Climate-Change Adaptation: The Role of Fiscal Policy

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Abstract

Climate change and natural disasters have important consequences on fiscal sustainability, especially for developing countries with limited financial resources and underdeveloped institutions. The paper contributes to shed light on the role of fiscal policy in climate-change adaptation, which aims at containing the economic damage of climate change. We use an overlapping generations (OLG) model for a small open economy in which adaptation reflects the extent to which public policies reduce the negative influence of climate change on the capital depreciation rate. Adaptation includes both preventive measures, i.e. investment in infrastructure, and remedial measures, i.e. post-disaster relief and reconstruction. Through model simulations we assess the costs and benefits of both remedial and preventive actions. We find that preventive intervention leads to higher GDP growth rates than either taking no action or waiting until remedial action is necessary. However, the evidence shows that, due to high costs of early adaptation and budgetary constraints, countries tend to focus on late corrective actions, also relying on international assistance. Given the expected increase in climate-related risks, a comprehensive strategy including both preventive and corrective actions would be desirable to strengthen resilience to shocks and alleviate the financial constraints, which particularly affect small countries.

JEL classification: C61, Q54, Q58, H54

Keywords: Dynamic Analysis; Natural Disasters and Their Management; Government Policy; Other Public Investment and Capital Stock

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1 Introduction

Climate change and climate-related natural disasters pose a growing threat to both developed and developing countries. However, developing countries are particularly vulnerable to climate change, as they have fewer financial and institutional resources to counter its negative impact. The capacity of developing countries to adapt to a changing climate or to cope with extreme weather events, such as floods, hurricanes, or droughts, tends to be far more limited than that of their wealthier peers. Underdeveloped private insurance markets compound the risks of climate change, particularly the threat they pose to lower-income households. In addition to their devastating cost in lives and property, climate change and natural disasters have important fiscal consequences. Gradual changes in temperature and rainfall can profoundly alter economic activities - especially in sectors that are highly sensitive to climatic conditions, such as agriculture, fishing, and tourism - with important implications for the level and composition of tax revenues. Meanwhile, natural disasters and weather-related shocks can exacerbate revenue volatility and slow potential GDP growth. Natural disasters can severely weaken a government's fiscal position, due to the short-term costs of disaster relief, the longer-term costs of reconstruction, and the foregone-revenue impact of damaged capital and depressed economic activity. Several factors influence the fiscal consequences of natural disasters and climate change, including the economy's degree of exposure, the level of protection already in place, and the state's liability for the damages incurred. The cost of dealing with these impacts can be extremely high, particularly in small island nations and very poor countries, which threatens their fiscal sustainability and the future of their development efforts.

Fiscal policy can play a key role in mitigating climate change and adapting to its effects, yet the international literature on the fiscal implications of climate change remains limited. This study aims to contribute to a better understanding of how fiscal policy can help countries adapt to the gradual long-term effects of climate change and cope with the severe short-term impact of climate-related natural disasters and extreme weather events. It uses a calibrated macroeconomic model of an open economy with overlapping generations in which climate change is assumed to affect the depreciation rate of the capital stock.

For illustrative purposes, the model differentiates between impacts of climate change that occur slowly, with costs mounting over time, ("gradual factors") and effects that manifest as sudden, unpredictable disasters ("extreme events"). In the baseline scenario, no attempt is made to adapt to climate change or address its negative impact on the capital stock. Against this baseline, the study evaluates the relative effectiveness of two different strategies: (i) preventive action, under which policymakers implement adaptation measures in anticipation of the effects of climate change, and (ii) remedial action, under which policymakers focus solely on responding to impacts that have already occurred. The analysis reveals that preventive action leads to higher GDP growth rates than either taking no action or waiting until remedial action is necessary. Preventive investments in climate-change adaptation, funded by taxes or by reduced spending in other areas, can increase the resilience of the capital stock, keep public debt dynamics manageable, and maintain adequate fiscal space to cope with natural disasters while responsibly accessing international capital markets. In this paper, we focus on adaptation investments financed only by an increase in public debt, leaving the analysis of alternative tax instruments, such as increasing tax rates or cutting spending, to future research.[1]

The paper is organized as follows. Section 2 briefly discusses the literature on the macroeco-

[1] The model includes several taxes, which allow to distinguish the different levers on which the government can act, namely tax rate on labor income, on capital income and on consumption (see for example [Forni et al. (2009)]). Indeed, it is standard practice to consider the different effect of financing government spending via different combination of these taxes as they have diverse effects on the budget constraints of the existing and future cohorts.

nomics of climate change and the role of fiscal policy in climate-change adaptation. Section 3 presents the proposed model and Section 4 describes how the main model parameters are calibrated. Sections 5 presents the results and Section 6 the robustness checks. Section 7 discusses the main policy implications. Section 8 concludes the analysis.

2 Literature review

The macroeconomic costs of climate change can be grouped into three categories: mitigation, adaptation, and residual costs. "Mitigation" includes all costs incurred by policies that slow the pace and limit the severity of climate change, particularly via reduced greenhouse gas emissions. "Adaptation" includes all costs incurred by efforts, both preventive and remedial, to reduce the social, environmental, and economic impact of climate change. "Residual costs" are effects of climate change that cannot be offset through mitigation or adaptation. Most macroeconomic models focus on assessing mitigation costs and residual costs. For example, [Stern 2007], [Nordhaus 2007, Nordhaus 2008], [Bonen et al. 2016] and others use integrated assessment models (IAMs) to quantify the damages caused by climate change and the cost of efforts to limit its extent. These models apply "damage functions" (see, e.g., [Bonen et al 2014]) that approximate the relationship between global temperature changes and climate-related phenomena such as rising sea levels, more frequent cyclones, lost agricultural productivity, and degraded ecosystem services. Most IAMs treat climate-related damages as a polynomial function of global mean temperatures and examine its impact on the stock of capital at either the regional or the global level.[2] [Bakkensen and Barrage (2018)] suggest a modified empirical approach that estimates cyclone impacts on the structural determinants of growth, namely total factor productivity, depreciation, and fatalities. In doing so, they estimate a cyclones damage function for a Dynamic Integrated model of Climate and the Economy (DICE), thus contributing to bridge the gap between empirical evidence and theoretical growth model. Some researchers have attempted to embed the effects of climate change in multi-country general equilibrium models. For example, [Kotlikoff et al. 2016] apply an overlapping generations model similar to the model used in this study. They find that a lack of intra-generational or intra-country coordination makes climate change mitigation more difficult. Moreover, the Paris Climate Accord may inadvertently intensify the so-called "green paradox," in which the adoption of emissions targets creates incentives for countries to increase their greenhouse gas output before the corresponding restrictions become binding.

By contrast, the literature on the macroeconomic implications of climate-change adaptation is relatively limited. Early IAMs either ignored adaptation or treated it as implicit in the damage function. However, more recent IAMs include a dynamic representation of both the costs and benefits of adaptation. These models find that optimal climate policies involve both adaptation and mitigation (see [Ingham et al. 2013]; [Tol 2007]; [Lecocq 2007b]; [de Briun et al. 2009], [Agrawala et al. 2011]).[3] [Bosello 2008] extends the Ramsey-Keynes growth optimization model - used in the Nordhaus DICE model - to show that mitigation and adaptation, together with

[2]For example, the Dynamic Integrated model of Climate and the Economy (DICE) aggregates all countries into a single economy ([Nordhaus 2007, Nordhaus 2008]). By contrast, the Regional Integrated model of Climate and the Economy (RICE) model divides the world into areas that trade with each other and can act in a cooperative way to cope with climate change ([Nordhaus and Yang 1996]; [Nordhaus 2009]). Both models are characterized by the presence of agents that optimize consumption over time and decide on investment in capital, education and technology. Recent revisions of these models are provided in [Nordhaus 2017]. Other models focus on policies to increase the level of R&D expenditure and knowledge that allow for technological changes to improve energy efficiency. The return on investment in R&D is assessed to be four times higher than investment in physical capital, and this should therefore encourage technology to move towards a more environmentally friendly dynamic path ([Bosetti et al. 2006b]).

[3]For a more complete literature review of these models, see Vivid Economics, Defra Final Report, 2013.

green R&D, could serve as strong complements to tackling the negative impact of climate change. [Bonen et al. 2016] show that when mitigation policy is subject to diminishing returns, it is optimal to combine mitigation with adaptation. However, there is no level of mitigation and adaptation that can fully compensate for the costs of climate change, so residual damage is always a factor.

Adaptation strategies strive to contain and manage the damaging effects of climate change and are closely related to broader economic development objectives ([IMF 2016c], sec. V). The International Panel on Climate Change (IPCC) defines adaptation as "the process of adjustment to the actual or expected climate and its effects. In human systems, adaptation seeks to moderate or avoid harm or exploit beneficial opportunities. In some natural systems, human intervention may facilitate adjustment to the expected climate and its effects." Whereas mitigation focuses on reducing the severity of climate change by, inter alia, reducing global carbon emissions, adaptation seeks to address the impact of a changing climate. Adaptation includes both preventive measures, such as investment in infrastructure designed to limit the damage caused by extreme weather events, and remedial measures, such as disaster relief and reconstruction. The lower costs of preventive adaptation - properly planned and spread out over time - are likely to outweigh the higher costs of remedial adaptation.[4]

[Lecocq and Shalizi 2007a] uses a partial equilibrium optimization model of climate policies to evaluate the role of mitigation, proactive adaptation (ex ante), and reactive adaptation (ex post), both in a context of certainty and uncertainty. They find that the benefits of proactive (preventive) adaptation over those of reactive adaptation are reduced in case of uncertainty on the location of the damage, implying that reactive adaptation takes precedence over proactive adaptation so as not to misallocate financial resources. However, relying on reactive adaptation implies that there must be an adequate availability of public resources to pay for remedial measures, which often require significant expenditure in a short period of time. Therefore, implementing reactive adaptation can be particularly difficult, especially for developing countries where budgetary constraints are tighter. Whatever the chosen adaptation action, the overarching objective of adaptation is to protect and restore the capital damaged by climate change while accommodating further economic and demographic growth. Conversely, a laisser-faire policy, that is a policy of non-action, will lead to high final damages, which can negatively influence growth and development strategies ([Lecocq and Shalizi 2007a]).

