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THE EFFECTS OF CLIMATE CHANGE ON A SMALL OPEN ECONOMY

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Abstract
We investigate the impact of climate change on the macroeconomic performance of a small open economy. The setup is a new Keynesian dynamic stochastic general equilibrium model of a small open economy without monetary policy independence in which a climate module that interacts with the economy has been incorporated. The model is solved numerically using common parameter values, fiscal data and projections about temperature growth from the Greek economy. Our results, suggest that climate change implies a significant output loss and a deterioration of competitiveness. Moreover, it seems that the loss of monetary policy independence is not a big loss, when we investigate the short- and long-term implications of climate change for a small open economy.

JEL classification: E5, E1, Q5
Keywords: Climate change, monetary policy, new Keynesian models

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1 Introduction

Climate change has been recognized as one of the greatest threats for humans' welfare. In particular, and in terms of economic growth, it has been argued that climate change and higher temperatures may reduce growth rates and output levels (e.g., Dell et al., 2009, 2012). Given this claim, a large and continuously growing literature has focused on investigating not only the impact of climate change on economic activity but also ways to moderate this impact (see, e.g., Nordhaus, 2007, 2014; and Stern, 2007, 2008).

Following the classic economic approach, economic policies for climate change that aim at mitigation focus on carbon taxes or cap-and-trade policies (e.g., Stern, 2007, chapter 14; Golosov et al., 2014). In this context, some recent papers (e.g. Fischer and Heutel (2013), Heutel (2012), Fischer and Springborn (2011), and Angelopoulos et. al (2010)) add in the basic real business cycle (RBC) framework pollution. Climate change policy has therefore been predominantly fiscal policy. However, Economides and Xepapadeas (2018) and Annicchiarico and Di Dio (2017), using new-keynesian models, showed that also monetary policy may have to play an important role and therefore there may be a role for Central Banks in the battle against climate change.

Most of this literature uses closed economy models, or large open economy models, and therefore is incapable of investigating the effects of climate change on a small open economy. This is important, because although a small open economy cannot seriously affect the dynamics of climate change, through its economic activity and the associated emmited pollution, it can suffer from the impact of climate change. The latter may be translated into output losses and a deteriorated competitiveness.

Therefore, this paper tries to fill this gap. In particular, our aim is to investigate the impact of climate change on a small open economy. The setup is a new Keynesian dynamic stochastic general equilibrium (DSGE) model of a small open economy featuring imperfect competition in product markets and Rotemberg-type nominal price fixities. The model of the economy is coupled with a climate module, and we assume that energy, produced by the processing of fossil fuels, enters as a separate factor in the firm's production function, thus increasing output. However, as already mentioned, the quantity of GreenHouse Gass (GHG) emissions produced in the small open economy is not large enough to affect global warming. This means that in our setup, there is a one-way link between climate change and a small open economy's economic activity. Namely, climate change, through higher temperatures, operates as a permanent negative TFP shock affecting adversely economic outcomes. Our framework could be thought of as an integrated assessment model (IAM) in the sense that we incorporate both an economic and a climate sector in a unified setup. The model is solved numerically using common parameter values, fiscal-public finance data, and data about temperature from the Greek economy.

In the above described context we focus on the importance of the exchange rate regime for a small open economy which is affected by climate change. We first study the case in which there is not monetary policy independence (i.e. fixed exchange rates, or equivalently, the small open economy participates in a monetary union), and then we also investigate the case with flexible exchange rates.

The main results are as follows. First, irrespective of the type of the exchange rate regime, climate change, for which we assume that it causes increases in the average temperature (which in turn is quantified using historical data and estimated projections for the evolution of temperature in Greece for the period extending from 2018 to 2100), implies a significant output loss and a deterioration in terms of trade. Second, it seems that the loss of monetary policy independence is not a big loss, at least in this class of New Keynesian models with Rotemberg-type nominal fixities, when we investigate the short- and long-term implications of climate change for a small open economy.

What is the value added of our paper? On the one hand, it investigates the impact of climate change on a small open economy when other - than fiscal policy - instruments are available. From this respect, it is closer to Economides and Xepapadeas (2018), Annicchiarico and Di Dio (2017), Fischer and Heutel (2013), Heutel (2012), Fischer and Springborn (2011), and Angelopoulos et. al (2010). On the other hand, although there are many papers using open economy models, aiming at studying both various fiscal policy reforms and monetary policy issues,[1] as far as we know, little attention has been paid to the interaction between an economy sector and a climate sector in order to investigate the impact of climate change on the macroeconomic performance of a small open economy.

The rest of the paper is organized as follows. Section 2 presents the model. Section 3 presents the parameter values. Section 4 discusses the dynamics of climate change. Section 5 presents the steady state solution, explains the methodology used and describes the policy experiments on which we focus. The main results are presented in section 6. Section 7 presents the case with flexible exchange rates. Section 8 concludes the paper.

[1] See e.g., among others, the papers by Coenen, Mohr, and Straub (2008), Forni, Gerali, and Pisani (2010a, 2010b), Almeida et al. (2013), Cogan et al. (2013), Erceg and Lindé (2013), Roeger and in 't Veld (2013), Schmitt-Grohé and Uribé (2003), Philippopoulos et al (2017a, 2017b)).

2 The model

Consider a small open economy where the interest rate premium is debt elastic (see, e.g., Schmitt-Grohé and Uribe, 2003, and Philippopoulos et al, 2017b). Our setup is the standard new Keynesian model of an open economy with domestic and imported goods featuring imperfect competition and Rotemberg-type nominal rigidities, and is extended to include a climate sector and state-contingent monetary and fiscal policy rules.

The economy is comprised of a representative household; of a representative firm, producing the final good, indexed by h, by using intermediate goods which are produced by N intermediate firms indexed by j; and of monetary and fiscal authorities. Similarly, there is an imported good, indexed by f, produced abroad.

In this setup, we also allow for an energy sector, in which energy is produced, and which in turn is used – together with the other factor inputs – by the intermediate firms to produce the intermediate varieties.

2.1 Aggregation and Prices

2.1.1 Consumption Bundles

Household's consumption bundle, c_t, is defined as:

$$c_t = \frac{\left(c_t^h\right)^{\nu}\left(c_t^f\right)^{1-\nu}}{\nu^{\nu}\left(1-\nu\right)^{1-\nu}} \tag{1}$$

where ν is the degree of preference for domestic goods.

2.1.2 Consumption Expenditure, Prices and Terms of Trade

Household's total consumption expenditure is:

$$p_t c_t = p_t^h c_t^h + p_t^f c_t^f \tag{2}$$

where p_t is the consumer price index (CPI), p_t^h is the price index of home tradable good, and p_t^f is the price index of foreign tradable good (expressed in domestic currency).

We assume that the law of the one price holds, meaning that each tradable good sells at the same price at home and abroad. Thus $p_t^f = s_t p_t^{h*}$, where s_t is the nominal exchange rate (where an increase in s_t implies a depreciation) and p_t^{h*} is the price of foreign good produced abroad denominated in foreign currency. A star denotes the counterpart of a variable or a parameter in the rest of the world. Note that the terms of trade are defined as $\frac{p_t^f}{p_t^h}(=\frac{s_t p_t^{h*}}{p_t^h})$, while the real exchange rate is defined as $\frac{s_t p_t^*}{p_t}$.

2.2 The representative household

The representative household acts competitively. Its objective is to maximize the expected discounted lifetime utility:

$$E_0 \sum_{t=0}^{\infty} \beta^t U(c_t, 1-h_t, g_t), \tag{3a}$$

where c_t is the household's total consumption defined in (1), h_t is the household's hours of work, g_t is per capita spending on public consumption, $0 < \beta < 1$ is the discount factor and E_0 is the rational expectations operator. In our numerical simulations, we use a utility function of the form (see e.g., Cooley and Prescott, 1995):

$$u(c_t, 1-h_t, m_t, g_t) = \mu_1 \log c_t + \mu_2 \log(1-h_t) + (1-\mu_1-\mu_2)\log g_t, \tag{3b}$$

where μ_1 and μ_2 are standard preference parameters.

The budget constraint of the household, written in real terms, is (notice that for simplicity, we assume a cashless economy; we report that our results do not depend on this):

$$(1+\tau_t^c)\left(\frac{p_t^h}{p_t}c_t^h + \frac{p_t^f}{p_t}c_t^f\right) + \frac{p_t^h}{p_t}x_t + b_t + \frac{s_t p_t^*}{p_t}f_t + \frac{\phi}{2}\left(\frac{s_t p_t^*}{p_t}f_t - \frac{sp^*}{p}f\right)^2 =$$

$$= (1-\tau_t^y)\left(\frac{p_t^h}{p_t}r_t k_{t-1} + w_t h_t + \widetilde{\omega}_t\right) + R_{t-1}^b \frac{1}{\pi_t} b_{t-1} + R_{t-1}^f \frac{s_t p_t^*}{p_t}\frac{1}{\pi_t^*} f_{t-1} + g_t^{tr}, \tag{4}$$

where $\pi_t = \frac{p_t}{p_{t-1}}$ and $\pi_t^* = \frac{p_t^*}{p_{t-1}^*}$ are the domestic and foreign gross inflation rates respectively; and where small letters denote real variables. Here, b_t, f_t, and $\widetilde{\omega}_t$ are the household's real values, of end-of-period domestic government bonds, of end-of-period internationally traded foreign assets denominated in foreign currency (if negative, it denotes foreign private debt), and of dividends paid by firms, respectively. Also, r_t is the real return to inherited capital; k_{t-1}, x_t is real domestic investment in physical capital in period t; w_t is the real wage rate; R_{t-1}^b and R_{t-1}^f are the gross nominal returns to domestic government bonds and international assets between $t-1$ and t; g_t^{tr} is a real transfer made to the household from the government; and $0 \leq \tau_t^c, \tau_t^y < 1$ are the tax rates on consumption spending, and on income from capital, labor and firm ownership, respectively. Letters without time subscripts denote steady-state values, apart from f which is an exogenously set threshold. The parameter $\phi \geq 0$ measures adjustment costs related to private foreign assets as a deviation from a target value, f; these adjustment costs help us to avoid excess volatility and get plausible short-term dynamics for private foreign assets following a policy change.

The motion of physical capital is given by:

$$k_t = (1-\delta)k_{t-1} + x_t - \frac{\xi}{2}\left(\frac{k_t}{k_{t-1}} - 1\right)^2 k_{t-1}, \tag{5}$$

where $0 < \delta < 1$ is the depreciation rate of capital and $\xi \geq 0$ is a parameter capturing adjustment costs related to physical capital.

The household acts competitively, taking prices and policy as given. The first-order conditions of its maximization problem include the budget constraint in (4) and:

$$\nu p_t^f c_t^f = (1-\nu)\, p_t^h c_t^h \tag{6a}$$

$$\frac{(1+\tau_{t+1}^c)c_{t+1}^h}{(1+\tau_t^c)c_t^h}\left[1+\xi\left(\frac{k_t}{k_{t-1}} - 1\right)\right] =$$

$$\beta\left[1-\delta-\frac{\xi}{2}\left(\frac{k_{t+1}}{k_t} - 1\right)^2 + \xi\left(\frac{k_{t+1}}{k_t} - 1\right)\frac{k_{t+1}}{k_t} + (1-\tau_{t+1}^y)r_{t+1}\right] \tag{6b}$$

$$\frac{(1+\tau_{t+1}^c)c_{t+1}^h}{(1+\tau_t^c)c_t^h} = \beta\frac{1}{\pi_{t+1}^h}R_t^b \tag{6c}$$

$$\frac{(1+\tau_{t+1}^c)c_{t+1}^h}{(1+\tau_t^c)c_t^h}\frac{s_t p_t^*}{p_t}\left(1+\phi\left(\frac{s_t p_t^*}{p_t}f_t - \frac{sp^*}{p}f\right)\right) =$$

$$\beta\frac{s_{t+1}p_{t+1}^*}{p_t}\frac{1}{\pi_{t+1}^*}R_t^f\frac{\pi_t}{\pi_t^h} \tag{6d}$$

$$\frac{\mu_2}{1-h_t}\frac{p_t^h}{p_t} = \frac{\mu_1 \nu w_t(1-\tau_t^y)}{(1+\tau_t^c)c_t^h} \tag{6e}$$

Equation (6a) is derived after we combine the first order conditions with respect to c_t^h and c_t^h respectively and denotes that the weighted spending volumes on the domestic and the imported good must be equal. Equations (6b), (6c) and (6d) are the standard Euler equations for capital, domestic bonds and foreign assets respectively. Equation (6e) is the optimality condition for work hours. Therefore, equations (6a-e) together with equation (4) summarize the optimal behavior of the representative household.

