Monetary policy stabilization in a new Keynesian model under climate change

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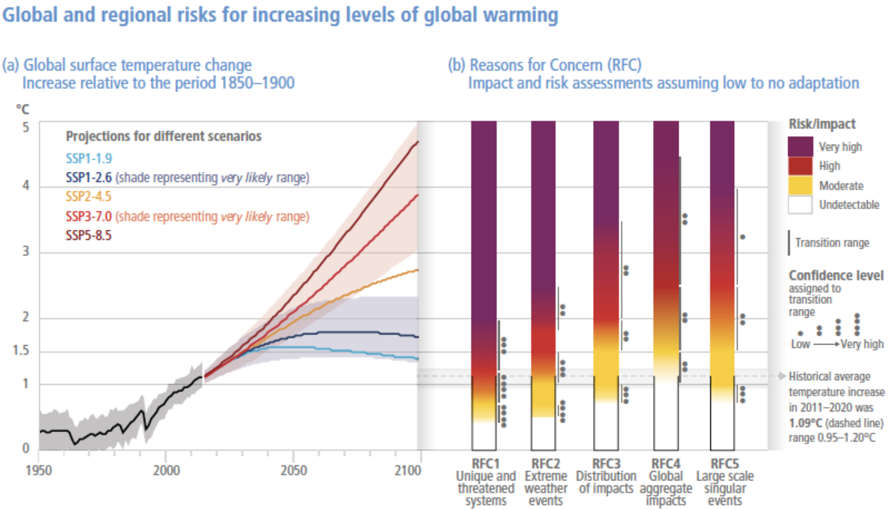
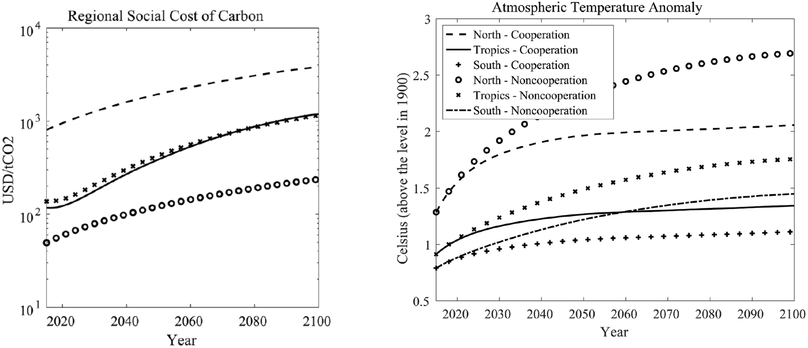
- Climate change has been recognized as the greatest externality of today's global economy.
- An anthropogenically-induced phenomenon which might have serious negative impacts on human wellbeing.
- A large body of literature studies focuses not only the effects of climate change, but also the ways to moderate these effects (see, e.g., Nordhaus, 2007, 2014; and Stern, 2007, 2008).



Temperature anomaly and associated risks

Source: IPCC, 2021, AR6.



Estimates of the regional SCC and temperature anomaly for cooperative and noncooperative climate policies

Source: Cai, Brock and Xepapadeas, 2023, Climate Change Impact on Economic Growth: Regional Climate Policy under Cooperation and Noncooperation. *Journal of the Association of Environmental and Resource Economists*, Vol. 10.

- The classic economic approach to correcting externalities: carbon taxes or cap-and-trade policies (e.g., Stern, 2007, chapter 14; Golosov et al., 2014).
- Climate change policy has therefore been predominantly fiscal policy.
- However, central bankers have already started discussing the financial stability implications of climate change (see e.g. Carney, 2015; Cœuré, 2018; Debelle, 2019; Kaplan, 2019; Rudebusch, 2019; and Villeroy, 2021, Drudi et al. 2021).
- Until recently (last decade) little attention has been paid, to the implications of climate change for the conduct of monetary policy and the role of Central Banks.

- The above observation can be justified on the grounds that Central Banks' traditional objectives of inflation and output stabilization are predominantly short-term – while climate change impacts could be regarded as long-term.
- However, under a business-as-usual scenario, or even under more climate-friendly scenarios with regard to the future path of GHG emissions, serious climate change effects are not that far off.

- As shown in previous figure the target of a maximum $1.5^{\circ}C$ temperature anomaly will be exceeded in the nest decade in all IPCC 2021 scenarios, while the $2^{\circ}C$ threshold will be exceed before the middle of the century in three out of five IPCC 2021 scenarios (SSP 4.5, 7.0, 8.5).
- Furthermore, extreme weather phenomena caused by climate change which occur now, such as summer heat waves have been associated with significant and robust negative effect on GSP growth (Colacio et al. 2019). These effects can be regarded as a short-term negative supply shock in certain sectors, by limiting crop production for example, but as a negative demand shock across sectors over the medium term (Drudi et al 2021).

- Under these conditions, the design and implementation of monetary policy may need to take on a wider role.
- Therefore, in addition to their traditional role – inflation and output stabilization – and the use of unconventional policies to help economic recovery since the 2008 world shock, Central Banks may also need to support climate change policies.
- This implies that Central Banks would need to address long-term as well as short-term issues.
- Thus, a vital question is whether climate change could affect the design of monetary policy in a non-trivial way.
- This is the purpose and the expected contribution of the present paper.

