarios already illustrated in Fig. 3. The

Table 1 Costs of the transition (USD₍₂₀₁₅₎ trillion). The scenarios depend on two damage functions (the optimistic (O): three columns on the left; and the pessimistic (P): three columns on the right). There are three levels of public subsidies (35% (low), 50% (moderate), and 65% (high)), and two target years to reach net-zero emissions: 2050 (first block above) and 2075 (second block below). The year t_{green} is when net-zero emissions objective is reached. The year $t_{A \leq 2\%}$ is when the abatement ratio drops below 2% of GDP after the transition. Costs without (resp. in) parentheses are the cumulative costs computed from 2015 to t_{green} (resp. $t_{A \leq 2\%}$). Cumulative costs to $t_{A \leq 2\%}$ are represented when the state in 2200 is growth (and not irreversible decline).

Public subsidies	O damages			P damages		
	Low	Moderate	High	Low	Moderate	High
Target year of transition: 2050						
In 2100: t_{green}^1 ($t_{A \leq 2\%}$) ²	decline 2054 (2097)	growth 2048 (2093)	growth 2043 (2088)	decline 2054 (2097)	growth 2048 (2093)	growth 2043 (2088)
Total	117	110 (373)	115 (394)	114	108 (341)	114 (387)
On public	-97	-45 (87)	13 (193)	-96	-44 (72)	12 (190)
On firms	214	155 (287)	103 (200)	211	153 (269)	102 (197)
Carbon tax	138	100 (100)	63 (63)	136	99 (99)	62 (62)
Output loss	13	11 (55)	8 (48)	18	14 (77)	11 (72)
Capital loss	20	16 (82)	13 (72)	27	21 (115)	17 (107)
Target year of transition: 2075						
In 2100: t_{green}^1 ($t_{A \leq 2\%}$) ²	decline 2080 (2119)	decline 2068 (2112)	growth 2061 (2104)	decline 2080 (2119)	decline 2068 (2112)	decline 2061 (2104)
Total	92	146	141 (427)	71	129	136
On public	-152	-76	-4 (181)	-141	-78	-5
On firms	244	222	145 (245)	212	207	141
Carbon tax	184	149	96 (96)	166	143	94
Output loss	25	26	20 (81)	36	42	29
Capital loss	38	39	30 (122)	54	62	43

^aThe year when net-zero emissions objective is reached.

^bThe year when the abatement drops below 2% of GDP after the transition.

amounts do not differ much between the two damage functions (compare the left three columns with the right ones), but it is naturally more challenging to make a successful transition with the P damage function.

We now focus on the case of the optimistic (O) damages. Table 1 shows that the later the transition, the more expensive it is (compare the two scenarios with high public subsidies that differ only in the target year of transition, 2050 vs. 2075). Indeed, regardless of the nature of the companies' activities, the later the transition, the costlier the amount of capital that needs to be "greened." However, the burden of firms' debt limits the speed at which this infrastructure can be modified. The private sector finds itself trapped between climate damages on one hand and the cost of the transition on the other, in a progressively narrowing ridge line over time. In

other words, a late transition forces the economy to accumulate the direct costs induced by global warming and the mitigation costs (compare the output and capital losses between these scenarios).

However, as already seen for the dotted red trajectory in Fig. 3, acting quickly but with insufficient public subsidies challenges the financial sustainability of the private sector (compare the "low," "moderate," and "high" columns). This financial stress may be too intense for companies to handle. For example, the top left scenario in Table 1 reaches the private-debt tipping point because of the excessive burden carried by the private sector: the total mitigation-adaptation bill is indeed close to USD₍₂₀₁₅₎ 214 tril., whereas public finances improve thanks to the revenues from the carbon tax: USD₍₂₀₁₅₎ -97 tril. Higher public subsidies (Table 1) allow the costs to be better shared between the two sectors: 103 and USD₍₂₀₁₅₎ 13 tril.

respectively for the private and public sectors in 2043; 200 and 193 in 2088.

In other words, our projections unambiguously confirm that the carbon price must follow a sufficiently steep path in order to provide strong enough incentives so that the net-zero GHG emissions objective is quickly achieved (compare the dashed with solid curves of the same color in Figs. 3(i,j)). Indeed, quick net carbon neutrality limits the emissions (Figs. 3(c,d)) and hence, economic damage (Figs. 3(g,h)). However, the quicker the transition, the higher the commitment of the public sector for this transition to be financially sustainable. For example, the scenario where net-zero emissions are reached as early as in 2052 but with low public subsidies (35%, solid blue curves) reaches the private-debt tipping point even for rather optimistic damages (Fig. 3(g)). This lack of financial sustainability is the outcome of too heavy a burden borne by the private sector, which is asked to pay a carbon tax representing 10% of world GDP in 2040 (Fig. 3(f)) for a carbon price trajectory exceeding USD₍₂₀₁₅₎ 400 per tCO₂e by 2050 (Fig. 3(a)).

While many decision-makers in the private sector invest in the very short term, this is not the case for all of them. “*We have no choice,*” said AXA’s then CEO Henri de Castries in 2015^[59]: “*A +2°C world might be insurable, a +4°C world certainly would not be.*” Thus, the results we present here should encourage the private decision-makers, as well as those in the public sectors such as central banks, to take into account these medium and long-term effects in future decision-making processes.

7 Conclusions

In summary, we investigate the prospective interplay between climate change, the world economy, and public policies via the new IAM IDEE, resulting from the coupling of the EMIC iLOVECLIM with a stock-flow-consistent (SFC) macroeconomic dynamics with endogenous growth, collateral, and default. Our results are:

1. Thanks to the predator–prey and out-of-equilibrium dynamics of our SFC model with climate backloop, we show that even with the most optimistic damage function, there exists a risk for the world economy to reach

a private-debt tipping point in scenarios without transition policies. This would lead to a “financial Minsky moment” (Carney) which, with the pessimistic damage function, would be reached as early as in the last quarter of the 21st century—and with the optimistic one, in the next century.

2. The temperatures of potential decline, associated with these private-debt tipping points, range from +2.3°C to +3.8°C, depending upon the chosen damage function. In addition to environmental and climate risks, this provides another new justification for the Paris Agreement target well below +2°C: financial stability requires the temperature anomaly is not too far from the +2°C limit.
3. A carbon tax policy helps considerably to avoid a catastrophic endgame without jeopardizing public finances. Moreover, it must be ambitious and quickly implemented: about USD₍₂₀₁₅₎ 400 per tCO₂e by 2050.
4. Moreover, we find that it must be accompanied by an equally ambitious public expenditure policy in order to enable the private sector to afford both the cost of mitigation and that of adaptation: public subsidies of at least 50% of the abatement costs are needed to avoid the private-debt tipping point. Fortunately, this expense never exceeds 10% of the current GDP. It enables to reach net-zero emissions worldwide before 2075, even with the pessimistic damages, and to stay broadly around a +2°C temperature elevation by 2100. The estimated global cost of the low-carbon transition—approximately 90 US\$ trillions up to 2035—is in good agreement with the 2018 New Climate Economy Report^[5].