[Agrawala et al. 2011] incorporate adaptation as a policy variable into two IAMs, i.e. DICE and World Induced Technical Change Hybrid (WITCH) models, and evaluate its interaction with mitigation policies.[5] They focus on adaptation actions concerning both stock and flow adaptation. The former includes investments in adaptation which bring costs and benefits over the same period (e.g. changes in farming practices, changes in heating and cooling expenditures and in the treatment of climate-related diseases). The latter include initial investments whose benefits extend beyond the period in which costs are incurred (e.g. investments in coastal defense infrastructure such as dams or water storage). As investments in adaptation stocks become effective with some delay, they should be implemented early. Moreover, the study focuses on the role of adaptive capacity in increasing effectiveness of adaptation activities (both stock and flow actions). Adaptive capacity is specific when related to climate change factors (such as R&D for drought resistant crops), and generic when referred to the economic development of a region (such as the level of infrastructure, knowledge, and technology). This implies that OECD countries, richer and more advanced, have larger adaptive capacity than non-OECD countries.

[4]Both preventive and remedial adaptation should be financed until the last dollar spent on the adaptation corresponds to exactly one dollar of avoided damage ([Lecocq 2007b]).

[5]The WITCH model is a neo-classical optimal growth model that allows to analyze optimal climate mitigation policies within a game-theoretical framework while considering an energy input detail and endogenous technical change ([Bosetti 2006]).

Both AD-WITCH and AD-DICE[6] models illustrate that the different climate policy options are substitutes, but both are necessary for the most effective solution of the climate change problem, consistent with the degree of development of the country and its financial resources.

[Millner and Dietz 2015], distinguish between adaptation to climate change and general economic development. They classify "development as the best form of adaptation": to prioritize investing in physical and human capital stocks over defensive investments aimed specifically at reducing vulnerability to climate change. [Noy 2009] finds that countries with a higher literacy rate, better institutions, higher degree of openness to trade, and higher levels of government spending are better able to withstand the climate related disaster and prevent further spillovers into the economy. The financial conditions are important as well, since countries with more foreign exchange reserves, and higher levels of domestic credit, but with less open capital accounts appear more robust and better able to endure natural disasters, with less adverse spillover into domestic production.

Estimates of the global need for adaptation investment are evolving, and researchers have identified infrastructure and coastal zones as the areas requiring the costliest interventions. Whenever adaptation resources are limited, rainy-day funds and international transfers can reduce the risk of not being able to react adequately at national level. International assistance and private investment can reduce the cost of adaptation at the country level. [Harris and Roach 2017] find that the adaptation cost estimates produced by the United Nations Environment Program (UNEP) exceed the annual amount committed by developed nations in the 2015 Paris Climate Accord by two to three times, and that "there will be a significant finance gap, [which is] likely to grow substantially over the coming decades, unless significant progress is made to secure new, additional and innovative financing for adaptation." [Bréchet et al. 2013] demonstrate that a country's financial, political, and technical capacity to implement long-term projects affects both the optimal mix of mitigation/adaptation and the degree of complementarity or rivalry of these policies. [Bonen et al. 2016] present an integrated assessment model calibrated to take into account country- and institution-specific factors, which play a key role in determining the share of public capital needed to adapt to/mitigate the impact of climate change.

While the explicit costs of adaptation are considerable, investing in adaptation is vital to limit the immense economic damage caused by climate change and extreme weather events. [UNDP 2007] and [World Bank 2009] (2009) argue that failing to adapt to climate change would severely affect the development process, and climate-related disasters are already seriously impacting growth in small states ([Cabezon et al. 2015]). The public and private sectors both have important roles to play in adaptation strategies. However, only public institutions can overcome free-rider problems related to climate change ([Bonen et al. 2016]). The private sector is the primary source of investment in human and physical capital, while the public sector is vital to coordinate the actions of individual agents into a collective response ([Mendelsohn 2012]). [Barrage 2015] studies the optimal policy mix between climate change mitigation and adaptation and argues for full public provision of adaptation policies and investments, even when those policies and investments are financed through distortionary taxes. In the short term, climate-change adaptation competes with other development objectives for scarce fiscal and aid resources. But over the long term, climate-change adaptation is consistent with, and in some cases integral to, the achievement of broader development goals.

Adaptation becomes less effective in presence of high climate damage, e.g. at higher temperatures. [Burke et al. 2015] argue that the impact of temperatures on productivity is not linear; rather, it is positive at low temperatures and peaks at an average temperature of 13°C, after which it becomes increasingly negative. They also find that wealthier and poorer countries are subject to similarly non-linear effects and that there is no evidence that experience gained in

[6] AD stands for "adaptation" in both the DICE and the WITCH models.

high-temperature contexts can accurately inform the global response to climate change. Once countries exceed a given threshold temperature, the correlation between their economic performance and further temperature increases becomes more intensely negative. In other words, the warmer a country is now, the more serious the economic damage from further warming will be. Consequently, a rapid rise in global temperatures would weaken the effectiveness of adaptation measures, and no amount of wealth, technology, and experience would enable countries to substantially reduce the economic losses incurred.

Adaptation strategies require various forms of public-sector intervention. Some strategies focus on public investments in infrastructure - financed through deficit or taxation - designed to increase social and economic resilience to climate change and extreme weather events. Others involve adopting policies that increase the prices of public assets (e.g., water resources) to promote conservation and sustainable management by aligning their individual value more closely with their social value. Regulations can be used to adjust patterns of human activity to reflect climate-related risks. For example, zoning regulations can bar construction in areas vulnerable to flooding. Finally, fiscal incentives can encourage private investment in adaptation. Environmental taxes raise questions about the need for sacrifices to be imposed on current generations to protect future generations. [Heijdra et al. 2006] use an overlapping generations model of a small open economy to assess the intergenerational impact of a current increase in environmental taxes. They show that an environmental policy accompanied by an appropriate public debt policy - debt accumulation at impact to ensure transfers to current generations and debt repayment in the new steady state - will ensure an improvement in the situation of both generations. [Karp and Rezai 2014] believe that the increase in asset prices - as a result of the increase in future environmental stocks brought about by higher taxation - will improve the welfare of current generations (asset owners), without public transfers to distribute income between generations. The intergenerational distribution of the tax burden related to adaptation policy can be studied in our model, which is designed to analyse the behaviour of overlapping generations. This aspect has also been studied in [Orlov et al. 2018] who extend the DICE model to the analysis of the intergenerational equity of mitigation policies. For a more detailed review of the various policy tools currently being used to promote climate-change adaptation, see [Mechler et al. 2016].

3 The Model

Macroeconomic modelling can shed light on the pivotal role of fiscal policy in supporting climate-change adaptation. We use an overlapping generations (OLG) model for a small open economy to capture impact of climate change on agents' behavior and economic growth. In this model, climate change is assumed to increase the depreciation rate of physical capital and, therefore, adaptation reflects the extent to which public policies reduce the negative influence of climate change on the capital depreciation rate.[7] The approach based on the overlapping generations makes it possible to analyze the determinants of capital accumulation in a general equilibrium growth model, i.e. the extent to which cohorts save, consume, work and thus affect capital accumulation. Moreover, this type of models allows us to introduce a quite detailed medialization of fiscal policy. Indeed, Ricardian equivalence does not hold, which means that public finance decisions affect private decisions, i.e. savings, consumption, investment and capital accumulation. This has significant implications when analyzing fiscal issues related to the financing of adaptation expenditure. As argued by [Schneider et al. 2012], there is also a question of intergenerational trade-offs related to climate policy, which can be properly addressed by an OLG model. The government can choose to finance adaptation investment by increasing public

[7] A possible extension would be to assume that climate change also affects the accumulation of human capital, but to keep the exposition as simple and transparent as possible, we leave this extension for future analysis.

debt or increasing taxation or cutting spending. Depending on the measure chosen, the cost of adaptation will be borne by the current working age cohorts rather than by future generations who will benefit from higher capital accumulation and a lower depreciation rate.

In order to analyse the interactions between agents and their behaviour in response to public investment to adapt to climate change, we consider a small open economy including three core sectors, namely households, firms and the government. The economy is populated by individuals divided into 101 age cohorts, with ages ranging from zero to a maximum of 100 years, split in 3 education levels (primary, secondary and tertiary). We feed the model with United Nations (UN) long-term population projections as in [Borsch-Supan et al. 2006]. This implies that cohorts are differently populated, based on the age distribution resulting from UN population projections, which provided a number of people for each age group, from 0 to 100+. We use UN population projections for the area "Less developed regions, excluding China" (medium variant scenario) to obtain a representative less developed country. Demographic dynamics are extremely important as they affect the potential growth of the economic system through labour and capital inputs. Households save and supply labor based on market-determined factor prices (i.e., wages and interest rates), which households take as given.[8] They decide how to allocate their disposable income between consumption and saving (which represents future consumption) in a lifecycle perspective, forming expectations about income flows. Typically, savings are accumulated during the working life to be able to consume during the retirement age. As a result, countries with a younger population have higher savings rates, which also finance more investment through increased demand for securities.

GDP growth rates are calculated via a production function that includes labor input, physical capital, and human capital. Total factor productivity depends on capital intensity (i.e., capital per worker) and the stock of human capital. The latter is computed based on the education level of the workforce and its growth rate over the simulation period, which reflects UN population projections.[9]

The small open economy trades and exchanges capital with the rest of the world. It is assumed that the domestic economy faces a borrowing constraint in the international financial markets, that means it can borrow up to a given credit limit.

The interest rate applied to external borrowing is the same rate that prevails on the international market, and therefore increased borrowing entails no risk premium. It is assumed that the country satisfies the intertemporal budget constraint, and default is not allowed.