- A rich literature on the interactions between fiscal and monetary policies: see, e.g., Leeper, 1991; Christiano et al., 2005; Schmitt-Grohé and Uribe, 2005, 2007; Kirsanova et al., 2009; Leeper et al., 2009, 2010; Christiano et al., 2011; and Philippopoulos et al., 2015, 2017a, 2017b).
- Few studies that have used a DSGE model to study the interrelation between climate change and economic (monetary) policy in a unified framework and then investigate the implications of the former with regard to the latter.
    - See, e.g. Heutel (2012), Punzi (2018), Benmir and Roman (2020), Ferrari and Nispi Landi (2022), Abiry et al. (2022), Papoutsi et al. (2022), Giovanardi et al. (2022).

- The closest work to our paper is that by Annicchiarico and Di Dio (2017).
    - Our work differs to their paper in that: (a) we allow for capital accumulation; and more importantly, (b) we treat energy as a separate factor of production, the use of which increases pollution and accelerates climate change.

- In particular, in this paper, we try to explore this issue and to demonstrate:
  1. The mechanism through which climate change can affect monetary policy and whether this effect is non-trivial, and
  2. Which could be the implications for the business cycle if a Central Bank behaves as if climate change does not affect economic activity.

- The setup is a new Keynesian dynamic stochastic general equilibrium (DSGE) model of a closed economy featuring imperfect competition and Rotemberg-type nominal price fixities.
- The model of the economy is coupled with a climate module.
- In particular, we assume that energy, produced by the processing of fossil fuels, affects the economy via two different channels.
  1. Energy enters as a separate factor in the firm's production function, thus increasing output.
  2. The processing of fossil fuels generates GHG emissions which increase the GHG concentration in the atmosphere, which in turn increases temperature. Higher temperatures negatively affect economic outcomes.
- Therefore, these two channels imply conflicting effects for an economy's productivity from the use of fossil fuels.

- 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 (for similar IAMs, see, e.g., Golosov et al. (2014), Nordhaus (2014) and Hassler et al. (2016), van der Ploeg and de Zeeuw 2018).
- Monetary policy is assumed to be conducted through the nominal interest rate on government bonds which follows a standard Taylor-type rule (see, e.g., Taylor, 1979, 1993, 1999).
- Since an analytical solution is not possible, the model is solved numerically, using US fiscal data and employing values for the structural parameters obtained from calibrating the model to the US economy.

There are two main results.

1. First, climate change seems to act as a new propagation mechanism of the various shocks (i.e. economic or climate) hitting an economy.
    - Specifically, climate change, as a propagation mechanism of the various shocks, seems not only to lengthen the duration of the effects of disturbances, but also - especially in the case of an economic shock- to trigger a non-monotonic behaviour in economic activity.
2. When the CB chooses optimally the coefficients of the Taylor-type rule that economic/climate shocks induce oscillating behavior along the path that converges to the steady state

- In the presence of the detrimental effects of climate change on the economy's productivity, the effect of a TFP shock is mitigated after the impact period.
- This happens because a positive (negative) TFP shock increases (decreases) both output and the demand for energy. The latter effect causes an increase (decrease) in the use of fossil fuels, which negatively (positively) affects the productivity of the economy (through the acceleration (slowdown) it causes in temperature rise).
- The strength of this negative (positive) effect depends on the magnitude of the damage elasticity of output which captures the detrimental effects of climate change on the economy's productivity.

- Thus, in an economy with climate change, and after the impact period, output falls (increases) below its steady state value, which does not happen in an economy without climate change, and at a faster pace relative to such an economy, before eventually converges again to the steady state, which however happens at a later period relative to an economy without climate change.
- On the other hand, the impact of a climate shock depends crucially on the size of the shock.
- In both cases however, it seems that incorporating climate change into a standard new Keynesian framework affects non-trivially the design of the appropriate monetary policies when the aim is short-term stabilization.

- Its objective is to maximize the expected discounted lifetime utility:

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

- In our numerical simulations, we use a utility function of the form (see e.g., Cooley and Prescott, 1995):

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

- The budget constraint of the household, written in real terms is:

$$(1+\tau_t^c)c_t + q_t + b_t - \left(\frac{1}{\pi_t}\right) b_{t-1} =$$

$$= (1-\tau_t^y)w_t h_t + r_t k_{t-1} + d_t + \left(\frac{R_{t-1}}{\pi_t}\right) b_{t-1} + g_t^{tr} \qquad (2b)$$

- The household acts competitively, taking prices and policy as given in its optimization.
- The motion of physical capital is given by:

$$k_t = (1-\delta)k_{t-1} + q_t \qquad (3)$$

- 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 – combined with the other factor inputs – by the intermediate firms to produce the intermediate varieties.
- The final good producer combines intermediate goods, $y_{t,j}$, to produce y_t. Using the Dixit-Stiglitz aggregator (Dixit and Stglitz, 1977), we define aggregate output as:

$$y_t = \left[\sum_{j=1}^{N} \lambda_j (y_{t,j})^{\theta} \right]^{\frac{1}{\theta}}, \tag{5}$$