2.3 Firms

We assume that there is only one firm producing the final good by using intermediate goods which are produced by N intermediate firms. In this setup, we also allow for an energy sector, in which energy is produced, and which in turn is used – together with the other factor inputs – by the intermediate firms to produce the intermediate varieties.

2.3.1 Final goods production

The final good producer combines intermediate goods, $y^h_{t,j}$, to produce y^h_t. Using the Dixit-Stiglitz aggregator (Dixit and Stglitz, 1977), we define aggregate output as:

$$y^h_t = \left[\sum_{j=1}^{N} \lambda_j (y^h_{t,j})^{\theta} \right]^{\frac{1}{\theta}}, \tag{7}$$

where $j = 1, 2, .., N$ are intermediate goods, and where in order to avoid scale effects we assume that $\sum_{j=1}^{N} \lambda_j = 1$. The parameter $\theta > 0$ is the elasticity of substitution across intermediate goods produced and measures the degree of imperfect competition in the intermediate goods market. Obviously, when $\theta = 1$, intermediate goods are perfect substitutes and thus their market is perfectly competitive.

The final good producer chooses $y^h_{t,j}$ to maximize its profits, which are given by:

$$p^h_t y^h_t - \sum_{j=1}^{N} p^h_{t,j} \lambda_j y^h_{t,j}. \tag{8}$$

Taking prices as given, the first-order condition with respect to $y^h_{t,j}$ yields:

$$y^h_{t,j} = y^h_t \left(\frac{p^h_t}{p^h_{t,j}} \right)^{\frac{1}{1-\theta}}, \tag{9a}$$

or equivalently:

$$p^h_{t,j} = p^h_t \left(\frac{y^h_t}{y^h_{t,j}} \right)^{1-\theta}. \tag{9b}$$

Equations (9a)-(9b) give the demand (inverse demand) faced by each intermediate firm for its product.

2.3.2 Intermediate goods production

There are N intermediate firms, each of which aims at maximizing the following profit function (written in nominal terms):

$$\widetilde{\Omega}^h_{t,j} = p^h_{t,j} y^h_{t,j} - p^h_t r_t k_{t-1,j} - W_t h_{t,j} - P^e_t E_{t,j} - T^e_t E_{t,j} -$$

$$\frac{x}{2} \left(\frac{p^h_{t,j}}{p^h_{t-1,j}} - \pi^h_j \right)^2 p^h_t y^h_t, \tag{10}$$

subject to equation (9b), and the following production function:

$$y_{t,j}^h = \widehat{A}_t k_{t-1,j}^{\alpha_1} h_{t,j}^{\alpha_2} E_{t,j}^{1-\alpha_1-\alpha_2}, \tag{11}$$

taking the domestic price level and aggregate output, p_t^h and y_t^h respectively, as given. $E_{t,j}$ is firm j's demand for energy, which in turn is used in the production process; P_t^e is the price of each unit of energy; and T_t^e is a carbon tax per unit of energy used, imposed by the government.

Notice that we follow Rotemberg (1982) and introduce sluggish price adjustment by assuming that the firm faces a resource cost that is quadratic in the inflation rate of the good it produces. This is captured by the last term in equation (10), where x measures the degree of price stickiness and π_j^h is the equilibrium gross inflation rate on the price of commodity j. This is similar to functional forms used by Schmitt-Grohe and Uribe (2004) and Bi et al. (2013). The specific adjustment costs penalize large price changes in excess of steady-state domestic inflation and make the firm's problem dynamic. Obviously, if $x = 0$, prices are fully flexible.

Finally, we assume that $\widehat{A}_t \equiv e^{-\psi^h(T_t - T_0)} A_t$ is an adjusted TFP factor which incorporates the detrimental effects of climate change into the production function, and where T_t is the average small open economy's temperature at time t, and T_0 is the average small open economy's temperature in the pre-industrial period. Thus $T_t - T_0$ can be interpreted as the temperature anomaly at time t relative to the pre-industrial period, and $e^{-\psi^h(T_t - T_0)}$ is a damage function defined in terms of the temperature anomaly. Parameter ψ^h measures the magnitude of damage due to climate change of home country and is known as the damage elasticity of output.

Therefore climate change exerts a detrimental effect on the production through the adjusted TFP parameter, $\widehat{A}_t$. Each intermediate firm does not internalize, when making its decisions, the aforementioned detrimental effect, hence it takes the environmental externality as given. The first-order conditions of firm's maximization problem with respect to factor inputs, $k_{t-1,j}$, $h_{t,j}$ and $E_{t,j}$ respectively, are:

$$-p_t^h (y_t^h)^{1-\theta} \left(y_{t,j}^h\right)^{\theta} \alpha_1 (1-\theta) k_{t-1,j}^{-1} + \alpha_1 p_{t,j}^h y_{t,j}^h k_{t-1,j}^{-1} - p_t^h r_t +$$

$$+x(\pi_{t,j}^h - \widetilde{\pi}^h) \left(p_t^h\right)^2 \left(p_{t-1,j}^h\right)^{-1} \left(y_t^h\right)^{1-\theta} \left(y_{t,j}^h\right)^{\theta-1} (1-\theta)\alpha_1 k_{t-1,j}^{-1} y_t^h -$$

$$-\beta^f x(\pi_{t+1,j}^h - \widetilde{\pi}^h) p_{t+1}^h p_{t+1,j}^h \left(p_{t,j}^h\right)^{-2} p_t^h \left(y_t^h\right)^{1-\theta} X$$

$$\left(y_{t,j}^h\right)^{\theta-1}(1-\theta)\alpha_1 k_{t-1,j}^{-1} y_{t+1}^h = 0 \tag{12a}$$

$$-p_t^h\left(y_t^h\right)^{1-\theta}\left(y_{t,j}^h\right)^{\theta}\alpha_2(1-\theta)h_{t,j}^{-1}+\alpha_2 p_{t,j}^h y_{t,j}^h h_{t,j}^{-1}-W_t+$$

$$+x(\pi_{t,j}^h-\widetilde{\pi}^h)\left(p_t^h\right)^2\left(p_{t-1,j}^h\right)^{-1}\left(y_t^h\right)^{1-\theta}\left(y_{t,j}^h\right)^{\theta-1}(1-\theta)\alpha_2 h_{t,j}^{-1}y_t^h-$$

$$-\beta^f x(\pi_{t+1,j}^h-\widetilde{\pi}^h)p_{t+1}^h p_{t+1,j}^h\left(p_{t,j}^h\right)^{-2}p_t^h\left(y_t^h\right)^{1-\theta}X$$

$$\left(y_{t,j}^h\right)^{\theta-1}(1-\theta)\alpha_2 h_{t,j}^{-1}y_{t+1}^h = 0 \tag{12b}$$

$$-p_t^h\left(y_t^h\right)^{1-\theta}\left(y_{t,j}^h\right)^{\theta}(1-\alpha_1-\alpha_2)(1-\theta)E_{t,j}^{-1}+(1-\alpha_1-\alpha_2)p_{t,j}^h y_{t,j}^h E_{t,j}^{-1}-P_t^e-T_t^e+$$

$$+x(\pi_{t,j}^h-\widetilde{\pi}^h)\left(p_t^h\right)^2\left(p_{t-1,j}^h\right)^{-1}\left(y_t^h\right)^{1-\theta}\left(y_{t,j}^h\right)^{\theta-1}(1-\theta)(1-\alpha_1-\alpha_2)E_{t,j}^{-1}y_t^h-$$

$$-\beta^f x(\pi_{t+1,j}^h-\widetilde{\pi}^h)p_{t+1}^h p_{t+1,j}^h\left(p_{t,j}^h\right)^{-2}p_t^h\left(y_t^h\right)^{1-\theta}X$$

$$\left(y_{t,j}^h\right)^{\theta-1}(1-\theta)(1-\alpha_1-\alpha_2)E_{t,j}^{-1}y_{t+1}^h = 0 \tag{12c}$$

where for β^f we assume that, ex post, it equals to $\frac{\beta(1+\tau_t^c)c_t}{(1+\tau_{t+1}^c)c_{t+1}}$ (see e.g. the discussion in Uribe and Schmitt-Grohe, 2017, pages 110-111).

2.3.3 Energy sector

In the energy sector, we assume a single firm which uses fossil fuels to produce energy. Therefore, the problem faced by this firm is to maximize its intertemporal profits, which in nominal terms, is given by:

$$\widetilde{\Omega}_t^e = \sum_{s=0}^{t}\beta^t(P_s^e - C^e)E_s, \tag{13a}$$

or in real terms is:

$$\widetilde{\omega}_t^e = \sum_{s=0}^{t}\beta^t(p_s^e - c^e)E_s, \tag{13b}$$

subject to:

$$\sum_{s=0}^{t} E_s \leq S_0, \tag{13c}$$

where S_0 is the stock of fossil fuels; c^e is the real cost of producing one unit of energy, which, for simplicity, we assume remains constant; and p_s^e is the relative price of each unit of energy. Maximization problem (13a), assuming that the resource constraint is not binding because fossil reserves are not exhausted during the planning horizon, implies that in each period t, the relative price of each unit of energy must be equal to the real marginal cost of producing this unit of energy. That is:

$$p_t^e = c^e \tag{13d}$$

which in turn implies zero real profits.

2.3.4 Government budget constraint

The budget constraint of the consolidated government sector, expressed in real terms and aggregate quantities, is:

$$d_t + \tau_t^c \left(\frac{p_t^h}{p_t} c_t^h + \frac{p_t^h}{p_t} c_t^f \right) + \tau_t^y (r_t \frac{p_t^h}{p_t} k_{t-1} + w_t h_t + \omega_t) + \tau_t^e \sum_{j=1}^{N} \lambda_j E_{t,j} =$$

$$= R_{t-1}^b \left(\frac{1}{\pi_t} \right) \lambda_{t-1} d_{t-1} + R_{t-1}^{f*} \frac{s_t p_t^*}{p_t} \frac{p_{t-1}}{p_{t-1}^* s_{t-1}} \frac{1}{\pi_t^*} \left(1 - \lambda_{t-1}\right) d_{t-1} +$$

$$\frac{p_t^h}{p_t} g_t + g_t^{tr} + \frac{\phi^g}{2} \left[(1-\lambda_t) d_t - (1-\lambda) d\right]^2 \tag{14}$$

where $d_t = \frac{B_t + s_t F_t^g}{P_t}$ is the real and per capita value of end-of-period total public debt, and where F_t^g denotes end-of-period internationally traded foreign assets denominated in foreign currency (if positive, it denotes public foreign debt). Thus, total nominal public debt, D_t, can be held by domestic private agents, $\lambda_t D_t$, as well as by foreign private agents, $\left(1 - \lambda_t\right) D_t$, where the fraction $0 \leq \lambda \leq 1$ is exogenously given. The parameter $\phi^g \geq 0$ measures adjustment costs related to public foreign debt; these costs are similar to those of the household in equation (4) above.

