Financial Risks and Monetary Policy under Climate Change

Anastasios Xepapadeas
Athens University of Economics and Business and University of Bologna

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1. Introduction
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3. Climate change and the financial system
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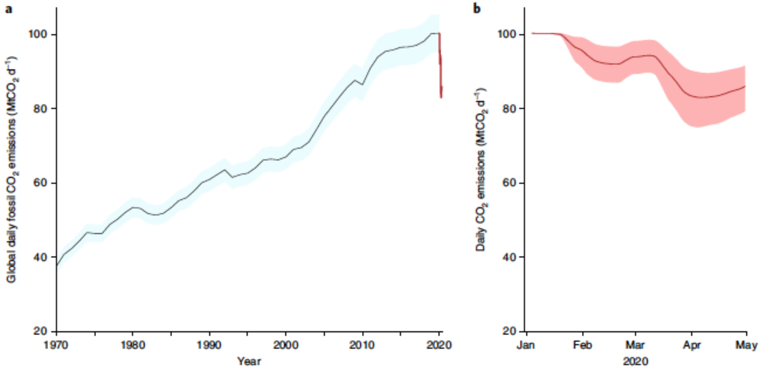
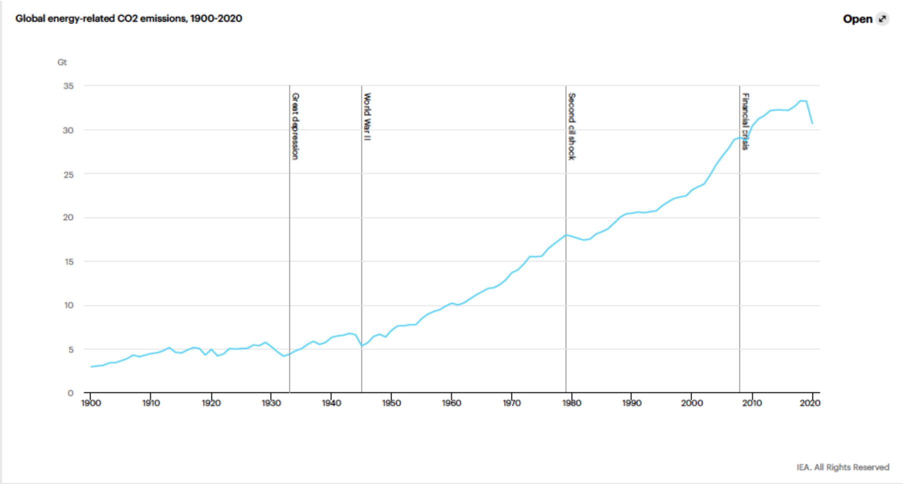


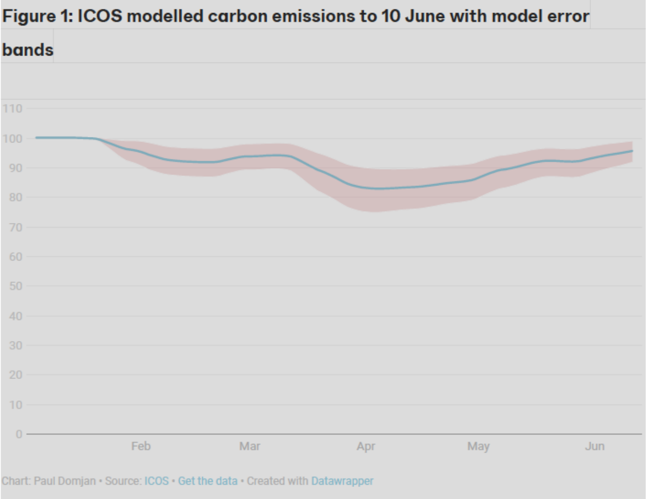
Fig. 3 | Global daily fossil CO_2 emissions ($MtCO_2$ d^{-1}). a, Annual mean daily emissions in the period 1970–2019 (black line), updated from the Global Carbon Project[1,3] (Methods), with uncertainty of ±5% (±1σ; grey shading). The red line shows the daily emissions up to end of April 2020 estimated here. **b**, Daily CO_2 emissions in 2020 (red line, as in **a**) based on the CI and corresponding change in activity for each CI level (Fig. 2) and the uncertainty (red shading; Table 2). Daily emissions in 2020 are smoothed with a 7-d box filter to account for the transition between confinement levels.