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

$$p_t y_t - \sum_{j=1}^{N} p_{t,j} \lambda_j y_{t,j}. \tag{6}$$

- Each intermediate firm aims at maximizing its expected intertemporal profits (written in nominal terms), $\Pi_{t,j}$:

$$\Pi_{t,j} = E_0 \sum_{s=0}^{\infty} \left(\beta^f_{t+s}\right)^t D_{t+s,j} \tag{8a}$$

  - where $D_{t,j}$ is profit per period, and is given by:

$$D_{t,j} = (1-\tau^{\pi}_t)(p_{t,j}y_{t,j} - p_t r_t k_{t-1,j} - p_t w_t h_{t,j} - P^e_t e_{t,j}) - \\ -\frac{x}{2}\left(\frac{p_{t,j}}{p_{t-1,j}} - \pi_j\right)^2 p_t y_t \tag{8b}$$

$$y_{tj} = \widehat{A}_t k^{\alpha_1}_{t-1} h^{\alpha_2}_{tj} e^{1-\alpha_1-\alpha L2}_{tj}. \tag{9}$$

- 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 (8), where x measures the degree of price stickiness and π_j is the equilibrium gross inflation rate on the price of commodity j.
- This is similar to functional forms used by Schmitt-Grohé and Uribe (2004) and Bi et al. (2013). The specific adjustment costs penalize large price changes in excess of steady-state inflation and make the firm's problem dynamic. Obviously, if $x = 0$, prices are fully flexible.

- Finally, we assume that:
- $$\widehat{A}_t \equiv [\exp(-\psi(T_t - T_0))]A_t$$

  is an adjusted TFP factor which incorporates the detrimental effects of climate change into the production function.
- T_t is the average global temperature at time t.
- T_0 is the average global temperature in the pre-industrial period.
- $T_t - T_0$ can be interpreted as the temperature anomaly at time t relative to the pre-industrial period.
- $\exp(-\psi(T_t - T_0))$ is a damage function defined in terms of the temperature anomaly.
- Parameter ψ measures the magnitude of damage due to climate change and is known as the damage elasticity of output.
- Each intermediate firm does not internalize, when making its decisions, the aforementioned detrimental effect, hence it takes the environmental externality as given.

- Following (Matthews et al., 2009, 2012, IPCC 2021) the approximately linear relationship between the temperature anomaly and cumulative carbon emissions, with Λ representing the transient climate response to cumulative carbon emissions (TCRE).

$$T_t - T_0 = \Lambda Q_t, \tag{11a}$$

where

$$Q_t = (1 - \delta^e) \sum_{s=0}^{t-1} e_s + e_t + \varepsilon_t^c \tag{11b}$$

where:

-
  - Λ is between 0.8-2.5°C per trillion tons of carbon (TtC) (MacDougal, 2016);
  - e_s are global carbon emissions, which in each period t are equal to $\sum_{j=1}^{N} e_{t,j}$;
  - e_0 are global pre-industrial emissions;
  - Q_t is the stock of global carbon emissions that have remained in the atmosphere at period t;
  - δ^e is an average carbon depreciation rate which indicates the fraction of carbon emissions that have been absorbed by nature,
  - and ε_t^c is a stochastic persistent climate shock (for similar environmental shocks see e.g. Agliardi and Xepapadeas, 2023).

- Then the exponential damage function with respect to the temperature anomaly, $\exp(-\psi(T_t - T_0))$, which is multiplicative to the production function, can be written as:

$$\widehat{A}_t \equiv [\exp(-\psi \Lambda Q_t)] A_t \tag{11c}$$

  where A_t is subject to standard stochastic TFP shocks.

- Therefore, in our economy we allow for both standard TFP shocks (through A_t) and climate shocks (through T_t).

- The budget constraint of the consolidated government sector, expressed in real terms is:

$$b_t - \left(\frac{1}{\pi_t}\right) b_{t-1} + \tau_t^c c_t + \tau_t^y w_t h_t + \tau_t^\pi (y_t - r_t k_{t-1} - w_t h_t - p_t^e e_t) =$$

$$= R_{t-1} \left(\frac{1}{\pi_t}\right) b_{t-1} + g_t + g_t^{tr} \qquad (12)$$

  where g_t is per capita spending on public consumption which in our setup is considered to be a waste.
- In each period, one of the fiscal policy instruments, τ_t^c, τ_t^y, τ_t^π, g_t, g_t^{tr} and b_t, has to follow residually to satisfy the government budget constraint.

- The DE is defined as a sequence of allocations, prices and policies such that:
  - (i) the household maximizes utility;
  - (ii) all firms maximize profits;
  - (iii) all constraints, including the government budget constraint, are satisfied; and
  - (iv) all markets clear.
- Notice that in a symmetric DE, it holds that $y_t \equiv y_{t,j}$, $k_t \equiv k_{t,j}$, $h_t \equiv h_{t,j}$, $e_t \equiv e_{t,j}$ and $p_t \equiv p_{t,j}$.