8 Methods

8.1 IDEE: Integrated Dynamic Environment-Economy

8.1.1 Macroeconomic improvements

The macroeconomic framework of the new Integrated Assessment Model (IAM) IDEE is based on the models already published by Bovari et al. (2018) and affiliated works^[9–11]. Nonetheless, the macroeconomic model in IDEE is

slightly different. We performed small modifications listed below with referred equations of the detailed presentation available in [Supplementary information](#):

1. Labor productivity is assumed to grow at some endogenous rate (constant in previous articles), depending on the GDP growth rate (Kaldor-Verdoorn stylized version, see Eq. (6)).
2. The price markup is assumed to be endogenously determined (constant in previous articles), depending on the return on capital (see Eq. (9)).
3. The Phillips curve (relying labor wage dynamics to employment and inflation) tends toward zero when the nominal labor wage tends toward 1 (see Eq. (10)). This bound was not embedded in previous articles, and the nominal wage may upreach one.
4. The carbon emission intensity of the economy is assumed to decrease at some endogenous rate (constant in previous articles), depending of the abatement rate (see Eq. (14)). The higher the abatement rate, the faster the rate of emission intensity decreases.
5. Similarly, the price of the backstop technology p_{BS} is assumed to decrease at some endogenous rate (constant in previous articles), depending of the abatement rate (see Eq. (15)). The higher the abatement rate, the faster the rate of p_{BS} decreases.
6. A fraction of the unpaid debt is forgiven by banks when owners default (see Eq. (21)). The debt was not collateralized in the previous articles (see Item 8).
7. The investment function tends non-linearly toward zero when the private debt tends to the total value of production assets (see Eq. (22)). The investment was only decreasing linearly with profits in the previous articles.
8. A fraction of the capital is seized by the banking sector as its owners default on their corporate debt (see Eq. (24)), i.e., the private debt is collateralized. Consequently, this fraction of capital is non-operating.

8.1.2 *i*LOVECLIM

The climate framework has been implemented in the code *i*LOVECLIM. *i*LOVECLIM is a code-fork of the Earth system Model of Intermediate Complexity (EMIC) LOVECLIM^[60]. Both models share the

same atmosphere, ocean, sea-ice, and terrestrial vegetation models. The atmospheric component has simplified physics and it is solved at low spatial resolution ($\sim 5.6^\circ \times 5.6^\circ$) on three vertical levels^[61]. The ocean component is a 3D model on a $3^\circ \times 3^\circ$ grid and includes a sea-ice model^[62]. A simple dynamic vegetation model representing grass and tree fractions is also implemented^[63]. Given its coarse resolution and simplified physics, *i*LOVECLIM is computationally cheap and enables exploration of multiple climatic scenarios. Despite its simplification, it has been shown to reproduce the large climatic transitions of the past^[64].

8.1.3 Interfacing the world economy with Earth's climate

The interface between the economy and the climate is relatively simple. The economy produces an amount of greenhouse gas (GHG) emissions, which are added to the atmosphere. Consequently, involving complex atmospheric, oceanic, and vegetation processes, computed in *i*LOVECLIM, the climate reacts, and the mean annual surface air temperature changes every year. This temperature change produces modifications in the world economy. A rate of the aggregated production capital is depreciated, and a portion of the aggregated production is immediately destroyed. These two damage terms are given by a damage function of temperature. For example, damage to output constitutes the fraction of the production loss due to climatic events, like corn loss due to extreme droughts, while damage to capital (capital depreciation) includes the fraction of coastal industries that cannot be fully exploited due to sea-level rise and frequent high tides^[65]. With such a setup we perform transient economy-climate coupled simulations covering the 2015-2200 timespan. *i*LOVECLIM starts the simulations in 1850, forced by historical GHG emissions. From 2015, GHG emissions are provided by the economic model only. The coupling frequency between the economy and climate is one year.

Carbon-cycle processes are not explicitly represented in the *i*LOVECLIM version used in the present study. Instead, we use a simple efficient method based on a scaling factor applied to the GHG emissions to convert them into GHG atmospheric concentrations. In ECBilt, at any year $n + 1$, we yearly increase the atmospheric CO₂e

concentration by 46% of total emissions. Fig. 6 (see [Extended data](#)) compares the 46% scaling with data computed with a complex carbon cycle in VanVuuren et al. (2011)^[66]. We observe that this simple method allows us to reproduce the Representative Concentration Pathways (RCP) intermediate scenarios RCP4.5 and RCP6.0 quantitatively. It underestimates the concentration in the high scenario RCP8.5 and overestimates it in the low scenario RCP2.6. However, Fig. 6 comforts us in using this scaling method since it is efficient in our range of interest for the intermediate scenarios.

8.2 Calibration of $\dot{\text{I}}\text{LOVECLIM}$ on SSP scenarios

It is of particular interest to determine whether $\dot{\text{I}}\text{LOVECLIM}$ is in agreement with the state of the art of current Earth System Models, especially Global Circulation Models (GCMs). For that purpose, $\dot{\text{I}}\text{LOVECLIM}$ has been run on the five main Shared Socioeconomic Pathways^[43] (SSP) scenarios, namely the SSP 1-1.9, 1-2.6, 2-4.5, 3-7.0, and 5-8.5, using the calibration proposed by Timm and Timmerman (2007)^[67]. These scenarios provide narratives of potential socioeconomic pathways and relate them to GHG emissions. We used the concentration pathways, providing an estimation of the GHG atmospheric concentrations from SSPs emissions^[68].

Figure 7 ([Extended data](#)) shows comparisons between: $\dot{\text{I}}\text{LOVECLIM}$'s results on the five main SSPs scenarios, and the mean global temperatures, provided in the last WG I Sixth Report^[1]. In Fig. 7, these global temperatures from IPCC are shown in the following way: the very likely long term temperature ranges on the period 2081-2100 (the transparent boxes), and the best mean estimate over the same period (the large but short horizontal lines and in the legend named IPCC AR6). We also show the mean over the same period for $\dot{\text{I}}\text{LOVECLIM}$ (in the legend named " $\dot{\text{I}}\text{LOVECLIM}$ on SSPs"). Note that $\dot{\text{I}}\text{LOVECLIM}$'s data are represented from 1850 to 2100 in anomaly according to the pre-industrial period (1850–1900).

These results are in good agreement with those from WG I. Indeed, we observe that $\dot{\text{I}}\text{LOVECLIM}$ is systematically in the range of IPCC's data. For high temperatures, obtained with scenarios 3-7.0, 5-8.5 $\dot{\text{I}}\text{LOVECLIM}$ is slightly in the lower range.

