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Macroeconomic Effects of Climate Change in an Aging World

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ABSTRACT: Climate and demographic changes are two major long-term trends that are evolving simultaneously. The global population is aging, while climate change is increasing the frequency and severity of weather-related disasters and lowering productivity. This paper examines the macroeconomic effects of these three changes in a common framework. Simulation results suggest that while aging drags down the real interest rate, climate change puts upward pressure on the real interest rate and inflation. As climate change intensifies, it will be the dominant factor shaping the macroeconomic variables. This results in higher inflation and a higher debt-to-GDP ratio, requiring tighter fiscal and monetary policies. The results further suggest that economic uncertainty induced by climate change amplifies these effects of climate change.

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WORKING PAPERS

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Contents

1. Introduction

Two simultaneous long-term trends are reshaping the world economy. On the one hand, climate change has become one of the defining challenges of modern times. Rising global temperatures and shifting and intensifying weather-related events are posing challenges to all countries. The frequency and severity of climate-induced natural disasters are also on the rise. Rising global temperatures are lowering productivity. On the other hand, the world economy is going through a structural shift posed by demographic changes. While the global population is expected to reach 8 billion in 2022 (and rise to 9.7 billion in 2050, and 10.4 billion in 2100), there has been a slowdown in workers' population growth and a substantial increase in longevity. These trends are expected to continue at least until the end of the century. Aging is more accentuated in advanced economies, while many developing economies, particularly in Sub-Saharan Africa, are not projected to face an aging population until much later this century (UN population projections, 2022).

These two trends, and their interaction, will have profound macroeconomic implications for both countries and the global economy. Unmitigated climate change will lead to increasingly costly economic and financial costs and hinder development (for example, IMF (2021)). The unpredictable nature of climate-induced natural disasters and the associated uncertainty is making economic decisions more complex. Many authors believe that demographic changes may have had profound effects on the key macroeconomic variables, especially on the equilibrium real interest rate (see, e.g. Miles (1999), Bean (2004) and Bernanke (2005)).[4][5]

Climate change and demographic trends have so far been studied separately,

[4] There is growing literature aiming to quantify the macroeconomic effects of aging population (see, e.g., Kara and Von Thadden(2016), Lunsford and West (2019) and Gagnon et al. (2021).

[5] In a recent paper Acemoglu and Restrepo (2021) show that aging is one of the most important factors leading to the adoption of robotics and other automation technologies. Potentially, automation could offset the negative impact of aging on productivity. However, the direct effect of such automation on the equilibrium interest rate may be limited, as aging mainly affects the equilibrium interest rate through its effects on savings. As workers expect to live longer, they save more, leading to lower interest rates.

but their simultaneous evolution brings about an important question: what are the macroeconomic implications of climate change in an aging world? This paper aims to provide an answer to this question. To do so, we employ a new Keynesian Dynamic Stochastic General Equilibrium (DSGE) model that is rich enough to capture the ongoing and projected demographic changes. We then use the model as a laboratory to understand the macroeconomic implications of climate-related natural disasters. This approach allows us to examine the macroeconomic implications of the two changes simultaneously within a common framework.

A key difference between our model and the standard DSGE model is that, following Gertler (1999), we allow for heterogeneity in the age structure of the population.[6] In the model, there are two groups of individuals: workers and retirees. Workers' population grow at a time-varying rate and there is a random transition from work to retirement. Retirees face a time-varying random probability (i.e. life expectancy) from retirement to death. The model further assumes that workers and retirees differ in the level and composition of wealth. Workers have labor income, while retirees consume from their savings. These differences give rise to heterogeneity in the marginal propensity to consume. With a plausible calibration, the marginal propensity to consume for retirees is higher than that of workers. Reflecting the overlapping generations structure, the dynamics of the model are affected by the fiscal policy, which is by construction non-neutral. The rest of the model is standard New Keynesian with capital accumulation.

We first calibrate the model according to the demographic estimates and projections compiled by the United Nations for advanced economies.[8] This choice is predicated on the idea that advanced economies play a greater role in shaping global

[6][7]. Other papers that employ the framework by Gertler (1999) include Ferrero (2010) and Kilponen et al. (2006).

[8]Specifically, we use the "more developed regions" classification by the UN population projections, which are available at http://esa.un.org/unpp. This classification includes 47 countries: 27 EU countries, 4 EU candidate countries (Albania, Montenegro, Serbia and Bosnia and Herzegovina), Japan, Belarus, Channel Islands, Iceland, North Macedonia, Norway, Republic of Moldova, Russian Federation, Switzerland, Ukraine, United Kingdom, Canada, US, Australia, New Zealand, Australia and New Zealand.

macroeconomic variables, especially interest rates. A change in global interest rates would affect economic growth in developing economies. We then study the macroeconomic effects of natural disaster shocks. We model such disasters as persistent stochastic shocks that destroy a fraction of the economy's capital stock. Using our model, we also study the macroeconomic implications of uncertainty regarding the magnitude of disaster shocks. The trend dimension of climate change is captured through a change in productivity.

We first study the macroeconomic effects of demographic changes. We find that the impact of demographic changes is similar to that of a positive demand shock. Our simulation results suggest that higher life expectancy is the dominant factor in aggregate dynamics. Higher life expectancy induces workers to save more, lowering the real interest rate. Longer life spans lead to higher consumption, crowding out investment. All of these cause higher inflation.

The macroeconomic implications of disaster shocks are similar to those of cost-push shocks. By assumption, the disaster shock wipes out a fraction of the capital stock, bringing about a fall in consumption and output. With the decrease in the capital stock, the rental cost of capital and, consequently, the real interest rate go up. A higher real interest rate increases inflation.[9] The shock will also give rise to a higher debt-to-GDP ratio.

We also find that uncertainty regarding the magnitude of the disaster shocks amplifies the effect of disaster shocks, making the trade-off induced by natural disasters harder to mitigate. With uncertainty shocks, output falls more and inflation increases more. The key to understanding the effects of uncertainty is to understand that workers and firms act in a way to protect themselves against such uncertainty. Workers increase their savings, lowering consumption and output. Similarly, firms set higher markups to protect their prices and profits.

Finally, we find that a decline in productivity induced by climate change leads

[9] Our model's prediction that there is a negative relationship between inflation and the growth rate of capital is consistent with the empirical evidence provided by Fischer (1993), and Barro (1995).

to lower output, but the productivity shock does not have as significant an effect as the disaster shock. This is because workers respond to the shock by working more, and the increase in labor supply and the fall in real wages appear to compensate for the fall in productivity, limiting the damaging effect of the shock on the economy.

Overall, the results suggest that the effects of climate change are likely to dominate the effects of population aging, resulting in higher real interest rates, inflation, and debt-to-GDP ratios. These effects are compounded in developing economies requiring more capital. The response to climate uncertainty also leads to a higher-than-optimal price level, magnifying the impact of climate change. For workers, these disruptions translate into a longer work life to maintain consumption spending.

There are four main policy implications of these findings. First, containing the physical costs and productivity loss from climate change requires a renewed emphasis on mitigation policies, which rely primarily on the largest polluters to deliver on the Paris objective of containing global temperatures to within 1.5 to 2 degrees Celsius. Even with mitigation, due to gases locked in the atmosphere, the cost of natural disasters and the associated uncertainty will weigh on economic prospects. Second, adaptation is necessary to contain the effects of climate change in all countries. Still, the need is more pressing in developing countries, where the urgency to protect capital due to existing vulnerabilities is magnified by demographic developments. Third, climate change will contribute to inflationary pressures through shocks and uncertainty, which in turn implies that central banks need to reconsider the equilibrium interest rate to incorporate these new dimensions. It will also require a tightening of fiscal policy to ensure debt-to-GDP ratios remain aligned with the target. Finally, there are significant distributional effects that arise. In the absence of workers' ability to cushion the impact of the shocks by adjusting the labor supply, other social safety nets need to be considered to protect workers during retirement.

This paper is closely related to the paper by Burke et al. (2017) and Cantelmo, Melina and Papageorgiou (2019). Burke et al. (2017) find that the effects of increasing temperatures on economic productivity are non-linear and that productivity falls strongly at higher temperatures. Our model suggests the productivity effects are small, to the extent workers adjust labor supply and real wages decline. If these adjustments do not take place, the decline in productivity would be as disruptive as the disaster shock. Different from us, Cantelmo et al. focus on the effects of disaster shocks on developing economies. They find that natural disasters can severely affect the economic growth and development path of small and low-income economies. Our finding that the real interest may be higher in advanced economies and fiscal policy may need to be tighter would further damage weigh on economic growth in such economies.

