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Climate-Change Adaptation: The Role of Fiscal Policy

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Abstract

Climate change and natural disaster 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. 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 simplified 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, it 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.

The paper is organized as follows. Section 2 briefly discusses the literature on the macroeconomics 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.[1] 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]).[2] [Bosello 2008] extends the Ramsey-Keynes growth optimization model - used in the Nordhaus DICE model - to show that mitigation and adaptation, together with 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.[3]

[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 poli-

[1] 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]).

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

[3] 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]).

cies.[4] 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. Both AD-WITCH and AD-DICE[5] 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

[4]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]).

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

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 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 the impact of climate change by estimating its effect on the depreciation rate of physical capital. In this model, adaptation reflects the extent to which public policies reduce the negative influence of climate change on the capital depreciation rate.[6] The model describes 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 100, split in 3 education levels. Households save and supply labor based on market-determined factor prices (i.e., wages and interest rates), which households take as given.[7] 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.[8]

The small open economy trades and exchanges capital with the rest of the world. It is assumed that the domestic economy can borrow up to a given credit limit, which is set exogenously, and that it cannot build a negative net foreign asset position greater than 150 percent of its GDP. 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 is modelled as an effect on the depreciation rate of capital. We assume that climate change accelerates the depreciation of the capital stock via two types of effects: (i) "gradual

[6]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.

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

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

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.[9] 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. While in reality climate trends are subject to significant uncertainty, the baseline scenario assumes "perfect foresight". In other words, the evolution of gradual factors and extreme events is known to all agents in advance. Uncertainty regarding the pace and trajectory of these trends in the real world should, if anything, further reinforce our conclusions - as risk-averse agents will attempt to hedge against downside risks. Ex-post, however, adaptation spending could result in over-adaptation. This could happen if global warming is milder than expected.

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.[10]

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.[11] 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 rate.

The model also includes the response of the private sector to both gradual factors and extreme events. As the model assumes perfect foresight, 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.

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

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

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

[9]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.

[10]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

[11]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.

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:

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

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:

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

The Euler equation for the intertemporal consumption choice is:

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

where u_c and u_l are marginal utility from consumption and leisure. Finally, we show the main aggregation for labor input, wealth, lump-sum taxation and public education expenditure (see section 3.3):

$$L_t = \sum_{i\in I}\sum_{s=s_{0,i}}^{T_r} h_{t-s,i}l_{t-s,i}P_{t-s,i}, \tag{5}$$

$$A_t = \sum_{i\in I}\sum_{s=s_0}^{T} a_{t-s,i}P_{t-s,i}, \tag{6}$$

$$If_t = \sum_{i\in I}\sum_{s=s_0}^{T} if_t P_{t-s,i}, \tag{7}$$

$$SC_t = \sum_{i\in I}\sum_{s=s_0}^{T} sc_{t-s,i}P_{t-s,i}, \tag{8}$$

where $s_{0,i}$ is the year in which the cohort aged $t-s$ with education level i becomes employed; $P_{t-s,i}$ is the population aged $t-s$ in year t; T_r denotes the number of years required in year t to retire and obtain a pension benefit. The variable $h_{t-s,i}$ denotes the human capital associated to the education level i and SC, sc are respectively the aggregate and per capita education spending. Equation (7) is used to get the per capita cohort invariant taxation level $if_t = If_t/P_t$, once the aggregate level is optimally determined by the government (see equation (24)).

3.2 Firms

The production sector is characterized by a representative firm which uses a Cobb-Douglas technology with increasing returns to scale which combines the capital stock, K_t with the effective labor input L_t:

$$Y_t = TFP_t K_t^{\beta} L_t^{1-\beta} \tag{9}$$

where β is the capital share, TFP_t the endogenous total factor productivity. Aggregate capital stock evolves according to

$$K_{t+1} = (1-\delta_t)K_t + I_t, \tag{10}$$

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

Firm's profits are defined as

$$\pi_t = Y_t - (r_t + \tau_{k,t} + \delta_t)K_t - w_t L_t \tag{11}$$

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

$$r_t = TFP_t \beta f'_K - \tau_{k,t} - \delta_t \tag{12}$$

$$w_t = TFP_t(1-\beta) f'_L. \tag{13}$$

where f_K and f_L are the marginal productivity of capital and labor, respectively. The economy is price taker, i.e. $r_t = r_{rw,t}$, where rw denotes the rest of the world. This implies that equation (12) 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, while TFP_t increases due to both capital/labor ratio and human capital per worker externalities, as follows:

$$TFP_t = \left(\frac{K_t}{N_t}\right)^g H_t^z, \tag{14}$$

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 (see section 4 for further details).