However, it is very close to the best estimates (at $\pm 0.2^\circ\text{C}$) for the low and intermediate scenarios 1-1.9, 1-2.6, and 2-4.5. Figure 7 comforts us in using $\dot{\text{I}}\text{LOVECLIM}$ for obtaining fine estimations of the surface air temperature elevations.

8.3 Calibration of IDEE's macroeconomic model

The calibration of the macroeconomic model of IDEE concerns its initial point and the set of parameter values. It has been made ensuring an initial point compatible with the socioeconomic values measured in 2015, already proposed by Bovari et al (2018)^[9]. Concerning the parameters, we took the values already proposed by Bovari et al. (2020)^[11]. All parameters are available in [Extended data](#) (Tables 3 and 4).

In practice, we start to run a simulation in 1800 with $\dot{\text{I}}\text{LOVECLIM}$ only, forced by the historical data of GHG concentrations. In 2015, the year of the initial point for the economy, the macroeconomic model replaces this historical forcing by adding its emissions to the level already reached in 2015.

8.4 Computing the private-debt tipping point

In contrast to static, equilibrium approaches built on the postulate that out-of-equilibrium scenarios can be ignored^[26], the macroeconomic model of IDEE is based on a Lokta-Volterra dynamics whose state variables are ω, λ, d^{-1} , representing respectively the wage share, the employment rate, and the inverse of the private debt ratio (see details in [Supplementary information](#)). For a broad range of parameters and with reasonable initial conditions, orbits may converge towards a long-run steady state.

There are typically two types of attractor. The first one is a "good" Solow-type equilibrium point, where employment, nominal wage, and private debt converge simultaneously toward non-zero finite limits, while the economy asymptotically follows a balanced growth path. For example, in the business-as-usual simulation (green curves in Fig. 1) computed over a large time scale, the "good" equilibrium that we found is the limit $l = (0.61, 0.72, 0.55)$ (Fig. 4 in [Extended data](#)). Note that we do not consider the material and physical limits that such a growth trajectory implies.

Therefore, IDEE only connects the economy to the environment in which it evolves through climate damages. A catastrophic outcome arises whenever climatic damages succeed in driving the economy out of the basin of attraction of this desirable equilibrium, and ultimately push it in the basin of attraction of the second “collapse” attractor, an alternative debt-deflationary long-run equilibrium, where these same variables converge toward zero $l = (0, 0, 0)$ (Fig. 5 in [Extended data](#)), representing a catastrophic endgame for the economy^[9].

Let us consider a complete simulation that converges toward the “collapse” equilibrium point. We define the private-debt tipping point (introduced in Fig. 1), the year from which the economy is irretrievably attracted by this attractor. To compute it, we perform a sequence of simulations that start at every year from the given trajectory. We take their values as new initial points, but we set new emissions to zero for the entire run, so the climate remains constant in these simulations, at the warming level of their initial points. Finally, we let running the simulation as long as needed to converge toward one of the two attractors. Note that since the climate remains constant, if the warming is not too high, the economy may still reach the “good” attractor. The oldest date from which the economy is not able to reach the “good” attractor is the private-debt tipping point.

8.5 Frequency and magnitude of deadly heatwaves

The figures pertaining to the risk of lethal heat (Figs. 2(a)-(d)) are obtained from the simulated data in the following way. First, the relation between the relative humidity and the lethal temperature was estimated from Figure 1b in Mora et al (2017), itself based on experimental data^[48]. From this figure, we use the red line called the “95% Support Vector Machine probability threshold.”

The iLOVECLIM simulations were carried out with a daily output of climate variables. For each point of the grid and every day of every simulated year, we obtain a value for the temperature and the relative humidity, which can be exploited to determine the proximity to the lethal threshold. The relative humidity and temperature data are corrected using ERA5 data, in order to

account for the bias present in iLOVECLIM. For each iLOVECLIM grid point, we compare the simulated time series to the available ERA5 averaged monthly temperature reanalysis data from January 1950 to December 1978. Averaging the data over this 29 years period of time yields a map of the temperature bias as the difference between the ERA5 data and the iLOVECLIM simulation.

This bias is added to the iLOVECLIM simulation data for all times, with the underlying assumption that the bias does not change over time. The ERA5 humidity data at 2 meters is computed using the combination of temperature and dew point temperature at 2 meters. For this purpose, equation (8) of reference^[69] is used. Contrary to the temperature, the humidity in iLOVECLIM is corrected multiplicatively, that is, a corrective factor between the two sets of data is computed by computing the ratio of the means of the two sets of data over the whole 29 years period.

Two types of maps are then computed: one map for the number of days that the lethal threshold is exceeded, and one map for the difference to the threshold. In the first case, for each grid-point, we simply add 1 to a counter every day that the temperature exceeds the threshold during one reference year. In the second type of map, we represent how much (in K) the threshold is exceeded when it is exceeded. To highlight the summer in the northern and southern hemispheres, the maps are computed by averaging the data either around the 1st of July, or around the 1st of January (see Fig. 8 in [Extended data](#)). We take the 15 days before and 15 days after the selected date, and average over 10 years centered on the selected date, to obtain a temperature. The relative humidity is also averaged over the same period, and the obtained number yields the lethal temperature threshold. When the average temperature is above the threshold, the map plots the difference with the threshold (how many degrees above the threshold) for each grid point. This informs on the severity of the conditions, in addition to knowing whether the threshold is exceeded or not.

9 Supplementary information

9.1 The accounting framework

To assess the macroeconomic impact of climate change and policies, we refine the modeling framework introduced by Bovari et al. (2018-2020)^[9–11] so as to cover a wide range of economic situations without precluding the endogenous occurrence of large imbalances.

Let us start with the closed system of accounts shown in Table 2. Each entry represents a time-dependent quantity and a dot corresponds to time differentiation. It describes the balance-sheet, income statement and transaction flow matrices featuring all the monetary flows across the sectors of the economy; see Fig. 9 (Extended data). Balance sheet items are stocks measured in money, and both transactions and the flows of funds are flows measured in monetary units per unit of time.

Our idealized economy is subdivided into households, firms, public sector, and banks; see Fig. 9. The relative simplicity of this model allows for the retrieval of some of its mathematical properties^[9–11, 23, 70–74]. Their balance sheet structure can be described as follows: the assets of households are bank deposits, M_h , and equity, E , owned by shareholders; the assets of the private productive sector are bank deposits, M_f , and the stock of capital in nominal terms, pK ; firms also have liabilities in the form of bank loans, L_f , and equity, E_f ; banks' liabilities are given by total deposits $M := M_h + M_f$ and equity, E_b , while loans, L_f , are their only assets.