This paper is structured as follows. Section 2 outlines the key features of the model. Section 3 discusses the numerical assumptions that are used to calibrate the model. Section 4 presents the main results of model simulations. Section 5 concludes. The Appendix presents the equations of the model.

2. The Model

The model is based on Kara and Von Thadden (2016)[10], which is built on the model by Gertler (1999)[11]. The model assumes a more realistic demographic structure than the standard new New Keynesian model. In this otherwise new Keynesian DSGE model, there are two types of households: workers and retirees. This assumption gives rise to life-cycle patterns which are different from a standard representative agent economy. The rest of the model is standard new Keynesian.

In this section, we present the main building blocks of the model. Note that since the model economy is subject to steady-state technological progress ($x > 0$) and population growth ($n > 0$), we express all variables in the model in terms of efficiency units per worker. If we denote size of the labor force in period t as N_t^w and

[10] Kara and Von Thadden (2016) introduce money into the model of Gertler (1999) by using the 'money-in-the-utility-function-approach. Here we consider a cashless limit of the model.

[11] The demographic structure in Gertler (1999) is similar to those in Yaari (1965) and Blanchard (1985).

labor augmenting technological progress as X_t, a generic variable v_t is de-trended as

$$\overline{v}_t = \frac{v_t}{N_t^w X_t} \tag{1}$$

where $\overline{v}_t$ is a generic de-trended variable. The full de-trended economy is presented in the Appendix.

2.1. Demographic structure

At time t, there are N_t^w workers and N_t^r retirees. In each period, workers face a probability ω_t to remain a worker and a probability $1 - \omega_t$ to retire. Newborn agents enter directly into the working-age population. The workforce grows at rate n_t^w. The labor force evolves according to the following equation:

$$N_{t+1}^w = (1 - \omega_t + n_t^w)N_t^w + \omega_t N_t^w = (1 + n_t^w)N_t^w \tag{2}$$

Retirees stay alive with probability γ_t. $(1-\gamma_t)$ denotes the probability of death of retirees. The number of retires is given by

$$N_{t+1}^r = (1 - \omega_t)N_t^w + \gamma_t N_t^r \tag{3}$$

The 'old-age dependency ratio' is denoted by $\psi_t = N_t^r/N_t^w$ and evolves according to

$$\psi_{t+1} = (1 + n_t^r) = \frac{1 - \omega_t}{\psi_t} + \gamma_t \tag{4}$$

2.2. Decision problems of retirees and workers

Both workers and retirees have Epstein and Zin (1989) preferences. Another key assumption of the model is that labor is supplied by workers − retirees do not work. The objective function of individuals is given by

$$\begin{aligned}
V_t^z &= \left[\left[(c_t^z)^{v_1}(1-l_t^z)^{v_2}\right]^\rho + \beta^z E_t\left[V_{t+1} \mid z\right]^\rho\right]^{\frac{1}{\rho}} \\
\beta^w &= \beta, \beta^r = \beta\gamma_t, l_t^r = 0 \\
E_t\left[V_{t+1} \mid w\right] &= \omega_t V_{t+1}^w + (1-\omega_t) V_{t+1}^r \\
E_t\left[V_{t+1} \mid r\right] &= V_{t+1}^r,
\end{aligned}$$

where V_t^z denotes the value function associated with the two states: working and retirement (i.e. $z = w, r$). E_t is the conditional expectations operator, c_t is consumption and $1-l_t$ is leisure. The effective discount rates of the two types of agents differ since retirees face a positive probability of death, while workers, when leaving their state, stay alive and switch to retirement.

The assumption that households have Epstein and Zin (1989) preferences rather than standard Von-Neumann/Mongenstern preferences is an important one. The reason for this assumption is that workers in our model face a greater challenge than a worker in an otherwise overlapping generation model without retirement. In our model, workers face income risk and need to ensure that they have enough savings for retirement. Epstein and Zin (1989) preferences help workers to deal with such risks.

A key difference between the two preferences arises in how individuals deal with risk. With standard preferences, workers would care about the mean of the next period's value function. On the other hand, with Epstein and Zin (1989) workers care about the certainty equivalent of the next period's utility. Once the certainty equivalent of the next period's utility is determined, workers decide how much to consume today and tomorrow. The parameter ρ allows for a smooth trade-off between consuming today versus consuming tomorrow.

Taken together, Epstein and Zin (1989) preferences differentiate between risk aversion and intertemporal elasticity of substitution. In the case of standard preferences, risk aversion and intertemporal elasticity of substitution are tied together. Consequently, Epstein and Zin (1989) preferences imply an early resolution of risk and, more generally, uncertainty.

2.2.1. Decision problem of the representative retiree

The representative retiree (with index j) maximises the following objective function

$$V_t^{rj} = \left[\left(c_t^{rj} \right)^{\rho} + \beta \gamma_t \left[V_{t+1}^{rj} \right]^{\rho} \right]^{\frac{1}{\rho}}$$

subject to the budget constraint

$$c_t^{rj} + a_t^{rj} = \frac{1 + r_{t-1}}{\gamma_{t-1}} a_{t-1}^{rj} + e_t^j$$

where a_t^{rj} denotes financial wealth. The retiree receives benefits e_t^j. The decision problem gives rise to consumption Euler equation for retirees

$$c_{t+1}^{rj} = \beta \left(1 + r_t \right) c_t^{rj},$$

This equation is in the same form as the consumption Euler equation implied by the standard new Keynesian model. Using the budget constraint, one can establish that the consumption function and the law of motion for $\epsilon_t \pi_t$ satisfy the relationships

$$c_t^{rj} = \epsilon_t \pi_t \left(\frac{1 + r_{t-1}}{\gamma_{t-1}} a_{t-1}^{rj} \right)$$

and

$$\epsilon_t \pi_t = 1 - \beta^{\sigma} \left(1 + r_t \right)^{\sigma - 1} \gamma_t \frac{\epsilon_t \pi_t}{\epsilon_{t+1} \pi_{t+1}}. \tag{5}$$

where $\epsilon_t \pi_t$ denotes the marginal propensity of retirees to consume out of wealth.

2.2.2. Decision problem of the representative worker

The representative worker maximises the following objective function:

$$V_t^{wj} = \left[\left[\left(c_t^{wj} \right)^{v_1} (1 - l_t^{wj})^{v_2} \right]^{\rho} + \beta \left[\omega_t V_{t+1}^{wj} + \left(1 - \omega_t \right) V_{t+1}^{rj} \right]^{\rho} \right]^{\frac{1}{\rho}}$$

subject to the budget constraint

$$c_t^{wj} + a_t^{wj} = \left(1 + r_{t-1} \right) a_{t-1}^{wj} + w_t l_t^{wj} + f_t^j - \tau_t^j,$$

where a_t^{wj} is total assets. The representative worker receives wage rate w_t, profits f_t^j and pays lump-sum taxes τ_t^j.

The consumption-Euler equation for workers is given by

$$\omega_t c_{t+1}^{wj} + (1-\omega_t)(\epsilon_{t+1})^{\frac{\sigma}{1-\sigma}} c_{t+1}^{rj} = \left[\beta(1+r_t)\,\Omega_{t+1}(\frac{w_t}{w_{t+1}})^{v_2\rho}\right]^{\sigma} c_t^{wj}$$

with

$$\Omega_{t+1} = \omega_t + (1-\omega_t)\,\epsilon_{t+1}^{\frac{1}{1-\sigma}} \tag{6}$$

This equation reflects the possibility that the worker may switch to retirement in the next period. Ω_{t+1} captures the fact that the worker, when switching into retirement, faces a different marginal propensity to consume. The marginal propensity to consume for the worker (π_t) is given by

$$\pi_t = 1 - \left[(\frac{w_t}{w_{t+1}})^{v_2\rho}\right]^{\sigma} \beta^{\sigma}((1+r_t)\,\Omega_{t+1})^{\sigma-1}\frac{\pi_t}{\pi_{t+1}} \tag{7}$$

One can show that the marginal propensity to consume for retirees is higher than that for workers ($\epsilon > 1$), implying $\Omega > 1$. This in turn indicates that workers discount future income streams at an effective interest rate $(1+r_t)\,\Omega_{t+1}$ which is higher than the pure interest rate, reflecting the expected finiteness of life.