The impact of climate change works through a modification of the depreciation rate, and therefore it is assumed to have a persistent effect, that is climate change acts as a factor that reduces the efficiency of the capital stock, unless it (or part of it) has been made more resilient via adaptation spending. It is close to the approach taken by [Fankhauser et al. (2005)] who state that the impact of extreme events on the longevity of capital can be captured by an increased speed of capital depreciation. On the contrary, the capital that has been made more resilient to climate change via adaptation spending is subject to a lower depreciation rate. This approach allows us to model investment in adaptation as a way to reduce the capital depreciation rate, that is as a way to counterbalance the negative effect of climate change on the capital downgrading. An alternative approach would be to model the impact of climate change as a destruction of the initial level of the capital stock. This option would not lead to significantly different results in the short run, but would have less persistent effects in the long run. If instead we assume that the climate change would lead to a repeated (period after period) destruction of the existing capital stock, we would obtain very similar results to the one we present in this

[8] Households set the life-cycle saving decision without a voluntary bequest motive.

[9] We calculate the share of population with specific education level using data provided by [Barro and Lee 2015].

paper.

We assume that climate change accelerates the depreciation of the capital stock via two types of effects: (i) "gradual factors," which are aspects of climate change that have a relatively slow but progressively intensifying economic impact, such as crop displacement and rising sea levels, and (ii) "extreme events", which are climate-related phenomena that severely affect the stock of physical capital in a brief period of time, such as tornados and droughts.[10] The model entails only one type of capital, but it applies an evolving depreciation rate, and the capital replaced in the wake of a natural disaster is assumed to be more climate resilient if the government has previously invested in adaptation. Moreover, reconstruction after an extreme event boosts growth by accelerating capital accumulation.

The baseline scenario assumes that current climate trends, both in terms of gradual factors and extreme events, will continue over the projection period. The baseline scenario indeed assumes perfect foresight, that is that the evolution of gradual factors and extreme events is known to all agents in advance. In fact, climate trends are subject to signicant uncertainty. Uncertainty regarding these trends should induce risk-averse agents to hedge against downside risks and might lead to overinvestment in adaptation spending. This might not bode well with what we observe in reality, as the uncertainty regarding climate trends could be one of the reasons why we observe in many countries a postponement of adaptation spending. But, probably, what drives current choices in adaptation in many countries is not uncertainty around an adverse climate change trend, but likely an hesitation to accept that a negative trend actually exists.

The assumption of perfect foresight allows us to incorporate the anticipatory effects of adaptation policies into the expectations of government and households. Adaptation policy will change the expected income and wealth today, consumer choices and thus investment and growth. In this approach, the model is standard and makes it possible to study the effect of policies to be implemented in the future, the effects of which are anticipated by firms and households.[11] Therefore, agents can accurately assess the capital-depreciation profile and anticipate the economic cost of rebuilding the capital stock, including the cost of internal resources when the country reaches the borrowing constraint. Households adjust to these anticipated costs by increasing private savings at the expense of consumption. However, per the model's parameters, internal private resources can fail to cover the full cost of reconstruction in cases of particularly extreme climate-related events.

The government holds the power to tax and spend. It mobilizes resources to invest in climate-change adaptation, and it internalizes the positive externalities generated by that investment. The model assumes that the government can provide resources to make the aggregate capital stock more resilient to climate change, including new capital investment that lowers the aggregate capital depreciation rate.[12] Specifically, we assume the public sector can limit the impact of climate change on the capital depreciation rate, though this comes at a fiscal cost. We also assume that adaptation spending reduces the depreciation rate not only of new capital but of all existing capital. This assumption does not weaken the generalizability of the results, as the alternative assumption that adaptation spending only affects the climate resilience of new capital would similarly reduce the impact of climate change on the overall capital depreciation

[10] We model the impact of global warming as an AR(1) process that direct affects the capital depreciation rate (see section 3.4). This general formulation is intended to capture the fact that capital depreciation is a function of temperature increases.

[11] This perspective is shared by [Semmler et al. 2018] but implemented in more detail through regime change techniques that allows to manage finite horizon behavior and the change in the structure of the economy incurred after the policy implementation.

[12] We assume that public spending on adaptation permanently reduces the depreciation rate, implying a negative relationship between the stock of adaptive capital and the depreciation rate. This is consistent with [Millner and Dietz 2015], who assume a negative relationship between the stock of adaptive capital and the damage function.

rate.

3.1 Households

Each cohort is represented by one household which maximizes the discounted lifetime utility by choosing consumption and leisure over the life cycle from entry to the labor market (at earliest age 15) to death (age 101). The households' life-cycle stream utility is given by

$$U = \sum_{t=s}^{s+T} q_{t-s} \frac{u\left[c_{t-s}, (e_t - l_{t-s})\right]^{1-1/\xi}}{1-\frac{1}{\xi}} \frac{1}{(1+\rho)^{t-s}}, \quad (1)$$

where T is longevity (101 years for all agents), ρ denotes the rate of time preference which is cohort invariant, and ξ defines the intertemporal elasticity of substitution. q_{ts} is the survival rate at age ts. c denotes consumption goods and l is the individual labor supply. Labor supply l is measured in efficiency units relative to the time endowment e. Households maximize utility in equation (1) w.r.t consumption and leisure subject to the dynamic budget constraint:

$$\begin{aligned} a_{t+1-s} &= \frac{1}{q_{t-s}} (1+r_t)\, a_{t-s} + (1-\tau_{l,t}) w_{t-s} h_{t-s} l_{t-s} + \\ & -(1+\tau_{c,t}) c_{t-s} - if_t + T_{t-s}, \end{aligned} \quad (2)$$

where a_{t-s} denotes the wealth at time t of the cohort born in the period s; r_t, w_{t-s} h_{t-s} l_{t-s}, T_{t-s} are respectively the interest rate, the post-tax labor income, and the social transfers at time t for the cohort aged $t-s$. τ_{lt} and $\tau_{c,t}$ respectively denote the exogenous tax rate on labor and consumption. if_t is a lump sum tax imposed by the government to reduce public debt as a precaution, for example in expectation of extreme events (see section 3.5). The optimal labor/leisure choice gives the following first order condition:

$$\frac{u_{l,t-s}}{u_{c,t-s}} = \frac{(1-\tau_{l,t})}{(1+\tau_{c,t})} w_t h_t. \quad (3)$$

The Euler equation for the intertemporal consumption choice is:

$$\frac{u_{c,t+1-s}}{u_{c,t-s}} = \frac{q_{t-s}}{(1+\rho)(1+r_{t+1})} \frac{1+\tau_{c,t-s}}{(1+\tau_{c,t+1-s})} \quad (4)$$

where u_c and u_l are marginal utility from consumption and leisure.

3.2 Firms

The production sector is characterized by a representative firm which uses a Cobb-Douglas technology with increasing returns to scale:

$$Y_t = TFP_t K_t^{\beta} L_t^{1-\beta} \quad (5)$$

where $0 \leq \beta \leq 1$ is the capital share, TFP_t the endogenous total factor productivity which combines the capital stock, K_t with the effective labor input $L_t = H_t N_t$, where H_t denotes human capital and N_t the aggregate hours worked.

The endogenous growth process is modelled linking physical capital per worker and human capital à la [Romer 1990] as follows:

$$TFP_t = \left(\frac{K_t}{N_t}\right)^g H_t^z, \tag{6}$$

where g and z denote the contribution of the production factors to TFP_t. In particular, g measures the capital-per-worker contribution in technology creation, and z is the contribution of human capital.[13]

Aggregate capital stock evolves according to

$$K_{t+1} = (1 - \delta_t)K_t + I_t, \tag{7}$$

where δ_t denotes the depreciation rate, which is affected by both gradual global warming and extreme events (see sections 3.4, 3.5).

Firm's profits are defined as

$$\pi_t = Y_t - (r_t + \tau_{k,t} + \delta_t)K_t - w_t L_t. \tag{8}$$

The first order conditions from profit maximization give the following wage and interest rates:

$$r_t = TFP_t \beta f'_K - \tau_{k,t} - \delta_t \tag{9}$$

$$w_t = TFP_t(1 - \beta)f'_L, \tag{10}$$

where f_K and f_L are the marginal productivity of capital and labor, respectively, and τ_k is the capital tax rate. The economy is price taker, i.e. $r_t = r_{rw,t}$, where rw denotes the rest of the world. This implies that equation (9) is used to determine the capital stock demand. Therefore, firms form their demand functions for capital and labor like in the constant returns to scale framework.

3.3 Government

The public sector consists of only three programs, namely the social security, education and adaptation to climate change. The government raises funds through public debt and taxes paid by households (at the exogenous labor income tax rate τ_l and VAT rate τ_c) and firms (at the capital tax rate τ_k). In order to manage the climate change adaptation strategy, the government uses two instruments: i) public investment I^{cc} to reduce the capital erosion due to climate change and ii) lump-sum tax on households' income If_t in order to raise funds that will be specifically used to reduce public debt (for example in anticipation of extreme climate change events). The government uses revenues to finance social transfers T_t to a number of beneficiaries

[13] Growth models, which include population projections, usually acknowledge the role of human capital and increasing return to scale. Indeed, the growth rate of the economy is proportional to the total amount of knowledge/ideas in the economy. An increase in the size of the population, other things equal, raises the average aggregate human capital and therefore leads to an increase in the per capita income. The inclusion of non-rivalrous input, such as human capital/ideas, linked to population dynamics, in the production function leads to increasing returns to scale ([Romer 1990]). Given the following production function $Y_t = H_t^{z+1-\beta} K_t^{g+\beta} N_t^{1-\beta-g}$, there are constant returns to scale in capital K_t and labour N_t, and increasing returns to human capital, where the degree of increasing returns is measured by $z + 1 - \beta > 0$ ([Jones 1999]), with $z > 0$ and $0 \leq \beta \leq 1$. In particular, we set $z = 0.43$, $\beta = 0.3$ and $g = 0.16$ (see section 4 for details). Human capital, H_t, in our model is exogenous, but not constant over time as it depends on exogenous population projections, as well as on education levels which are also exogenous. We introduce human capital in our analysis in order to better calibrate the model to a representative less developed country, typically less well educated than advanced countries.