We therefore follow Bovari et al. (2018)^[11] and several preceding articles (see the references therein) by adopting the simplifying assumption that households do not take out bank loans directly. Note that this possibility can be added and would not qualitatively alter our results. The presence of equity in the balance sheet implies that the net worth of firms is the value of corporate equity *plus* the difference between nominal capital, pK , and net money debt, D . For simplicity, the net worth of banks and firms is assumed to be identically zero at all times. In particular, the corporate nominal debt, D , satisfies

$$D := L_f - M_f = pK - E_f = E_b + M_h - pK_b.$$

Taxes and public subsidies are restricted to the firms' sector and limited to climate policies, which is the main focus of this article. Say's law is postulated so that the model remains supply-driven. Dropping this restriction, e.g., is left for further research, together with the introduction of transfer payments to, and taxes from, households^[73].

Consistently with our assumed constant net worth of banks, the short-run interest rate, $r_f \geq 0$, paid by firms to banks must be related to the return on deposit, $r_M \geq 0$, paid to households, the dividends paid by banks to their shareholders, Π_b , and the change in equity of the banking sector

$$\dot{E}_b = S_b = r_f L_f - r_M M - \Pi_b.$$

We assume that banks issue or buy back shares accordingly. And similarly, for firms

$$\dot{E}_f = \Pi_r + \dot{p}K,$$

where Π_r stands for the retained earnings of firms, K , for the real stock of capital and p , for a price deflator. The flow of funds presented in Table 2 reflects the standard stock-flow-consistency condition^[8]: financial balances for each sector are used to change their holdings of balance-sheet items. For example, central to the model is the fact that firms finance investment using both their financial balance and net borrowing from the banking sector according to the accounting identity (see last row of Table 2 for the productive sector)

$$p\dot{K} - \Pi_r = \dot{D}. \quad (1)$$

9.2 The financial macro-dynamics

We now turn to the evolution of this macroeconomic accounting backbone by adding a continuous-time dynamics to its key entries. We present the continuous-time dynamics of the macrofinancial model. As short-term demand fluctuations are not the primary focus of this article, consumption treated as a residual of the accounting identity, $C := Y - I$. Relaxing this assumption is left for further research.

Table 2 Balance sheet, transactions, and flow of funds.

	Households	Productive sector ¹		Banks	Sum
Balance Sheet					
– Deposits	M_h	M_f		$-M$	
– Loans		$-L_f$		L_f	
Sum ²	M_h	$-D$		$D - M_h$	
– Capital stock		pK		pK_b	$p(K + K_b)$
– Equities	E	$-E_f$		$-E_b$	
Net worth (sum)	$M_h + E$	$X_f = 0$		$X_b = 0$	$p(K + K_b)$
Transactions		Current	Capital		
– Consumption	$-pC$	pC			
– Investment		pI	$-pI$		
– Wages	W	$-W$			
– Capital depreciation ³		$-p\delta_D K$	$p\delta_D K$		
– Carbon taxes	pT_f	$-pT_f$			
– Interest on Loans		$-r_f L_f$		$r_f L_f$	
– Banks dividends	Π_b			$-\Pi_b$	
– Firms dividends	Π_f	$-\Pi_f$			
– Interest on deposits	$r_M M_h$	$r_M M_f$		$-r_M M$	
Balance (sum) ⁴	S_h	Π_r	$p(\delta_D K - I)$	S_b	
Flow of funds					
Changes:					
– in deposits	\dot{M}_h		\dot{M}_f	$-\dot{M}$	
– in loans			$-\dot{L}_f$	\dot{L}_f	
Sum ⁵	S_h		$-\dot{D}$	S_b	
Changes:					
– in capital stock			$\dot{p}K + p\dot{K}$	$\dot{p}K_b + p\dot{K}_b$	$\dot{p}(K + K_b) + p(\dot{K} + \dot{K}_b)$
– in equities	\dot{E}_f		$-(\Pi_r + \dot{p}K)$		
– in bank equity	\dot{E}_b			$-S_b$	
Change in net worth (sum)	$S_h + \dot{E}$		0	0	$\dot{p}(K + K_b) + p(\dot{K} + \dot{K}_b)$

^aAlso called: “firms” in this table.^bPrivate debt is $D = L_f - M_f$.^cThe depreciation rate of capital is $\delta_D := (\delta + D_K)$.^dBy definition, the GDP is equal to $pY := pC + pI$.^eBy assumption, the households’ deposits vary with the difference of the revenues and spending, i.e., $\dot{M}_h = S_h$.

9.3 Endogenous growth and underemployment

Absent climate change, firms can produce a potential real amount, $Y^0 \geq 0$, of a unique, synthetic consumption good by combining the available workforce, $N > 0$, and capital, $K \geq 0$, as complementary factors of production

$$Y^0 := \min \left\{ \frac{K}{\nu}; aN \right\}, \quad (2)$$

where $1/\nu, a > 0$ stand respectively for (constant) capital productivity and Harrod-neutral labor-augmenting progress. The constancy of the capital-output ratio is in agreement with most of the post-Keynesian literature devoted to ecological macroeconomics^[75]. Depending on the level of available capital, firms minimise their costs by hiring the required amount of labour at full capacity, $L := Y^0/a = K/(\nu a)$. The employment rate, $\lambda \in [0, 1]$, is endogenously given by

$$\lambda := \frac{L}{N}. \quad (3)$$

Economic activities release greenhouse gas (GHG) emissions that are subject to a carbon tax levied by the public sector. To ease the tax burden, the productive sector may engage abatement activities. Thus, an abatement fraction of output Y^0 (Fig. 3(e)), A , is removed from the commodity market and used as an intermediary consumption to reduce emissions. This abatement of firms' activities means that a part of the labor paid by the companies does not generate private profit. On the contrary, this labor is, for example, that of the R&D sectors, which is not immediately profitable but accelerates the transition toward an ecological industry. Moreover, as in DICE^[26], a proportion, D_Y , of the remaining production is destroyed by global warming. As a result, the final production level is

$$Y := (1 - \delta_Y)Y^0, \quad (4)$$

with $\delta_Y := 1 - (1 - D_Y)(1 - A)$.

Global workforces, N , are assumed to grow according to a sigmoid inferred from the 15–64 age group in the U.N. median fertility scenario^[76]

$$\dot{N} := \delta_N N \left(1 - \frac{N}{\bar{N}}\right), \quad (5)$$

where $\bar{N} \sim 7.056 \times 10^9$ is the upper limit of global workforces and $\delta_N > 0$ drives the convergence speed. According to our calibration, and in accordance with the UN median scenario, this plateau is reached shortly before 2100. Labour productivity is assumed to grow at some endogenous rate

$$\frac{\dot{a}}{a} := \max(\alpha_{\min}, \alpha + \gamma_g g), \quad (6)$$

with $\gamma_g \geq 0$ and where g stands for the real growth rate, $g := \dot{Y}/Y$, of the world economy, following the Kaldor-Verdoorn stylized version of endogenous growth^[77]. Equation (6) introduces hysteresis, i.e., path-dependence, in the overall economic dynamics^[74]. The resulting economy still admits a Solovian equilibrium (Fig. 4) and a catastrophic one (Fig. 5).