Finally, the first-order condition with respect to leisure is

$$1 - l_t^{wj} = \frac{v_2}{v_1}\frac{c_t^{wj}}{w_t} \tag{8}$$

2.3. Firms

The supply-side of the economy is standard New-Keynesian. There is a continuum of firms indexed by $z \in [0,1]$ that has monopoly power over a specific good. These goods are combined to produce the final consumption good (y_t). The aggregation is done according to the CES technology:

$$y_t = \left[\int_0^1 y_t(z)^{\frac{\theta-1}{\theta}} dz\right]^{\frac{\theta}{\theta-1}} \tag{9}$$

The corresponding price index is given by

$$P_t = \left[\int_0^1 P_t(z)^{1-\theta} dz \right]^{\frac{1}{1-\theta}} \tag{10}$$

Firm z operates with a technology that produce output using labor ($l_t(z)$), capital ($k_t(z)$) subject to labor augmenting technical progress (Xt):

$$y_t(z) = (X_t l_t(z))^{\alpha} k_t(z)^{1-\alpha},$$

We assume that X_t grows at a constant rate, i.e.$X_t = (1+x)X_{t-1}$ with $x > 0$. Markets for the two inputs are competitive. The real wage rate is w_t and the real rental rate is r_t^k. Both of these prices are taken as given. Cost minimization implies

$$\frac{w_t l_t(z)}{\alpha y_t(z)} = \frac{r_t^k k_t(z)}{(1-\alpha) y_t(z)} = mc_t,$$

where mc_t denotes real marginal costs, which are identical across firms. Profits of firm z are given by

$$f_t(z) = \left(\frac{P_t^*(z)}{P_t} - mc_t \right) y_t(z).$$

Firms set their prices according to Calvo pricing. In each period, only a fraction $(1-\zeta)$ of firms can reset their price optimally, while the price remains unchanged for a fraction ζ of firms. The (real) reset price ($P_t^*(z)$) is given by

$$\frac{P_t^*(z)}{P_t} = \frac{\theta}{(\theta-1)} \frac{\sum_{i=0}^{\infty} (\zeta\beta)^i \left(\frac{1}{P_{t+i}}\right)^{1-\theta} y_{t+i} mc_{t+i} \frac{P_{t+i}}{P_t}}{\sum_{i=0}^{\infty} (\zeta\beta)^i \left(\frac{1}{P_{t+i}}\right)^{1-\theta} y_{t+i}}. \tag{11}$$

where P_t is the aggregate price level and is given by

$$P_t = \left(\zeta P_{t-1}^{1-\theta} + (1-\zeta) {P_t^*}^{1-\theta} \right)^{\frac{1}{1-\theta}}. \tag{12}$$

2.3.1. Capital goods

There exists a continuum of capital goods-producing firms, indexed by $u \in [0,1]$, renting out capital to intermediate goods firms. In each period, after the production of intermediate and final goods is completed, the representative capital goods-producing firm combines its existing capital stock $k_t(u)$ with investment goods $i_t^k(u)$ to produce new capital goods $k_{t+1}(u)$ according to the constant returns technology. At the aggregate level, the capital stock is a predetermined variable, implying that

$$k_{t-1} = \int_0^1 k_t(z)dz = \int_0^1 k_t(u)du. \tag{13}$$

Therefore, the aggregate capital stock is given by

$$\begin{aligned} k_t &= \phi(\frac{i_t^k}{k_{t-1}})k_{t-1} + (1-\delta)k_{t-1} & (14) \\ 1 &= p_t^k \phi'(\frac{i_t^k}{k_{t-1}}). & (15) \end{aligned}$$

We consider a disaster shock that directly hits the capital stock, wiping out a fraction of capital. The following equation shows the (de-trended) capital accumulation equation with the added disaster shock (d_t):

$$\overline{k}_t = \bar{\phi}\frac{\overline{k}_{t-1}}{\left(1+n_{t-1}^w\right)(1+x)} + (1-\delta)\frac{\overline{k}_{t-1}}{\left(1+n_{t-1}^w\right)(1+x)} - d_t \tag{16}$$

where $\bar{\phi} = \phi(\frac{\overline{i_t^k}}{\overline{k}_{t-1}}\left(1+n_{t-1}^w\right)(1+x))$. We assume that d_t follows an AR(1) process:

$$d_t = \rho_d d_{t-1} + \sigma_{dt} \tag{17}$$

where ρ_d measures the persistence parameter of the disaster shock and σ_{dt} is an i.i.d. innovation to the shock. The aggregate resource constraint of the economy is given by

$$y_t = c_t + g_t + i_t^k, \tag{18}$$

where g_t denotes government expenditures in terms of the final output good.

2.4. Government

The government's budget constraint is given by

$$b_t = (1+r_{t-1})b_{t-1} + g_t + e_t - \tau_t \tag{19}$$

where b_t denotes real government debt. Note that the budget of the pension system is nested in the government's budget constraint. The pension system can be thought of as running on a PAYG basis. This is because all benefits received by retirees (e_t) are financed by taxes (τ_t) paid by workers. Real government debt (b_t) and real capital holdings ($p_t^k k_t$) are assumed to be perfect substitutes by the private sector, leading to the following definition of total private sector non-human wealth:

$$a_t = p_t^k k_t + b_t \tag{20}$$

The familiar arbitrage condition is given by

$$1 + r_t = \frac{r_{t+1}^k + p_{t+1}^k(1-\delta)}{p_t^k}. \tag{21}$$

We assume that the government follows the following fiscal rule:

$$\frac{\tau_t}{y_t} = \tau^* + \gamma_1 \left(\frac{b_t}{y_t} - b^* \right) + \gamma_2 \left(\frac{b_t}{y_t} - \frac{b_{t-1}}{y_{t-1}} \right), \tag{22}$$

where τ^* denotes the tax ratio (τ_t/y_t), b^* is the fiscal target and $\gamma-$ coefficients are the parameters on the targeting variables. Fiscal policy aims to stabilise a certain target b^* of the debt ratio (b_t/y_t) by the tax rate τ_t.

Monetary policy is set according to an inflation-targeting Taylor rule under which the nominal interest rates react to changes in the inflation rate.

$$i_t = \rho i_{t-1} + (1-\rho)\left(r_t + \gamma_\pi \pi_t^p\right) \tag{23}$$

where π_t^p is the inflation rate and ρ denotes the interest rate smoothing parameter.

3. Calibration and Demographic trends

To calibrate demographic parameters, we use the population projections provided by the United Nations. Figure 1 plots the working-age population growth rate and life expectancy projections for advanced economies. We use these projections as a time-varying deterministic input in our model to calibrate the paths for n_t^w and γ_t.

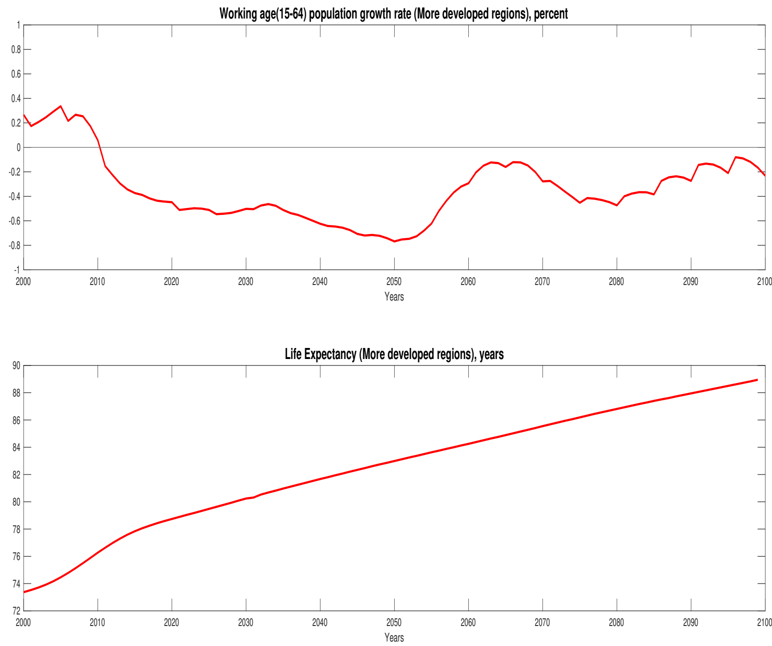

Figure 1: **Projections for the working age population growth rate and life expectancy (Developed regions)**

Notes: This figure shows the projections for the working-age population growth rate and life expectancy. The projections are made by the UN for 'more developed regions. The countries included in this classification are listed in footnote 4. Projections are available at http://esa.un.org/unpp.

As the figure shows, the workers' population growth rate has been slowing down since 2000. The growth rate was 0.5% in 2000. It turned negative in 2010 and it has been negative since then. It is expected to remain negative until the end of the century. Figure 1 also shows that there has been a gradual increase in life expectancy since 2000. This trend is expected to continue until the end of the century. In 2000, life expectancy was around 75 years and is expected to be about 90 years in 2100.

The rest of the parameter values are the same as those in Kara and von Thadden (2016) and are standard in the literature. The calibration of Kara and von Thadden is for EU countries. Given that most of the countries in our sample are EU countries. We use EU countries as a proxy. Some parameter values are fixed in simulations and some are implied by the steady-state relationships of the model. Table 1 shows the parameters that are set, while Table 2 reports those that are implied.