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

$$\Delta B_t \quad = \quad r_t B_t - \tau_{l,t} w_t L_t - \tau_{c,t} C_t - \tau_{k,t} K_t - \Delta RF_t + r_t RF_t - d_t + \zeta_t T_t + I_t^{cc} + SC_t, \tag{15}$$

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. $\xi_t T_t$ 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. The financial constraint on the international market for the home country is given by:

$$F_t < \bar{F}_t, \tag{16}$$

where $\bar{F}$ denotes a multiple of the NFA of the country in the gradual global warming case, without adaptation. The net foreign asset position of the country affected by climate change is given by

$$F_t = A_t - K_t - B_t, \tag{17}$$

We assume that is 30% of GDP, i.e. 1.5 times the NFA in the baseline. In order to manage future extreme events in order to avoid the occurrence of borrowing constraints, the government chooses the optimal level of If_t by minimizing the following disutility function:

$$\min_{d_t, If_t, RF_{t+1}, B_{t+1}} -U = \sum_i \Lambda_{t+i} \left[\frac{If_{t+1}^{1+\sigma_f}}{1+\sigma_f} - \frac{d_{t+1}^{1-\sigma_d}}{1-\sigma_d}\right], \tag{18}$$

where grant funds d_t reduce the disutility associated with the climate event 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 disutility minimization is subject to the constraint (14) and the following

$$\begin{aligned} RF_{t+1} &= (1 + r_{f,t})RF_t + If_t & (19) \\ F_t &= A_t - K_t - B_t & (20) \\ F_t &\geq \bar{F}_t & (21) \\ d_t &\leq \bar{d}_t, & (22) \end{aligned}$$

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 as follows:[12]

$$r_{f,t} = r_t + \iota \left[exp\left(\frac{RF_t}{Y_t} - \frac{\bar{RF}_t}{Y_t} \right) - 1 \right]. \quad (23)$$

$F_t \geq \bar{F}_t$ 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, $\bar{d} = \alpha_{id} Y_t$. This allows to get the intertemporal optimal policy for taxation and donors:

$$If_t^{\sigma_f} = E_t \frac{1}{(1 + r_{t+1})} \left[If_{t+1}^{\sigma_b}(1 + r_{f,t+1}) + \theta_{1,t+1} - \theta_{2,t+1} \right] \quad (24)$$

$$d_t = \left[\theta_{1,t} + \theta_{2,t} \right]^{-\frac{1}{\sigma_d}}, \quad (25)$$

where $\theta_{1,t}$ and $\theta_{2,t}$ are the lagrange multipliers associated with the international and grant constraint, respectively. Equations (24) shows the optimal policy given the expected value of taxation If_t. This depends intertemporally on the long-run target If_T that is fixed to the arbitrary target level of GDP. Solving equation (24) recursively gives the discounted tax stream

$$If_t = E_t \left[If_T \prod_{j=1}^{T} \frac{1 + r_{f,t+1}}{1 + r_{t+1}} + \sum_{k=0}^{T} \prod_{j=0}^{k} \left(\frac{1 + r_{f,t+k}}{1 + r_{t+k}} \right)^j \left(\frac{\theta_{1,t+k+1} - \theta_{2,t+k+1}}{1 + r_{t+k+1}} \right)^{\frac{1}{\sigma_b}} \right]. \quad (26)$$

Equation (25) describes the intertemporal optimal policy for grants demand. Equation (23) describes the optimal reserve fund policy. Precautionary savings depend on the expected present value of the net benefit of receiving external grants when the country is rationed on the credit market. When the marginal utility of grants exceeds the disutility of being rationed, the moral hazard mechanism reduces the incentive to accumulate saving funds. We use equation (24) as an intertemporal transmission channel in order to anticipate signal of borrowing constraints through Lagrange multipliers θ_1 and θ_2 in equation (25). Whenever the constraint in equation (21) is binding, i.e. the country cannot get all the needed financial resources (F_t) and grants intervene. In particular, when ((21) is binding, from equation (20) we get a binding level for the public debt, $\bar{B}_t$, and from equation (15) we get the level d_t:

$$d_t = \begin{cases} B_t - \bar{B}_t, \text{ and } \theta_{1,t} = d_t^{-\sigma_d}, \ \theta_{2,t} = 0, & \text{if } F_t < \bar{F}_t \text{ and } d_t < \bar{d}_t \\ \bar{d}_t, \text{ and } \theta_{1,t} = (B_t - \bar{B}_t)^{-\sigma_d}, \ \theta_{2,t} = \bar{d}_t^{-\sigma_d}, & \text{if } F_t < \bar{F}_t \text{ and } d_t > \bar{d}_t \\ 0 \text{ otherwise.} \end{cases} \quad (27)$$