Finally, the link between the real and nominal spheres of the economy is provided by two relationships^[23]. First, denoting the consumption price by $p \geq 0$, an inflation dynamics emerges from the relaxation of current prices at a speed, $\eta > 0$, toward their endogenous long-run value, given by

a markup, $\mu \geq 1$, times the unitary labor cost ω , i.e.,

$$i := \frac{\dot{p}}{p} := \eta(\mu\omega - 1), \quad (7)$$

where

$$\omega := \frac{W}{pY} = \frac{wL}{pY}. \quad (8)$$

At variance with most of the literature quoted above (where it is taken as an exogenously given constant), the markup μ is endogenously determined as a function of the return on capital:

$$\mu := \max(1, \mu_0 + \pi_K), \quad (9)$$

where $\mu_0 \geq 1$ and $\pi_K := \Pi/pK$. In words, the power market of firms—as measured by the markup—is an increasing, linear function of the return on capital.

The second channel that links the real sphere with the nominal one is provided by a short-run Phillips curve^[78, 79] which links the growth rate of nominal wages to unemployment:^[9, 11]

$$\frac{\dot{w}}{w} := \sqrt{1 - \omega}(\varphi(\lambda) + \gamma_w i), \quad (10)$$

where w is the money wage *per capita*, $\varphi(\cdot)$ is a continuous increasing function taking values in $[0; 1]$, and $\gamma_w \in (0, 1)$ is a measure of money illusion. The factor $\sqrt{1 - \omega}$ simply ensures that the wage share, ω , cannot exceed 1.

9.4 Taxation and abatement

The nominal profit before dividends, Π , is defined as nominal output *minus* the cost of production, see Transactions in Table 2:

$$\Pi := pY - wL - p\delta_D K - rD - pT_f, \quad (11)$$

where the total cost is determined by: (i) the money wage bill, $wL = W$; (ii) the capital depreciation, $p\delta_D K$, with

$$\delta_D := \delta + D_K, \quad (12)$$

where $\delta > 0$ stands for the usual depreciation rate and D_K for the fraction of capital destroyed by climate change (to be defined shortly); (iii) the debt service repayment, rD , with $r \geq 0$ being the

short-run nominal interest rate paid by firms to the banking sector, and D the total nominal debt of firms, and (iv) the carbon tax, pT_f .

A fraction $\Delta(\omega, r, d) \in (0, 1)$ of nominal output is paid to the households as dividends, provided profit before dividends Π is non-negative. Consequently, the retained earnings of the corporate sector, Π_r , are given by $\Pi_r = \Pi - \Pi_f$ (see Table 2), with $\Pi_f := \Delta(\omega, r, d)pY$ if $\Pi > 0$ and $\Pi_f = 0$ otherwise.

Depending on the level, p_C , of the carbon price (labeled in USD₍₂₀₁₅₎ per tCO₂e), firms endogenously choose their emission reduction rate, $n \in (0, 1)$. The economic activities release GHG emissions, expressed here in GtCO₂e, that are proportional to the aggregated production, Y^0 , according to

$$E_{ind} := \sigma(1 - n)Y^0, \quad (13)$$

where $\sigma > 0$ refers to the carbon emission intensity of the economy. It is assumed to follow some semi-endogenous sigmoid function of time following:

$$\frac{\dot{\sigma}}{\sigma} := e^{\delta_{g\sigma}} g_{\sigma_0} - \gamma_{\sigma} A, \quad (14)$$

where $\delta_{g\sigma}$ is a scalar, $\gamma_{\sigma} \geq 0$, $g_{\sigma_0} < 0$ is a given parameter, and A is the abatement rate, defined later in Eq. (15) that accelerates the emission intensity toward greener technology in Eq. (14).

As in model DICE^[26], the abatement technology, A , is assumed to be a convex function of the emission reduction rate normalized by the emission intensity of the economy, σ , and the semi-endogenous price of a backstop technology, p_{BS} , labeled in USD₍₂₀₁₅₎ per tCO₂e. For the sake of concreteness, p_{BS} grows at a constant (negative) rate, $\delta_{p_{BS}}$. It follows that

$$A := \frac{\sigma p_{BS}}{\theta} n^{\theta}, \text{ with } \frac{\dot{p}_{BS}}{p_{BS}} := \delta_{p_{BS}} - \gamma_{p_{BS}} A, \quad (15)$$

where $\delta_{p_{BS}} \leq 0$, $\gamma_{p_{BS}} \geq 0$, where $\theta > 0$ controls the convexity of the cost, and n is the emission reduction rate, i.e., the fraction of production processes that is “de-polluted,” defined by Eq. (16). Note that similarly to the evolution of the emission intensity, the abatement A accelerates the decrease of the backstop technology price p_{BS} in Eq.(15).

Turning to the public sector, the instrument used to foster the transition towards a zero-carbon economy is the carbon tax, $T_f := p_C E_{ind}$, that is levied on GHG emissions, E_{ind} . The fraction, s_A of abatement costs paid by firms is subsidized by the public sector for a global transfer $S_f = s_A A Y^0$, resulting in net transfers from the public to the private sector $S_f - T_f$. Faced with the policy implemented by the public sector, firms choose the emission reduction rate, n , that minimizes abatement costs *plus* carbon tax,

$$\min_{n \in [0,1]} A Y^0 + T_f - S_f \quad \text{s.t.} \quad \begin{cases} A &= \frac{\sigma p_{BS}}{\theta} n^{\theta}, \\ T_f &= p_C \sigma (1 - n) Y^0, \\ S_f &= s_A A Y^0. \end{cases}$$

Consequently, the optimal aggregate abatement rate of GHG emissions is

$$n = \min \left\{ \left(\frac{p_C}{(1 - s_A) p_{BS}} \right)^{\frac{1}{\theta-1}} ; 1 \right\}. \quad (16)$$