Table 1: Parameters Values

Intertemporal elasticity of substitution	σ	1/3
Discount factor	β	0.99
Cobb-Douglas share of labor	α	2/3
Depreciation rate of capital	δ	0.05
Growth rate of technological progress	x	0.01
Elasticity of demand	θ	10
Preference parameter: consumption	v_1	0.64
Preference parameter: leisure	v_2	0.358
Debt-to-output-ratio	b^*	0.7
Government spending share	g/y	0.18
Replacement rate	$\mu = e^j/w$	0.47
Direct adjustment parameter in debt rule	γ_1	0.04
Smoothing parameter in debt rule	γ_2	0.3
Inertial parameter in the Taylor-rule	ρ_i	0.7
Inflation coefficient in the Taylor-rule	γ_π	1.5
Calvo survival probability of contracts	ζ	0.2
Elasticity of investment function ($\eta = -\frac{\phi''(v)}{\phi'(v)}v$)	η	0.25

The intertemporal elasticity of substitution is set to 1/3 and the discount factor is assumed to be 0.99. The labor share is calibrated at 2/3. The leisure preference parameter is assumed to be 0.36/. The steady-state growth rate of technological progress is set to 1% and the debt-to-GDP ratio is calibrated at 70%. We specify the share of government spending as 18%. We assume an annual depreciation rate of 5%. The replacement rate is assumed to be 0.47, leading to a share of total retirement benefits in output (e/y) of 0.11. These are consistent with the evidence for the EU (see European Economy (2009)).

Next, we describe the calibration of the fiscal feedback rule. Following Mitchell et al. (2000), we assume $\gamma_1 = 0.04$ and $\gamma_2 = 0.3$. For the monetary policy rule, we set $\rho_i = 0.7$ and $\gamma_\pi = 1.5$. We assume that $\eta = 0.25$ and that $\zeta = 0.2$. The assumption of $\zeta = 0.2$ implies an average duration of prices of 1.25 years, which is in accordance with euro area empirical evidence, as summarized in Altissimo et al. (2006).

Table 4 : Endogenous variables

Real interest rate	r	0.039
Share of consumption in output	c/y	0.60
Share of investment in output	i^k/y	0.22
Share of taxes in output	τ/y	0.31
Share of total benefits in output	e/y	0.11
Capital-output ratio	k/y	3.50
Distribution of wealth	λ	0.23
Participation rate of workers	$\overline{l^w} = l^w/N^w$	0.70
Consumption share of workers	c^w/y	0.47
Consumption share of retirees	$\psi c^r/y = c/y - c^w/y$	0.13
Propensity to consume out of wealth (workers)	π	0.05
Propensity to consume out of wealth (retirees)	$\epsilon\pi$	0.09
Relative discount term	Ω	1.05

Table 4 reports the rest of the parameter values implied by our assumptions summarised in Table 1. A few parameter values are worth pointing out. The implied value of the steady-state real interest rate (r) is 3.9%. The share of taxes in output (τ/y) is 0.31. The marginal propensity to consume out of wealth is greater than that of workers (0.09 vs. 0.05). The share of consumption in output is 60%, while that of investment is 22%.

4. Macroeconomic Effects of Demographic Changes and Disaster Shocks

In this section, we examine the effects of natural disasters and demographic changes within a common framework. We do this in three steps. First, we compute the dynamic responses of selected macroeconomic variables to demographic changes. Second, we examine how the interaction between demographic changes and natural disasters affects the macroeconomy. Finally, we note that there is a great deal of uncertainty regarding the magnitude of disaster shocks. We study how such uncertainty affects the economy.

4.1. Macroeconomic effects of demographic changes

We start by considering the macroeconomic effects of demographic changes. Figure 2 shows the impulse Response Functions ($IRFs$) of the key macroeconomic variables to demographic changes.[12] We compare two different assumptions regarding price setting. In one of the cases, we assume prices are sticky, while in the other flexible. In the case of flexible prices, the interest rate corresponds to the equilibrium interest rate ($r*$) and output is the natural level of output ($y*$).

It is helpful to start the analysis by focussing on the case in which prices are flexible. As Figure 2 shows, the decrease in population growth and the increase in life expectancy together affect the key macroeconomic variables. Reflecting the nature of demographic changes, the responses are small but persistent.

[12] As we have noted, demographic projections complied by the UN are available until 2100. Using these projections as deterministic inputs, we conduct simulations until 2100. Once the demographic adjustment is completed, model variables converge to their new steady-state values. Whenever we report simulations from the model, we only report them for the next 40 years (until 2060). This horizon is more than sufficient for our purposes (i.e., understanding the key implications of climate change and demographic changes) and policymaking.

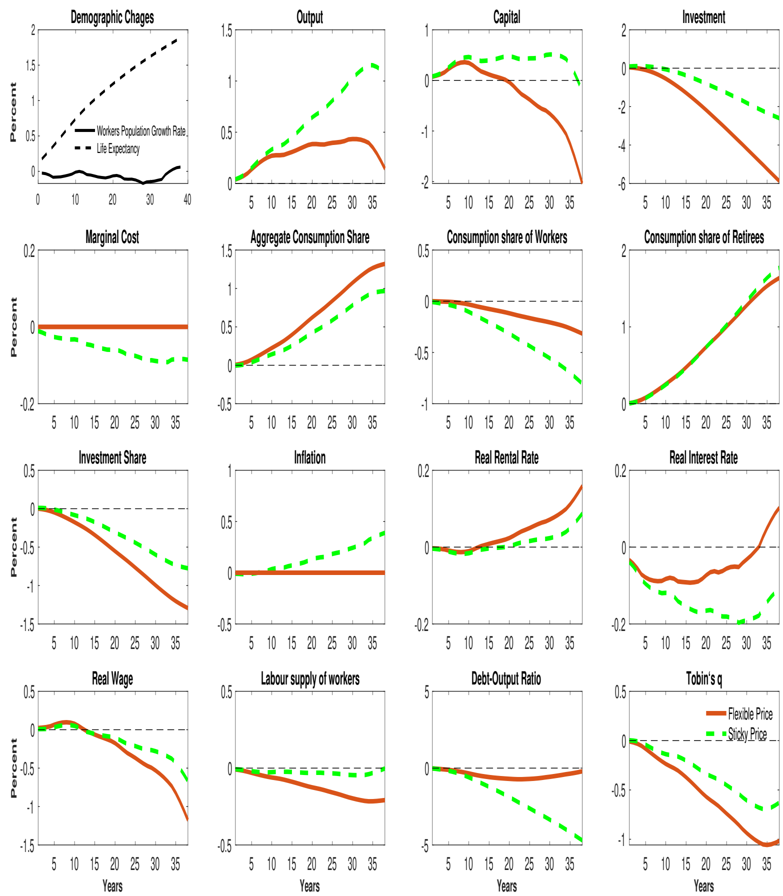

Figure 2: **Simulated responses to demographic changes: sticky prices vs. flexible prices**

Notes: This figure plots simulated responses to demographic changes for sticky prices and flexible prices.

An interesting result that comes out of the figure is that demographic changes affect both the level and the composition of consumption. The consumption share in the economy is higher and there is intertemporal substitution toward future consumption. Workers consume less and retirees consume more. Higher consumption brings about lower investment and capital stock. Consequently, the rental rate of capital is higher.

If we look at the effect of demographic changes on r_t^*, we see that there is a small but persistent decline. The decline in the interest rate peaks around period 15. After that, the equilibrium rate starts to recover and it becomes positive towards the end of the simulation period. The maximum decline in equilibrium interest rate is around 0.1%. Similarly, we see a slight but persistent increase in y_t^*.

Next, we consider how demographic changes affect real wages and labor supply. The fall in the population growth rate results in a lower labor supply. At the beginning of the simulation period, real wages increase. But then mirroring the fall in investment, real wages start to fall. Finally, it is worth noting that the debt-to-GDP does not change significantly.

We now turn to examine the case with sticky prices. There are two key differences between the sticky price and flexible cases. In the sticky price case, inflation is higher and the real interest rate is lower than in the flexible price case. In the case of sticky prices, the fall in the real interest rate is almost twice as large as the case with flexible prices. This finding suggests that to stabilise inflation, central banks will need to respond more aggressively to inflation than they have been.

As one would expect, reduced real interest rates affect consumption dynamics. While the consumption share of retirees is more or less the same as before, the consumption share of workers is lower. As a result, with sticky prices, the total consumption is lower and the investment share is higher. As a consequence of higher investment, the capital stock is higher, resulting lower rental rate of capital. If we look at labor supply, we see a slight fall in it. Given that the capital stock is higher, there is about a 1% increase in output.