ξ aged 65+, education and public investment for adaptation. The government issues new debt in order to finance the deficit:

$$\Delta B_t \;=\; r_t B_t - \tau_{l,t} w_t L_t - \tau_{c,t} C_t - \tau_{k,t} K_t - \Delta RF_t + r_t RF_t - d_t + \zeta_t T_t + I_t^{cc} + SC_t, \quad (11)$$

where r_t B_t denotes the interest repayment on public debt and $\Delta B_t = B_{t+1} - B_t$ denotes public debt change. $\tau_{l,t} w_t L_t$, $\tau_{c,t} C_t$, and $\tau_{k,t} K_t$ denote revenues from labor, consumption and capital. RF_t is the amount of revenue from household's income taxation used to build up a reserve fund. $\zeta_t T_t$ and SC_t indicate respectively the expenditure for social transfers and the public spending on education. I_t^{cc} denotes the public investment to adapt to climate change and d_t denotes resources from donors' grants. They are assumed to be earmarked to public spending, therefore they reduce the financing needs of the government and do not enter into households' and firms' budget constraints. We introduce donors' grants since they represent one of the main tools for remedial action, especially for developing countries.[14] They have been typically the main way used by international organizations and governments to provide financial relief after natural disasters. However, foreign aid is not a substitute for, but a complement to other forms of national safeguards from the consequences of natural disasters, such as a "rainy day" or reserve fund. In general, ex-post donor funds could lead to moral hazard by reducing incentives to implement ex-ante adaptation policies. In this sense, donors are an important element to include in our analysis.

The financial constraint on the international market for the home country is given by:

$$F_t \geq \bar{F}_t, \quad (12)$$

where F denotes the NFA position of the small country and $\bar{F}$ denotes the credit limit equal to 160% of GDP.[15] The net foreign asset position of the country affected by climate change is given by

$$F_t = A_t - K_t - B_t, \quad (13)$$

where A_t denotes aggregate internal saving. To manage future extreme events in order to avoid the occurrence of borrowing constraints, the government chooses the optimal level of If_t by maximizing the following utility function:

$$\max_{d_t, If_t, RF_{t+1}, B_{t+1}} W = \sum_i \Lambda_{t+i} \left[\frac{d_{t+1}^{1-\sigma_d}}{1-\sigma_d} - \frac{If_{t+1}^{1+\sigma_f}}{1+\sigma_f} \right], \quad (14)$$

where grant funds d_t increases the utility with the elasticity σ_d. The government discounts the future taking into account the average discount rate $\Lambda_t = \sum_{s=0}^{T} \frac{q_{t-s}}{1+\rho} \lambda_{t-s} \frac{P_{t-s}}{P_t}$ as a weighted average of the cohort stocastic discount factor. The utility maximization is subject to the constraint (14) and the following

$$\begin{aligned} RF_{t+1} &= (1 + r_{f,t}) RF_t + If_t && (15)\\ F_t &= A_t - K_t - B_t && (16)\\ F_t &\geq \bar{F}_t && (17)\\ d_t &\leq \bar{d}_t, && (18) \end{aligned}$$

[14] [Yang 2008] points out that official foreign aid increases significantly after disasters, especially in developing countries, where 73% of the damage caused by disasters is ultimately covered ex-post by aid inflows. Moreover, [Becerra et al. 2014] find that the median aid surge increases after a disaster but covers only a small fraction of estimated direct damages caused by disasters, thus requiring complementary sources of financing during the recovery phase, especially for most vulnerable countries.

[15] To calibrate the credit limit, we used the standard deviation of the NFA to GDP ratio of the emerging countries (excluding China, Source: IMF).

where RF_t is the debt reduction amount and F_t is the NFA position of the small open economy. The reserve fund RF_t is collected through lump sum taxation. It is a liquid fund kept in the form of numeraire good. It is assumed to be deposited abroad and receive an interest rate equal to the prevailing global risk free rate. The accumulated reserve fund RF is remunerated by an interest rate rf_t which differs from the interest rate r_t prevailing on the financial markets by a spread depending on its deviation from the target level of the reserve fund.[16] $F_t \geq \bar{F}_t$ denotes an occasionally binding constraint on the international financial markets. This implies that the country cannot get into foreign debt beyond the threshold $\bar{F}_t$. Similarly, $d_t \leq \bar{d}$ denotes the constraint on the availability of external grants. $\bar{d}$ is set to be equal to a certain percentage of GDP, $\bar{d} = \alpha_{id} Y_t$.

Whenever the constraint in equation (17) is binding, i.e. the country cannot get all the needed financial resources (F_t), donors intervene. In particular, when (17) is binding, from equation (16) we get a binding level for the public debt, $\bar{B}_t$. In this context, there are two possible cases: (i) the required donor grants are less than the maximum amount available ($d_t < \bar{d}_t$) and sufficient to cover the excess debt ($d_t = B_t - \bar{B}_t$) needed for reconstruction; (ii) the desired donor grants exceed the available amount $d_t > \bar{d}_t$, so they are bound at the maximum amount but are not sufficient to cover the total debt excess ($B_t - \bar{B}_t$).

$$d_t = \begin{cases} B_t - \bar{B}_t, & \text{if } F_t < \bar{F}_t \text{ and } d_t < \bar{d}_t \\ \bar{d}_t, & \text{if } F_t < \bar{F}_t \text{ and } d_t > \bar{d}_t \\ 0 & \text{otherwise.} \end{cases} \tag{19}$$

3.4 Gradual global warming factors

Let's assume that the small open economy faces both gradual warming factors, which tend to be global in nature, and idiosyncratic extreme events. The impact of gradual global factors occurs at a slow pace but more and more intensively over time (typically the rise in temperatures), thus progressively eroding the stock of physical capital. On the contrary, extreme events are sudden episodes (as hurricanes and tornadoes) that bring along a strong damage to the physical capital in a short period of time. The impact of both these factors/events is captured in the model via the depreciation rate of capital. In particular, the gradual process of global warming leads to a continuous smooth increase in the capital depreciation rate δ_t. For instance, starting from an initial value δ_0 equal to 3%, under the gradual warming scenario the depreciation rate δ_t progressively increases over time and stabilizes in the long run at a level $\bar{\delta}_t$ equal to 10%.

In particular, we model the gradual global warming process, which defines our baseline, as an exogenous AR(1) process:

$$m_t = \rho_{m,t} m_{t-1} + \epsilon_{m,t}, \tag{20}$$

where $\rho_{m,t} > 1$ indicates the persistence parameter that defines the time path of m_t, which represents the climate-related gradual factor. With a $\rho_{m,t}$ greater than unity, we assume that the climate event is a non-stationary process. $\epsilon_{m,t} > 0$ is the error term. The relationship between the climate-related gradual factor, m_t, and the rate of capital depreciation is given by the following dynamic logistic equation:

$$\delta_t(m_t) = \frac{(\bar{\delta} - \beta_k \bar{I}_t^{cc})\delta_0 e^{(a_0 m_t)}}{(\bar{\delta} - \beta_k \bar{I}_t^{cc}) + \delta_0 [e^{(a_0 m_t)} - 1]}. \tag{21}$$

[16] The interest rate rf_t is defined according to: $r_{f,t} = r_t + \iota \left[exp\left(\frac{RF_t}{Y_t} - \frac{\bar{RF}_t}{Y_t} \right) - 1 \right]$. This stabilizing mechanism allows for global equilibrium existence and stability as in [Schmitt and Uribe 2003]. Moreover, it ensures a positive reserve fund in the long run.

where a_0 is the damage transmission parameter. Equation (21) allows the depreciation rate δ_t to range between δ_0 and $\bar{\delta}_t$, if there is no public intervention ($\bar{I}_t^{cc} = 0$), that is, only the exogenous climate event m_t determines the dynamic of the capital depreciation rate. In this case, we assume two possible values for $\bar{\delta}_t$: moderate (10%) or high (20%). Assuming $\bar{\delta}_t = 10\%$, Figure 1 (panel a) shows how the depreciation rate evolves over a period of 100 years under different values of a_0.

In the model, however, the government can provide resources to make the aggregate capital stock more resilient to climate change. This can be achieved both by investing in new resilient capital and by using resources to make the existing capital more resilient. In practice, we assume that public investment can offset, at least partially, the impact of global warming m_t on the depreciation rate of capital δ_t and that public investment in adaptation has an irreversible effect, i.e. the improved resilience of the physical capital to climate change is permanent.

The government has a target level of adaptation investment, $\bar{I}_t^{cc}$, which is exogenously fixed as a share of GDP, and given by

$$\bar{I}_t^{cc} = \alpha_{cc} Y_t, \quad \alpha_{cc} = 1\%. \tag{22}$$

When adaptaion investment occurs, the depreciation rate of capital in equation (21) will increase up to $\bar{\delta} - \beta_k \bar{I}_t^{cc}$, with β_k indicating the degree of effectiveness of public intervention. This means that the depreciation rate will be affected by both the exogenous positive impact of the gradual global warming m_t and by the endogenous offsetting effect of public investment. The effectiveness of the public investment on the capital depreciation rate will depend on the calibration of β_k. Figure 1 (panel b) shows the depreciation rate under early adaptation and different values of β_k.[17]

3.5 Extreme weather events

Extreme events are defined as disasters that occurs suddenly causing a sharp increase in the depreciation rate of capital, in addition to the increase caused by gradual global warming. This implies that the resulting depreciation rate of capital after both gradual and extreme climate events, is given by

$$\delta_t^f = \delta_t + m_t^f, \tag{23}$$

where δ_t is the depreciation rate affected by the gradual global warming that evolves according to the logistic function in equation (21), and m_t^f is the additional transitory exogenous event. This implies that, when extreme event occurs at a given time t, the resulting depreciation rate entering the law of motion of capital (equation (7)) will be δ_t^f, which increases even more than in the gradual factors baseline and leads to a further slowdown in capital recovery. However, in the long-run, the capital depreciation rate will still converge to the $\bar{\delta}_t$ implicit in gradual global warming (or $\bar{\delta}_t - \beta_k \bar{I}_t^{cc}$ if there is a public investment in adaptation, see section 3.4), since the extreme event m_t^f will occur at a certain point in time, with a sharp increase in the depreciation rate, but will vanish rather quickly. It therefore has no permanent effects. Similarly to the gradual global warming, the extreme event evolves according to the following:

$$m_t^f = \rho_{f,t} m_{t-1}^f + \epsilon_{f,t}, \quad \rho_{f,t} < 1, \quad \epsilon_{f,t} > 0, \tag{24}$$

where the persistence parameter, $\rho_{f,t}$, will define the time path evolution of the extreme event and $\epsilon_{f,t}$ is the error term.