3.4 Gradual global warming factors

Let's assume that the small open economy faces both gradual global warming factors and extreme events. The impact of these factors/events is reflected in an increase in the depreciation rate of capital which

[12]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.

tends to increase over time. Gradual global warming factors define our baseline. In this scenario, in order to adapt to climate change, the government can increase public investment aimed at limiting the increase in the depreciation rate due to climate change. The gradual global warming process is modeled as follows:

$$m_t = \rho_{m,t} m_{t-1} + \epsilon_{m,t}, \quad \rho_{m,t} > 1, \quad \epsilon_{m,t} > 0, \tag{28}$$

where m_t represents all climate-related gradual factors related to increasing global temperatures that affect the economic activity. The target level of public investment to adapt to gradual global warming trends is exogenously fixed and given by

$$\bar{I}_t^{cc} = \alpha_{cc} Y_t, \quad \alpha_{cc} = 1\%. \tag{29}$$

We assume that public investment in adaptation is an irreversible good, i.e. once spent the improvement in physical capital resilience to climate change is never lost. Moreover, we assume a certain degree of persistence in physical capital accumulation, meaning that actual investment takes time to reach the targeted level. In fact, the actual level of investment, $\hat{I}^{cc}$, is gradually adjusted to the target according to a persistence parameter $\rho_{cc,t}$, thus reproducing the effect of capital adjustment costs:

$$\hat{I}_t^{cc} = \rho_{cc,t} \hat{I}_{t-1}^{cc} + (1 - \rho_{cc,t}) \bar{I}_t^{cc}. \tag{30}$$

In the presence of gradual climate factors, the depreciation rate of capital is assumed to follow a dynamic logistic equation:

$$\delta_{t+1}(m) = \delta_t(m) + a_0 \delta_t(m) \frac{\delta_t^k(m) - \delta_t(m)}{\delta_t^k(m)},$$

whose solution used in the model is:

$$\delta_t = \frac{\delta_t^k \delta_0}{\delta_0 + \left[\delta_t^k - \delta_0 exp(a_0 m_t)\right]}, \tag{31}$$

that allows the depreciation rate δ_t to range between δ_0 and δ_{tk} , where $\delta_t^k = \bar{\delta} - \beta_k \bar{I}_t^{cc}$, over the observed period. δ_0 is a parameter indicating the starting level of the depreciation rate, while captures the maximum level of the depreciation rate in absence of adaptation spending. We assume two possible values for $\bar{\delta}$: moderate (10%) or high (20%). β_k is an adaptation resilience parameter, and a_0 is the damage transmission parameter. In the baseline, investment in adaptation is financed by increasing the public deficit:

$$\Delta B_t = \Delta \bar{B}_t + I_t^{cc,*}, \tag{32}$$

where $\Delta \bar{B}_t$ without adaptation spending.

3.5 Extreme weather events

Extreme events are defined as disasters that occurs suddenly causing a sharp increase in the depreciation rate of capital with respect to the baseline (which incorporates gradual global warming factors). 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. 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. Similarly, to the gradual global warming, the extreme event evolves according to the following:

$$m_t^f = \rho_{f,t} m_t^f + \epsilon_{f,t}, \quad \rho_{f,t} < 0.4, \quad \epsilon_{f,t} > 0. \tag{33}$$

Therefore, the new depreciation rate of capital is given by

$$\delta_t^f = \delta_t + m_t^f. \tag{34}$$

Equation (34) implies that, when extreme event occurs, the depreciation rate increases even more than in the baseline and leads to a further slowdown in the capital recovery.

4 Calibration

In the table 1 we report the main parameters of the model. 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 2006]. The human capital H_t is exogenous and computed as a Törnqvist index based on ONU population projections and [Barro and Lee 2015] education data (see [Catalano and Pezzolla 2016]). Only when aptation is financed through a cut in education spending, the human capital is endogenously determined as follow

$$H_t = H_{t-1}(1 + g_{h,t}), \tag{35}$$

where $g_{h,t}$ is a function of education spending. 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 2006]). For g and z we refer to the values used in Catalano and Pezzolla (2016) based on the estimation of the long-run relation

$$\log(TFP) = g\log(K/N) + z\log(H) + \epsilon_{tfp}. \tag{36}$$

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 0.7 to allow for extreme event persistence.