- To proceed with the solution, we need to define the policy regime.
- Regarding monetary policy, we assume, as is usually the case, that the nominal interest rate on government bonds, R_t, is used as a policy instrument.
- Regarding fiscal policy, we assume that tax rates and public spending, τ_t^c, τ_t^y, τ_t^e, g_t, and g_t^{tr}, are set exogenously, while the end-of-period public debt, b_t, follows residually from the government budget constraint.
- The dynamic DE system consists of 10 equations in 10 endogenous variables, $\{y_t, c_t, h_t, k_t, e_t, b_t, r_t, w_t, p_t^e, d_t, \pi_t\}_{t=0}^{\infty}$, given the independently-set policy instruments, $\{R_t, \tau_t^c, \tau_t^y, \tau_t^{\pi}, g_t, g_t^{tr}\}_{t=0}^{\infty}$, technology $\{A_t\}_{t=0}^{\infty}$, climate shocks $\{\varepsilon_t^T\}_{t=0}^{\infty}$, the relative price per unit (ton) of energy $\{p_t^e\}_{t=0}^{\infty}$ and initial conditions for the state variables. (For details see the Appendix)

- Following the related literature we focus on simple rules for the exogenously-set monetary and fiscal policy instruments, which means that the monetary and fiscal authorities react to a small number of macroeconomic indicators.
- In particular, we allow the nominal interest rate, R_t, to follow a standard Taylor rule, meaning that it can react to inflation and output as deviations from policy targets. More specifically, we use a monetary policy rule of the functional form:

$$\log\left(\frac{1+R_t}{1+\widetilde{R}}\right)=\alpha^R\log\left(\frac{1+R_{t-1}}{1+\widetilde{R}}\right)+\phi^\pi\log\left(\frac{\pi_t}{\widetilde{\pi}}\right)+\phi^y\log\left(\frac{y_t}{\widetilde{y}}\right), \tag{15a}$$

  - where $\widetilde{R}$ is a policy constant
  - $\widetilde{\pi}$ and $\widetilde{y}$ denote target values,
  - and $\phi^\pi \geq 0$, $\phi^y \geq 0$ are parameters governing monetary policy reaction to inflation and output.

- We assume that both types of spending, g_t and g_t^{tr}, are shares of GDP. We assume that:

$$g_t = s_t^g y_t, \tag{15b}$$

$$g_t^{tr} = s_t^{tr} y_t, \tag{15c}$$

  where s_t^g and s_t^{tr} are policy instruments.

- Moreover, and in order to ensure dynamic stability along the transition path, we allow public transfers as a share of GDP, s_t^{tr}, to react to deviations of public debt over output from a target. We assume that:

$$s_t^{tr} = s^{tr} - \phi^{tr} \left[\frac{b_t}{y_t} - \frac{\widetilde{b}}{\widetilde{y}} \right] \tag{15d}$$

  where $\frac{\widetilde{b}}{\widetilde{y}}$ denotes a target value, and ϕ^{tr} is a feedback fiscal policy coefficient. In the steady state it holds that $\frac{b_t}{y_t} = \frac{\widetilde{b}}{\widetilde{y}}$, and therefore $s_t^{tr} = s^{tr}$.

- Given the feedback policy coefficients, the final equilibrium system consists of the 10 DE equations (see the Appendix) plus the monetary and fiscal policy rules shown in (15a)–(15d).
- To solve this non-linear difference equation system, we use an algorithm for solving stochastic models as implemented in DYNARE.
- We proceed as follows.
  - We first solve numerically for the long-run equilibrium of this model employing parameter values calibrated using data from the US economy.
  - Then, we will study the various policy experiments.

- Regarding structural parameters for technology and preferences, most of them will be calibrated on the basis of US data, while, for the rest, we will use commonly employed values by the relevant literature.
- The model's parameter values, as well as the values for the exogenous variables, are listed in Table 1 in the Appendix, where in the fourth column we report whether the value for the specific parameter has been chosen on the basis of calibration or has been set.

Table 2
Steady-State Solution

Variable	Description	Value	Data
k/Y	Capital to GDP ratio	3.6289	3.7743
c/Y	Consumption to GDP ratio	0.6177	0.62
$(p^e e)/Y$	Energy expenditure to GDP ratio	0.0762	0.0764
b/Y	debt to GDP ratio	0.8097	0.8097
h	fraction or time devoted to work	0.3551	0.3575

- In our setup, the role of policy is only to stabilize the economy against temporary shocks. **These shocks can be either economic shocks, or climate shocks, or shocks to the energy prices**.
- Thus the policy question is how the nominal interest rate should react to deviations from targets.
- We reconsider the above policy question in a new Keynesian framework in which the innovative feature is that the effects of climate change have been incorporated. In particular, we investigate whether the reaction of the nominal interest rate is affected, and towards what direction, by the assumption that climate change affects the economy's productivity.

- Regarding the stochastic process that rules the motion of TFP productivity after a shock, we assume that:

$$\log(A_t) = (1-\varphi^A)\log(A) + \varphi^A \log(A_{t-1}) + \varepsilon_t^A \tag{16a}$$

where:

- A is a constant
- φ^A is an autoregressive parameter and
- $\epsilon_t^A \sim iid\left(0,\sigma^2\right)$ are random shocks to productivity.
- In particular, in the simulations that follow we fix φ^A at 0.5 and shock the standard deviation of technology, σ^A, by 1%.

- Regarding the stochastic process that rules the motion of the exogenous climate shocks, ε_t^T, we assume that they are characterized by persistence, and evolve according to:

$$\log(1+\varepsilon_t^c) = (1-\varphi^c)\log(1+\varepsilon^c) + \varphi^c \log(1+\varepsilon_{t-1}^c) + \nu_t^c \quad (16b)$$

where:

  - ϵ^c is a constant (set equal to 0 in the numerical simulations),
  - φ^c is an autoregressive parameter and
  - $\nu_t^c \sim iid\left(0, \sigma^2\right)$ are random disturbances.
  - In the baseline simulations that follow, we fix φ^c at 0.5 and shock the standard deviation of the disturbance, σ^c, by 1%.