In case of extreme events, in addition to domestic resources and international market financing, the country can also rely on grants to deal with the damages caused by these events (see section

[17] The real GDP growth rate and the dynamics of the debt-to-GDP ratio consistent with these calibration exercises on a_0 and β_k are reported in the section 6.

3.3). Extreme events are important not only for the sharp decline in GDP and consumption, but also because they lead to prolonged funding limitations. When the intensity of events is extreme enough to bring the economy to hit the financing constraints, capital stock recovery could require long periods of time. This adverse loop could motivate a precautionary activation of fiscal policy (see section 5.3).

4 Calibration

The model that we use is an overlapping generation (OLG) model à la [Auerbach and Kotlikoff 1987], that is a model where agents can live a maximum of 101 years. These models have well-known properties, which are similar to those of the two-period OLG models, but provide more realistic dynamics. Indeed, they allow to calibrate the population dynamics using populations projections (we use the United Nations ones). Moreover, it is well known that analytical results can be obtained only for rather stylized versions of OLG models, typically those with agents living for two periods and with specific utility and production functions. As soon as more than two generations are taken into account, the analytical aggregation of consumer choices becomes difficult and model must be solved with numerical simulations ([Fehr and Thøgersen (2009)]). Therefore, the complexity of the model described in section 3 requires numerical simulation technique in order to explore the implications of economic relations underlying the model. Papers that use the Auerbach and Kotlikoff approach are [Rasmussen 2003], [Lugovoy and Polbin 2016] and [Kotlikoff et al. 2016]. In order to assess the robustness of our results to the choice of parameters, we provide a sensitivity analysis to the values of the most relevant parameters (in particular the tax rates, see section 6, and the depreciation rate, section 3.4)[18].

In the table 1 we report the main parameters of the model in the baseline. Calibration of the model parameters is based on the literature and on some targets built to match data. We set the intra-temporal elasticity of substitution ϵ to 1 in order to avoid trends in labor to consumption ratio as in [Auerbach and Kotlikoff 1987] and the inter-temporal elasticity of substitution, ξ to 0.5. We assume that total time endowment e grows at the human capital growth rate $\dot{h}$, that is $e_{t+1} = e_t(1 + \dot{h})$ as in [Borsch-Supan et al. 2006]. The human capital H_t is exogenous and computed as a Törnqvist index based on UN population projections and [Barro and Lee 2015] education data, thus it strictly depends on the population age structure.[19]

In line with [Vogel et al. 2014] we set ρ at 0.011 and the depreciation rate of physical capital δ to 0.03. We allow the capital share β equal to 0.3, in line with the values commonly assumed in the literature (0.3-0.4) ([Borsch-Supan et al. 2006]). For g and z we refer to the values used

[18] For example, [Auerbach and Kotlikoff 1987] go a great length in explaining the main characteristics of a closed economy version of the model using simulations to analyze both the effect of fiscal policy on capital formation and economic growth and the efficiency of alternative policies over time and across generations. For an open economy versions of a simulated OLG model see [Borsch-Supan et al. 2006] that take into account the important role of international capital mobility. For analytical results of an OLG model related to environmental issues see for example [Fodha and Seegmuller 2014] and [Kotlikoff et al. 2016].

[19] The human capital index is computed as:

$$H_t = \sum_i h_{i,t} = \frac{1}{2}\sum_{i=1}^{I} \Delta p_{i,t} \left(\frac{\lambda_t P_{i,t}}{\sum_{i=1}^{I} \lambda_{i,t} P_{i,t}} + \frac{\lambda_{t-1} P_{i,t-1}}{\sum_{i=1}^{I} \lambda_{i,t-1} P_{i,t-1}} \right), \quad (25)$$

where I is the total number of education types (i.e. 3 for primary, secondary, and tertiary) and $h_{i,t}$ the human capital per education level i which enters in the households labor income; $P_{i,t} = \sum_s P_{t-s,j,i}$ denotes people with education level i in year t; $\lambda_{i,t}$ is a quality index for education level i (i.e., 8 years of study for the primary level, 13 years for the secondary level, and 18 for the tertiary level). $\Delta p_{i,t}$ is the variation in the number of people with education i in year t compared with the base year t_0, i.e. $\Delta p_{i,t} = ln\left(\frac{P_{i,t}}{P_{i,t_0}}\right)$.

in [Catalano and Pezzolla 2016] based on the estimation of the long-run relation

$$\log(TFP) = g\log(K/N) + z\log(H) + \epsilon_{tfp}. \tag{26}$$

β_k and ρ_{cc} are set equal to 100 and 0.4 respectively in order to obtain a reasonable elasticity of the depreciation rate in response to adaptation policies. ρ_f is equal to 0.4 to allow for transitory extreme event.

ρ_m is equal to 1.01 to get an exponential trend in the gradual factor of climate change and a_0 to 0.66 to allow for the desired depreciation rate shape in response to climate change.[20] σ_d and σ_b are both equal to 2, as common in the literature.

5 Results

In order to facilitate the understanding of how the model works and the interactions between variables, we show, first of all, the dynamics of the main variables of interest in the absence of any climate shock. We evaluate the convergence of the model to the equilibrium when the transition phase is only driven by the demographic dynamics, which drive the economy towards a natural long-run growth path.

Second, we assess the effect of both the gradual global warming (baseline) and the extreme climate events and the relative effectiveness of preventive and remedial strategies in leveraging limited fiscal resources to adapt to climate change. In the model, both strategies reduce the capital depreciation rate, and greater investment in adaptation leads to a faster diffusion of climate-resilient technology across the entire capital stock. The model simulates the effects of these strategies on GDP and debt dynamics, when the necessary investment is financed by increasing the deficit. A high public debt level could prevent the country from accessing international capital markets even in the face of an extreme event, and in this circumstance donor grants could alleviate financial constraints.

5.1 Scenario without climate change

This section assesses the behaviour of a less developed economy in the absence of both gradual global warming and extreme events. The long-run dynamics of economic development depend on various factors such as the growth and structure of the population, its level of education (which determines human capital) and the level of innovation and technological progress. These drivers of long-run growth interact with each other through the structural relationships of the OLG model, which reflect their effects on the main macroeconomic variables. To put it simply, without climate change and public intervention for adaptation, the potential growth rate of GDP will depend only on demographic dynamics and technological progress, which affect the formation of labour and capital inputs and their productivity.

A greater stock of physical capital installed per worker and of human capital favours the use and accumulation of technology. Investments in physical and technological capital are the result of the consumer/saving capacity of domestic households that decide how to allocate their disposable income between consumption and saving (which represents future consumption) in a lifecycle perspective, forming expectations about income flows. Domestic savings and possible financial constraints on international markets will affect the country's overall financial resources and its ability to borrow on the international market to finance domestic investments.

[20] We calibrate the model to mimic the global change surface temperature as in the scenarios provided in the 5th IPCC assessment (AR5, [IPCC 2014]) that it is included in the variable m. We calibrate the "damage transmission parameter" a_0 in order to fit the logistic hypothesis for the damage function with final depreciation rate equal to 10% according to [Tsigaris and Wood 2016].

Household savings choices will be strongly influenced by population evolution and changes in its age distribution over time, as it is the working-age population that saves more and works, thus contributing to savings accumulation, investment capacity and productivity of the economy.

Less developed countries generally have a younger population and higher population growth rates than advanced countries, but on the other hand a lower level of human capital, which has a negative impact on the level of technological progress. The technological level will therefore be determined mainly by labour productivity and the stock of physical capital which is also generally low in these countries. This makes them potentially fragile in the face of climate events, especially extreme ones. A low level of initial physical capital and the arrival of an extreme climatic event can therefore prove fatal for a country with weak financial and technological conditions and for which physical capital is the main driver of growth. The dynamics of GDP growth follow the dynamics of the capital stock, which decreases over time due to the declining population, which implies a downward trend in human capital with negative consequences on total factor productivity and hence on long-term growth.

5.2 Using fiscal policy to adapt to gradual impact of climate change

In this and the following sections, we focus on a representative less developed country and assess the impact of climate change on its long-run growth. In general, climate events, whatever their severity, lead to a decrease in capital stock and GDP growth. We assess the effect of public investment in adaptation to reduce the negative impact of such climate events in the medium and long term.

Under the baseline scenario of a gradual global warming process, the depreciation rate of capital is assumed to increase gradually from 3 percent in 2018 to 10 percent in 2100. We assume that public resources can be used to contain the rise of the depreciation rate and that such spending would be deficit-financed. Adaptation spending, therefore, causes an initial increase in the debt stock. As the capital depreciation rate falls relative to the baseline, output increases and the debt-to-GDP ratio stabilizes. To illustrate the non-linear nature of the challenge posed by climate change and assess the impact of investment timing, we simulate both an early intervention and a late intervention. For illustrative purposes, the early intervention starts in 2018, while the late intervention starts in 2040. The simulations reveal that early investment is more effective than late investment in reducing the negative impact of gradual factors associated with climate change. We model the public intervention as an increase in adaptation spending of 1 percent of GDP per year starting in 2018 (early) or in 2040 (late).

The early intervention keeps the depreciation rate below the baseline level throughout the period (Figure 2a), and GDP remains above both the baseline level and the level of the late-intervention scenario (Figure 2c). Early adaptation spending initially boosts the public debt-to-GDP ratio about 7 percent above the baseline, but the ratio eventually falls below the baseline as faster growth increases the denominator (Figure 2b). Under the early-intervention scenario, 1 percent of GDP in annual adaptation spending permanently reduces the capital depreciation rate by about 5 percentage points.

The evolution of the debt-to-GDP ratio also depends on the intensity of the climate shock, but early intervention is still clearly superior to late intervention. If we assume that this rate reaches 20 percent (Figure 3a), even early adaptation spending cannot prevent a contraction in real GDP (Figure 3c), with deeply negative implications for fiscal sustainability (Figure 3b). However, the alternatives to early adaptation spending are far direr. The late intervention does less to counter the decline in real GDP, and debt dynamics worsen even more dramatically. These simulations highlight the importance of early intervention regardless of the pace and severity of climate change. Deficit financing would temporarily increase the debt-to-GDP ratio, but this effect would reverse toward the end of the period, as GDP growth would outpace the growth of the debt stock. In these scenarios we assume that a rising debt-to-GDP ratio does not increase government costs.