So far, we have looked at the combined effects of changes in working-age population growth and life expectancy. It is informative to look at the effects of each factor on aggregate dynamics. Figure 3 shows the responses to changes in working-age population growth and the combined effect (as reported in Figure 2) for the sticky price case. The difference between the two responses shows the contribution of changes in life expectancy to aggregate dynamics.

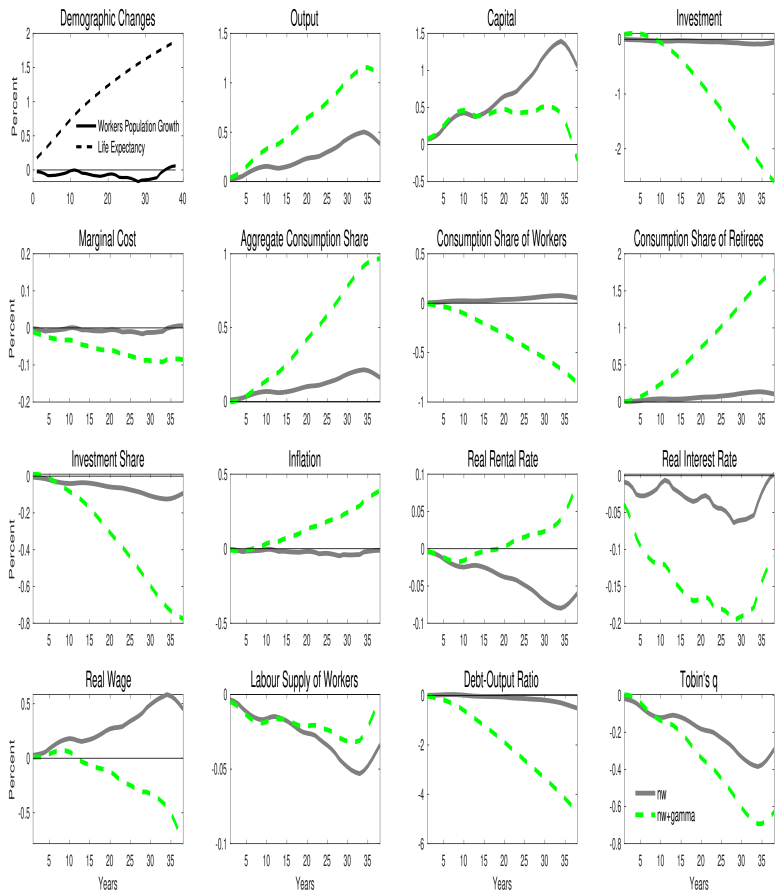

Figure 3: **Simulated responses to changes in workers population growth**

Notes: This figure plots simulated responses to changes in workers' population growth as well as to the combined responses that account for changes both in workers' population growth and life expectancy.

A key insight from this figure is that changes in life expectancy almost entirely drive consumption and real interest rate dynamics. In anticipation of higher life expectancy, workers undertake additional savings, leading to a fall in workers' consumption. It is obvious from the figure that higher life expectancy is the cause of a higher share of retirees' consumption. Increased savings lead to lower real interest rates. As the greater share of output is allocated to consumption, the investment share is lower. The increase in capital stock is muted, bringing about an increase in the rental rate of capital.

The fall in the workers' population growth lowers the labor supply. The increase in life expectancy forces workers to work more, leading to a higher labor supply and lower real wages.

4.2. Macroeconomic effects of disaster shocks

We now turn to study the effects of a natural disaster shock on the macroeconomy. We consider a highly persistent shock and assume that $\rho_d = 0.99$. We calibrate the size of the shock (σ_{dt}) in a way that gives rise to about a 1% fall in output at the end of the simulation period (in 40 years). Figure 4 reports the IRFs to a disaster shock.

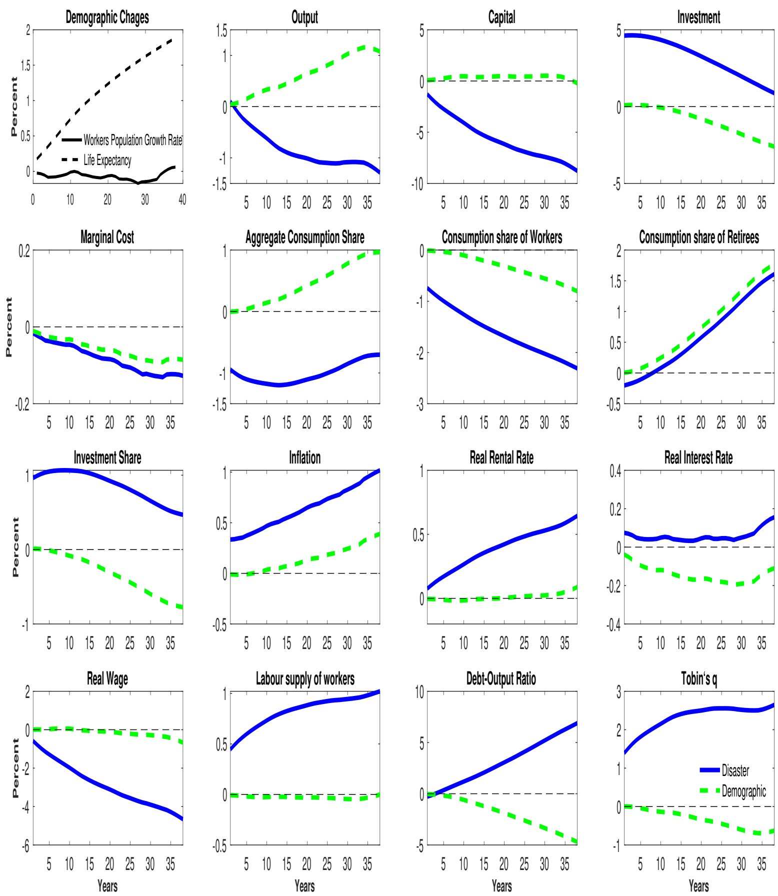

Figure 4: **Simulated responses to a disaster shock**

Notes: This figure plots simulated responses to a persistent disaster shock along with simulated responses to demographic changes (the sticky price case).

On the impact of the shock, the fall in the capital stock is around 1%. By assumption, the disaster shock is highly persistent. The persistent shock brings about a persistent fall in the capital stock. The maximum decline in the capital stock is around 10% of the steady-state, which happens towards the end of the simulation period. The persistent fall in capital stock gives rise to a persistent fall in output. The fall in output is around 1% throughout the simulation period.

The decrease in capital and output has a declining effect on consumption. While the consumption of retirees does not change significantly, there is a significant reduction in workers' consumption. The consumption share of workers falls around 1% on the impact of the shock. Since retirees' consumption does not change much, the fall in workers' consumption brings about a fall in aggregate consumption. The fall in the consumption share is similar to the fall in output and is around 1%. Reflecting the fall in aggregate consumption, the share of investment is 1% higher. As capital becomes scarce after the shock, the rental rate of capital is higher. However, the fall in real wages is larger, resulting in lower marginal costs. We see from the figure that the shock induces workers to work more and there is a persistent increase in labor supply. Consequently, real wages are lower.

A striking result from the figure is that inflation increases persistently after the disaster shock. At the end of the simulation period, inflation is around 1% higher. Despite the fall in output, the increase in inflation is an important result. It suggests that a natural disaster shock may resemble the effects of a cost shock. Higher inflation requires a higher real interest rate. Given that the nominal interest rate in our model is set according to the Taylor rule with a coefficient on inflation greater than one, we see from the figure that the real interest rate is higher. Note also that the destruction of the capital stock requires an increase in the fraction of output that is saved and invested. Therefore, consumption should be lower. Lower consumption and higher savings require higher real interest rates. Higher inflation requires a tighter monetary policy.

Another important result that arises from the figure is that the debt-to-GDP ratio persistently increases. This result suggests that the fiscal policy rule in Equation (22) is no longer sufficient to stabilise the debt-to-GDP and there is a need for a more aggressive fiscal policy. In experiments we don't report here (available upon request), we find that with a higher value of γ_1 the debt-to-GDP ratio is stabilised more. When $\gamma_1 = 1.4$, the debt-to-GDP is on target. Of course, a tighter fiscal policy response comes at the cost of lower output.

4.2.1. *Isolating the contribution of demographic changes*

This section isolates the effects of demographic changes. To achieve this, we compare the IRFs implied by our model with demographic changes to those suggested by a version of the model where demographic variables are set to their steady-state values. Figure 5 reports the IRFs from this experiment.