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
β_d	0.1	capital adjstument cost
ρ_f	0.7	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

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.[13] σ_d and σ_b are both equal to 2, as common in the literature.

[13] 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].

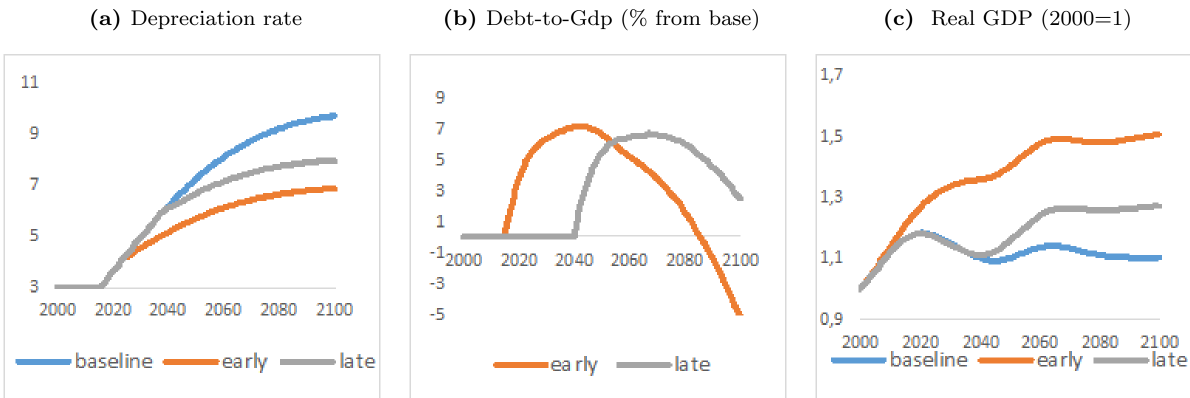
5 Results

This section assesses 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 also simulates the effects of these strategies on GDP and debt dynamics, including whether the necessary investment is financed by distortionary taxation, a reduction in other spending, or 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 Using fiscal policy to adapt to gradual impact of climate change

Under the baseline scenario, the depreciation rate of capital is assumed to increase gradually from 3 percent in 2018 to 10 percent in 2100. In the first adaptation scenario, 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 early intervention as an increase in adaptation spending of 1 percent of GDP per year starting in 2018, while in the late intervention the same increase begins in 2040. The early intervention keeps the depreciation rate below the baseline level throughout the period (Figure 1a), and GDP remains above both the baseline level and the level of the late-intervention scenario (Figure 1c). 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 1b). Under the early-intervention scenario, 1 percent of GDP in annual adaptation spending permanently reduces the capital depreciation rate by 4 percentage points. However, these results are highly sensitive to how the model is calibrated (see section 4).

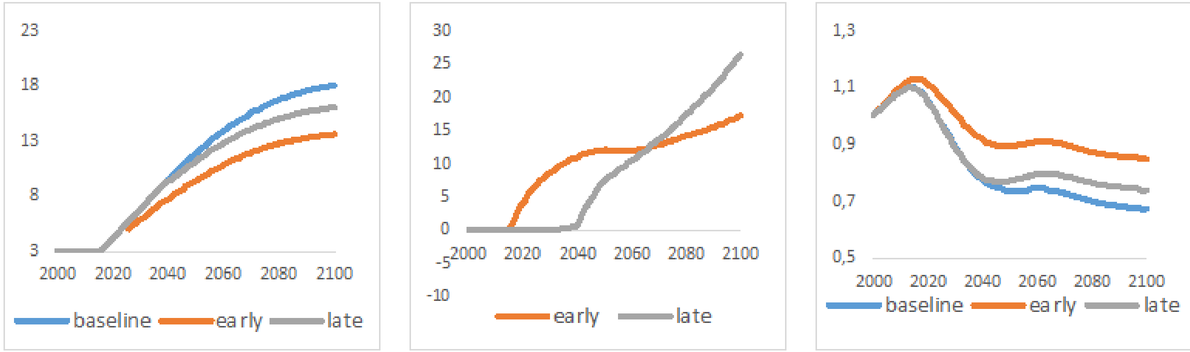
Figure 1: The Effects of Early and Late Investment in Climate-Change Adaptation on Capital Depreciation, Debt Dynamics, and Economic Output (Depreciation Rate Ceiling: 10%)



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. In the scenario presented above, climate change pushes the depreciation rate of capital to 10 percent by 2100. If we assume that this rate reaches 20 percent (Figure 2a), even early adaptation spending cannot prevent a contraction in real GDP (Figure 2c), with deeply negative implications for fiscal sustainability (Figure 2b). 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.