5.3 Using fiscal policy to adapt to extreme events associated with climate change

In addition to the gradual factors described above, climate change is increasing the frequency and severity of extreme events such as hurricanes, floods, and droughts. We model extreme events as sudden and temporary spikes in the capital depreciation rate, which represent large-scale damage to the capital stock (Figure 4). Under the baseline scenario of an extreme event, which assumes no adaptation spending, GDP falls after the event and then slowly recovers. We have calibrated the cost of the extreme event so that the country hits the borrowing constraint (equation (12)).

Even if adaptation spending increases the resilience of the capital stock and boosts GDP growth over the long term, the financing necessary to rebuild after an extreme event could exceed both a country's available domestic resources and its external borrowing capacity. To ease the borrowing constraint when an extreme event occurs, a country could reduce the public debt-to-GDP ratio in advance, establish a reserve fund in anticipation of extreme events (equations (15)), or rely on donor grants to partially finance the recovery process. The projections below assume that lump-sum taxes reduce the debt stock by 1 percent of GDP per year for ten years prior to the extreme event and that donor grants equal 1 percent of GDP per year for ten years following the extreme event. Relying on deficit financing, ex ante debt reduction/reserve funds, or donor grants leads to similar outcomes in term of GDP growth, but very different outcomes in terms of debt dynamics (Figures 6 and 7). The GDP growth trajectory is broadly similar under all three scenarios, but early adaptation spending, whether financed by borrowing or by debt reduction/reserve funds, dramatically reduces the debt-to-GDP ratio relative to the baseline by increasing the climate resilience of the capital stock. Ex ante debt reduction or the accumulation of reserve funds has a more positive impact on the debt-to-GDP ratio than deficit financing alone, as greater borrowing space or domestic resource mobilization enables the country to restore the capital stock more quickly after the extreme event. Reliance on donor grants has little effect on debt dynamics relative to the baseline, and since donor funding is only provided after an extreme event has occurred, GDP recovers more slowly than in cases where the government invested early in boosting the climate resilience of the capital stock (Figure 7). A strategy combining adaptation spending and ex ante debt reduction can achieve multiple goals. The following scenarios examine adaptation spending combined with ex ante debt reduction (Figure 8) and adaptation spending combined with both ex ante debt reduction and donor grants (Figure 9).

The availability of donor funding allows the country to restore its capital stock more rapidly and exit the recession with a higher level of GDP, but this difference is relatively modest. The impact of donor spending is dwarfed by the much larger impact of early adaptation investment, which increases the resilience of the capital stock, and ex ante debt reduction, which allows the country to more fully utilize international capital markets.

As noted above, our model includes no risk premium, and borrowing costs are independent from the debt level. However, this may be an oversimplification, as multiple real-world countries have experienced sovereign defaults. In addition, the model includes just one homogeneous good that is traded depending on the savings-investment balance, which implies that there are no nominal exchange-rate fluctuations and no possibility of exchange-rate crises. Due to the absence of risk premiums and unstable exchange rates, external borrowing in our model is likely safer and less costly than it is in the real world. The model's results highlight the importance of investing in climate-change adaptation before an extreme event occurs.

The results reflect the model's underlying assumptions about how climate change impacts the economy and how adaptation spending can counterbalance its effects. While we have tried to set realistic parameters (see section 4), these simulations are not empirically rigorous, and given the complexity of climate change and the model's degree of abstraction, the results should be interpreted with caution. Nevertheless, we believe the model includes all the core components necessary for this type of analysis: a private sector, a public sector, an external sector, a channel through which the effects of climate change are transmitted to the economy, borrowing constraints, and an economy that functions in general equilibrium. In addition, in the following section, we provide a sensitivity analysis in order to evaluate the robustness of our results.

6 Robustness

To assess the robustness of our results, we examine the sensitivity of the model to changes in the most relevant parameters, i.e. those affecting how the adaptation affects the debt-to-GDP. In particular, we explore changes in parameters a_0 and β_k which denote respectively the damage transmission parameter, the adaptation resilience parameter in eq. (30). We assess how these parameters affect the fiscal response when both an early intervention and a late intervention occurs in the case of gradual factors of climate change (Figure 2) and when an early adaptation occurs in case of extreme whether events (Figure 5).

Figure 10a shows the effect of changes in a_0 on public debt. A weaker (stronger) damage transmission parameter implies a faster (slower) recovery in the debt-to-GDP ratio, as a result of a lower (higher) depreciation rate (see equation (21)). Conversely, an increase (decrease) in β_k causes a stronger (weaker) impact of public investment on the capital depreciation rate that decreases more (less) than in the baseline as shown in Figure 10b. Both experiments shows that the conclusion on early actions benefits are robust with an overall change of about 80% in the value of the parameters.

We also evaluate the robustness of our results to a different calibration of tax rates when the government invests to adapt early to gradual global warming. Figure 11 shows that our results are relatively more sensitive to capital taxation. A reduction (increase) in the capital tax rate determines, ceteris paribus, a higher (lower) growth (Figure 11, Panel b) and therefore greater (lesser) availability of resources to finance reconstruction. Therefore, this will result in a larger (smaller) reduction in the capital depreciation rate compared to the baseline. Changes in the taxation of consumption and labour, on the other hand, produce similar results, closer to the baseline. The sensitivity analysis in Figure 12 shows how demographic projections affect GDP dynamics. Population is one of the main drivers of long-term growth, as underlined in the section 5.1. Through agents' savings and consumption choices, there is a greater or lesser growth depending on the age distribution of the population. This will in turn result in a greater or smaller investment in adaptation, in the presence of a larger and smaller population, respectively.

7 Implications for policymakers

Countries around the world have made limited and uneven progress in incorporating climate-related issues into their macroeconomic policy frameworks. Adaptation policies - especially preventive action - often face competing priorities, including social and economic development objectives, as well as the imperative of maintaining healthy fiscal and debt dynamics. Smaller and less-developed countries may assume that they lack the resources and capacity necessary to adapt to climate change, and they may instead choose to rely on donor assistance in the wake of extreme events. Donors in turn may reinforce this tendency by focusing on remedial action, such as disaster response and recovery, as opposed to preventive action. In addition, countries that embrace mitigation policies (such as the Paris Climate Accords) may be subject to moral hazard: policymakers may assume, incorrectly, that global mitigation efforts will effectively address the problem of climate change and become less inclined to invest in adaptation. Indeed, the available evidence indicates a clear bias in favor of remedial action over preventive action. Countries tend to stabilize budget revenues - for example, by mobilizing tax revenues - only after experiencing the effects of climate change, as opposed to saving revenues in advance ([Gerling 2017]). Governments may be especially likely to focus on remedial action if their fiscal policies are already procyclical. Although most governments make budgetary provisions for unforeseeable events - some even specifically designed to respond to natural disasters - the resources provided are often insufficient to cope with the exorbitant costs of climate change.[21]

Enhancing resilience to climate change requires a multifaceted strategy that includes both preventive and remedial action. Preventive action can support a higher long-term growth trajectory and greater macroeconomic stability by reducing the output and welfare losses associated with climate change. Preventive spending should be proportional to each country's capital stock, and therefore it should be no more onerous for smaller countries than it is for larger ones. Preventive actions include both investments in physical infrastructure and the creation of policy buffers designed to enhance resilience to shocks and ease borrowing constraints, including lower debt levels, stronger fiscal balances, and greater reserves.[22]

To fully leverage the support of the international community, adaptation strategies should be designed and implemented in close collaboration with bilateral development partners and multilateral institutions.

A number of tools should be used to inform and manage adaptation spending decisions. Cost-benefit assessment and decision tools such as real options and other robust decision making techniques should be used to select among the different types of adaptation spending. It is important also to incorporate adaptation spending into fiscal planning. Indeed, public financial management, budget and expenditure management should be used to better inform spending decisions. To this regard, the use of climate change public expenditure reviews, climate reporting in budget appropriations, and tools for mainstreaming climate issues into national development planning are all practices that should be further developed.

Expanding the use of risk-pooling mechanisms could strengthen fiscal resilience and accelerate post-disaster reconstruction. These mechanisms include private or sovereign insurance systems, multilateral safety nets, and regional catastrophic-insurance schemes. So far, participation in these mechanisms, and disbursements under them, have both been limited. However, membership in multilateral organizations can also be viewed as a type of risk-pooling mechanism.

8 Conclusion

This study contributes to the nascent literature on fiscal policy and climate-change adaptation. It uses a standard macroeconomic model to analyze the effectiveness of various adaptation

[21][Guerson 2016] assesses the potential effectiveness of a reserve fund in the case of Dominica based on several assumptions regarding the contribution rate to the fund (between 0.1 and 0.3 per cent of GDP yearly). The simulations show that a 0.2 percent contribution enables the debt-to-GDP ratio to fall below a safe threshold of 60 percent, while also leaving adequate fiscal space to cope with the expected impact of climate-related events.

[22][IMF 2016a] discusses the public finance and debt-management policies necessary to implement this type of preventive strategy. The IMF-supported program for the Solomon Islands represents practical application of the proposed framework ([IMF 2016b]). The World Bank's Comprehensive Debt and Development Framework (also called the "4-3-2 Initiative") proposed in 2012 for the Caribbean small states was a way of providing long-term solutions for growth and debt issues while at the same time addressing climate risks from frequent natural disasters in these countries. This translated into development plans in a number of Caribbean states thereafter.

strategies in addressing both the gradual factors associated with climate change and the impact of extreme climate-related events. The model's baseline scenarios of both gradual global warming and extreme events assume that if no action is taken to adapt to its impact, climate change will substantially reduce GDP, widen fiscal deficits, and increase debt stocks. The study's key finding is that early, preventive action to address climate change is always superior to late, remedial action. Waiting to act simply means that larger and costlier adjustments will be needed in the future. Increasing spending on adaptation early, before gradual factors have eroded the capital stock and before extreme events have damaged it further, can increase fiscal and economic resilience, reducing the need for future spending. Early action is necessary, but not sufficient, to manage extreme events associated with climate change. Small countries facing recurrent natural disasters may assume that investing in adaptation is futile, as the scale and frequency of extreme events require much larger investments than they could realistically finance. These countries could combine public adaptation spending with public debt reduction (or the accumulation of savings in a reserve fund), as investing in adaptation increases the resilience of the capital stock, while containing or reducing the debt burden improves financial sustainability and eases future borrowing constraints. To date, both national policymakers and the international community have tended to focus on remedial action over preventive action. Due to fiscal constraints and competing priorities, countries tend to underinvest in climate-change adaptation or build sufficient fiscal buffers to prepare for extreme events. No consensus has yet been reached regarding best practices for preventive action, and this uncertainty compounds incentives to delay investment in adaptation. Moral hazard and overreliance on international assistance further encourage remedial action over preventive action. However, as the social and economic impact of global warming continues to grow, further delay will likely necessitate much more extensive and costly interventions in the future, reducing long-run growth and destabilizing fiscal balances.