9.5 Investment and endogenous default

The row titled column sum (balance) of transactions in Table 2 gives the equality:

$$pI - p\delta_D K = S_h + S_b + \Pi_r, \quad (17)$$

where I designates gross investment, and the row entitled column sum of Flow of funds in Table 2 gives

$$\dot{D} = S_h + S_b. \quad (18)$$

Combining Eq. (17) and (18) with (1) finally leads to the following capital accumulation equation:

$$\dot{K} = I - (\delta_{DK} + \Gamma(d))K, \quad (19)$$

where $\Gamma(d) \in [0, 1]$ (to be defined shortly) is the fraction of capital seized by the banking sector as its owners default on their corporate debt. We denote by $K_b(t)$ the stock of (non-operating) capital forfeited by banks. Its evolution is

$$\dot{K}_b = \Gamma(d)K - \delta K_b. \quad (20)$$

The evolution of private debt is

$$\dot{D} = pI - \Pi_r - p(\delta_D + \gamma_{\Gamma} \Gamma(d))K, \quad (21)$$

where $\gamma_T \geq 1$ measures the “debt forgiveness ratio.” Turning to investment, as in Bovari et al. (2020)^[11], real gross investment, I , is then driven by the return on assets, π_K , capturing the risk appetite of the productive sector

$$I^d = \kappa(\pi_K)Y \left(1 - \frac{(1 - \delta_Y)d}{\nu}\right)^{\frac{1}{4}}, \quad (22)$$

where δ_Y is defined in Eq. (4), $\kappa(\cdot)$ is an increasing function (depending here on our state variables, ω, d and r) taking values in $[0; 1]$, and where

$$d := \frac{D}{pY}. \quad (23)$$

Current profits may not suffice to finance the whole of I , in which case firms will have to borrow from the banking sector. However, as much lending in modern economies, corporate debt is secured by some collateral, which can only be the current stock of capital valued at its market price, pK . We assume that collateral is held and used by the borrower and that forfeiture of collateral is the only consequence of default. In particular, there are no penalties for default other than forfeiture of the collateral, and there is no destruction of property in the seizure of collateral. Borrowers will therefore always deliver the minimum of what is promised and the value of the collateral. Knowing this, lenders need not worry about the identity of the borrowers but only about the future value of the collateral. As a consequence, we can restrict attention to firms’ aggregate debt, and simply assume that, as it grows closer to its upper-bound, pK , a growing number of companies go bankrupt, following complex microeconomic patterns whose nitty-gritty is not covered here. Rather, as a proxy, we posit that the production sector no longer invests whenever $D = pK$, i.e., $(1 - \delta_Y)d = \nu$. Default is accompanied by a transfer of ownership over the collateral from borrowers to lenders. For simplicity, we posit that, for a given debt ratio, d , the proportion $\Gamma(d) \in [0, 1]$,

$$\Gamma(d) := 1 - \exp\left(-\frac{A((1 - \delta_Y)d)^2}{\nu^2 - ((1 - \delta_Y)d)^2}\right), \quad (24)$$

of capital is seized by the banking sector, and therefore no longer operating. For $A > 0$ large

enough, Eq. (24) amounts to approximating a Dirac mass at $(1 - \delta_Y)d = \nu$. As a consequence, the private debt ratio is endogenously bounded from above.

Again, the dynamics with default admits at least the two equilibria we are now familiar with. However, both tend now to be unstable for a wide range of reasonable parameters—as in the case of endogenous growth. Since the phase space, $[0, 1]^2 \times [0, \nu]$ is compact, there must exist a compact attractor which is locally asymptotically stable: either a limit-cycle or some compactum, of which no single point is individually stable^[74].

9.6 Public sector and policies

The influence of the public sector is summarized by two variables and one parameter. The variables are p_C , the real carbon price, r_{CB} the short-term nominal interest rate, and the parameter is s_A , the rate of public subsidies. Both variables affect the profit share, hence the entire macro-dynamics via investment flows. For the purpose of our policy scenarios, this price will then be assumed to follow an exogenous path given by the Report of the High-level Commission on Carbon Prices^[55]. The real price of carbon, p_C , is assumed to grow exogenously at a given rate, following a simple parametric carbon price function:

$$\frac{\dot{p}_C}{p_C} := a_{p_C} + \frac{b_{p_C}}{t}, \quad (25)$$

where $a_{p_C} \geq 0$ stands for a long-term growth rate trend of the carbon price, and $b_{p_C}/t \geq 0$ represents the time-varying component of the growth rate, with t the number of years since the policy is active (i.e., $t_{2016} = 1$ in 2016, the starting point of our simulations). Finally, the short-term interest rate r will follow a standard Taylor rule^[80]

$$r_{CB} = \max\{0; r^* + i + \phi(i - i^*)\}, \quad (26)$$

$$\dot{r} = \frac{1}{\eta_r}(r_{CB} - r), \quad (27)$$

where $r^* \geq 0$ stands for the long-term real interest rate targeted by the Central banking system, i^* the inflation rate commonly targeted by the monetary policy authority, and $\phi > 0$ a parameter that controls the magnitude of the central bank’s

response to inflation (or the lack of it) and $\eta_r > 0$ is a relaxation parameter of the interest rate.

9.7 The damage functions

The functional form and calibration of the damage functions are taken from Dietz and Stern (2015)^[28]. Let ΔT be the mean air temperature elevation. The size of damages is given by

$$\text{Dam} = 1 - \frac{1}{1 + \pi_1 \Delta T + \pi_2 \Delta T^2 + \pi_3 \Delta T^{\zeta_3}}, \quad (28)$$

where π_1, π_2, π_3 are positive scalars, and ζ_3 is a positive exponent.

A portion D_K of Dam affects the capital by accelerating its depreciation, which is now given by $\delta_{D_K} := \delta + D_K$, while D_Y affects the total output Y^0 (Eq. (4)). The damage rates D_K and D_Y are computed such that [11]

$$D_K = f_K \text{Dam}, \quad \text{and} \quad D_Y = 1 - \frac{1 - \text{Dam}}{1 - D_K}, \quad (29)$$

where $f_K \in [0, 1]$ quantifies the fraction of damage borne by the capital stock.

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10 Extended data

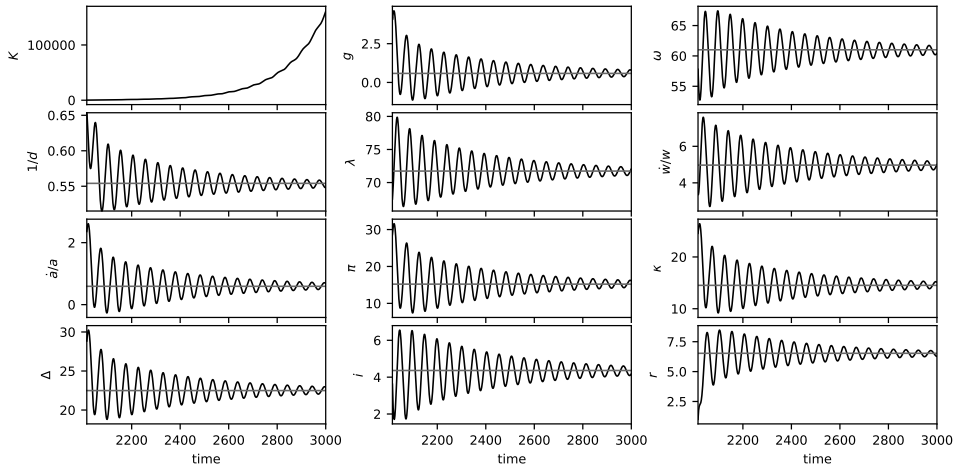


Fig. 4 Solovian equilibrium.