In each period, one of the fiscal policy instruments, τ_t^c, τ_t^y, τ_t^e, λ_t, g_t, g_t^{tr} and d_t, has to follow residually to satisfy the government budget constraint.

2.3.5 Resource Constraint and Balance of Payments

The market-clearing equation in the domestic market for goods and services is given by:

$$c_t^h + k_t - (1-\delta)k_{t-1} + \frac{\xi}{2}(\frac{k_t}{k_{t-1}} - 1)^2 k_{t-1} + g_t + p_t^e \frac{p_t}{p_t^h} E_t + c_t^{f*} =$$

$$y_t^h - \frac{x}{2}\left(\pi_t^h - \widetilde{\pi}^h\right)^2 y_t^h \tag{15}$$

where c_t^{f*} depict foreign imports or, equivalently, domestic exports. The balance of payments from the view point of the domestic economy is given by:

$$\frac{p_t^f}{p_t} c_t^f + \frac{\varphi^g}{2}\left[(1-\lambda_t)d_t - (1-\lambda)d\right]^2 + \frac{s_t p_t^*}{p_t} f_t^h + \frac{\phi}{2}\left(\frac{s_t p_t^*}{p_t} f_t - \frac{s p^*}{p} f\right)^2 +$$

$$+ R_{t-1}^f \frac{s_t p_t^*}{p_t} \frac{p_{t-1}}{s_{t-1} p_{t-1}^*} \frac{1}{\pi_t^*}(1-\lambda_{t-1})d_{t-1} =$$

$$= (1-\lambda_t)d_t + R_{t-1}^f \frac{s_t p_t^*}{p_t} \frac{1}{\pi_t^*} f_{t-1} + \frac{p_t^h}{p_t} c_t^{f*} \tag{16}$$

2.4 The Debt-Elastic Interest Rate premium

As said above, here, we endogenize the interest rate faced by the domestic country when it borrows from the world capital market, R_t^f. In particular, following Schmitt-Grohe and Uribé (2003), García-Cicco, Pancrazi, and Uribe (2010) and Philippopoulos et al. (2017b), we assume that the country premium between t and $t+1$, namely $R_t^f - R_t^*$, is an increasing function of the end-of-period total nominal public debt as share of nominal GDP, $\frac{D_t}{p_t^h y_t^h}$, when the latter exceeds a certain threshold. In particular:

$$R_t^f = R_t^* + \psi^Q \left(\frac{d_t}{\frac{p_t^h}{p_t} y_t^h} - \overline{d} \right) \tag{17}$$

where R_t^* is the world interest rate (given for the domestic economy), $\overline{d}$ is the abovementioned exogenous public debt threshold, and and the parameter ψ^Q measures the elasticity of the interest rate with respect to deviations of total public debt from its threshold value.

2.4.1 Exchange Rate and Fiscal Policy Regimes

To solve the model, we need to specify the exchange rate and the fiscal policy regimes. Concerning exchange rate policy, we solve it for a case without monetary policy independence.[2] In particular, we assume that the nominal exchange rate, s_t, is exogenously set and, at the same time, the domestic nominal interest rate on domestic government bonds, R_t^b, becomes an endogenous variable. Concerning fiscal policy, we assume that, along the transition, the residually determined public financing policy instrument is the end-of-period total public debt, D_t.

Before we turn to fiscal policy rules in the next subsection, it is worth clarifying that, along the transition path, nominal rigidities imply that monetary policy and the exchange rate regime are not neutral, and in particular, matter to the real economy.

2.4.2 Fiscal Policy Rules

Without monetary policy independence, only fiscal policy can be used for policy action. Here, we focus on simple rules, meaning that the fiscal authorities react to a small number of easily observable macroeconomic indicators capturing the current state of the economy.

Specifically, we allow total transfers as share of output, s_t^g to react to the ratio of total public debt to GDP as a deviation from a target value, $(d_{t-1} - d)$, as well as to the contemporaneous GDP gap, $(y_t - y)$, where $y_t = TT_t^{\nu-1} y_t^h$ (TT_t depict terms of trade and equals to $\frac{p_t^f}{p_t^h}$), according to the simple linear rule:[3]

$$s_t^{tr} - s^{tr} = -\gamma^d (d_{t-1} - d) - \gamma^y (y_t - y) \tag{18}$$

where γ^d and γ^y are feedback policy coefficients on public debt to GDP and output target, respectively. Notice that, in the above rules, a policy target value will be the steady-state value of the corresponding variable.

2.4.3 Exogenous Processes and Shocks

In this subsection, we define the exogenous processes that drive extrinsic fluctuations in our model.

In particular, we assume that foreign imports or, equivalently, domestic exports, c_t^{f*}, are a function of terms of trade, $TT_t = \frac{p_t^f}{p_t^h}$:

[2] However, in section 7 below, we also study the case with flexible exchange rates.

[3] For similar rules, see, e.g., Schmitt-Grohé and Uribe (2007), Bi (2010), and Cantore et al. (2012). As said above, see European Commission (2011) for similar fiscal reaction functions used in practice. On the other hand, see Kliem and Kriwoluzky (2014) for a critical approach.

$$c_t^{f*} = TT_t^{\gamma} \tag{19}$$

where $0 < \gamma < 1$ is a parameter denoting the elasticity of foreign imports with respect to changes in terms of trade. The idea is that foreign imports rise as the domestic economy becomes more competitive.

Finally, apart from changes in temperature, fluctuations are also coming from shocks to TFP. In particular, after the realization of the (positive or negative) shock, A_t (i.e., TFP productivity) evolves according to the following deterministic AR(1) rule:

$$A_t = (A)^{1-\rho_A} (A_{t-1})^{\rho_A} \tag{20}$$

where the persistence parameter ρ_A is set at 0.9,[4] while the value of A (i.e., the steady-state TFP productivity) is set at 1.

2.4.4 Decentralized equilibrium (for Any Feasible Policy)

We now combine all the above equations to present the decentralized equilibrium (DE) which is for any feasible policy. The DE is defined to be a sequence of allocations, prices, and policies such that (i) households maximize utility; (ii) firms maximize profits; (iii) all constraints, including the government budget constraint and the balance of payments, are satisfied; (iv) markets clear; and (v) policymakers follow the feedback rules assumed in subsection 2.4.2. In particular, the DE is summarized by the following equations:

$$c_t = \frac{\left(c_t^h\right)^{\nu} \left(c_t^f\right)^{1-\nu}}{\nu^{\nu} (1-\nu)^{1-\nu}} \tag{21a}$$

$$\nu TT_t c_t^f = (1-\nu)\, c_t^h \tag{21b}$$

$$\frac{(1+\tau_{t+1}^c)c_{t+1}^h}{(1+\tau_t^c)c_t^h} \left[1 + \xi\left(\frac{k_t}{k_{t-1}} - 1\right)\right] =$$

$$\beta\left[1 - \delta - \frac{\xi}{2}\left(\frac{k_{t+1}}{k_t} - 1\right)^2 + \xi\left(\frac{k_{t+1}}{k_t} - 1\right)\frac{k_{t+1}}{k_t} + (1-\tau_{t+1}^y)r_{t+1}\right] \tag{21c}$$

$$\frac{(1+\tau_{t+1}^c)c_{t+1}^h}{(1+\tau_t^c)c_t^h} = \beta \frac{1}{\pi_{t+1}^h} R_t^b \tag{21d}$$

$$\frac{(1+\tau_{t+1}^c)c_{t+1}^h}{(1+\tau_t^c)c_t^h} TT_t^{2\nu-1}\left(1 + \phi\left(TT_t^{2\nu-1} f_t - TT^{2\nu-1} f\right)\right) =$$

[4] Our results do not depend qualitatively on the value of ρ_A.

$$\beta TT_{t+1}^{2\nu-1}\frac{1}{\pi_{t+1}^{*}}R_t^f\frac{\pi_{t+1}}{\pi_{t+1}^h} \tag{21e}$$

$$\frac{\mu_2}{1-h_t}TT_t^{\nu-1}=\frac{\mu_1\nu w_t(1-\tau_t^y)}{(1+\tau_t^c)c_t^H} \tag{21f}$$

$$y_t^h=\widehat{A}_t k_{t-1}^{\alpha_1}h_t^{\alpha_2}E_t^{1-\alpha_1-\alpha_2} \tag{21g}$$

$$\widetilde{\omega}_t^h=TT_t^{\nu-1}y_t^h-TT_t^{\nu-1}r_tk_{t-1}-w_th_t-p_t^eE_t-\tau_t^eE_t-$$

$$\frac{x}{2}\left(\pi_t^h-\pi^h\right)^2TT_t^{\nu-1}y_t^h \tag{21h}$$

$$r_tk_{t-1}=\alpha_1\theta y_t^h+x(\pi_t^h-\widetilde{\pi}^h)\pi_t^h(1-\theta)\alpha_1y_t^h-$$

$$-\beta^f x(\pi_{t+1}^h-\widetilde{\pi}^h)\left(\pi_{t+1}^h\right)^2(1-\theta)\alpha_1y_{t+1}^h \tag{21i}$$

$$TT_t^{1-\nu}w_th_t=\alpha_2\theta y_t^h+x(\pi_t^h-\widetilde{\pi}^h)\pi_t^h(1-\theta)\alpha_2y_t^h-$$

$$-\beta^f x(\pi_{t+1}^h-\widetilde{\pi}^h)\left(\pi_{t+1}^h\right)^2(1-\theta)\alpha_2y_{t+1}^h \tag{21j}$$

$$TT_t^{1-\nu}\left(p_t^e+\tau_t^e\right)E_t=(1-\alpha_1-\alpha_2)\theta y_t^h+x(\pi_t^h-\widetilde{\pi}^h)\pi_t^h(1-\theta)(1-\alpha_1-\alpha_2)y_t^h-$$

$$-\beta^f x(\pi_{t+1}^h-\widetilde{\pi}^h)\left(\pi_{t+1}^h\right)^2(1-\theta)(1-\alpha_1-\alpha_2)y_{t+1}^h \tag{21k}$$

$$d_t+\tau_t^c\left(TT_t^{\nu-1}c_t^h+TT_t^{\nu}c_t^f\right)+\tau_t^y(r_tTT_t^{\nu-1}k_{t-1}+w_th_t+\widetilde{\omega}_t^h)+$$

$$+\tau_t^eE_t=$$

$$=R_{t-1}^b\left(\frac{1}{\pi_t}\right)\lambda_{t-1}d_{t-1}+R_{t-1}^fTT_t^{2\nu-1}TT_{t-1}^{1-2\nu}\frac{1}{\pi_t^*}\left(1-\lambda_{t-1}\right)d_{t-1}+$$

$$+TT_t^{\nu-1}g_t+g_t^{tr}+\frac{\varphi^g}{2}\left[(1-\lambda_t)d_t-(1-\lambda)d\right]^2 \tag{21l}$$

$$c_t^h+k_t-(1-\delta)k_{t-1}+\frac{\xi}{2}(\frac{k_t}{k_{t-1}}-1)^2k_{t-1}+g_t+p_t^eTT_t^{1-\nu}E_t+c_t^{f*}=$$

$$y_t^h - \frac{x}{2}\left(\pi_t^h - \widetilde{\pi}^h\right)^2 y_t^h \quad (21m)$$