Source: Le Quéré et al., *Nature Climate Change*, July 2020.



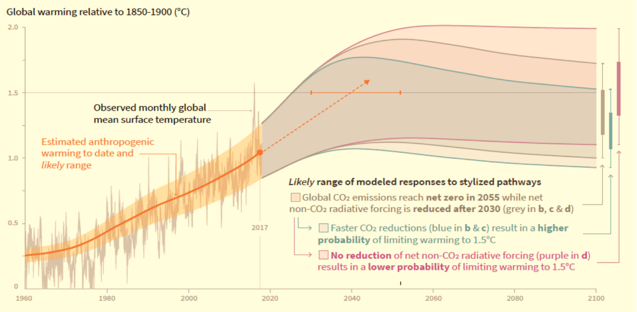
Source: International Energy Agency, Flagship report, April 2020.

- Global CO_2 emissions are expected to decline during 2020, to 30.6 $GtCO_2$, which is 8.3% lower than in 2019 (36.8 $GtCO_2$) (Global Carbon Project 2019). This would be the lowest level since 2010, and six times larger than the previous record reduction of 0.4 Gt in 2009 due to the financial crisis.
- Does this means that climate change is not such a big problem?
- A recent report – in June 2020 – states that new data show a V-shaped recovery in carbon emissions, with carbon emissions declining from February 2020, reaching a minimum in April and then recovering slowly towards the February levels (Tellimer, 2020).

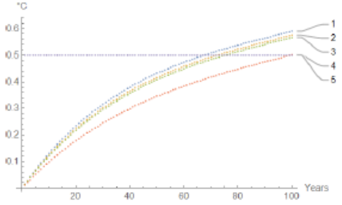


Source:
https://tellimer.com/article/carbon-emissions-come-roaring-back-will-the-e

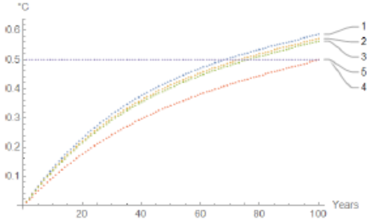
If extended and persistent lockdowns do not take place globally, which however cannot be regarded as the most likely scenario, the projected time period for crossing the 1.5 °C threshold to the business-as-usual scenario in around 2040 (IPCC, 2018) is not expected to be affected in a significant way.



Source: IPCC Special Report, "Global Warming of 1.5°C", October 2018.



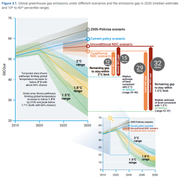
a



b

a : Pre-COVID unconstrained optimal paths for the temperature anomaly
b : Post-COVID unconstrained optimal paths for the temperature anomaly
Source: Agliardi E. and A. Xepapadeas (2020), Temperature Targets, Deep Uncertainty, and Extreme Events in the Design of Optimal Climate Policy in the post COVID-19 Era, mimeo.

The **emissions gap** is defined as the difference between global total GHG emissions from least-cost scenarios that keep global warming to 2°C and 1.5°C with varying levels of likelihood and the estimated global total GHG emissions resulting from a full implementation of the **Nationally Determined Contributions** (NDCs).



Source: Emissions Gap, UNEP, 2019.

The emissions gap in 2030 between current policies and the emissions necessary to keep the temperature anomaly below 1.5 °C in 2100 is approximately 34–39 $GtCO_2$. The COVID impact on emissions in 2020 is expected to reduce the gap by approximately 6 $GtCO_2$, which falls short of the gap that needs to be closed.

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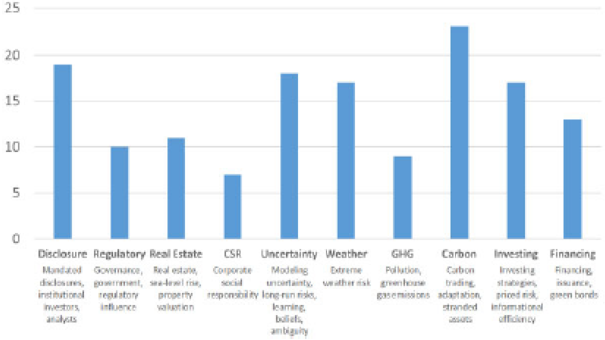
- The main question is to determine the climate change risks which emerge from climate change and explore whether they are substantial.
- If the risks are substantial, the next question – in the context of the financial system – is whether these climate-related risks are properly reflected in asset pricing (Monnin, 2018).