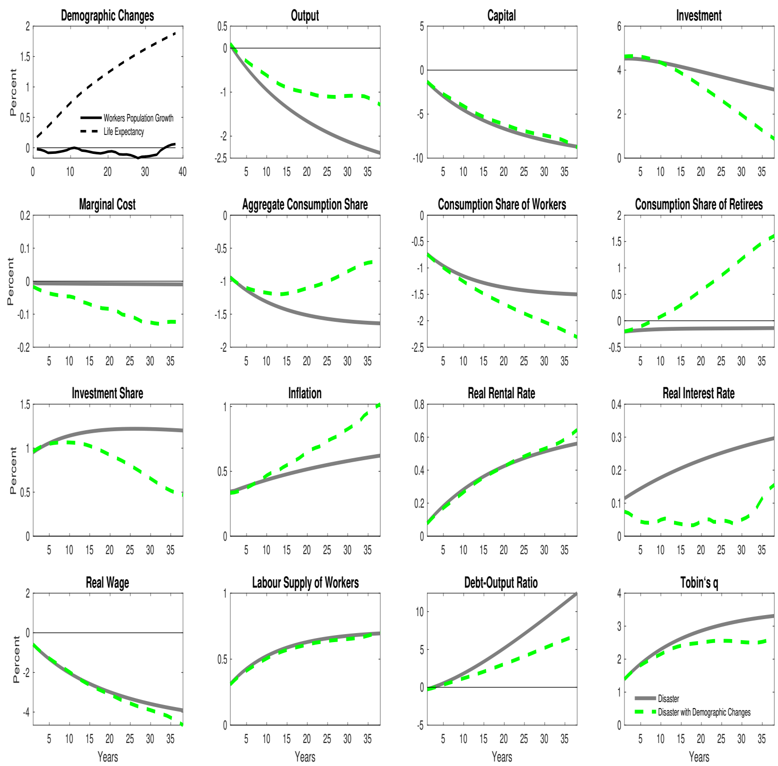

Figure 5: **Simulated responses to a disaster shock with and without demographic changes.**

Notes: This figure compares simulated responses to a persistent disaster shock with and without demographic changes.

The key difference between the two cases arises when it comes to consumption. Therefore, we first focus on consumption. Consumption falls more when demographic changes are not accounted for. This is because the model without demographic changes cannot capture the changes in consumption due to the aging population. As is evident from the figure, in the version of the model with demographic changes, the consumption of retirees increases. It is true that workers' consumption decrease, too. However, the increase in retirees' consumption is large enough to mitigate the destructive effect of the disaster shock on consumption. The smaller fall in consumption means that the investment share is lower. The smaller fall in consumption also limits the fall in output. Reduced fall in output brings about higher inflation.

Finally, we look at the effects of demographic changes on the real interest rate. With demographic changes, workers' consumption and savings are higher, resulting in lower real interest rates.

Taken together, demographic changes are the main determinant of key macroeconomic variables, such as the equilibrium interest rate. It is essential to account for them, especially when considering persistent shocks such as climate change.

4.3. Macroeconomic effects of uncertainty shocks

We now examine the macroeconomic implications of uncertainty regarding the magnitude of disaster shocks in the macroeconomy. To capture this uncertainty, we modify the disaster shock process in the following way:

$$d_t = \rho_d d_{t-1} + \sigma_{d,t}\epsilon_{d,t} \tag{24}$$

$$\sigma_{d,t} = (1 - \rho_{\sigma_d})\,\sigma_d + \rho_{\sigma_d}\sigma_{d,t-1} + \sigma_{\sigma_d}\epsilon_{\sigma_{d,t}} \tag{25}$$

where $\epsilon_{\sigma_{d,t}}$ is a second-moment shock (i.e. the uncertainty shock) and follows a standard normally distributed $i.i.d$ shock process. ρ_{σ_d} measures the persistence of the shock. The rest of our assumptions are the same as before. Figure 6 shows the effects of an uncertainty shock on macroeconomic variables.

The figure shows that uncertainty amplifies the contractionary effects of disaster shocks. The fall in the capital stock in the case of uncertainty is greater than without. Two other results stand out from the figure. First, there is a fall in output. Second, inflation is higher.

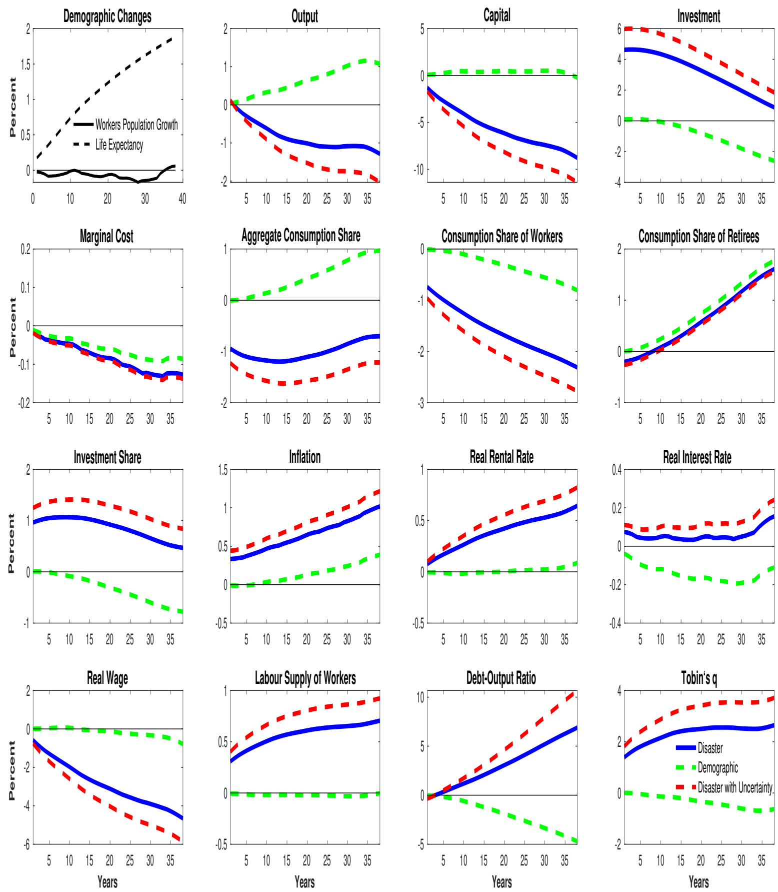

Figure 6: **Simulated responses to changes in an uncertainty shock**

Notes: Simulated responses to an uncertainty shock are superimposed to the previous figure, which shows responses to demographic changes and a disaster shock.

We first consider the fall in output. There are two reasons for this fall. First, increased uncertainty leads to a fall in demand. This is mainly because households increase their savings to protect themselves against increasing uncertainty. Consequently, consumption is lower than before. Second, as the capital stock is lower, the economy cannot produce as much as before, leading to lower output. An increase in uncertainty has both demand and supply effects, lowering output.

We now turn to understand why inflation is higher. To understand this result, first, note that prices are sticky. Firms increase their price markups to protect their prices against increasing uncertainty during the period for which prices are fixed. While the fall in demand has a deflationary effect on prices, the increase in precautionary mark-ups has an inflationary effect. The increase in the precautionary markups is large enough to lead to a rise in inflation, despite the fall in output.

In experiments we do not report but are available upon request, we look at the effects of larger uncertainty shocks. As one would expect, the greater the magnitude of uncertainty shocks, the more disruptive uncertainty becomes. In particular, while the capital stock and output fall more, inflation increases more. This finding suggests that holding other factors constant, the cost of climate change can rapidly increase with growing uncertainty.

4.4. A comparison with developing countries

Climate change is happening at a time when the global population is aging, but the process is asynchronous. Many developing countries still have to manage youthful populations. During the simulation period, the aging process also kicks in developing countries and the size of demographic shocks in developing countries is larger than in developed countries. Figure 7 reports the responses for developing countries. Since our aim is to understand the role of demographic changes, the rest of the parameter values are assumed to be the same as before.