$$TT_t^{\nu} c_t^F + \frac{\varphi^g}{2}\left[(1-\lambda_t)d_t - (1-\lambda)d\right]^2 + TT_t^{2\nu-1} f_t +$$

$$+R_{t-1}^f TT_t^{2\nu-1} TT_{t-1}^{1-2\nu} \frac{1}{\pi_t^*}(1-\lambda_{t-1})d_{t-1} =$$

$$= (1-\lambda_t)d_t + R_{t-1}^f TT_t^{2\nu-1} \frac{1}{\pi_t^*} f_{t-1} + TT_t^{\nu-1} c_t^{f*} \quad (21n)$$

$$c_t^{F*} = TT_t^{\gamma} \quad (21o)$$

$$R_t^f = R_t^* + \psi^Q \left(\frac{d_t}{\frac{p_t^h}{p_t} y_t^h} - \overline{d} \right) \quad (21p)$$

$$\pi_t = \left(\pi_t^h\right)^{\nu} \left(\pi_t^f\right)^{1-\nu} = \left(\pi_t^h\right)^{\nu} \left(\frac{TT_t}{TT_{t-1}}\right)^{1-\nu} \quad (21q)$$

$$\pi_t^h = \frac{TT_{t-1}}{TT_t} \epsilon_t \pi_t^{h*} \quad (21r)$$

where $\epsilon_t = \frac{s_t}{s_{t-1}}$ is the depreciation rate. In the case without monetary policy independence $\epsilon_t = \frac{s_t}{s_{t-1}} = 1$. We thus end up with a first-order non-linear dynamic system of eighteen equations (21a-21r) in eighteen unknown variables, namely, c_t, c_t^h, c_t^f, h_t, k_t, f_t, $\widetilde{w}_t^h$, y_t^h, r_t, w_t, E_t, R_t^b, R_t^f, c_t^{f*}, TT_t, π_t, π_t^h and d_t. This DE is given the values of feedback policy coefficients in the policy rule (18); the exogenous variables; and initial conditions for the state variables.

3 Parameterization

Table 1 reports the baseline parameter values for policy, technology and preferences used to obtain the values of the endogenous variables. We use conventional values. We note at the outset that our main results are robust to changes in these parameter values. Thus, although our numerical simulations below are not meant to provide a rigorous quantitative study, they illustrate the qualitative dynamic features of the model in a robust way.

Table 1 here

Parameterization

The time unit is a year. Regarding preference parameters, we use values employed by most of the related literature. The discount factor, β, and the depreciation rate of physical capital, δ, are set equal to 0.98 and 0.05 respectively,[5] to be consistent with a value for the after tax real interest rate on capital of about 7% per year.[6]

The degree of preference for domestic goods, ν, is set at 0.5. The weights given to private consumption and leisure, μ_1 and μ_2 are set equal to 0.45 and 0.5 respectively. The weight given to public goods and services then follows residually and is equal to 0.05 (see, e.g., Cooley and Prescott, 1995).

The parameters φ and φ^g, measuring adjustment costs associated with changes in private and public foreign assets, are both set to 0.3. These values give plausible short-run dynamics for private foreign assets and, in turn, for the country's net foreign debt. However, we report that our results do not depend on this. Similarly, the value of ξ measuring capital adjustment costs is set equal to 0.3.

Regarding technology parameters in the production function of goods (see equation (21g)), the Cobb-Douglas exponents of physical capital and labor, α_1 and α_2, are set equal to 0.33 and 0.60 respectively, so that the exponent of energy input follows residually and is equal to 0.07. These values are within standard ranges (see, e.g., Cooley and Prescott, 1995). The scale parameter in the same function, A, is set at 1. Following Bi et al. (2013), we set the parameter x, which measures the degree of price stickiness, equal to 5. Following Eggertsson et al. (2014), we use a value equal to 0.95 for the elasticity of substitution across intermediate goods produced, θ, which is also a measure of imperfect competition.

The steady-state values of the exogenously-set fiscal policy instruments are set close to their data averages for the Greek economy, using Eurostat data. For instance, the consumption tax rate, τ_t^c, and the income tax rate, τ_t^y, are set equal to 0.19 and 0.33 respectively, which are close to the averages of the respective effective tax rates in the data. These values are kept constant during the planning horizon. Moreover, we set the government consumption, g_t, and total transfers, g_t^{tr}, both as a share of GDP, s_t^g and s_t^{tr}, equal to 0.2. During the planning horizon, s_t^g remains constant, whereas – in order to ensure dynamic stability – we allow s_t^{tr} to react to deviations of debt over output from its steady-state value, as well as to deviations of real income from its steady-state value (see also equation (18)). Regarding

[5] The value of the discount factor implies an annual rate of time preference of around 2%. There has been a long discussion about the choice of the time discount rate (see, e.g., Dasgupta, 2008). Our choice of 2% is within the range regarded as appropriate in the relevant literature. The discount factor of Golosov et al. (2014) implies an annual rate of time preference 1.5%. Note that our results are robust to changes in rate of time preference choices around 2%.

[6] This value for the after tax real interest rate on capital is in line with e.g. Mehra and Prescott (1985), Piketty (2014) and Mankiw (2015).

the carbon tax, τ^e_t, we set its value equal to 0.3 so as the associated tax revenues represent a fraction of total tax revenues close to the data.[7] Also, λ, which is the fraction of total public debt held by domestic private agents is set at 0.3, which is again a value very close to the data. Finally, regarding the feedback policy coefficients on public debt to GDP and output target, γ^d and γ^y respectively (see equation (18)), we set them to be 0.2 and 0.105 respectively.

The real cost of producing energy, c^e, is set equal to 1.1. Notice however that our results do not depend qualitatively on the value of c^e.

In our baseline parameterization, the threshold parameter value of the public-debt-to-GDP ratio above which sovereign interest rate premia emerge, $\overline{d}$, is set at 0.9 (see equation (17)). This value is consistent with evidence provided by, e.g., Reinhart and Rogoff (2010) and Checherita-Westphal and Rother (2012) that, in most economies, the adverse effects of public debt arise when it is around 90–100 percent of GDP. It is also within the range of thresholds for sustainable public debt estimated by the European Commission (2011). In turn, the associated premium parameter, ψ^Q, is set to be 0.0505 which means that a 1 percentage point increase in the debt-to-GDP ratio leads to an increase in the interest rate premium by 5.05 basis points. This is a rather reasonable assumption, however we report that our results do not depend on this. The exogenously set threshold of foreign assets, f, is set equal to 0.3 (our results do not depend on this). The elasticity of foreign imports with respect to changes in terms of trade, γ, is set equal to 0.9.

Finally, regarding the exogenous part of the foreign interest rate, R^*_t, and the gross rate of domestic inflation in the foreign country, π^{h*}_t, we assume that they are constant over time and equal to 1.01 and 1 respectively at all t.

4 Climate Change Damages

To quantify the impact of climate change on a small open economy we need to provide an estimate of these damages. More specificaly in terms of the new Keynesian model developed in this paper an estmate of the parameter ψ^h is required. In this section we provide such an estimate for the Greek economy.

4.1 The aggregate damage function for the Greek economy

When analyzing climate change impacts for a small country it should be noted that the small country cannot affect the global climate change through its own emissions policy, i.e. mitigation, because these emissions are very

[7] The aforementioned fiscal policy mix produces a long-run public debt-to-output ratio, $\frac{d_t}{y_t}$, equal to around 1.26, which is close to the value of greek public debt in 2010.

small relative to the global emissions. On the other hand the small country suffers the impact of climate change, which in this case is exogenous and independent of the small country's mitigation policy.

Therefore, the damage function for the small country should determine damages in the country's GDP resulting from changes in the local temperature. It is important however to emphasize that the local temperature does not depend on the country's mitigation or fossil fuel policy, but it is the result of the way that global climate change shapes the evolution of local temperature. In a sense local temperature depends on global mitigation, since local mitigation is an infinitesimal share of global mitigation, so that it cannot affect local temperature changes.

Thus to determine the local damage function, we need to link the local temperature anomaly, that is the change in the local temperature relative to the preindustrial period, with losses in local GDP. There is a large literature on damage functions from global warming measuring damages as proportions of GDP (see for example the surveys by Nordhaus and Moffat (2017) and Tol (2018)), with values ranging from +0.1% to -6.7% of GDP. These values correspond to alternative assumptions about the change in temperature relative to the preindustrial period which range from 1°C to 6°C (see table 1 in Tol (2018)). The majority of these estimates correspond to global GDP. For the small country analysis, however, the local impact on GDP from changes in the local temperature is required, with the local temperature determined by global climate change.

Tol (2018, Appendix C) provides the following linear regression equation with dependent variable the impact I_c of climate change as a proportion of GDP in country c and independent variables GDP per capita y_c and average temperature T_c in country c .

$$\begin{array}{ccccccc} I_c & = & \underset{(8.7)}{-13.4} & + & \underset{(079)}{1.70 \log y_c} & - & \underset{(0.14)}{0.46 T_c} \end{array} \tag{22}$$

The impact of GDP per capita is to reduce damages from climate change, since developed countries have greater ability to reduce the impact of climate change through adaptation. To use this regression for Greece data on GDP per capita and average temperature are needed. Using the most recent estimate of Greek GDP per capita, which is, in 2017, is 23027.4 in constant 2010 US$[8] , and an average temperature of 15.4°C as reported in Tol (2108)[9]) the climate change impact as proportion of GDP is -3.41%. This estimate is not, however, useful for future predictions. Using it to estimate future damages would imply that GDP per capita and average temperature will remain constant, which is not a realistic assumption. In the next section

[8] The source of all GDP data is the World Bank. https://data.worldbank.org/indicator/NY.GDP.PCAP.KD?locations=GR&view=chart.

[9] http://users.sussex.ac.uk/~rt220/totalimpactreep.xlsx

we provide estimates of climate change damages as proportions of GDP for the period up to 2100, which is the typical period covered by most climate models' forecasts.

4.2 Prediction of aggregate climate change damages for the Greek economy as proportion of GDP: 2018 - 2100[10]

The first step for this prediction is to provide a forecast of the evolution of the Greek GDP per capita. In the figure below this evolution is depicted for the period 1960-2017.

Figure 1 here

Greece, GDP per capita in constant 2010 US$

The average annual growth rate of the Greek GDP per capita for this period was 2.125%, while for the Eurozone the corresponding rate was 2.286%. To make the long-term predictions for the period 2018-2100 we consider four scenarios.

1. S1: The GDP per capita grows, from the initial value of 23027.4 in 2017, at an average annual rate of 1%.
2. S2: The GDP per capita grows, from the initial value of 23027.4 in 2017, at its historic average annual rate of 2.125%.
3. S3: The GDP per capita growth converges in average to the Eurozone historic growth rate, and grows from the initial value of 23027.4 in 2017, at the average annual Eurozone rate of 2.286%.
4. S4: The GDP per capita growth converges to the level of Eurozone GDP per capita in 2100 with the Eurozone GDP per capita growing at is annual average historic growth rate of 2.286%. The implied average annual growth rate for the Greek GDP in this case is 2.98%.

Clearly S1 is the pessimistic scenario and S4 is the most optimistic. We obtain the average GDP per capita during 2018-2100 for each scenario as.

$$y_{AV_j} = \frac{1}{T} \sum_{i=1}^{T} y_{2017} \left(1 + g_{\mathrm{S}j}\right)^T, T = 2100 - 2017, j = 1, 2, 3, 4. \quad (23)$$

[10] This section uses average IPCC temperature data. A more refined estimate of climate change damages in Greece will be obtained by using the recent climate data calculated for Greece at regional, seasonal and global level, by Zerefos and Kapsomenakis, Athens Academy (2018). This is our future research task.