Source: Hong, H., Karolyi, G.A. and J. Scheinkman (2020), Climate Finance, *Review of Financial Studies*, doi:10.1093/rfs/hhz146.

Bansal, R., Kiku, D and M. Ochoa, Price of Long-Run Temperature Shifts in Capital Markets, December 2017,
https://faculty.fuqua.duke.edu/~rb7/bio/lrrc_climate_change.pdf.

Economy and Climate

$$\Delta c_{t+1} = \mu + \sigma \eta_{t+1} + D_{t+1} \ , \ \Delta c_{t+1} = \log \left(\frac{C_{t+1}}{C_t} \right), \eta_{t+1} \sim i.i.d.N\left(0,1\right)$$

where $D_{t+1}$is climate-related disasters

$$D_{t+1} = N_{t+1} d \ , \ d < 0.$$

N_{t+1} is a Poisson process with time-varying intensity that increases with temperature

$$\begin{aligned} \pi_t &= l_0 + l_1 T_t \ , \ T_{t+1} = v T_t + \chi \mathcal{E}_{t+1}, \\ \mathcal{E}_{t+1} &= \Theta \left(\mu + \sigma \eta_{t+1} \right) + \sigma_\zeta \zeta_{t+1}, \end{aligned}$$

where $\mathcal{E}_t$ are industrial emissions of CO_2 and $\zeta_{t+1} \sim i.i.d.N\left(0,1\right)$.

Preferences

Preferences are recursive (e.g., Epstein and Zvi).

$$U_t = \left\{ (1-\delta)\, C_t^{1-\frac{1}{\psi}} + \delta \left(\mathbb{E}_t \left[U_{t+1}^{1-\gamma} \right]^{\frac{1-\frac{1}{\psi}}{1-\gamma}} \right) \right\}^{\frac{1}{1-\frac{1}{\psi}}}$$

δ is the rate of time preference, γ is the coefficient of relative risk aversion, and ψ is the intertemporal elasticity of substitution (IES).

Risk Premium

$$R_{t+1} - r_t^f = \gamma\sigma^2 + TempRP + DisastserRP$$

$\gamma\sigma^2$is the standard risk premium, *TempRP* is the temperature risk premium and $DisastserRP = \gamma d^2 \left(l_0 + l_1 T_t \right)$ is the disaster risk premium.

- "Brown assets" are assets related to carbon-intensive activities (e.g., coal-fired power plants, coal mines).
- "Green assets" are all the rest.
- There are three main types of climate-related risks relevant to market participants:

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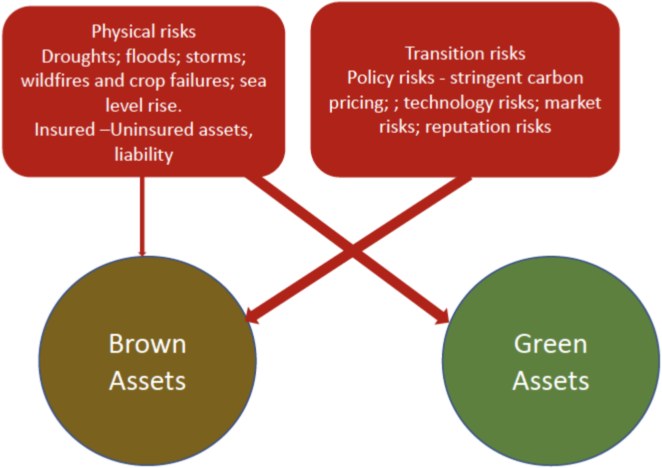
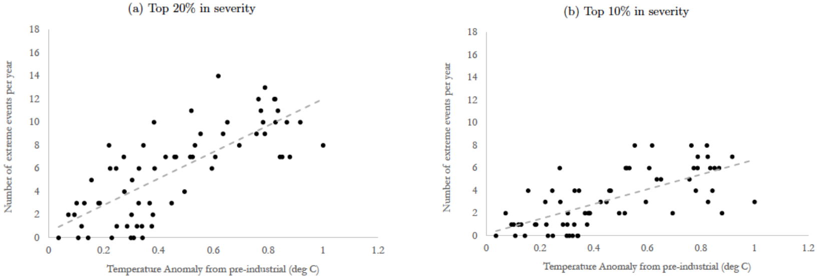
- transition risks.