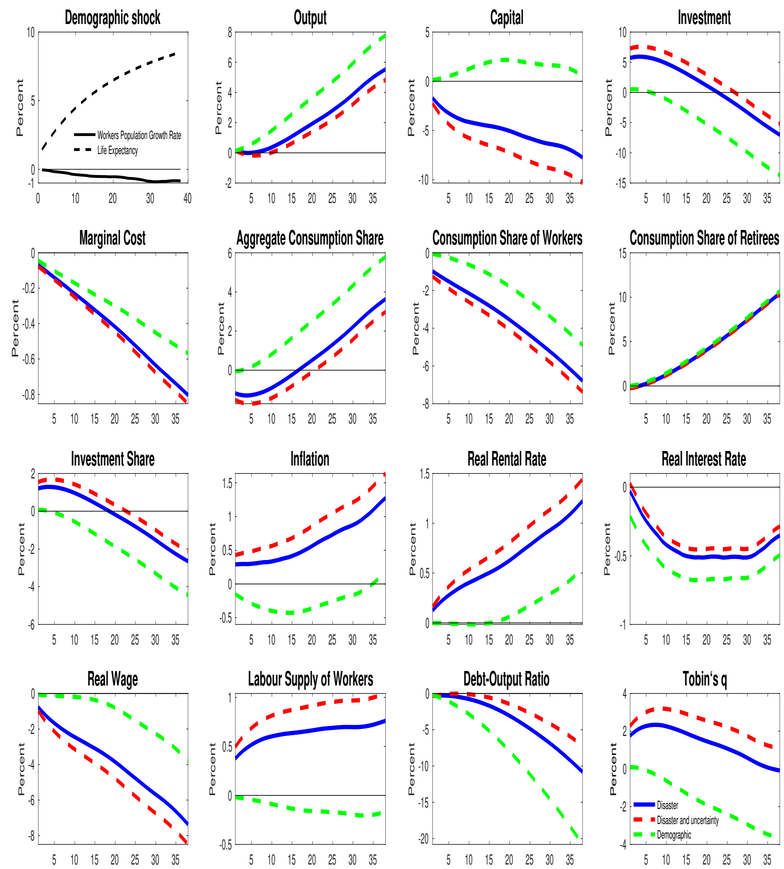

Figure 7: **Simulated responses for developing countries**

Notes: Simulated responses for developing countries. Except for demographic changes, all the assumptions are the same as before.

The main insights that arise from the model are the same as before. Consumption increases due to aging, causing crowding out of investment. As a result, the investment share is lower. However, the demographic shocks facing developing countries are larger. Therefore, consumption increases more. Consequently, the crowding-out effect on investment in developing countries is larger than that in developed countries.

5. Climate Change as a Negative Productivity Shock

So far, we have considered cases in which climate change affects the economy through its destructive effects on capital stock. A consequence of climate change is rising average temperatures. It is estimated that increasing temperatures have adverse effects on productivity (see Deryugina and Hsiang (2017))[13]. We now consider the macroeconomic effects of decreasing productivity. In particular, we consider a TFP shock (z_t) in the production function.

$$\overline{y}_t = z_t \left(\bar{l}_t\right)^{\alpha} \left(\overline{k}_{t-1}\right)^{1-\alpha} \tag{26}$$

The TFP follows the following AR(1) process:

$$z_t = \rho_z z_{t-1} - \sigma_{zt} \tag{27}$$

where ρ_z measures the persistence of the shock and σ_{zt} follows a standard normally distributed i.i.d. shock process. We assume a highly persistent negative total factor productivity shock (i.e. $\rho_z = 0.99$). We choose the shock size to generate a 1% fall in output, similar to the one in the previous section. The IRFs from this experiment are reported in Figure 7.

[13] To the best of our knowledge, the possible negative link between increasing temperatures and productivity is first noted by Mackworth (1946).

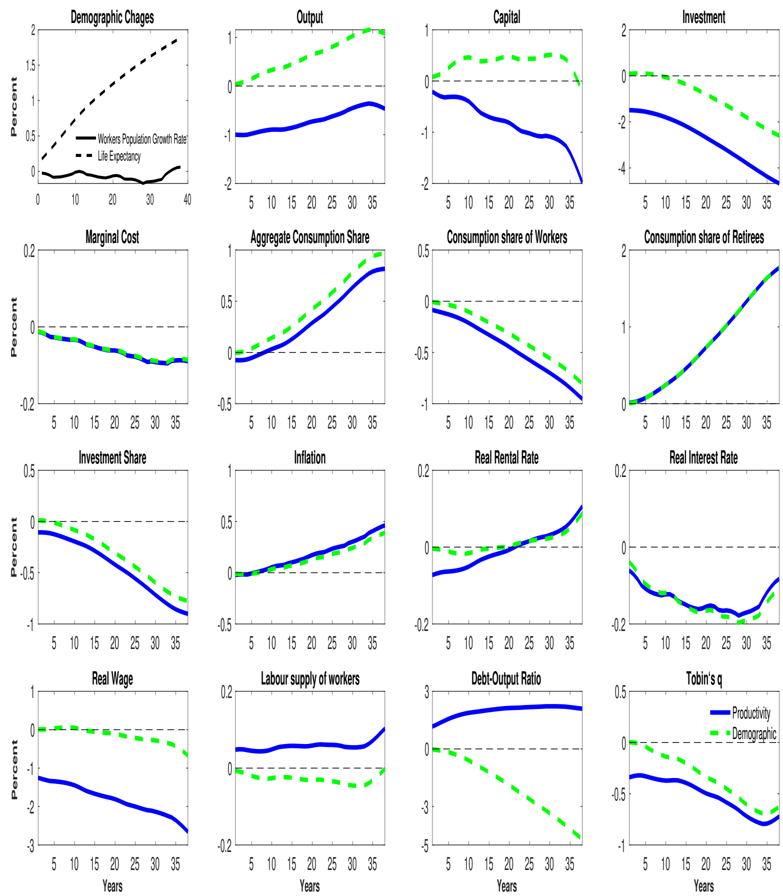

Figure 8: **Simulated responses to changes in a negative productivity shock**

Notes: This figure plots simulated responses to a negative productivity shock.

A comparison between Figures 4 and 8 shows that the two shocks affect the aggregate dynamics differently. This is true despite both shocks leading to a similar fall in output. It appears that the productivity shock does not have as significant an effect as the disaster shock. This is because workers respond to the shock by working more. Real wages are also lower. The increase in labor supply and the fall in real wages appear to compensate for the fall in productivity, limiting the damaging effect of the shock on the economy.

While on the impact of the shock, there is a fall in output; output recovers towards the end of the simulation period. Investment is lower, bringing about a fall in the capital stock. Importantly, consumption does not change much. The effect of the shock on the real interest, inflation and the rental rate of capital appears to be small.

The findings lower productivity results in higher labour supply and lower real wages require an explanation. The reason for lower wages is lower productivity. Lower productivity lowers the marginal product of labour, resulting in lower wages. The increase in labour supply, despite the fall in wages, is due to negative wealth effects: persistent decreases in productivity and lower wages have a negative effect on private wealth, resulting in lower consumption. To offset the impact of the negative wealth effect, workers choose to work more.

6. Results Summary and Policy Implications

The results pertaining to demographics alone are standard:

- A slowdown in population growth leads to increased consumption, lower interest rates, lower capital accumulation, and a slowdown in growth over the projection period.
- An increase in life expectancy leads to a rebalancing of consumption increases savings for retirement and lowers real interest rates, while forcing workers to work longer, thereby reducing real wages through an increase in labor supply.
- The effects are more pronounced with sticky prices. With flexible prices, inflation increases as consumption increases, resulting in higher real interest rates by the end of the projection period.
- The effect of population growth is small relative to the change in life expectancy.

The demographic dynamics are dominated by the disaster shock. The latter suggests:

- The decline in capital leads to a decline in output, and this decline is higher if the persistence of the shock is high. Workers' consumption is lower. The decline in capital leads to an increase in the cost of capital, which leads to a decline in real wages, which leads to workers increasing their wage supply. Reflecting the cost-push nature of the shock, inflation is permanently higher. Higher inflation requires the real interest rate to be higher over the projection period.

- The disaster shocks lead to an increase in the deficit and debt-to-GDP ratios, thus requiring a tightening of fiscal policy to align debt with the target.

- The uncertainty induced by climate shocks results in firms maintaining a higher level of mark-up to hedge against unanticipated shocks (with sticky prices). The contractionary effect on output and inflation is higher in this scenario. Output is lower as households increase savings (and lower consumption) due to increased uncertainty, and the lower capital stock from the disaster reduces productive capacity. The deflationary impact of lower consumption is countered by the inflationary impact of higher mark-ups.

- The effect of climate change through the productivity channel is smaller than the disaster shock as workers increase their labor supply and the decline in real wages compensates for the lower productivity.

The main policy implications of the results are:

- It is critical to contain the impact of climate change. The model's focus on the physical aspects of climate change emphasize the need for mitigation and adaptation policies. Global mitigation policies remain critical to contain the cost of climate change global emissions and reduce the macroeconomic impact of climate change. As pointed out elsewhere, to contain global temperatures within the Paris target, the bulk of the effort will have to come from the largest emitters (IMF, 2021). However, with greenhouse gases already locked in the atmosphere, the effects of climate change are expected to continue to worsen in the near-term (IPCC, 2021), which requires adaptation policies to enhance the resilience of economies to climate shocks.