Figure 2: 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)



Financing investment in adaptation trough taxation or spending cuts is more efficient than deficit financing. Even if taxes are increased by the amount necessary to leave the budget balance unchanged, tax-financed adaptation spending is more sustainable than deficit-financed spending despite its distortionary impact (Table 2).

Table 2: Alternative Mechanisms for Financing Investment in Adaptation to Gradual Climate Factors: Impact on Economic Output (Real GDP, deviation from the baseline projection)

Factor	Instrument	2020	2030	2040	2050	2060	2070	2080	2090	2100
Gradual	Debt	4.8	15.6	21.4	24.8	28.0	28.9	30.6	32.9	34.1
	Capital	17.6	27.1	34.4	39.1	43.4	46.6	50.2	53.6	55.3
	Consump.	11.5	24.4	33.4	39.1	44.7	48.6	52.5	56.1	57.9
	Labor	11.0	23.3	31.9	37.5	42.8	46.5	50.2	53.7	55.4
	Education	-11.7	-24.7	-33.9	-39.7	-45.3	-49.3	-53.2	-56.9	-58.7
	Transfers	11.7	24.7	33.8	39.7	45.3	49.3	53.2	56.8	58.9

Table 3: Alternative Mechanisms for Financing Investment in Adaptation to Gradual Climate Factors: Impact on Debt Dynamics (Debt-to-GDP ratio, % deviation from the baseline projection)

Factor	Instrument	2020	2030	2040	2050	2060	2070	2080	2090	2100
Gradual	Debt	3.2	5.7	6.2	5.7	4.3	2.9	1.0	-1.6	-4.9
	Capital	-5.0	-6.5	-7.9	-8.7	-8.9	-9.8	-10.7	-11.2	-11.8
	Consump.	-1.6	-3.3	-4.6	-5.4	-5.7	-6.5	-7.2	-7.8	-8.2
	Labor	-1.6	-3.1	-4.4	-5.1	-5.5	-6.2	-6.9	-7.4	-7.9
	Education	1.6	3.3	4.6	5.4	5.7	6.5	7.2	7.8	8.3
	Transfers	-1.5	-3.5	-4.5	-5.3	-5.7	-6.4	-7.2	-7.7	-8.2

This result continues to hold even under the strong assumption that a rising debt-to-GDP ratio does not increase government borrowing costs. Deficit financing has a less-positive effect on GDP due to the consumption-smoothing behavior of households, both in the case of gradual factors and extreme events. Because financing adaptation costs through taxes or spending cuts leaves households worse off, they compensate by increasing the labor supply, boosting economic activity.

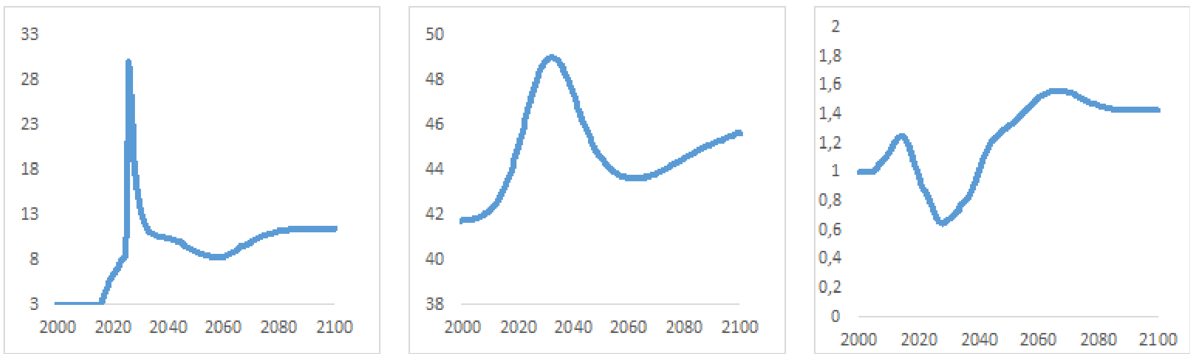
Because consumption taxes tend to be less distortive than taxes on labor and capital, increasing consumption taxes to finance adaptation spending has a less-negative impact on GDP. While capital and labor taxes have similar long-term effects, capital taxes have a more positive short-term impact on GDP, as the rigidity associated with capital-adjustment costs limits the extent to which higher capital taxes reduce investment. By contrast, cutting education spending negatively affects human capital, depressing productivity and pushing the GDP growth rate well below the baseline. Using capital taxes to finance investment in adaptation also has positive implications for debt dynamics. Capital taxes are consistently associated with the lowest debt-to-GDP ratios across the entire projection period. 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. Financing adaptation expenditures through consumption taxes, labor taxes, and reduced fiscal transfers would have comparable effects on debt dynamics. Each instrument would reduce household income, and households would compensate by boosting the labor supply. Finally, financing adaptation expenditures by cutting education spending would push the debt-to-GDP ratio above the baseline over the entire projection period (Table 3).