Risks in Financial Markets

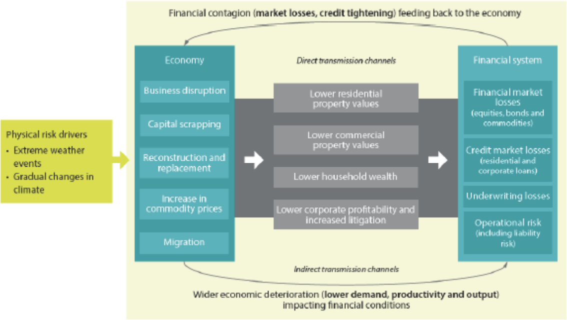
- Physical risks are associated with physical damages to assets.
  - Event-driven (such as droughts, floods, storms, wildfires and crop failures)
  - Chronic, related to long-term climate shifts (such as more frequent and stronger heat waves, intensification of droughts, rise in the sea level of coastal areas increasing frequency of heavy precipitation, change in tropical cyclones and risk of river flooding)
- Insurance sector relevant: physical risks are separated into direct and indirect risks.
  - Direct physical risks for general insurance liabilities such as property insurance and classes of business such as marine, aviation and transport.
  - Indirect physical risks which may arise from a disturbance of business lines, financial loss, agriculture losses or political risk.
- If the affected assets were not insured, physical risks could create difficulties in financing their replacement.

The frequency and severity of environmental events associated with physical risks is expected to increase as a result of rising global temperatures (Karydas and Xepapadeas, 2019).



Source: Karydas, C. and A. Xepapadeas, Pricing climate change risks: CAPM with rare disasters and stochastic probabilities, ETH Zurich, WP 2019-1, 2019.

From physical risk to financial stability risks

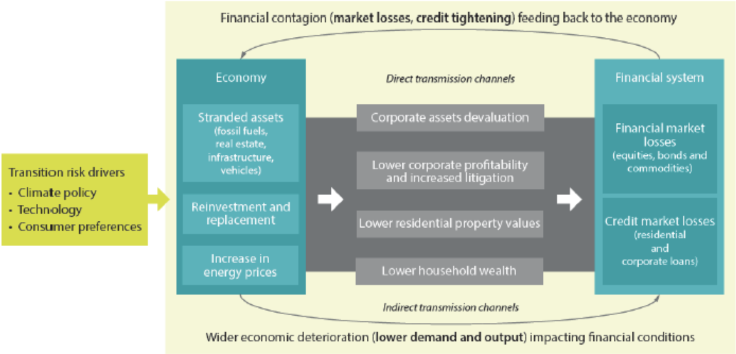


Source: Network for Greening the Financial System, "A call for action: Climate change as a source of financial risk", 2019

One study found that almost 2% of the world's financial assets are at risk if the global mean surface temperature rises by 2.5°C compared to pre-industrial levels (Dietz et al., "Climate value at risk of global financial assets", ***Nature Climate Change***, 2016). Warming of 5°C could result in losses equal to 5% of the global stock of manageable assets ("The cost of inaction: Recognising the value at risk from climate change, ***The Economist Intelligence Unit***, 2015).

- Transition risks include policy risks which emerge from:
    - potential introduction of stringent carbon-pricing policies,
    - progress of low-carbon technology, or
    - shift in investor preferences.
- Stringent climate change policies are expected to negatively affect returns of assets related to carbon-intensive technologies or processes.
- Carbon-intensive financial assets are expected to face a negative impact during the transition procedure to a lower-carbon economy.
- Given that investments in the carbon-based economy are mostly irreversible, stringent climate policies and a low-carbon world economy are likely to make the operation of carbon-intensive firms unprofitable, and thus leave assets stranded.