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9 Appendix

Figure 1: Logistic function for the depreciation rate of capital

(a) depreciation rate, different a_0, $\beta_k = 100$ **(b)** depreciation rate, different β_k, $a_0 = 0.66$

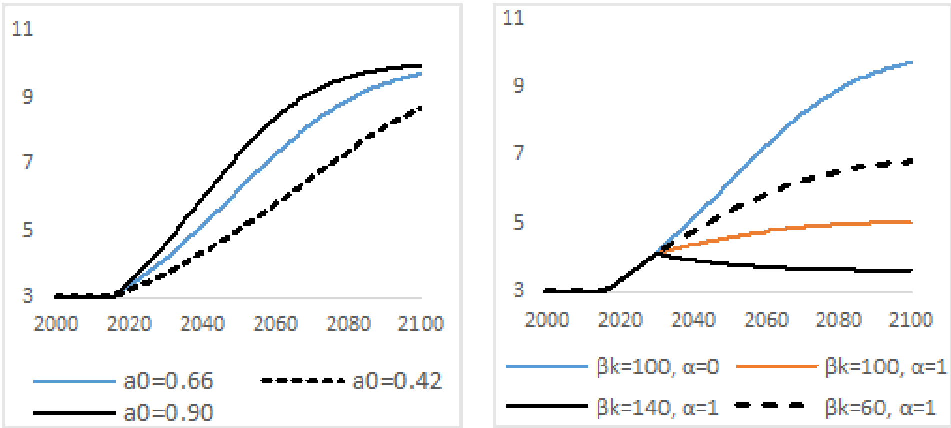


Figure 2: The Effects of Early and Late Investment in Climate-Change Adaptation on Capital Depreciation, Debt Dynamics, and Economic Output (Depreciation Rate Ceiling: 10%)

(a) Depreciation rate **(b)** Debt-to-Gdp (% from base) **(c)** Real GDP (2000=1)

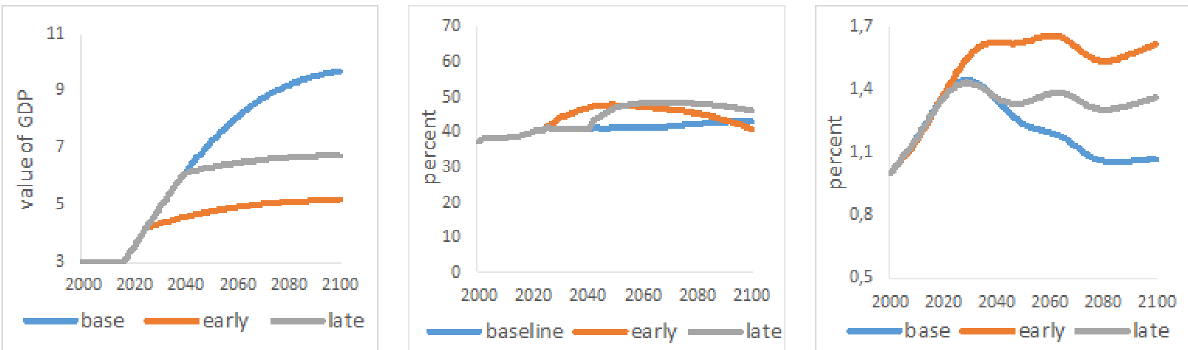


Figure 3: The Effects of Early and Late Investment in Climate-Change Adaptation on Capital Depreciation, Debt Dynamics, and Economic Output (Depreciation Rate Ceiling: 20%)

(a) Depreciation rate **(b)** Debt-to-Gdp (% from base) **(c)** Real GDP (2000=1)

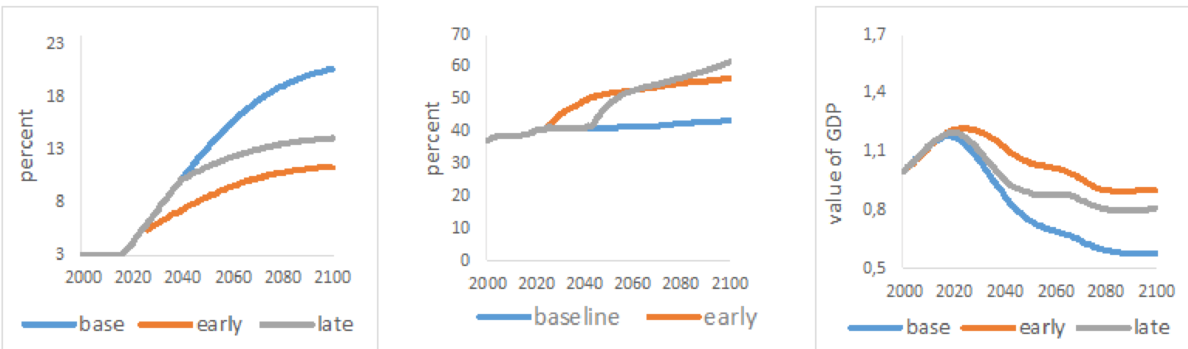


Figure 4: The Impact of Extreme Events on Capital Depreciation, Debt Dynamics, and Economic Output: Baseline Scenario

(a) Depreciation rate (%) **(b)** Debt-to-Gdp (% from base) **(c)** Real Gdp (2000 = 1)

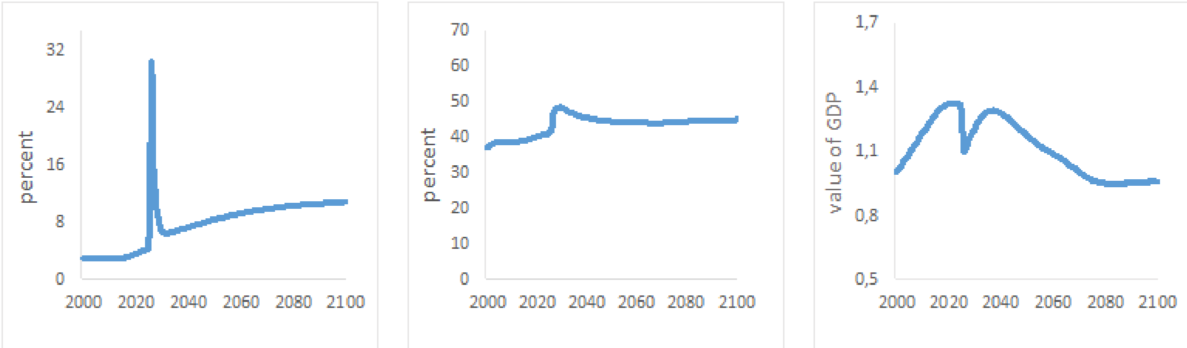


Figure 5: Adaptation to Extreme Events: Deficit-Financed Early Investment

(a) Depreciation rate (%) **(b)** Debt-to-Gdp (% from base) **(c)** Real GDP (2000=1)

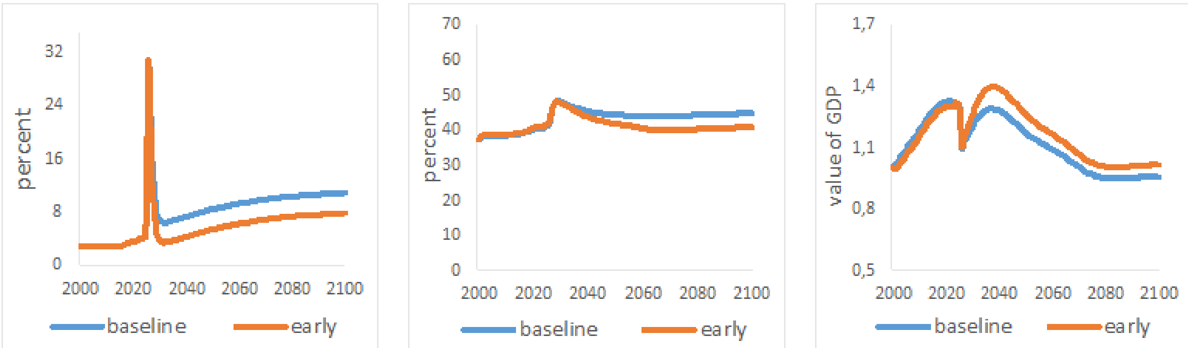


Figure 6: Adaptation to Extreme Events: Ex Ante Debt Reduction/Reserve Fund

(a) Depreciation rate (%) **(b)** Debt-to-Gdp (% from base) **(c)** Real GDP (2000=1)

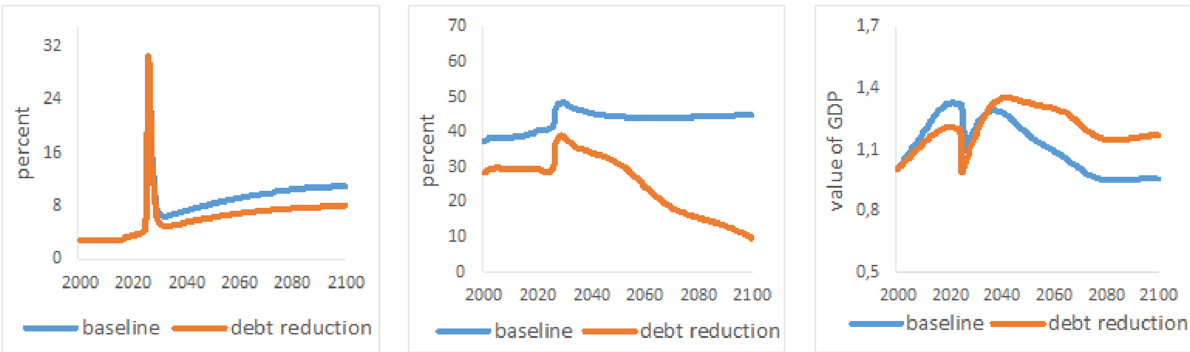


Figure 7: Adaptation to Extreme Events: Donor Grants

(a) Depreciation rate (%) **(b)** Debt-to-Gdp (% from base) **(c)** Real GDP (2000=1)