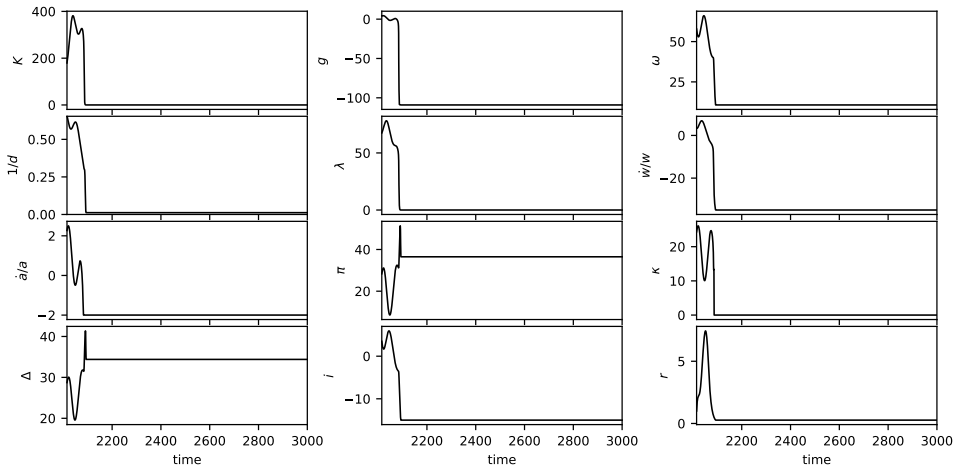


Fig. 5 Catastrophic equilibrium.

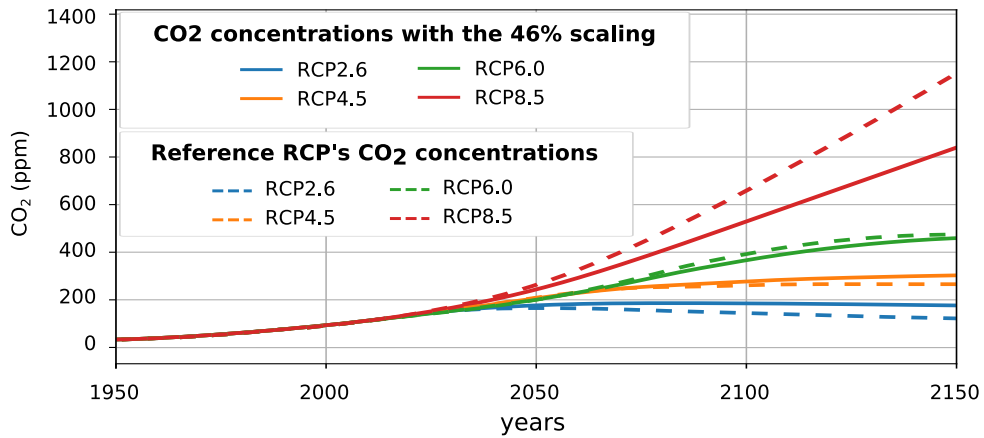


Fig. 6 Scaling of GHG emissions. The dashed curves represent the CO₂ concentration for the four main RCP scenarios, computed by a complex carbon cycle model^[66]. The solid curves are obtained with the 46% GHG emission scaling in place of this complex carbon cycle.

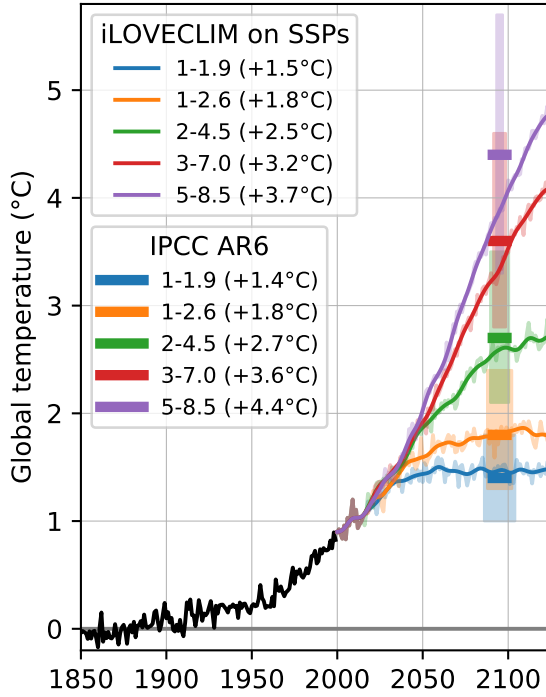


Fig. 7 Validation runs of iLOVECLIM on the five main SSP scenarios. The time evolution of the global mean temperature obtained with iLOVECLIM is compared with reference GCMs data from the IPCC's sixth report. The mean temperature range from IPCC, represented by the boxes (note that the box thickness is just for visibility) are very likely long term expected temperatures (2081-2100). The best estimates are given in legends (in brackets).

Table 3 Initial values of the economic model (2015)

Symbol	Description	Value	Units	Eq.
λ	Employment rate	0.675		(3)
Y	Agregated production	58.7	USD ₍₂₀₁₅₎ tril.	(4)
N	Workforce	4.83	workers bil.	(5)
i	Inflation	0.018		(7)
p	Normalized price	1		(7)
ω	Wage share ratio	0.578		(8)
E_{ind}	Emissions due to economic activities	51.8	GtCO ₂ e	(13)
$g\sigma_0$	Initial drop parameter of the carbon emission intensity of the economy	-0.0152		(14)
p_{BS}	Price of the backstop technology	1500	USD ₍₂₀₁₅₎ /tCO ₂ e	(15)
n	Emission reduction rate	0.03		(16)
d	Private debt ratio	1.53		(23)
r	Interest rate	0.01		(27)
ΔT	Global annual mean air surface temperature anomaly	1.07	°C	(28)