5.2 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 3). Under the baseline scenario, which assumes no adaptation spending, GDP falls substantially after an extreme event and then slowly recovers. This pattern reflects two key specifications of the model: (i) we have calibrated the cost of the extreme event so that the country hits the borrowing constraint, and (ii) we assume that adjustment costs slow the reconstruction of the capital stock.

Figure 3: 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)



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, 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. 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 (Figure 4 and Figure 5). 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 6). 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 7) and adaptation spending combined with both ex ante debt reduction and donor grants (Figure 8).

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

Figure 4: Adaptation to Extreme Events: Deficit-Financed Early Investment

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

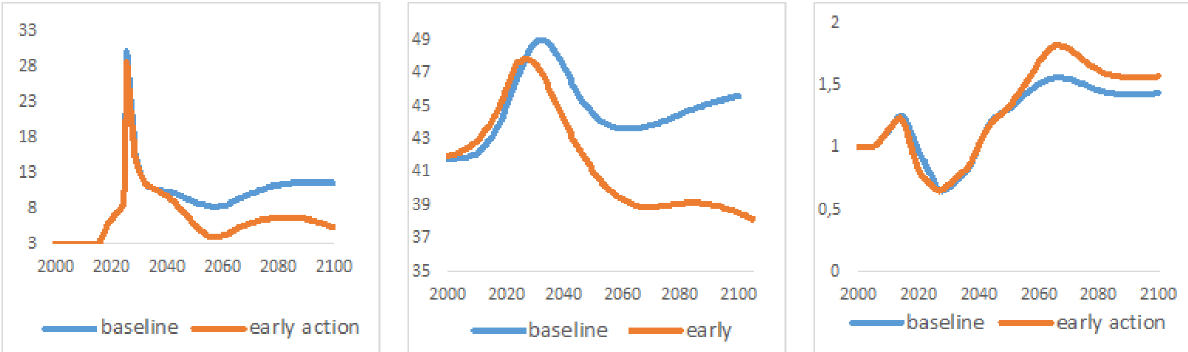


Figure 5: Adaptation to Extreme Events: Ex Ante Debt Reduction/Reserve Fund

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

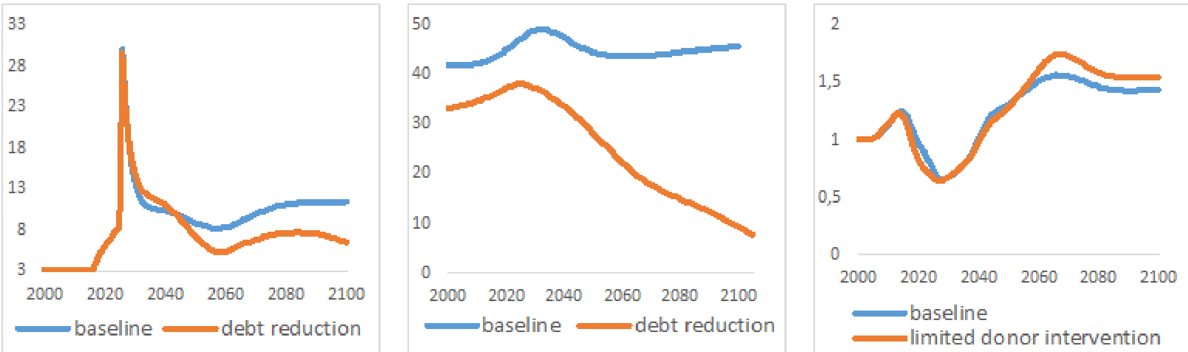
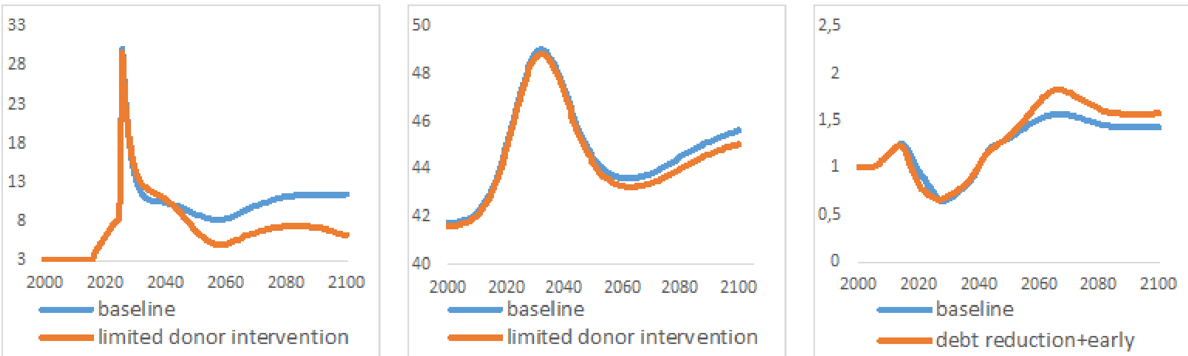