From transition risk to financial stability risks



Source: Network for Greening the Financial System, "A call for action: Climate change as a source of financial risk", April 2019

This part follows Karydas C. and A. Xepapadeas, Climate change financial risks: pricing and portfolio allocation, mimeo ETH Zurich, October, 2019.

- We consider an aggregate portfolio consisting of riskless bond holdings, and risky capital assets differentiated between general capital assets K_G and brown capital assets K_B such that total capital is $K = K_G + K_B$. Prices follow jump-diffusion stochastic processes.

$$\frac{dp_{Gt}}{p_{Gt}} = \mu_G dt + \sigma_G dW_{Gt} + (e^{Z_G^M} - 1)dY_t^M + (e^{Z_G^E} - 1)dY_t^E,$$
$$\frac{dp_{Bt}}{p_{Bt}} = \mu_B dt + \sigma_B dW_{Bt} + (e^{Z_G^M} - 1)dY_t^M + (e^{Z_G^E + \pi X_t} - 1)dY_t^E,$$

  with $\mu_i, \sigma_i > 0$ being, respectively, the asset-specific drift and volatility parameters and $i \in \{B, G\}$. While diffusion refers to a standard Brownian motion W_i, jumps refer to infrequent adverse Poisson events that result in economic losses and are related to two types of shocks (disasters), macroeconomic (M) and environmental (E).
- Y^j represents the Poisson jump process, with a time-varying intensity $\lambda^j > 0$.

- The return on the risk-free asset is r.
- The increasing frequency and intensity of climate-related disasters are expected to accelerate the introduction of policies towards the transition to a low-carbon economy. To capture this correlation, we assume that the Poisson intensity of policy risk is a fraction $\pi \in [0, 1]$ of the intensity of environmental disasters.

- Our main methodological contribution lies in establishing the link between climate change and the intensity λ^E of the Poisson process related to environmental disasters Q^E. Climate shocks are triggered by emissions caused by the use of brown assets K_B. Effective CO_2 emissions are

$$E_t = \phi K_{Bt},$$

with ϕ emissions intensity.

- Following the transient climate response to cumulative carbon emissions (TCRE), the global temperature anomaly dynamics are

$$\dot{T}_t = \frac{1}{H}(\Lambda E_t - \delta T_t), \qquad T_0 = 0.$$

Arrival rates are time varying

$$d\lambda_t^M = \kappa^M \left(\bar{\lambda}^M - \lambda_t^M\right) dt + \sigma_\lambda^M \sqrt{\lambda_t^M} dW_{\lambda t}^M.$$

The Poisson intensity for natural disasters λ^E depends linearly on the temperature anomaly, i.e.,

$$\lambda_t^E = \tilde{\lambda}^E + \xi T_t,$$

$$d\lambda_t^E = \kappa^E (\bar{\lambda}_t^E - \lambda_t^E) dt + \sigma_\lambda^E \sqrt{\lambda_t^E} dW_{\lambda t}^E,$$

where $\kappa^E \equiv \delta / H$ and $\bar{\lambda}_t^E \equiv \tilde{\lambda}^E + \xi(\Lambda/\delta)E_t$, with $E_t = \phi K_{Bt}$, and W_λ^E a standard Brownian motion.

Preferences are represented by a recursive Epstein-Zvi type utility function

$$
\begin{aligned}
U_t &= \mathbb{E}_t \int_t^{\infty} f\left(C_v, U_v\right) dv, \\
f\left(C_t, U_t\right) &= \rho\left(1-\gamma\right) U_t \left(\log C_t - \frac{1}{1-\gamma} \log\left(1-\gamma\right) U_t\right),
\end{aligned}
$$

where $\rho > 0$ is the rate of time preference, and $\gamma > 1$ measures relative risk aversion.