Having obtained the average GDP per capita for the period 2018-2100, the next step is to obtain an estimate of the average temperature in Greece during the same period.

The Intergovernmental Panel on Climate Change (IPCC) (2014) estimates suggest that the temperature anomaly in the Mediterranean area for the period 1901-2012 was in the range of $1^{\circ} - 1.5^{\circ}$C. The NASA data on the temperature anomaly[11] indicate the in the zone 22^{o} N-44^{o} N , which includes Greece the temperature anomaly in 2017 relative to the average of 1951-1980 was 1.3°C .

Therefore the use of the value of 15.4°C for the average surface temperature in 2017 in Greece seems reasonable. For the future we adopt central predictions of the two polar IPCC scenarios the RPC2.6 (optimistic) and the RPC8.5 (pessimistic). The RPC2.6 predicts an increase of approximately 1°Cfor the period 2000-2100, while the RPC8.5 predicts an increase of approximately 4°C for the same period. Given these estimates we assume point estimates of the average temperature in Greece for 2018-2100, of 15.9°C for the optimistic scenario (OPT) and 17.4° C for the pessimistic scenario (PES).

Using the estimates for the average GDP per capita and average temperature in equation (22) we obtain the following average impacts of climate change on Greek GDP for the period up to 2100.

Table 2 here

Climate change damages as % of GDP. Average 2018-2100

Assigning arbitrary subjective probabilities $\{0.1, 0.4, 0.4, 0.1\}$ to the growth scenarios S1-S4 respectively results in an expected GDP per capita average annual growth of 2.16%.[12] Assigning probabilities $\{0.5, 0.5\}$ to climate scenarios {OPT,PES} respectively, results in an expected average temperature of 16.65, which implies an anomaly of 2.65°C relative to the preindustrial period. Combining these results the average damage as proportion of GDP is

$$\text{Average Damage} = -2.25\% \tag{24}$$

Assuming an exponential damage function in terms of the temperature anomaly T^{a} of the form

$$D\left(T_{t}^{a}\right) = e^{\psi^{h}\left(T_{t}^{a} - T_{0}\right)}, T_{0} = 14^{\circ}\text{C}. \tag{25}$$

the parameter ψ^{h} can be calibrated by using

$$1 - 0.0225 = e^{\psi^{h} \times 2.65} \tag{26}$$

[11] https://data.giss.nasa.gov/gistemp/

[12] We report that sensitivity analysis around the probabilities does not suggest any substantial changes in the result. In any case, in (28) each scenario is treated differently.

resulting in

$$\psi^h = -0.0085914 \tag{27}$$

To determine damages for different values of the anomaly we use a simple approach, instead of trying to specify an exact annual path. Thus we assume that in each temperature scenario the anomaly increases by equal amounts per decade. This assumption results in the following paths for the anomaly at the PES and OPT climate scenarios.

Table 3 here
The temperature anomaly 2018-2100

4.3 Prediction of aggregate climate change damages for the Greek economy : 2018 - 2100.

Having determined climate change damages as proportions of GDP a next step would be the estimation of these damages in value terms. Since the evolution of per capita GDP is predicted by the four scenarios, the estimate of the evolution of GDP requires prediction of population. The evolution of the population of Greece between 1950 and 2015 is shown in Figure 2.

Figure 2 here
The population of Greece

The population of Greece peaked in 2010 at 11,446,000 and since then it follows a downwards trend which could be attributed to the economic crisis. We assume that the population will recover and will tend to an average value of 11.5 million for the examined period.[13] Given this estimate the present value of climate change damages during the period 2018-2100 can be obtained as:

$$D_{ij} = \alpha_{ij} \sum_{t=1}^{T} (23047.4 \times 11,500,000) \left(\frac{(1 + g_{Sj})}{(1 + r)} \right)^t, i = \text{OPT,PES}, j = 1, 2, 3, 4 \tag{28}$$

where α_{ij} are damages as proportion of GDP, g_{Sj} is the GDP per capita growth rate in each scenario and r is the social discount rate (SDR).

We use two values for the SDR $r = \{0.015, 0.02\}$. As it is well known the deterministic Ramsey formula for the SDR

$$r = \rho + \sigma \frac{\dot{c}}{c}, \tag{29}$$

[13] Given the growth scenario, the relation between damages and population is increasing. So a smaller population seems to imply smaller aggregate damages. On the other hand, a sharp decline in population, as indicated by the 2018 Ageing Report, might affect the GDP growth rates which might drop below the examined scenarios because of human capital loss. This could impede the adaptation capabilities of the Greek economy which in turn could increase damages as a proportion of GDP. The endogeneity between population growth and damages in terms of GDP requires further research.

where ρ is the utility discount rate, σ is the elasticity of marginal utility, for isoelastic utility function, and $\dot{c}/c$ is the consumption rate of growth, results in a SDR above 2% for commonly accepted values of parameters . However, it has been established in the relevant literature that the deterministic SDR should be reduced under conditions of uncertainty, in order to incorporate precautionary concerns, and should be reduced even further to account for environmental damages in the long run. A detailed analysis of these two effects on the SDR for the Greek economy is an area of future research. Thus, for the purpose of this preliminary estimate we use the ball park values or 1,5% and 2%. The results are shown in the table below.

Table 4 here

Aggregate Climate Change Damages in Greece, 2018-2100

The sensitivity of the results to the choice of the SDR is clear.

5 Steady state, methodology and policy experiments

In this section, we present the steady solution of the model presented in section 2, discuss the methodology used, and explain the experiments we focus on and how the effects of these experiments are computed. Recall that, nominal rigidities imply that monetary and exchange rate policy matter to the real economy. Recall also that, along the transition path, different counter-cyclical policy rules, and hence different values of feedback policy coefficients, can have different implications.

5.1 Steady state

The third column of Table 5 reports the steady-state solution of the small open economy new Keynesian model presented in section 2, when we use the parameter values and the policy instruments discussed in sections 3 and 4 and presented in Table 1. The resulting long-run solution is well defined and intuitive.

Table 5 here

Steady State Solutions

In what follows, this steady-state solution, called status quo, will serve as a point of departure to study the impact of climate change.

5.2 Methodology

Using the above numerical values, we solve the system described by equations (21a)-(21r) by using a Newton-type non-linear method as implemented in DYNARE. DYNARE uses a relaxation algorithm in order to numerically solve the non-linear equations. We solve the model under perfect foresight in the sense that the distribution of shocks with which we feed the model is known to the agents of the economy. In other words, the dynamics of our model will be driven by the projected changes in temperature due to climate change as well as by temporary changes in the value of A_t.

5.3 Policy experiments

The main experiment we want to consider in this paper is the case in which the economy departs from the status quo and travels over time - due to climate change - to a new steady state (see the fourth column of Table 5). We will investigate the impact of climate change on the evolution of per capita real income, capital, energy, domestic production, private consumption, private investment, government spending, terms of trade, imports and exports with and without monetary policy independence (i.e. under fixed and flexible exchange rates). Moreover, we will compare the impact of a standard TFP shock with and without climate change. As mentioned above, temperature anomaly for Greece is estimated using data projections about the evolution of temperature for the period extending from 2018 to 2100.

6 Main results in the case without monetary policy independence

This section presents the main results of our numerical simulations. As already mentioned, the focus will be on investigating both the effect of climate change on our small-open economy's per capita real income, capital, energy, domestic production, private consumption, private investment, government spending, terms of trade, imports and exports. Notice that in our model setup, climate change is represented by a continuous increase in temperature relative to the temperature in the pre-industrial period. This change in tempretarure affects TFP productivity through $\widehat{A}_t$ (see equation (11) above) and operates as a permanent negative TFP shock.

6.1 Climate change and macroeconomic performance

The paths of the per capita real income, capital, energy, domestic production, private consumption, private investment, government spending, terms of trade, imports and exports, all as percentage deviations from their values at the initial steady state, are presented in Figures 3a-3j below.

Figures 3a-3j here

As can be seen in Figure 3a, climate change seems to imply significant income losses for the small-open economy, which, cummulatively, account for more than 80% of current real income. With the exception of hours of work, h_t, which remain relatively constant along the whole path,[14] the rest of the productive inputs, namely capital, k_t, and energy, E_t, as can be seen in Figures 3b-3c, decrease monotonically. These developments can explain the decrease in domestic production, y_t^h, in Figure 3d. The decrease in domestically produced output can in turn explain the drop in private consumption, private investment and government spending, observed in Figures 3e-3f-3g. Moreover, as can be seen in Figure 3h, climate change is associated with a deterrioration of small-open economy's competitiveness, which is being reflected in a worsening of terms of trade, TT_t. This is reasonable, since climate change causes a decrease in domestic production, which in turn increases domestic price level, worsening the terms of trade which are given by the ratio $\frac{p^f}{p^h}$. Thereby, naturally, imports increase (see Figure 3i), although slightly, and exports decrease (see Figure 3j).

Finally, as can be seen in Figure 3k below, in the presence of climate change, the impact of a 1%temporary negative TFP shock on real per capita income, at least in the impact period, does not differ, neither qualitatively nor quantitatively, to the case in which there is no climate change.

Figure 3k here

7 The same economy with monetary policy independence

This section solves the baseline model developed in section 2 under the assumption of flexible exchange rates, other things being equal. In terms of modeling, the only difference from the model in section 2 is that now the exchange rate becomes an endogenous variable. Thus, R_t^b and s_t exchange places. The former was endogenous in section 2, while now it is the latter that becomes endogenous, with the former being free to follow a national Taylor-type rule for the nominal interest rate (see e.g. Taylor, 1979, 1993, 1999). In particular, we assume that:

$$R_t^b = R^b + \gamma^\pi \left(\pi_t - \widetilde{\pi}\right) \tag{30}$$

where γ^π is a feedback monetary policy coefficient on price inflation, as deviation from its steady-state value.[15] Regarding the feedback monetary

[14] The Figure of hours of work is available upon request.

[15] We report that the results would not change qualitatively in case we assumed a richer Taylor-type rule of the following form: $R_t^b = R^b + \gamma^\pi \left(\pi_t - \widetilde{\pi}\right) + \gamma^y \left(\pi_t - \widetilde{\pi}\right) + \gamma^\epsilon \left(\epsilon_t - \widetilde{\epsilon}\right)$,

policy coefficient, and following most of the relevant literature, we assume that $\gamma^{\pi} = 1.5$.

As before, the main experiment we want to consider is the case in which the economy departs from the status quo (see the third column of Table 5) and travels over time - due to climate change - to a new steady state (see the fourth column of Table 5).

We will again investigate the impact of climate change on the evolution of per capita real income, capital, energy, domestic production, private consumption, private investment, government spending, terms of trade, imports and exports, the dynamic paths of which, all as percentage deviations from their values at the initial steady state, are presented in Figures 4a-4j below. Also in Figure 4k below, the impact of a 1% temporary negative TFP shock on real per capita income, with and without climate change, is presented.

Figures 4a-4k here

As can be seen, the qualitative results remain analogous to those presented in section 5.

In other words, the loss of monetary policy independence is not a big loss, at least in this class of New Keynesian models with Rotemberg-type nominal fixities, when we investigate the short- and long-term implications of climate change for a small open economy. This can be seen in Figures 5a-5b below in which we compare the path of per capira real income, as well as, the impact of a 1% temporary negative TFP shock, under fixed and flexible exchange rates respectively.