- Regarding the stochastic process that rules the motion of energy prices after a shock, we assume that:

$$\log(p_t^e) = (1-\varphi^e)\log(p^e) + \varphi^e \log(p_{t-1}^e) + \varepsilon_t^e \tag{16c}$$

  where:

  - p^e is a constant
  - φ^e is an autoregressive parameter and
  - $\epsilon_t^e \sim \mathit{iid}\left(0, \sigma^2\right)$ are random shocks to energy prices.
  - In particular, in the simulations that follow we fix φ^e at 0.5 and shock the standard deviation of energy prices, σ^e, by 1%.

- We compute the responses of the key endogenous variables (measured as deviations from their model-consistent long-run values) to a 1% temporary positive economic shock, or to 1% temporary positive climate shock, or to 1% temporary positive shock to energy prices.
- We choose shocks to be positive because it is the specific types of shocks that, according to our modelling approach, are expected to increase temperature anomaly and thereby accelerate the climate change process.
- The coefficients of the Taylor rule are set arbitrarily following the literature and attributes substantially more weight on the inflation gap relative to the output gap.

Fig 1a: % deviation of adjusted TFP from its SS value

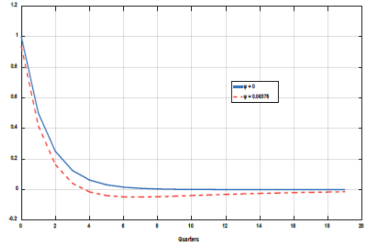


Fig 1b: % deviation of output from its SS value

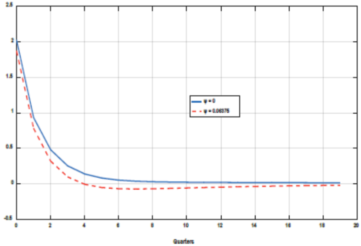


Fig 1c: % deviation of inflation from its SS value

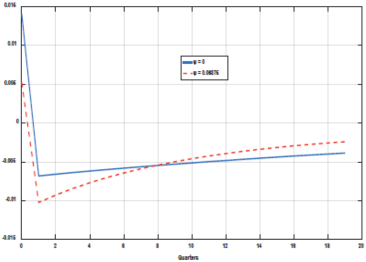


Fig 1d: % deviation of nominal interest rate from its SS value

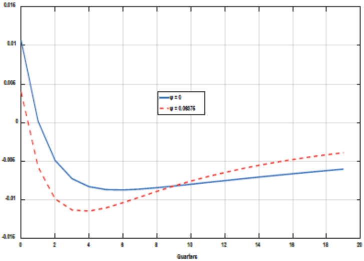


Fig 1l: % deviation of temperature anomaly from its SS value

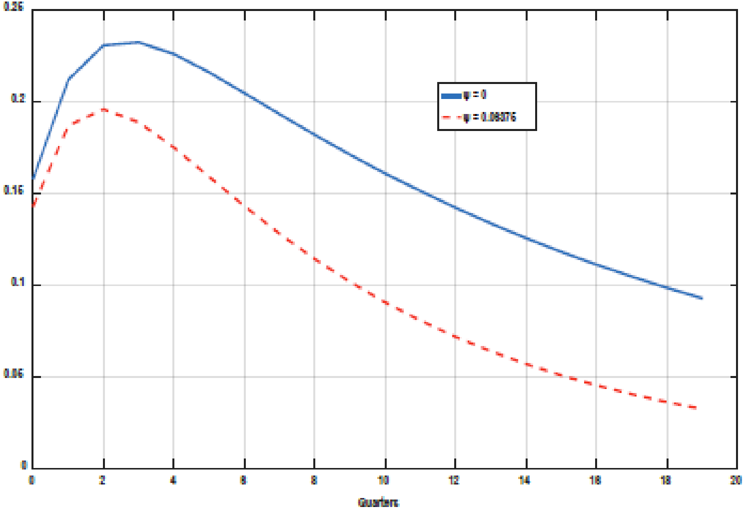


Fig 2a: % deviation of adjusted TFP from its SS value

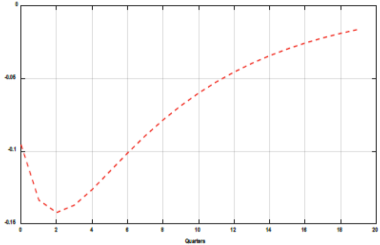


Fig 2b: % deviation of output from its SS value

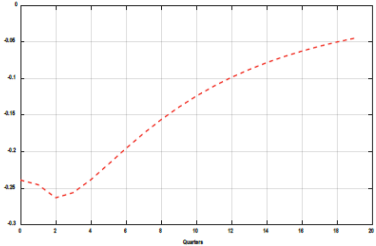


Fig 2c: % deviation of inflation from its SS value

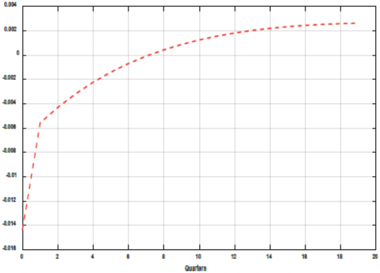


Fig 2d: % deviation of nominal interest rate from its SS value

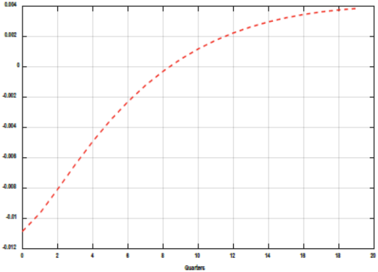


Fig 2l: % deviation of temperature anomaly from its SS value

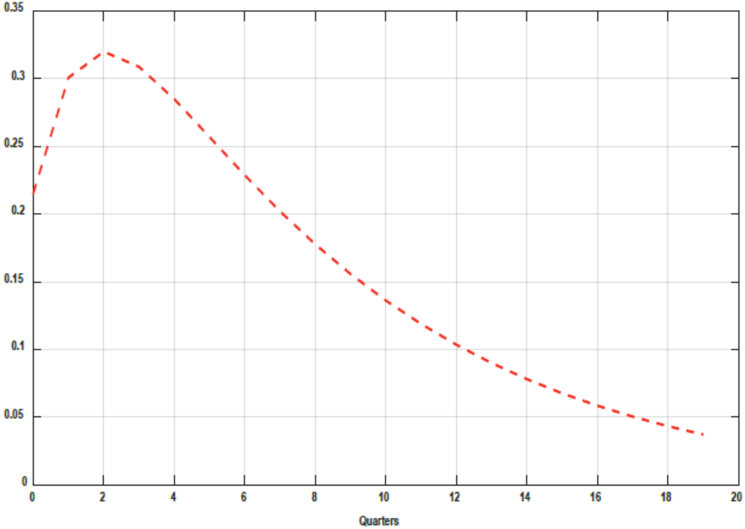


Fig 3a: % deviation of output from its SS value

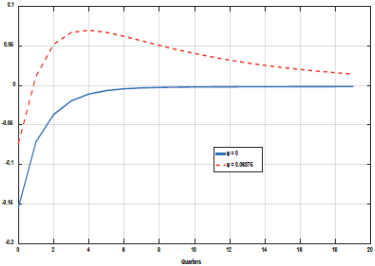


Fig 3b: % deviation of inflation from its SS value

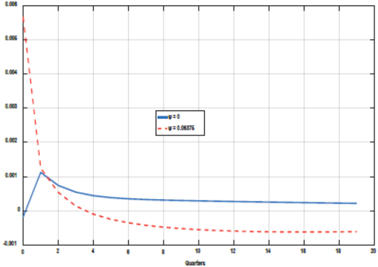