Wealth dynamics are given by

$$
\begin{aligned}
& dA_t = (A_t n_t(\mu_{Ct} - r_t + \beta) + A_t r_t - C_t)dt + \\
& A_t n_t \left(\sigma_{At} dW_{At}^T + J_{At} dY_t^T\right) \ , \ n \equiv \frac{K_G + K_B}{K}, n_B \equiv \frac{K_B}{K_G + K_B}.
\end{aligned}
$$

With A, λ^M and λ^E as state variables, and $V(A, \lambda^M, \lambda^E)$ the value function, the optimal consumption and portfolio choices must satisfy the following Hamilton-Jacobi-Bellman equation:

$$\sup_{C,,n,n_B}\{f(C_t, V) + V_A(A_t n_t(\mu_{Ct} - r_t + \beta) + A_t r_t - C_t) + \frac{1}{2}V_{AA}A_t^2 n_t^2 \sigma_t^2 + \sum_{j=\{M,E\}}(V_{\lambda^j}\kappa^j(\bar{\lambda}_t^j - \lambda_t^j) + \frac{1}{2}V_{\lambda^j\lambda^j}(\sigma_\lambda^j)^2\lambda_t^j + \lambda_t^j \mathbb{E}_{z^j}[\tilde{V}^j - V]) + \pi\lambda_t^E[\tilde{V}^X - V]\} = 0.$$

The discount rate

$$r = \underbrace{\rho + \mu_C - \gamma\sigma^2}_{\text{standard model}} + Externality\ \ Cost + \sum_{j=\{M,E\}} \underbrace{\lambda^j \mathbb{E}_{z^j}\left[e^{-\gamma Z^j}\left(e^{Z^j} - 1\right)\right]}_{\text{macroec. \& environ. risk}} + \underbrace{\pi\lambda^E\left[\left(1 + n_B\left(e^X - 1\right)\right)^{-\gamma} n_B\left(e^X - 1\right)\right]}_{\text{policy risk}}$$

- Volatility aside, the risk-free rate is decreasing in the time-varying disaster probabilities λ^j , and in the exposure to these disasters through Z^j.
- Ceteris paribus, a higher share of brown capital n_B leads to greater aggregate portfolio emissions which affects the risk-free rate in the following ways: it reduces it by inducing a higher externality cost (second term), by increasing the probability of natural disasters E and the exposure to environmental policy.

The market's equity premium

$$R - r = \eta\gamma\sigma^2 - \sum_{j\in\{M,E\}} \overbrace{\lambda^j \frac{1}{G}\frac{\partial G}{\partial \lambda^j}}^{\epsilon_j} b^j (\sigma_\lambda^j)^2$$
$$- \sum_{j\in\{M,E\}} \lambda^j \mathbb{E}_{z^j}\left[(e^{-\gamma Z^j} - 1)(e^{\eta Z^j} - 1)\right]$$
$$-\pi\lambda^E \left[(1 + n_B(e^X - 1))^{-\gamma} - 1\right]\left[(1 + n_B(e^X - 1))^{\eta} - 1\right]$$

- The first term is the risk premium in the standard CAPM, while the second term arises from the stochastic nature of the time variation in disaster risk, and further increases the equity premium.
- The part of the sums referring to environmental disasters is the part of the equity premium due to climate change risk.
- The novelty of our model lies in establishing the link between emissions and the probability of extreme environmental disasters.