Figures 5a-5b here

8 Concluding remarks

In this paper we extended the standard new Keynesian model of a small open economy by allowing for climate change effects. Within this setup, our objective was to investigate the impact of climate change on the economic outcomes of the small open economy with and without monetary policy independence. Our results suggest that climate change implies a significant output loss and a deterioration of competitiveness. These results are independent of the type of the exchange rate regime. Moreover, we argue that the loss of monetary policy independence is not a big loss, at least in this class of New Keynesian models with Rotemberg-type nominal fixities, when we investigate the short- and long-term implications of climate change for a small open economy. It should be noted that these results are robust to parameter changes.

where γ^{y} and γ^{ϵ} are feedback monetary policy coefficients on output, and exchange rate depreciation.

The present model could be extended along different dimensions. Since a criticism to IAMs is the damage function (see Pindyck, 2013), different functional forms and parametrizations for the damage function could be explored, along with the explicit introduction of tipping points. Moreover, the current setup could be augmented by introducing a properly modeled financial sector to investigate the financial risks associated with climate change.

Finally, in the case with monetary policy independence, it would be interesting to focus on optimal policies by examining what should be the optimal coefficients of reaction to deviations from target in the simple Taylor rule, when for instance the objective is the maximization of households' intertemporal welfare.

We leave these extensions for future work.

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Table 1: Parameterization		
Parameters and policy variables	Description	Value
β	discount factor	0.98
ν	degree of preference for domestic goods	0.5
μ_1	weight given to consumption	0.45
μ_2	weight given to leisure	0.5
$1-\mu_1-\mu_2$	weight given to public consumption	0.05
α_1	exponent of physical capital	0.33
α_2	exponent of labour	0.6
$1-\alpha_1-\alpha_2$	exponent on energy	0.07
A	TFP productivity	1
δ	depreciation rate of physical capital	0.05
x	degree of price stickiness	5
θ	measure of imperfect competition	0.95
τ_t^c	consumption tax rate	0.19
τ_t^y	income tax rate	0.33
τ_t^e	carbon tax rate	0.3
ψ^Q	interest rate premium parameter	0.0505
$\overline{d}$	threshold parameter of public debt over output	0.9
γ	terms of trade elasticity of foreign imporrts	0.9
ξ	adjustment cost parameter on physical capital	0.3
φ	adjustment cost parameter on private Foreign debt	0.3
φ^g	adjustment cost parameter on foreign public debt	0.3
λ	fraction of total public debt held by domestic agents	0.3
$\frac{g_t}{y_t}$	government cons/GDP	0.2
$\frac{g_t^{tr}}{y_t}$	government transf/GDP	0.2
ψ^h	damage effect	0.0085914
c^e	real cost per unit of energy	1.1

Table 2				
Climate change damages as % of GDP. Average 2018-2100				
$T \backslash y$	**Scenario 1**	**Scenario 2**	**Scenario 3**	**Scenario 4**
OPTIMISTIC	-2.89	-1.95	-1.81	-1.17
PESIMISTIC	-3.58	-2.64	-2.48	-1.86

Table 3		
The temperature anomaly 2018-2100		
PERIOD	**PESIMISTIC SCENARIO**	**OPTIMISTIC SCENARIO**
2018-2030	15.9	15.7
2031-2040	16.4	16.1
2041-2050	16.9	16.4
2051-2060	17.4	16.4
2061-2070	17.9	16.4
2071-2080	18.4	16.4
2081-2090	18.9	16.4
2091-2100	19.4	16.4

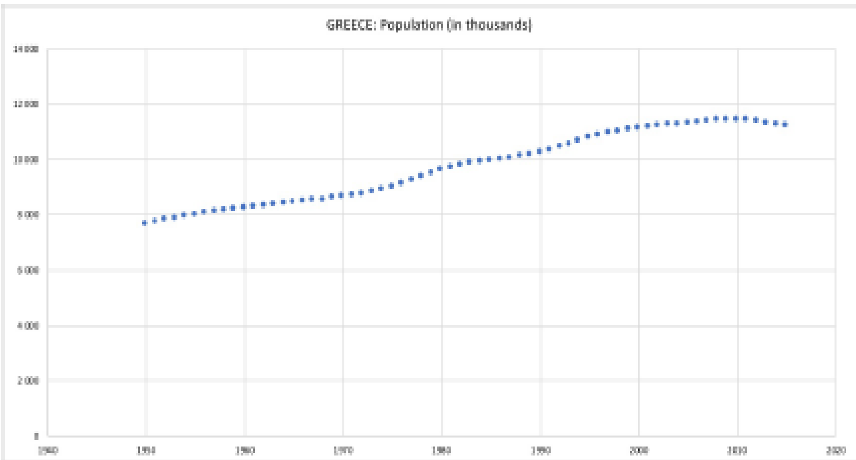
Table 4: Aggregate Climate Change Damages in Greece, 2018-2100			
(Present value in billion 2010 US\$)			
Damages as % of GDP in parentheses			
SCENARIOS		$r = 1.5\%$	$r = 2\%$
	S1	560.8	441.7
		(−2.98%)	(−2.98%)
	S2	600.1	484.4
OPTIMISTIC		(−1.95%)	(−1.95%)
	S3	550.4	442.4
		(−1.81%)	(−1.81%)
	S4	713.6	563.1
		(−1.17%)	(−1.17%)
AVERAGE		648.1	522.7
		(−2.25%)	(−2.25%)
	S1	637.6	530.7
		(−3.58%)	(−3.58%)
	S2	747.4	603.4
PESIMISTIC		(−2.64%)	(−2.64%)
	S3	760.2	611.1
		(−2.50%)	(−2.50%)
	S4	780.5	616.1
		(−1.81%)	(−1.81%)

Table 5: Steady-State Solutions			
Variable	Description	Steady State 1	Steady State 2
y	real income	1.380	1.352
y^h	production of home good	0.475	0.453
k	physical Capital	1.417	1.351
h	labour supply	0.332	0.332
e	energy	0.065	0.064
c	consumption	0.801	0.784
c^h	consumption of home good	0.137	0.131
c^f	consumption of foreign good	1.164	1.171
TT	terms of trade	0.118	0.112
d/y	debt over output ratio	1.259	1.260
$(1-\lambda)d/y$	foreign public debt to output ratio	0.881	0.882
g	public consumption	0.095	0.090
g^{tr}	government transfers	0.276	0.270
w	wage	2.368	2.319
r	real return to capital	0.105	0.105
R^b	nominal return to goverment bonds	1.020	1.020
R^f	nominal return to international assets	1.028	1.028
c/y	consumption over output ratio	0.577	0.5804
inv/y	investment over output ratio	0.1492	0.1492
W	welfare	-0.419368	-0.430983