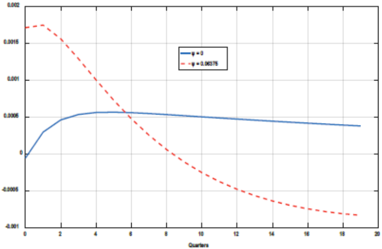


Fig 3c: % deviation of nominal interest rate from its SS value



- Following Schmitt-Grohé and Uribe (2007, JME), we wish to find the welfare-maximizing monetary- and fiscal-policy-rule combination (i.e., a value for ϕ^{π}, ϕ^{y}, ϕ^{str}).
- We impose three requirements:
  1. The rule must ensure local uniqueness of the rational expectations equilibrium,
  2. The rule must induce nonnegative equilibrium dynamics for the nominal interest rate,
  3. Wwe limit attention to policy coefficients in the interval $[0, 4]$.

- We focus on the case in which the Central Bank reacts to the current values of inflation and output:

$$\log\left(\frac{1+R_t}{1+\widetilde{R}}\right)=\alpha^R\left(\frac{1+R_{t-1}}{1+\widetilde{R}}\right)+\phi^\pi\log\left(\frac{\pi_t}{\widetilde{\pi}}\right)+\phi^y\log\left(\frac{y_t}{\widetilde{y}}\right)$$

  where, R is the net interest rate in government bonds and π is the gross inflation rate.

- Formally, we look for policy parameters that maximize:

$$V_0=E_0\sum_{t=0}^{\infty}\beta^t U(c_t,1-h_t)$$

Optimized Coefficients			
	$\psi = 0$	$\psi > 0$	
		econ shock	**clim shock**
ϕ^{π}	3.0944	3.0943	3.0943
ϕ^{y}	0.0292	0.0225	0.1102
ϕ^{str}	0.4264	0.5056	0.3684

<table>
<tr><th colspan="3">Optimized Coefficients</th></tr>
<tr><td></td><td rowspan="2">$\psi = 0$</td><td>$\psi > 0$</td></tr>
<tr><td></td><td>en pric shock</td></tr>
<tr><td>ϕ^{π}</td><td>3.2642</td><td>2.6981</td></tr>
<tr><td>ϕ^{y}</td><td>0.0656</td><td>0.1164</td></tr>
<tr><td>ϕ^{str}</td><td>0.2210</td><td>0.1776</td></tr>
</table>

- We study two model economies.
- In the first one, which we shall call Model A, we assume that the Central Bank acknowledges the detrimental effects of climate change and takes them into account when designing monetary policy.
- In the second one, which we shall call Model B, we assume that, although climate change occurs and affects real economic activity, the Central Bank behaves as if climate change does not affect the business cycle.
- Technically, in the economy of Model B, the Central Bank sets the (optimized) feedback parameters in the Taylor rule as if $\psi > 0$, whereas in the economy of Model A, the Central Bank sets the (optimized) feedback parameters in the Taylor rule as if $\psi = 0$ (although climate change affects macroeconomic variables).