Figure 5: IPCC projected carbon emissions

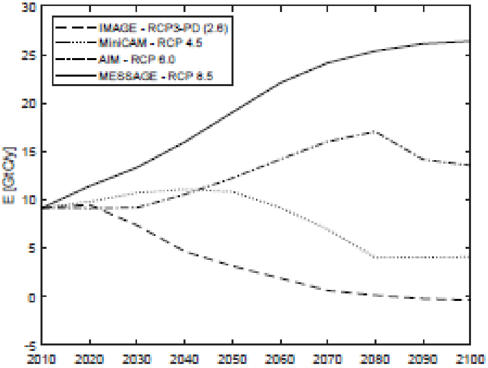


Figure 8: **The premium of climate change risk (annual terms)**

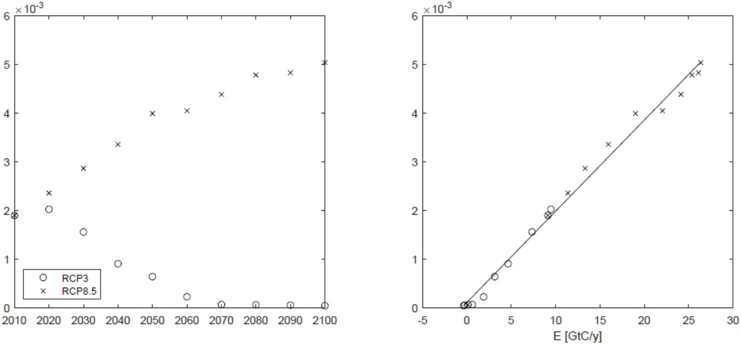
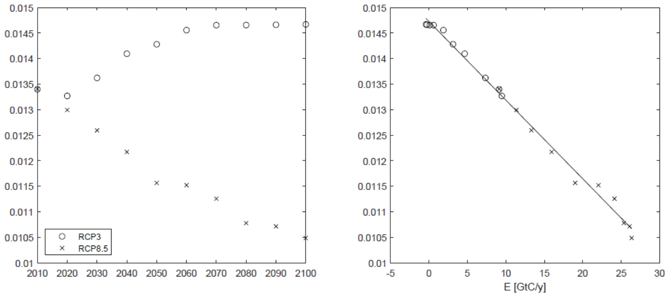
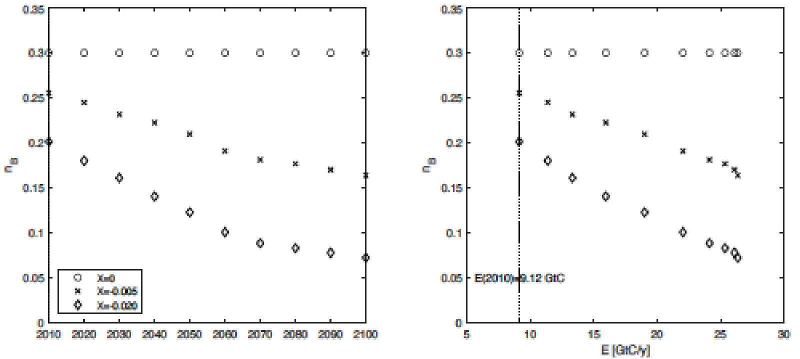


Figure 10: **The effect of emissions on government bond yield (annual terms)**





The effect of policy risk on portfolio participation of brown assets. Emissions follow the worst IPCC scenario (RCP8.5)

$$corr\left[dW_G, dW_B\right] = 0$$

In the optimal solution, the representative investor acknowledges the fact that higher portfolio emissions have a negative feedback on the economy, raising the risk of severe climate-related disasters and the subsequent policy they trigger. For our calibration, there is no solution to n_B within $[0, 1]$. This means that including the full cost of climate change allows for no brown assets in the optimal portfolio of our model.

- Stranded assets are defined as those investments which have already been made but which, at some time prior to the end of their economic life (as assumed at the investment decision point), are no longer able to earn an economic return (IEA, 2013, p. 98).
- The Carbon Tracker Initiative uses this definition and links the economic losses to those that are "a result of changes associated with the transition to a low-carbon economy" (Carbon Tracker Initiative, 2017).
- The energy sector is more exposed to stranded asset risks which are transition risks. Given the importance of the energy sector this could induce systemic financial stability event.
- Bretchger and Sorenz (2018) study the emergence of stranded assets when the climate policy process is uncertain.
- Kalkuh et al. (2018) examine the emergence of stranded assets as a result of time-inconsistent second best carbon taxes.
- Rozenberg et al. (2020) demonstrate that, in principle, governments could use alternative instruments to avoid stranded assets and premature retirement in the transition to clean capital.

- Green bonds are debt instruments used to finance green projects that deliver environmental benefits. A green bond is differentiated from a regular bond by its commitment to use the funds raised in order to finance or refinance "green" projects, assets or business activities.
- An important issue with green bonds is whether there is a difference in yield between a conventional bond and a green bond with similar characteristics, the so-called "greenium". There is preliminary evidence that the average green bond premium was positive (Zerbib, 2019).
- Baker et al. (2018) study the US market and introduce, in a simple asset pricing framework, preferences for non-pecuniary attributes – that is, preferences for green bonds – and conclude that:
  - Green bonds will sell at a premium relative to regular bonds, and
  - Green bond ownership is more concentrated.