Figure 1: Greece, GDP per capita in constant 2010 US$

Source: The World Bank

Figure 2: The population of Greece



Source: UN, World Population Prospects: The 2017 Revision population data

Figure 3a
% Deviation of real income from the initial Steady State

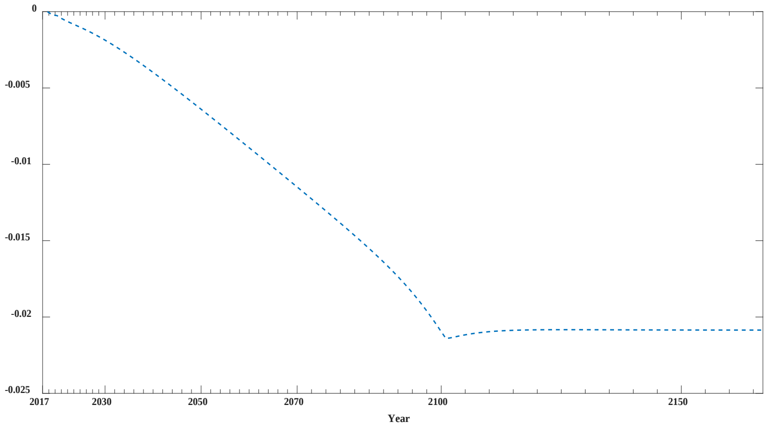


Figure 3b
% Deviation of capital from the initial Steady State

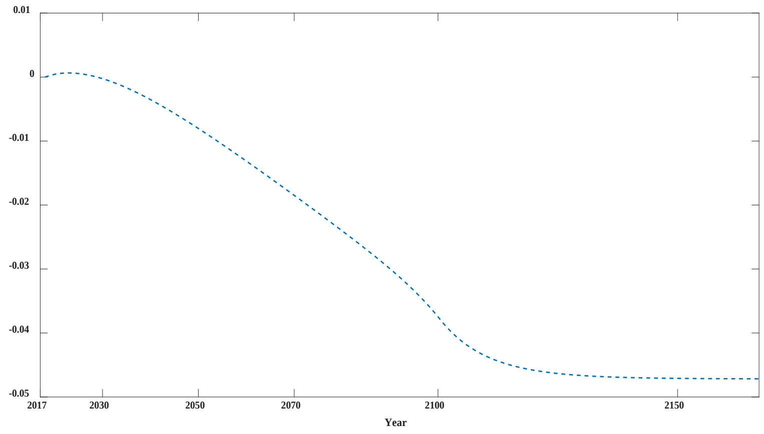


Figure 3c
% Deviation of energy from the initial Steady State

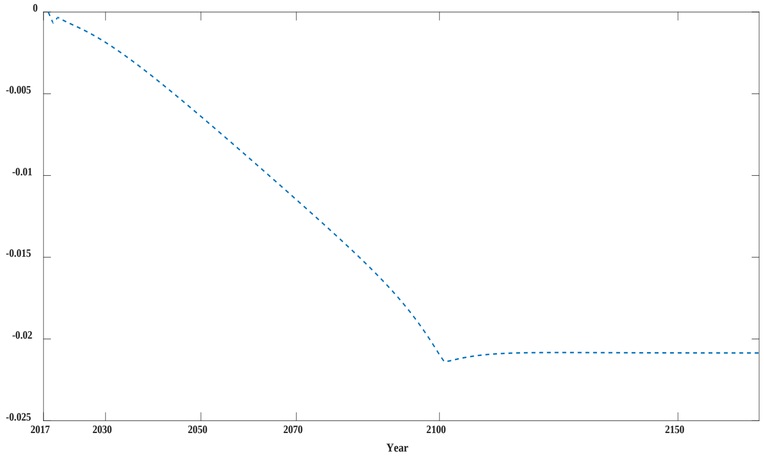


Figure 3d
% Deviation of domestic production from the initial Steady State

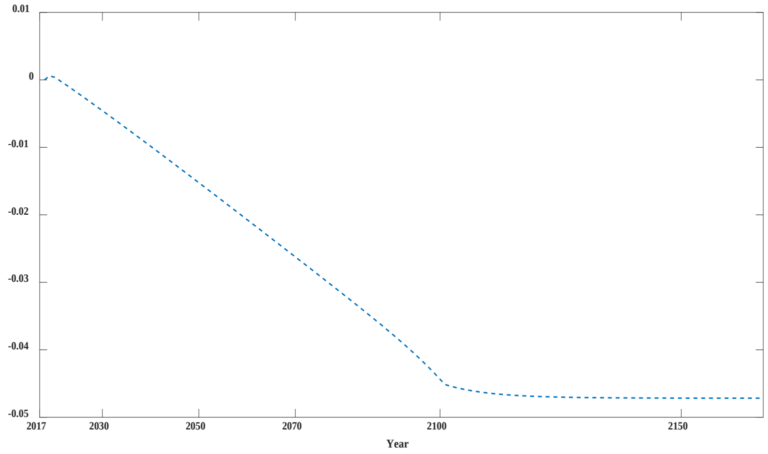


Figure 3e

% Deviation of private consumption from the initial Steady State

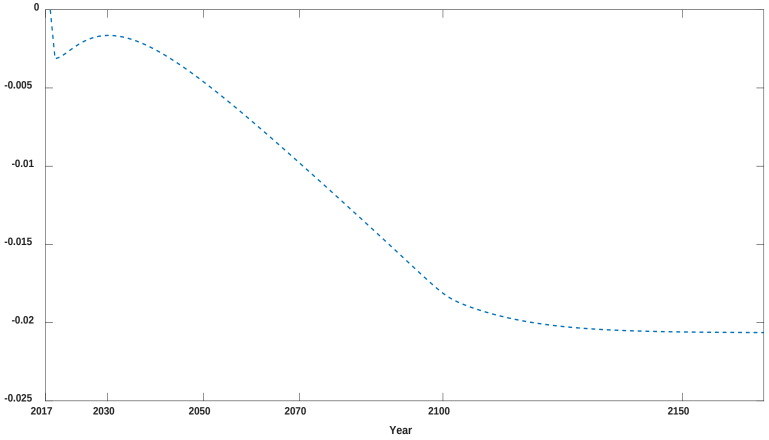


Figure 3f

% Deviation of private investment from the initial Steady State

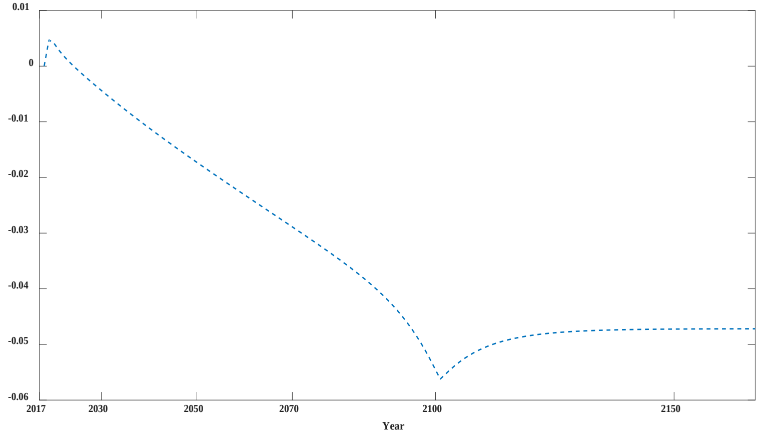


Figure 3g

% Deviation of government spending from the initial Steady State

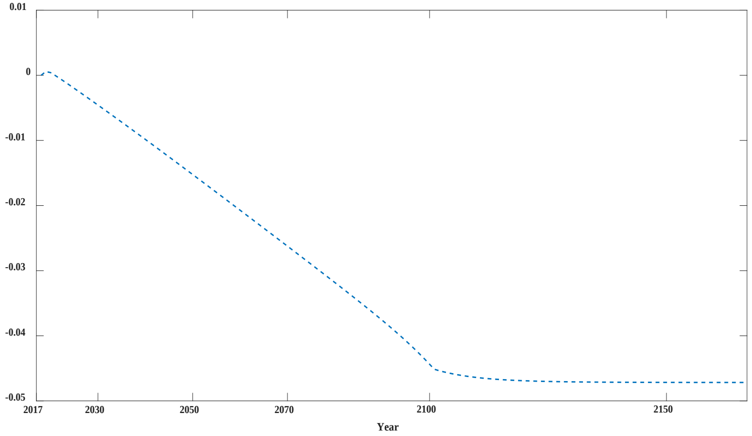


Figure 3h

% Deviation of terms of trade from the initial Steady State

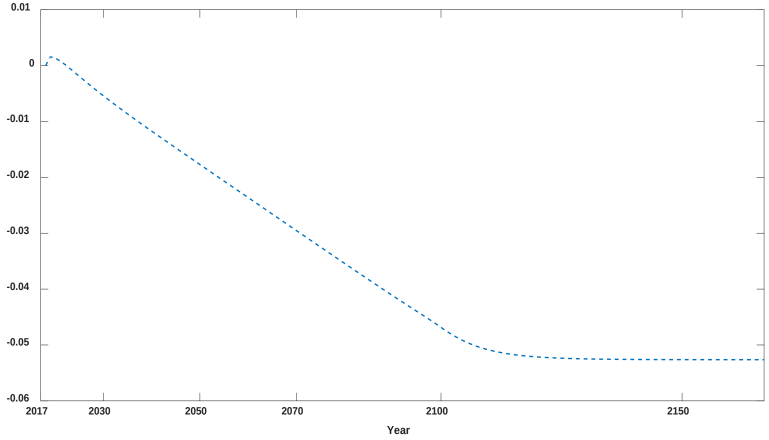


Figure 3i

% Deviation of imports from the initial Steady State

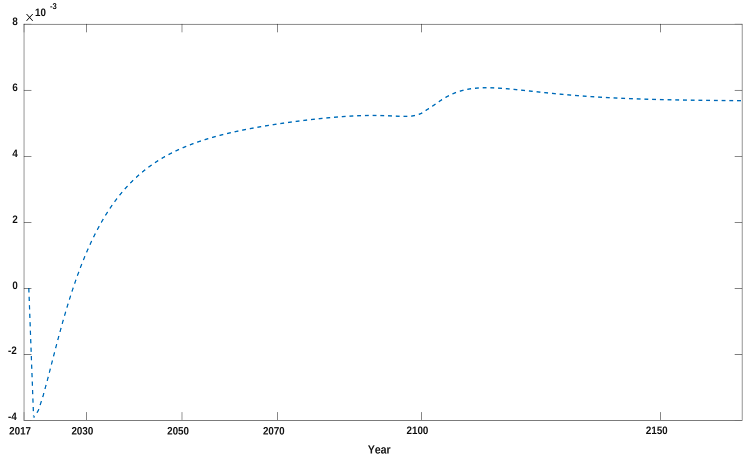


Figure 3j

% Deviation of exports from the initial Steady State

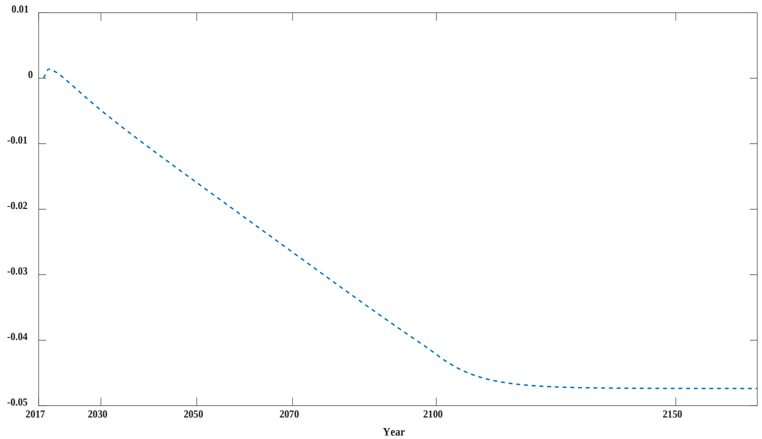


Figure 3k

% Deviation of real income from the initial Steady State

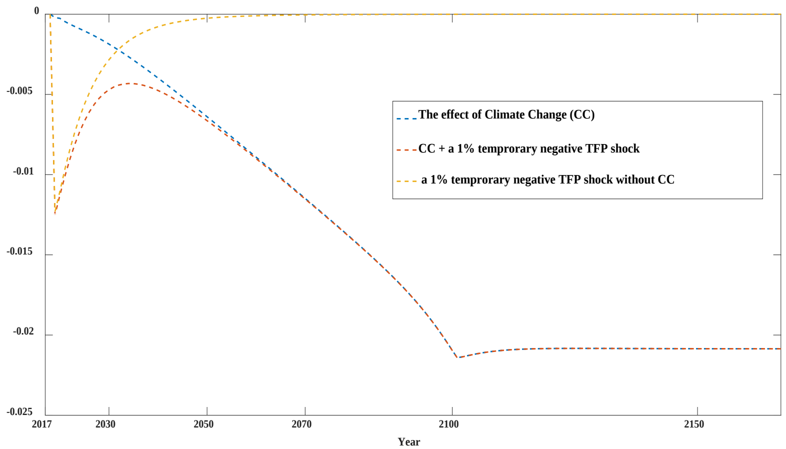


Figure 4a
% Deviation of output from the initial Steady State