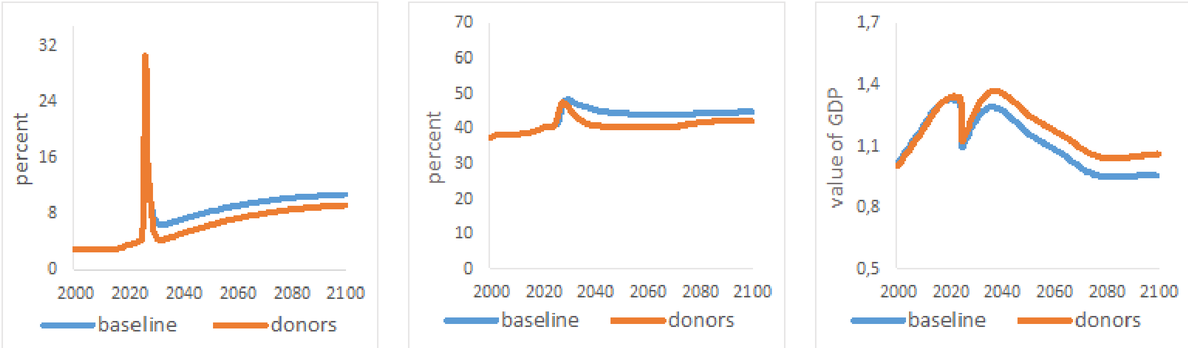


Figure 8: Extreme Events: Early Adaptation Spending Combined with Ex Ante Debt Reduction

(a) Depreciation rate (%) **(b)** Debt-to-Gdp (% from base) **(c)** Real GDP (2000=1)

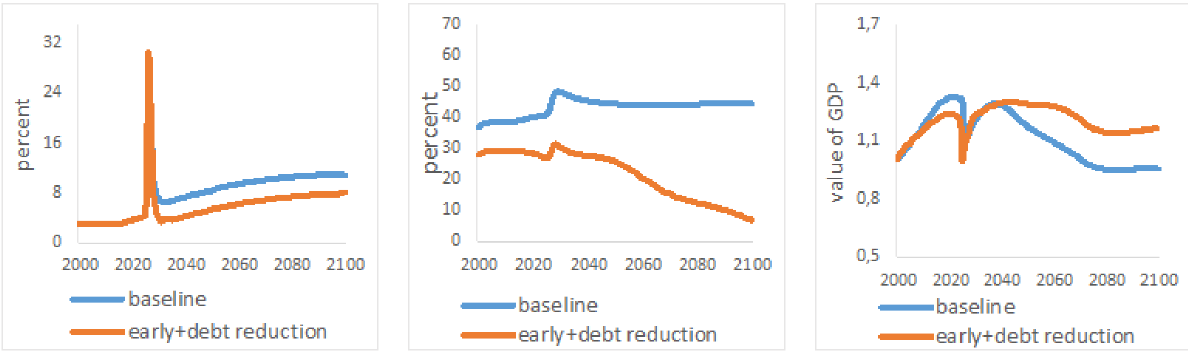


Figure 9: Adaptation to Extreme Events: Early Adaptation Spending Combined with Ex Ante Debt Reduction and Donor Grants

(a) Depreciation rate (%) **(b)** Debt-to-Gdp (% from base) **(c)** Real GDP (2000=1)

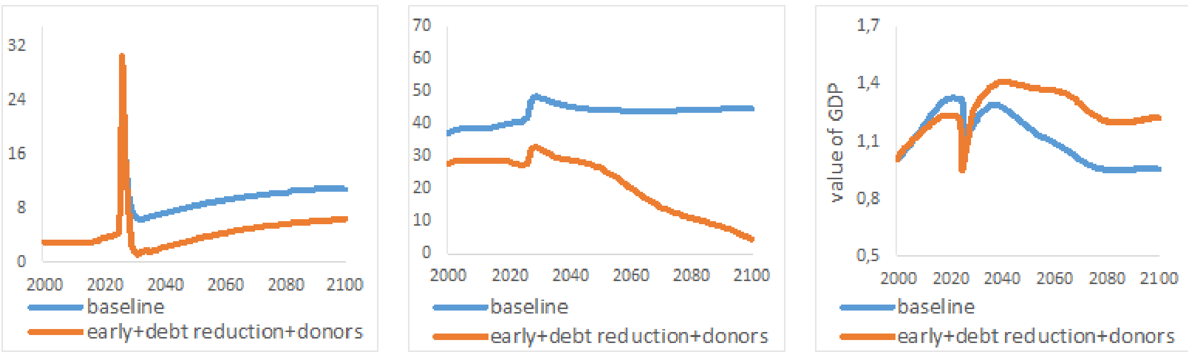
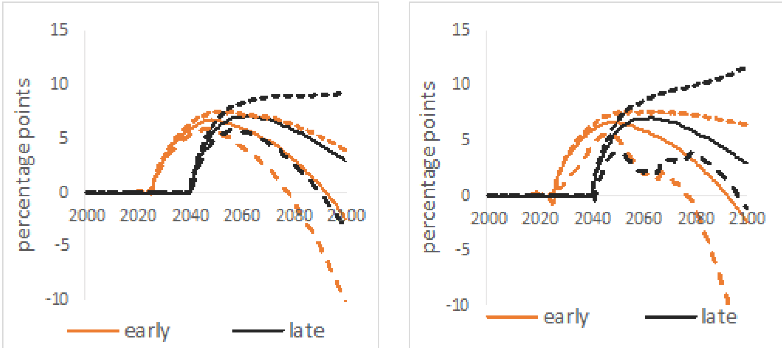


Figure 10: Early and late adaptation in the case of gradual impact of climate change: debt-to-GDP robustness check (changes to a_0 and β_k).

(a) a_0 **(b)** β_k



Note: Upper and lower intervals indicate respectively an increase and a decrease of parameter a0 with respect to the baseline ($a_0+ = 0.90$ and $a_0- = 0.42$). Similarly, β_k+ and β_k- denote respectively an increase and decrease of the adaptation resilience parameter with respect to the baseline ($\beta_k+ = 140$ and $\beta_k- = 60$).

Figure 11: Sensitivity of results to a different calibration of tax rates: case of early adaptation to gradual global warming

(a) depreciation rate (%) **(b)** Real GDP (2000=1)

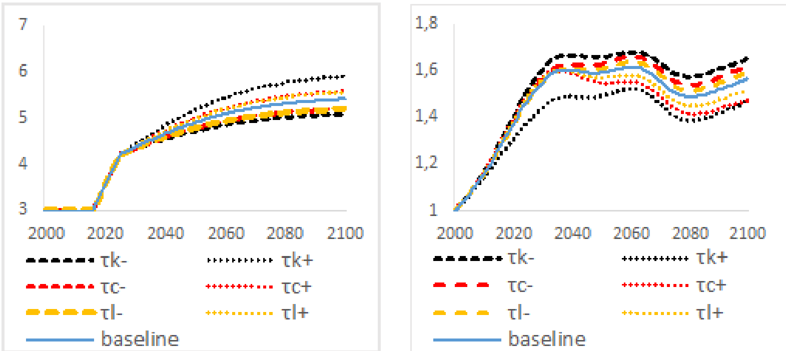
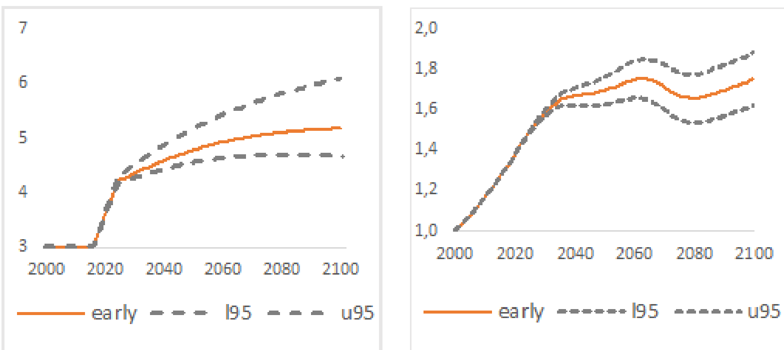


Figure 12: Sensistivity to probabilistic projections of total population

(a) depreciation rate (%) **(b)** Real GDP (2000=1)



Note: u95 and l95 denote respectively Upper 95 and Lower 95 percent prediction interval, 2015 - 2100, for a representative less developed countries. To build them, we use UN probabilistic projections for less developing countries, excluding China.

Parameter	Value	Description
ϵ	1	labor-consumption elasticity of substitution
ξ	.5	intertemporal elasticity of substitution
ρ	0.011	pure time impatience rate
$\bar{\delta}$	0.1-0.2	final steady state depreciation rate
δ_0	0.03	normal depreciation rate
β_k	100	adaptation adoption rate
ρ_f	0.4	extreme persistence shock
ρ_{cc}	0.4	early action investment policy persistency
ρ_m	1.01	exponential climate change rate
a_0	0.66	damage transmission parameter
α_{cc}	0.01	early action to - gdp policy
α_{id}	0.01	donors to - gdp policy
σ_d	2	intertemporal substitution elasticity
σ_b	2	intertemporal substitution elasticity
z	0.43	human capital contribution to TFP
g	0.16	capital-per-worker contribution to TFP
β	0.3	capital share
τ_l	0.25	labor tax rate
τ_c	0.2	VAT rate
τ_k	0.01	tax rate on capital

Table 1: Model Calibration