- Central banks need to pay more attention to climate change in formulating monetary policy, especially with the uncertainty-induced increase in markups. The cost-push dimension of natural disasters will lead to inflation being higher than otherwise, and the distributional effects of these would also need to be monitored. [14]

- A increase in the debt-to-GDP ratio and its deviation from the debt rule requires a tightening of fiscal policy through higher taxes or lower expenditure.

- The long-term design of social safety nets also needs reconsidering. While the assumption is workers would adjust their labor supply, this is not always feasible and could lead to retirees facing a lower amount of savings than is needed to sustain consumption.

7. Summary and Conclusions

We have studied the macroeconomic implications of climate change using a DSGE model that can capture demographic changes and climate change. Our model has two groups of individuals: workers and retirees. Each group has realistic average durations of work and retirement. Due to the heterogeneity in the population's age structure and preferences, workers and retirees differ in the level and composition of wealth. The two groups respond differently to shocks. The model's demographic parameters can be calibrated using demographic projections. We first model climate change as persistent natural disaster shocks that directly hit and destroy some of the

[14] In this paper, we focus on a closed economy. Alternatively, in the sprint of Gali and Monacelli (2005), our model can be thought of as a region among the continuum of regions making up the world economy. Still allowing for open economy features may be useful to understand the possible effects of climate change, for example, on exchange rates and capital flows. Capital and labor might reallocate from disaster-prone regions to less affected regions. If economic activity concentrates more on certain regions, due to Jensen's inequality, this might have a negative effect on world output too: in those regions marginal diminishing returns would kick in, lowering output.

capital stock. In an alternative scenario, we consider climate change as a negative productivity shock, as increasing temperatures are expected to lower productivity.

Our simulation results suggest that climate change will have a long-lasting negative impact on economies by reducing output and increasing inflation. Our analysis further indicates that climate change will also have adverse indirect effects through increasing uncertainty. These costs can increase rapidly unless more climate action is taken, emphasizing the need for global action to support mitigation. Adaptation is also a priority to enhance resilience to climate change, and the need is even more pressing in climate-vulnerable developing countries where demographic developments will increase the demand for capital. Social safety nets also need reconsideration.

Finally, both fiscal and monetary policies will need to be revised to account for climate change. Climate change will bring about a rise in the debt-to-GDP ratio, requiring a tighter fiscal policy. Inflationary pressures from climate developments and their effects on the equilibrium interest rate and potential output require increased vigilance from central banks. In a world with increased climate disasters and uncertainty surrounding the equilibrium interest rate and potential growth, monetary policy would be harder to implement. We leave the design of optimal monetary policy in the era of climate change as a matter for further research.

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Appendix: Summary of (detrended) model equations

We denote detrended variables with a bar. Consider generic variables v_t, then

$$\overline{v_t} = \frac{v_t}{N_t^w X_t} \tag{.1}$$

$$\epsilon_t \pi_t = 1 - \left[(\frac{\overline{w}_t}{\overline{w}_{t+1}} \frac{1}{1+x})^{v_2 \rho} \right]^\sigma \beta^\sigma (1+r_t)^{\sigma-1} \gamma_t \frac{\epsilon_t \pi_t}{\epsilon_{t+1} \pi_{t+1}} \tag{.2}$$

$$\Omega_{t+1} = \omega_t + (1-\omega_t)\, \epsilon_{t+1}^{\frac{1}{1-\sigma}} \tag{.3}$$

$$\pi_t = 1 - \left[(\frac{\overline{w}_t}{\overline{w}_{t+1}} \frac{1}{1+x})^{v_2 \rho} \right]^\sigma \beta^\sigma ((1+r_t)\Omega_{t+1})^{\sigma-1} \frac{\pi_t}{\pi_{t+1}} \tag{.4}$$

$$1 - \overline{l}_t^w = \frac{v_2}{v_1} \frac{\overline{c}_t^w}{\overline{w}_t} \tag{.5}$$

$$\overline{h}_t^w = \overline{d}_t^w + \frac{\omega_t}{\Omega_{t+1}} \frac{1+x}{1+r_t} \overline{h}_{t+1}^w \tag{.6}$$

$$\overline{d_t^r} = \frac{\overline{e}_t}{\psi_t} \tag{.7}$$

$$\overline{d}_t^w = \overline{w}_t \overline{l}_t^w + \overline{f}_t - \overline{\tau}_t \tag{.8}$$

$$\overline{c}_t^r (1 + \frac{v_2}{v_1}) = \epsilon_t \pi_t \left(\frac{1+r_{t-1}}{\left(1+n_{t-1}^r\right)(1+x)} \lambda_{t-1} \overline{a}_{t-1} \right) \tag{.9}$$

$$\overline{c}_t^w (1 + \frac{v_2}{v_1}) = \pi_t \left(\frac{1+r_{t-1}}{\left(1+n_{t-1}^w\right)(1+x)} (1-\lambda_{t-1}) \overline{a}_{t-1} + \overline{h}_t^w \right) \tag{.10}$$

$$\overline{c}_t = \overline{c}_t^w + \overline{c}_t^r \psi_t \tag{.11}$$

$$\lambda_t \overline{a}_t = \omega_t \left[(1-\epsilon_t \pi_t) \left(\lambda_{t-1} \frac{(1+r_{t-1})}{\left(1+n_{t-1}^w\right)(1+x)} \overline{a}_{t-1} \right) + \overline{d}_t^r \psi_t \right] + (1-\omega_t) \overline{a}_t \tag{.12}$$

$$\overline{y}_t = \overline{l}_t^\alpha \overline{k}_{t-1}^{1-\alpha} \tag{.13}$$

$$\frac{1}{\left(1+n_{t-1}^w\right)(1+x)} \frac{\overline{k}_{t-1}}{\overline{l}_t} = \frac{\overline{w}_t}{r_t^k} \frac{1-\alpha}{\alpha} \tag{.14}$$

$$mc_t = \left(\frac{\overline{w}_t}{\alpha} \right)^\alpha \left(\frac{r_t^k}{1-\alpha} \right)^{1-\alpha} \tag{.15}$$

$$\frac{P_t^*}{P_t} = \frac{\theta}{\theta-1} \frac{E_t \sum_{i=0}^\infty (\zeta\beta)^i \left(\frac{1}{P_{t+i}} \right)^{1-\theta} \overline{y}_{t+i} N_{t+i}^w X_{t+i} mc_{t+i} \frac{P_{t+i}}{P_t}}{E_t \sum_{i=0}^\infty (\zeta\beta)^i \left(\frac{1}{P_{t+i}} \right)^{1-\theta} \overline{y}_{t+i} N_{t+i}^w X_{t+i}} \tag{.16}$$

$$P_t = \left(\zeta P_{t-1}^{1-\theta} + (1-\zeta) {P_t^*}^{1-\theta}\right)^{\frac{1}{1-\theta}} \tag{.17}$$

$$\overline{k}_t = \phi\left(\frac{\overline{i}_t^k}{\overline{k}_{t-1}} \left(1+n_{t-1}^w\right)(1+x)\right) \cdot \frac{\overline{k}_{t-1}}{\left(1+n_{t-1}^w\right)(1+x)} + (1-\delta)\frac{\overline{k}_{t-1}}{\left(1+n_{t-1}^w\right)(1+x)} \tag{.18}$$

$$1 = p_t^k \phi'\left(\frac{\overline{i}_t^k}{\overline{k}_{t-1}} \left(1+n_{t-1}^w\right)(1+x)\right), \tag{.19}$$

$$\overline{y}_t = \overline{c}_t + \overline{g}_t + \overline{i}_t^k \tag{.20}$$

$$1 + i_t = (1+r_t)\left(\frac{P_{t+1}}{P_t}\right) \tag{.21}$$

$$\overline{b}_t = (1+r_{t-1})\left(\frac{\overline{b}_{t-1}}{\left(1+n_{t-1}^w\right)(1+x)}\right) + \overline{g}_t + \overline{e}_t - \overline{\tau}_t \tag{.22}$$

$$\overline{e}_t = \mu_t \overline{w}_t \psi_t \tag{.23}$$

$$\overline{a}_t = p_t^k \overline{k}_t + \overline{b}_t \tag{.24}$$

$$1 + r_t = \frac{r_{t+1}^k + p_{t+1}^k(1-\delta)}{p_t^k} \tag{.25}$$

$$\frac{\overline{\tau}_t}{\overline{y}_t} = \tau^* + \gamma_1\left(\frac{\overline{b}_t}{\overline{y}_t} - b^*\right) + \gamma_2\left(\frac{\overline{b}_t}{\overline{y}_t} - \frac{\overline{b}_{t-1}}{\overline{y}_{t-1}}\right) \tag{.26}$$

$$i_t = \rho i_{t-1} + (1-\rho)\left(r_t + \gamma_\pi \pi_t^p\right) \tag{.27}$$