Figure 6: Adaptation to Extreme Events: Donor Grants

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



resilience of the capital stock, and ex ante debt reduction, which allows the country to more fully utilize international capital markets.

Financing investment through tax increases or expenditure cuts in other areas appears to be more effective than deficit financing. Every alternative financing scenario results in a lower debt-to-GDP ratio and higher final GDP level-with the exception of cuts to education spending, due to their negative effect on human-capital formation (Table 4). Financing mechanisms other than deficit spending (or cuts to education spending) offer even greater advantages in the case of extreme events than they do in the case of gradual factors. Coping with extreme events requires a large amount of funding in a short amount of time, which causes the country to reach its borrowing limit in the capital market. Financing adaptation spending via taxes or spending cuts in other areas reduces the need for external borrowing and, per the model's calibration, enables the country to remain within its borrowing limit.

Figure 7: 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)

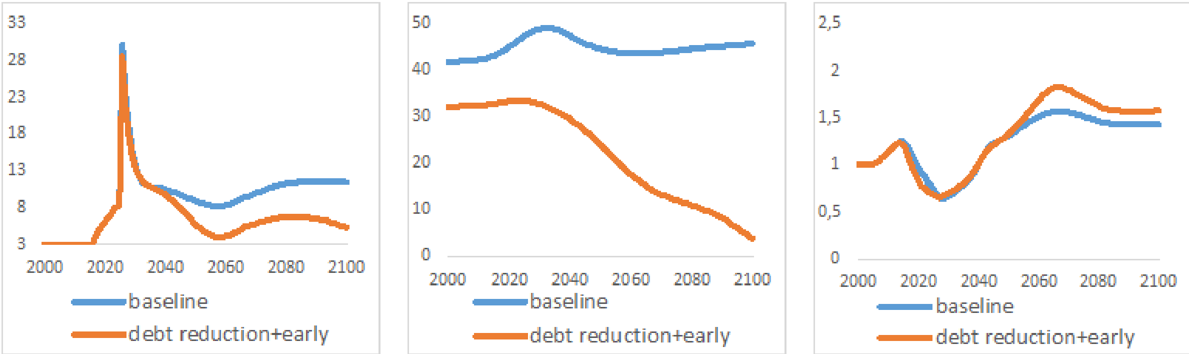


Figure 8: Adaptation to Extreme Events: Early Adaptation Spending Combined with Ex Ante Debt Reduction and Donor Grants

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

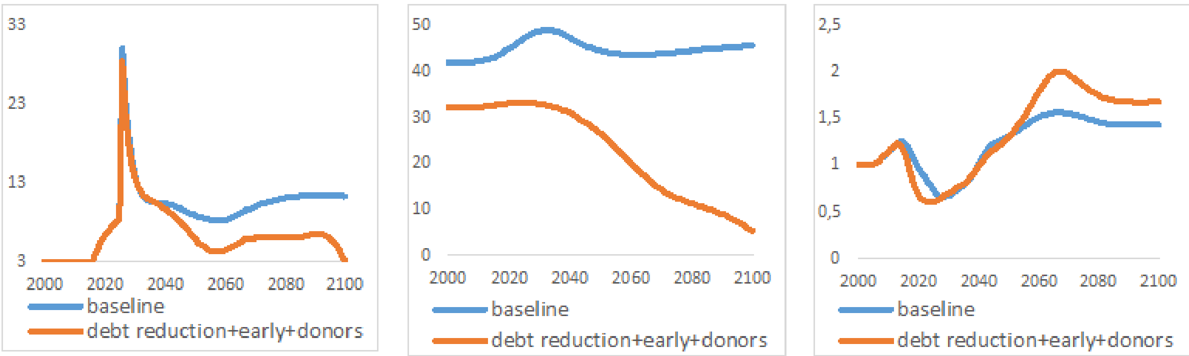


Table 4: Alternative Mechanisms for Financing Investment in Adaptation to Extreme Events: Impact on Economic Output (Real GDP, % deviation from the baseline projection)