Fig 4a: % deviation of inflation from its SS value

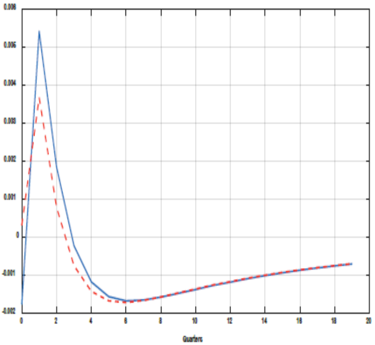
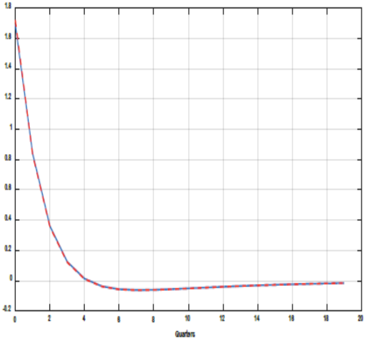


Fig 4b: % deviation of output from its SS value



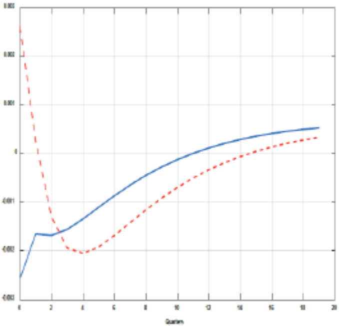


Fig 4c: % deviation of inflation from its SS value

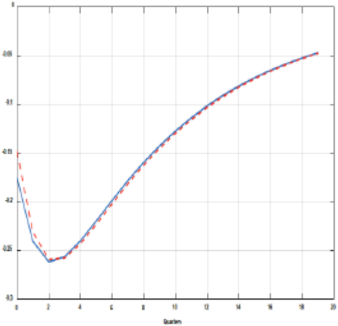


Fig 4d: % deviation of output from its SS value

Fig 4e: % deviation of inflation from its SS value

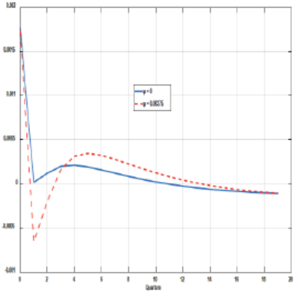
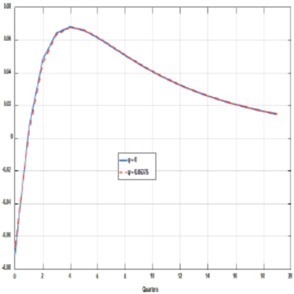


Fig 4f: % deviation of inflation from its SS value



- We extended the standard new Keynesian model by allowing for climate change effects.
- Climate change seems to act as a new propagation mechanism of the various shocks hitting an economy, which appears to lengthen the duration of the effects of disturbances and to affect in a non-trivial way the design of monetary policy.
- Monetary policy conducted by a myopic Central Bank, meaning that it behaves as if climate change does not affect economic activity, exhibits non-trivial differences relative to monetary policy conducted by a climate-change-conscious Central Bank especially regarding the path of the inflation rate after a (economic/climate) shock.
- The above results seem to be in line with the belief that more frequent climate-related shocks may increasingly affect the analysis of the medium-term macroeconomic behaviour of an economy.

- Different functional forms and parametrizations for the damage function could be explored, along with the explicit introduction of tipping points.
- Standard environmental policy instruments could be incorporated, such as carbon taxes or subsidies aiming, for instance, at mitigating the impact of climate change or the economy's adaptation to climate change, in order to investigate if and how the standard environmental policy instruments are interrelated with the conduct of monetary policy.
- The modeling of the energy sector of the economy could be extended by introducing two types of firms producing "brown" and "green" energy.

- The current setup could be augmented by introducing a properly modeled financial sector to investigate the financial risks associated with climate change and how monetary policy could deal with them.
- Ambiguity and ambiguity aversion regarding temperature dynamics.

Thank you!