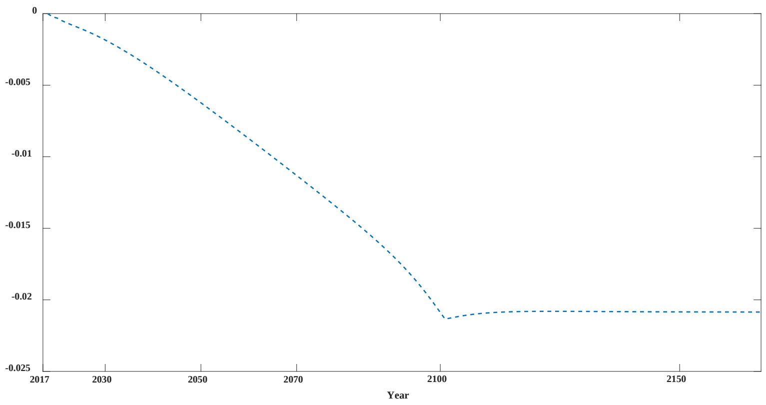


Figure 4b
% Deviation of capital from the initial Steady State

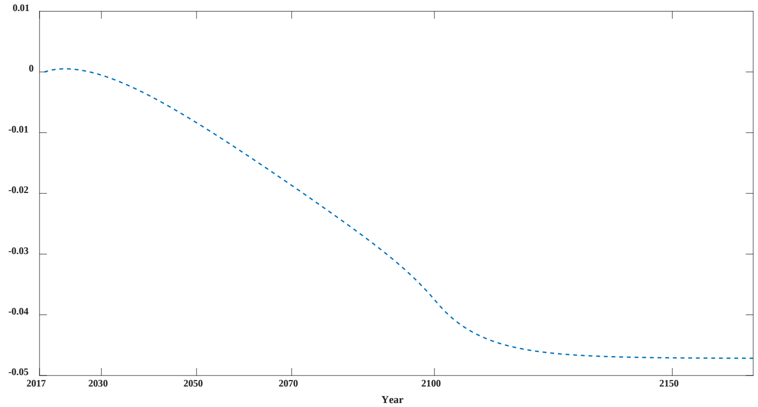


Figure 4c
% Deviation of energy from the initial Steady State

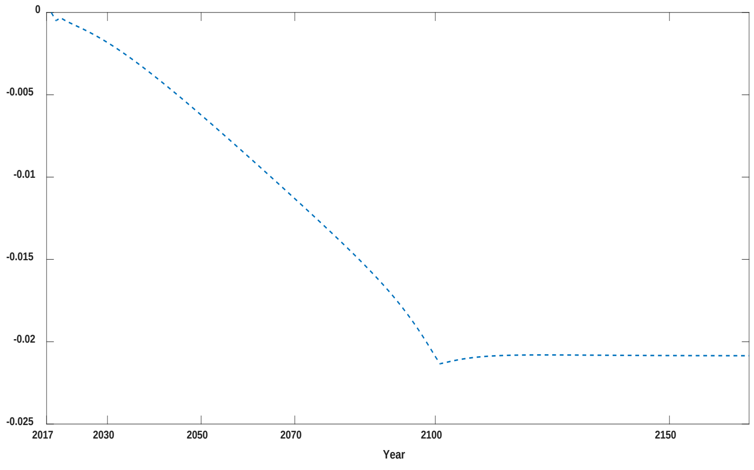


Figure 4d
% Deviation of domestic production from the initial Steady State

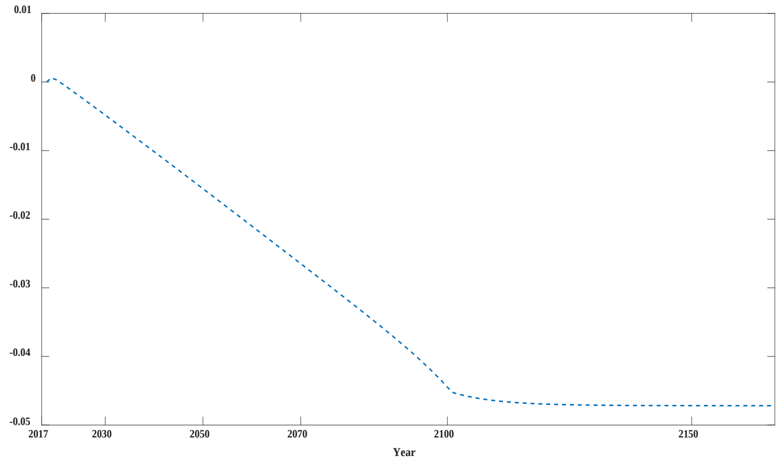


Figure 4e
% Deviation of private consumption from the initial Steady State

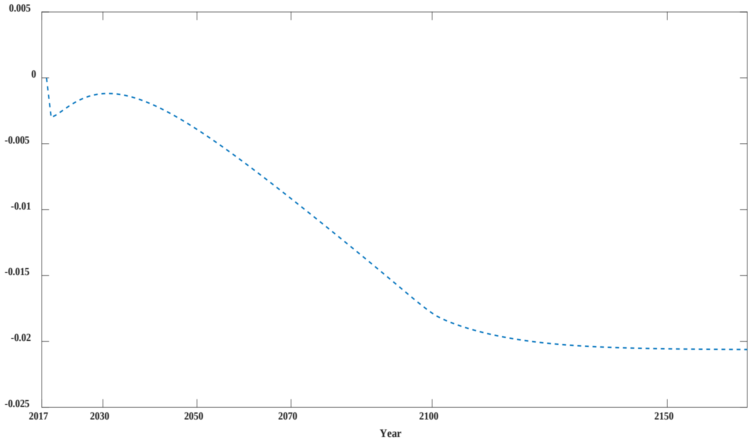
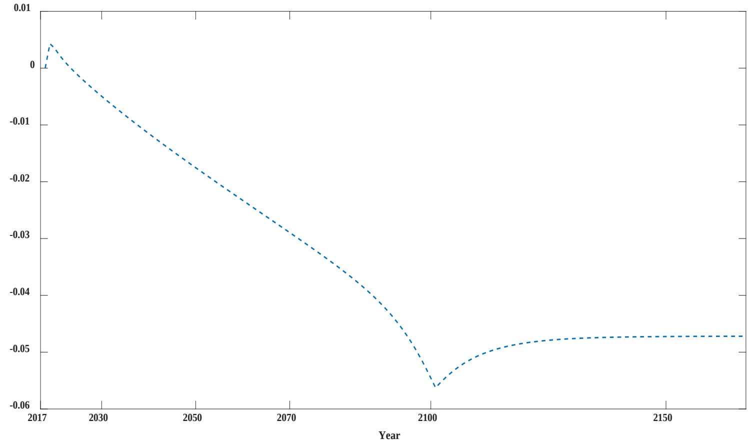


Figure 4f
% Deviation of private investment from the initial Steady State



Fi

Figure 4g
% Deviation of government spending from the initial Steady State

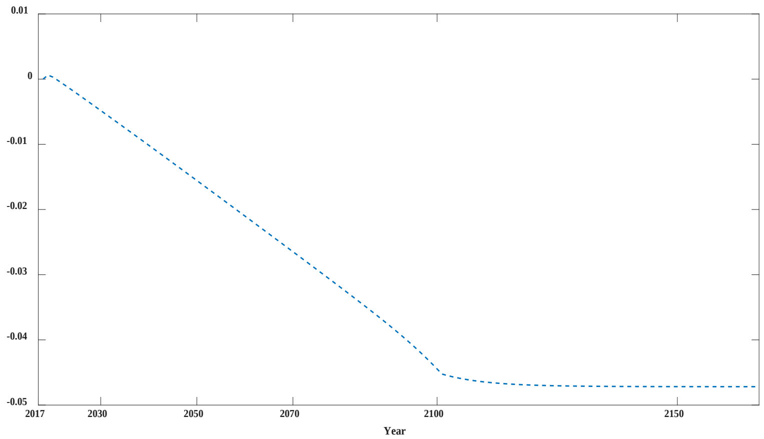


Figure 4h
% Deviation of terms of trade from the initial Steady State

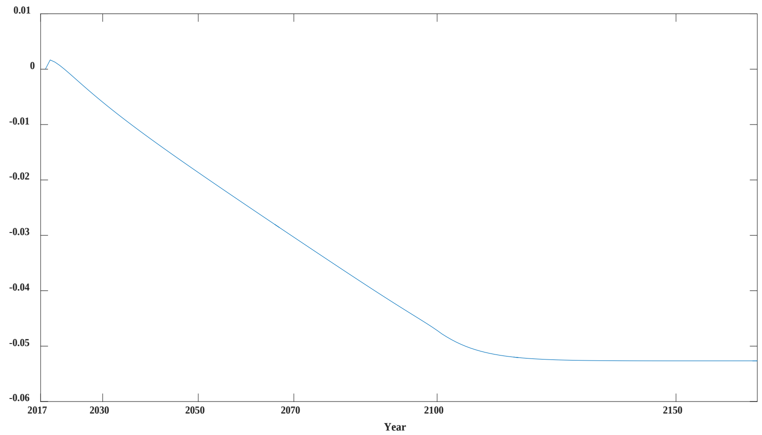


Figure 4i

% Deviation of imports from the initial Steady State

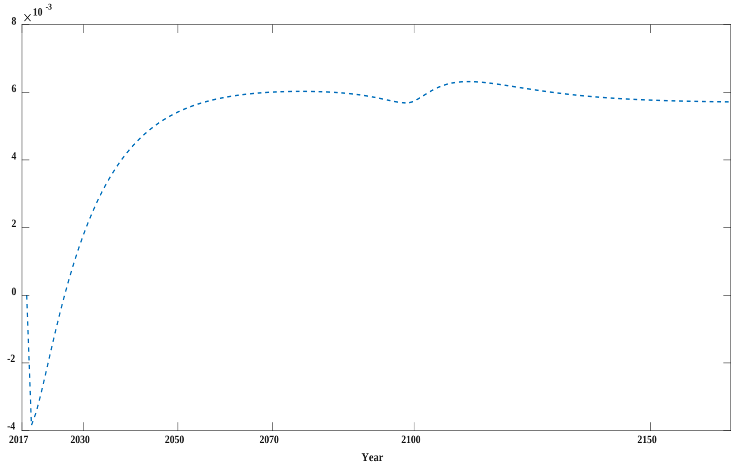


Figure 4j

% Deviation of exports from the initial Steady State

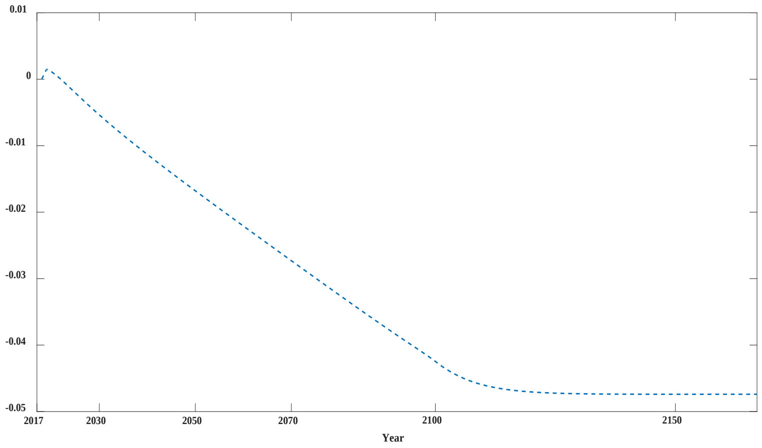


Figure 4k

% Deviation of real income from the initial Steady State

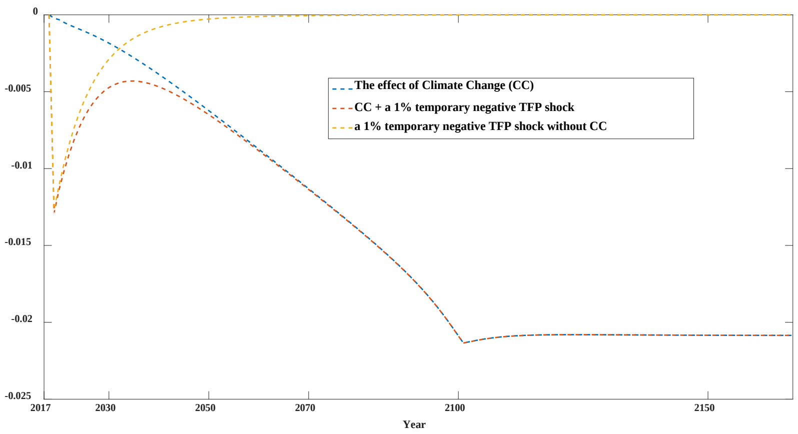


Figure 5a

% Deviation of real income from the initial Steady State
(The effect of Climate Change)

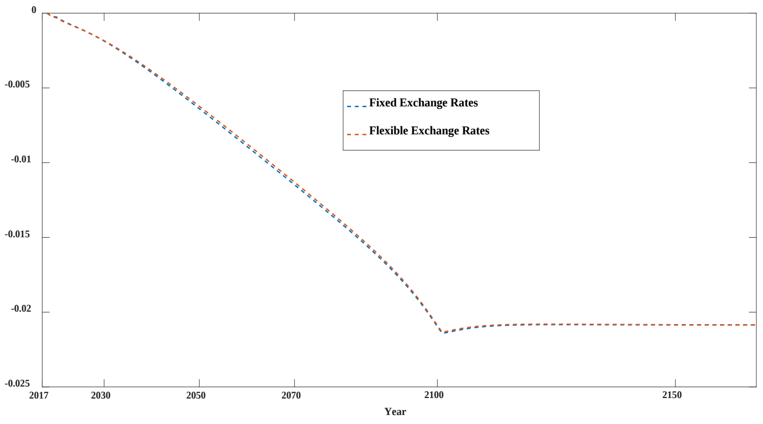
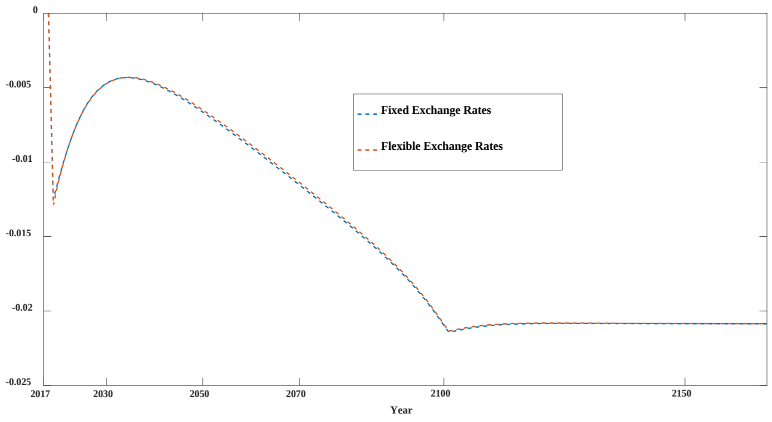


Figure 5b

% Deviation of real income from the initial Steady State
(A temporary 1% negative TFP shock in the presence of CC)



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