Factor	Instrument	2020	2030	2040	2050	2060	2070	2080	2090	2100
Extreme	Debt	-5.0	-9.0	5.0	19.0	42.0	52.0	39.0	32.0	29.0
	Capital	-4.0	-9.0	3.0	16.0	42.0	73.0	90.0	98.0	77.0
	Consump.	-4.0	-10.0	-2.0	5.0	24.0	51.0	73.0	104.0	114.0
	Labor	-6.0	7.0	19.0	21.0	36.0	49.0	40.0	64.0	73.0
	Education	-3.2	-8.0	-1.6	-4.0	-19.2	-40.0	-57.6	-80.8	-87.2
	Transfers	-6.0	4.0	24.0	35.0	42.0	56.0	42.0	85.0	77.0

Table 5: Alternative Mechanisms for Financing Investment in Adaptation to ExtremeEvents: Impact on Debt Dynamics (Debt-to-GDP ratio, % deviation from the baseline projection)

Factor	Instrument	2020	2030	2040	2050	2060	2070	2080	2090	2100
Extreme	Debt	6.9	5.9	0.2	-3.9	-8.4	-10.5	-8.9	-7.7	-7.2
	Capital	7.9	4.6	-0.9	-5.0	-9.9	-14.6	-17.9	-19.4	-17.2
	Consump.	6.7	4.3	0.9	-1.9	-6.5	-11.8	-16.2	-20.2	-21.4
	Labor	2.3	-2.9	-6.0	-6.9	-9.2	-11.8	-11.2	-15.6	-28.2
	Education	6.0	3.9	0.8	1.7	5.9	10.6	14.4	17.8	18.8
	Transfers	2.4	-2.0	-7.2	-9.9	-10.3	-12.8	-11.4	-18.3	-30.3

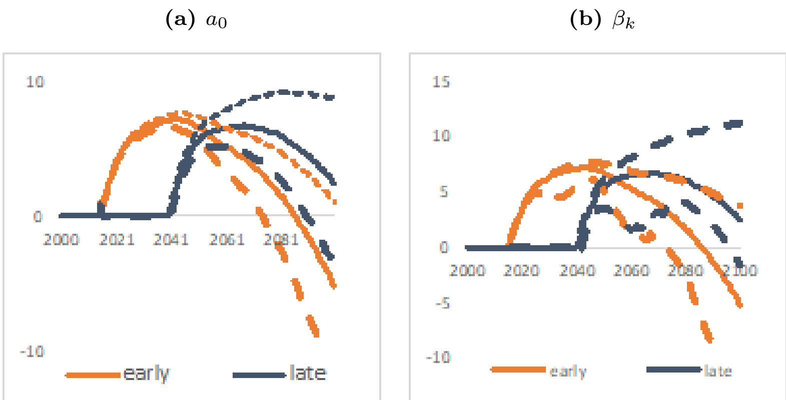
Moreover, external borrowing may be costlier than we have assumed, further underscoring the superiority of taxation or spending cuts in other areas over deficit financing. As noted above, our model includes no risk premium, and borrowing costs are independent from the debt level. However, this may be 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. While maintaining a low debt level or saving assets in a reserve fund would facilitate post-disaster reconstruction, these measures would do nothing to strengthen the resilience of the capital stock ex ante. However, if a country invests in adaptation prior to an extreme event, its capital stock becomes more resilient to the effects of climate change, and the depreciation rate after the event is lower than it would be otherwise. Capital-adjustment costs slow reconstruction, even given abundant fiscal resources, and the less reconstruction is necessary, the faster the economy recovers.

Finally, it is important to stress that these are illustrative simulations and that the results strictly depend on the calibrated parameter values. In other words, 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.

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 1) and when an early adaptation occurs in case of extreme whether events (Figure 4). Figure 9a shows the effect of changes in a_0 on public debt. A weaker (stronger) damage transmission

Figure 9: 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).



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 $\beta_k- = 60$).

parameter implies a faster (slower) recovery in the debt-to-GDP ratio, as a result of a lower (higher) depreciation rate (see equation (31)). 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 9b. Both experiments shows that the benefits of the conclusion on early actions benefits are robust with an overall change of about 80% in the value of the parameters.

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.[14]

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.[15]

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.

[14] [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.

[15] [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.

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 revenue and expenditure strategies in addressing both the gradual factors associated with climate change and the impact of extreme climate-related events. The model's baseline scenario assumes 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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