Therefore, the DE of the above economy is given by:

$$\frac{1}{(1+\tau_t^c)c_t} = \beta E_t \left[\frac{1-\delta+r_{t+1}}{(1+\tau_{t+1}^c)c_{t+1}} \right] \tag{13a}$$

$$\frac{1}{(1+\tau_t^c)c_t} = \beta E_t (\frac{1+R_t}{\pi_{t+1}(1+\tau_{t+1}^c)c_{t+1}}) \tag{13b}$$

$$\frac{\mu_2}{1-h_t} = \frac{\mu_1 w_t (1-\tau_t^y)}{(1+\tau_t^c)c_t} \tag{13c}$$

$$(1+\tau_t^c)c_t + k_t - (1-\delta)k_{t-1} + b_t - \left(\frac{1}{\pi_t}\right) b_{t-1} =$$

$$= (1-\tau_t^y) w_t h_t + r_t k_{t-1} + d_t + \left(\frac{R_{t-1}}{\pi_t}\right) b_{t-1} + g_t^{tr} \tag{13d}$$

$$y_t = [\exp(-\psi \Lambda Q_t)] A_t k_{t-1}^{\alpha_1} h_t^{\alpha_2} e_t^{1-\alpha_1-\alpha_2} \tag{13e}$$

$$(1-\tau_t^{\pi})r_t k_{t-1} = (1-\tau_t^{\pi})(\alpha_1\theta y_t) +$$

$$+x(\pi_t-\widetilde{\pi})\pi_t(1-\theta)\alpha_1 y_t - E_t\left(\beta_t^f x(\pi_{t+1}-\widetilde{\pi})\pi_{t+1}^2(1-\theta)\alpha_1 y_{t+1}\right) \tag{13f}$$

$$(1-\tau_t^{\pi})w_t h_t = (1-\tau_t^{\pi})(\alpha_2\theta y_t) +$$

$$+x(\pi_t-\widetilde{\pi})\pi_t(1-\theta)\alpha_2 y_t - E_t\left(\beta_t^f x(\pi_{t+1}-\widetilde{\pi})\pi_{t+1}^2(1-\theta)\alpha_2 y_{t+1}\right) \tag{13g}$$

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

$$(1-\alpha_1-\alpha_2)y_t - -E_t\left(\beta_t^f x(\pi_{t+1}-\widetilde{\pi})\pi_{t+1}^2(1-\theta)(1-\alpha_1-\alpha_2)y_{t+1}\right) \tag{13h}$$

$$d_t = (1-\tau_t^{\pi})\left(y_t - r_t k_{t-1} - w_t h_t - p_t^e e_t\right) - \frac{x}{2}\left(\pi_t - \widetilde{\pi}\right)^2 y_t \tag{13i}$$

$$b_t - \left(\frac{1}{\pi_t}\right) b_{t-1} + \tau_t^c c_t + \tau_t^y w_t h_t + \tau_t^{\pi}\left(y_t - r_t k_{t-1} - w_t h_t - p_t^e e_t\right) =$$

$$= R_{t-1}\left(\frac{1}{\pi_t}\right) b_{t-1} + g_t + g_t^{tr} \tag{13j}$$

- where $p_t^e \equiv \frac{P_t^e}{p_t}$ is the relative price per unit (ton) of energy.
- Assuming a perfectly competitive energy sector implies that p_t^e equals the real production cost per unit (ton) of energy.
- The above dynamic DE system consists of 10 equations in 10 endogenous variables, $\{y_t, c_t, h_t, k_t, e_t, b_t, r_t, w_t, p_t^e, d_t, \pi_t\}_{t=0}^{\infty}$, given the independently-set policy instruments, $\{R_t, \tau_t^c, \tau_t^y, \tau_t^\pi, g_t, g_t^{tr}\}_{t=0}^{\infty}$, technology $\{A_t\}_{t=0}^{\infty}$, environmental shocks $\left\{\varepsilon_t^Q\right\}_{t=0}^{\infty}$, the relative price per unit (ton) of energy $\{p_t^e\}_{t=0}^{\infty}$ and initial conditions for the state variables.

Table 1
Parameterization

Parameters and policy variables	Description	Value	
β	discount factor	0.994	calibr
μ_1	weight given to cons	0.457	calibr
μ_2	weight given to leis	0.543	calibr
α_1	exp of phys capital	0.308	calibr
α_2	exponent of labour	0.6157	calibr
$1-\alpha_1-\alpha_2$	exponent on energy	0.0763	calibr
A	TFP productivity	1	set
δ	depr rate of phys capi	0.0152	calibr
x	degree of price stick	100	liter
θ	meas of imperf compet	0.9298	calibr

Table 1 cont.
Parameterization

Parameters and policy variables	Description	Value	
τ_t^c	eff cons tax rate	0.0691	data
τ_t^y	eff lab inc tax rate	0.2889	data
τ_t^π	eff corp tax rate	0.2589	data
s_t^g	gov cons/GDP	0.153	data
s_t^{tr}	gov transf/GDP	0.074	calibr
ϕ^π	react to infl gap	1.5	liter
ϕ^y	react to output gap	0, 0.125	liter

Table 1 cont.
Parameterization

Parameters and policy variables	Description	Value	
ϕ^{tr}	reaction to fiscal imbal	0.3	liter
Λ	TCRE	1.65	liter
ψ	damage effect	0-0.13	liter
δ^{e}	carbon depr rate	0.07	set
c^{e}	real cost/unit of energy	0.141	calibr
φ^{A}	pers of economic shock	0.9	set
φ^{Q}	pers of envir shock	0.9	set
σ	st.dev. of shocks	0.01	set

Table 2
Steady-State Solution

Variable	Description	Value	Data
k/Y	Capital to GDP ratio	3.6289	3.7743
c/Y	Consumption to GDP ratio	0.6177	0.62
$(p^e e)/Y$	Energy expenditure to GDP ratio	0.0762	0.0764
b/Y	debt to GDP ratio	0.8097	0.8097
h	fraction or time devoted to work	0.3551	0.3575