Table 4 Parameters of the economic model

Symbol	Description	Value
Workforce		
δ_N	Growth rate of workforce	0.0305
\bar{N}	Maximum workforce	7.06
Wage & Affine Philips curve		
φ_0	Constant of the Philips curve	-0.292
φ_1	Slope of the Philips curve	0.469
γ_w	Inflation coefficient in wage equation	0.5
Productivity of workers		
γ_g	Growth coefficient in productivity equation	0.5
α	Constant growth rate in productivity equation	0.003
α_{\min}	Maximum degrowth rate of productivity	-0.02
Capital		
δ	Capital depreciation rate	0.04
ν	Constant capital-to-output ratio	3
γ_Γ	Forgiveness parameter	1.05
Affine dividend function		
div_0	Constant of the dividend function	0.051
div_1	Slope of the dividend function	0.473
div_{\min}	Minimum of the dividend function	0
div_{\max}	Maximum of the dividend function	0.3
Affine investment function		
κ_0	Constant of the investment function	0.0397
κ_1	Slope of the investment function	0.719
κ_{\min}	Minimum of the investment function	0
κ_{\max}	Maximum of the investment function	0.3
Inflation		
η	Relaxation parameter of inflation	0.193
μ_0	Constant term in the markup of prices	1.95
Monetary policy		
i^*	Inflation rate targeted by the monetary policy	0.02
ϕ	Reactivity of the monetary policy	0.5
η_r	Realaxation parameter of the interest rate	10
r^*	Long-term interest rate target	0.01
Abatement		
θ	Parameter of the abatement function	3.4
Back-stop technology price		
$\delta_{p_{BS}}$	Growth rate of the back-stop technology price	-0.0026
$\gamma_{p_{BS}}$	Abatement Coefficient in the p_{BS} equation	0.5
Carbon price		
a_{p_C}	Carbon price parameter	-0.0189 (target y. 2050) -0.004 (target y. 2075)
b_{p_C}	Carbon price parameter	2.165 (target y. 2050) 1.749 (target y. 2075)
Public subsidies		
s_a	Share of public subsidies	0.35 (low) 0.5 (moderate) 0.65 (high)
Damage function		
π_1	Parameter of the damage function	0
π_2	Parameter of the damage function	0.00236
π_3	Parameter of the damage function	0 (o damages)
ζ_3	Parameter of the damage function	0.0000819 (p damages)
f_K	Share of damages on capital	6.75 0.333
Emission intensity		
$\delta_{g\sigma}$	Parameter in emission intensity dynamic	-0.0175
γ_σ	Abatement coefficient in emission intensity	0.2

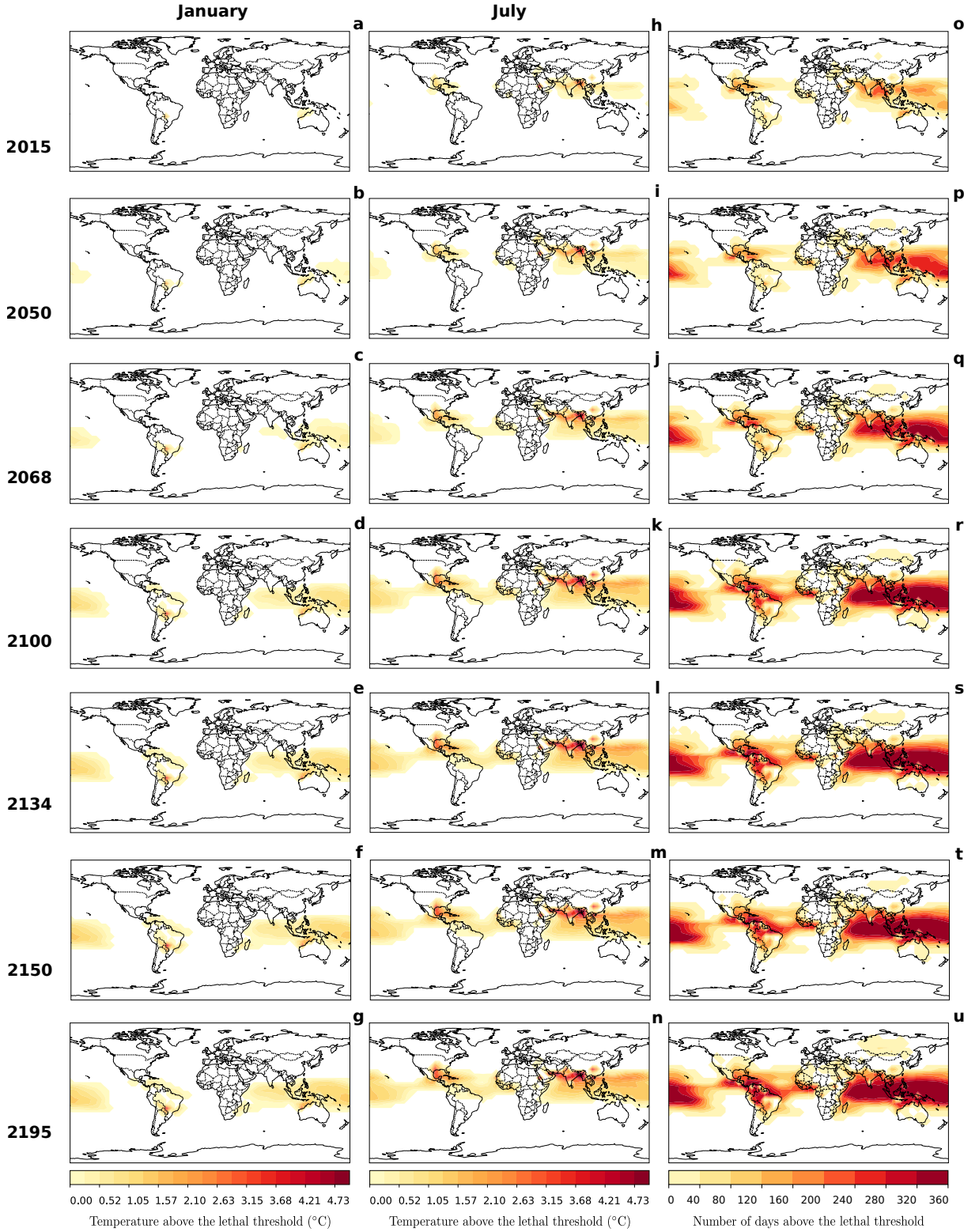


Fig. 8 Deadly heatwaves from 2015 to 2195. **a-g** Maps represent the average relative temperature above the lethal threshold^[48] for January. **h-n** Maps represent the average relative temperature above the lethal threshold for July. **o-u** Maps represent the number of days above the lethal threshold.

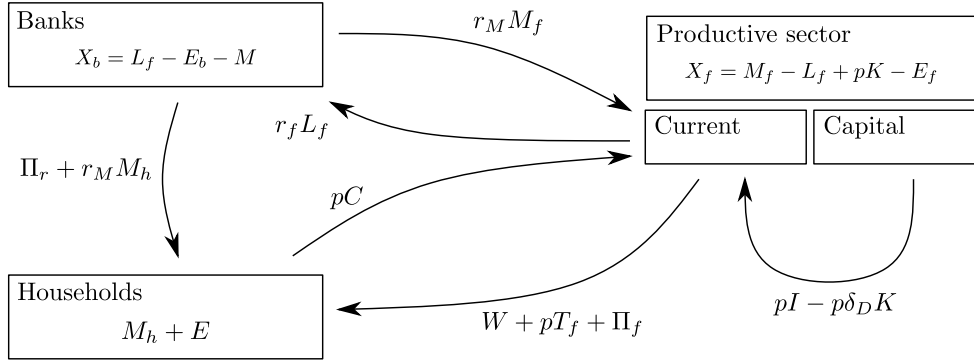


Fig. 9 Stocks and flows in the economy.