- Agliardi and Agliardi (2019) provide an expression for the green bond value which depends on factors such as asset volatility, tax rates, effectiveness of the green technology and a parameter measuring the sustainability advantage. They show that the greenium increases if asset volatility increases, the parameters governing the green technology and the sustainability advantage increase, and corporate tax rates are decreased.

  They suggest that in order to accelerate the green bond market:

  - green bonds should have some kind of tax exemption.
  - policy makers should invest in environmentally-responsible education and information.
  - provision to encourage consumers-investors' demand for green bonds.
  - transparency should be increased on green projects, so as to improve the issuer's credibility.
  - the cost of obtaining and monitoring the green label should be reduced.

This part follows Economides G. and A. Xepapadeas (2020), Is the monetary stabilization policy of central banks affected by climate change? Should it be?

- Climate change policy has been predominantly fiscal policy and, although central bankers have already started discussing the financial stability implications of climate change, very little attention has been paid, thus far, to the implications of climate change for the conduct of monetary policy and the role of Central Banks (see e.g. Cœuré, 2018).
- The above seemingly paradoxical observation can be justified by the fact that fiscal instruments have been considered to be sufficient, since – as economic theory suggests – externalities should be corrected by taxes or similar types of instruments on the externality-generating activity.
- Furthermore, since the Central Banks' traditional objectives of inflation and output stabilization are predominantly short term – while climate change impacts could be regarded as long term – it is plausible to assume that the link between monetary policy and climate change is weak, and thus climate change policy considerations are outside the main concerns of monetary policy.

- However, under a business-as-usual scenario, or even under more climate-friendly scenarios with regard to the future path of GHGs emissions, serious climate change effects are not that far off.
- Since the horizon at which climate change impacts the economy has shortened (see e.g. Cœuré, 2018), the very likely impact of climate change on growth and future output paths might require more involvement of monetary policy which, while aiming at short-term output and employment stabilization, would take into account the impact of climate change on output, as well as the potential impact of climate-change-related fiscal policy measures on inflation.

- Under these conditions, the design and implementation of monetary policy may need to take on a wider role, in the sense that policy actions aiming at short-term output and employment stabilization should be adjusted in order to account for climate change impacts.
- Thus, although strictly speaking monetary policy cannot be regarded as a climate policy instrument, a vital question is whether climate change and the fiscal instruments used to control it could affect the design of monetary policy in a non-trivial way.
- The purpose and the contribution of the present paper is to explore this issue and to demonstrate how and to what extent monetary policy should be adjusted under conditions of climate change.

- The objective the paper is to identify the main features of monetary policymaking in an economy which is affected by climate change.
- 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, and we assume that energy, produced by the processing of fossil fuels, affects the economy via two different channels.
- On the one hand, energy enters as a separate factor in the firm's production function, thus increasing output. On the other hand, 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
- In our model, 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).

1. Climate change seems to act as a new propagation mechanism of total factor productivity (TFP) shocks, which seems not only to lengthen the duration of the effects of disturbances, but also to trigger a non-monotonic behavior in economic activity.
2. In the presence of the detrimental effects of climate change on the economy's productivity, the effect of a negative TFP shock is mitigated after the impact period. This happens because the negative TFP shock decreases both output and the demand for energy.
3. If a Central Bank behaves myopically, in the sense that it conducts monetary policy without internalizing the detrimental effects of climate change on the economy's productivity, which in other words means that the nominal interest rate follows the path it would have followed in the absence of climate change, then the economy will suffer from increased fluctuations, especially in the short run. Myopic behavior increases output fluctuations, especially in the short run.
4. Climate policies, in the form of carbon taxes, seems to imply a short-term cost in terms of output but is growth enhancing in the long-run.

The main message of the paper could be summarized as follows: Even in a context in which technological change can completely offset the detrimental effects of global warming, climate change matters, and affects – non-trivially – the conduct of monetary policy when the monetary policy is used to deal with output fluctuations caused by a temporary TFP disturbance.

- The representative household maximizes expected discounted lifetime utility:

$$\mathbb{E}_0 \sum_{t=0}^{\infty} \beta^t U(c_t, 1 - h_t, m_t, g_t),$$

where c_t is the household's consumption, h_t is the household's hours of work, m_t is the household's real money balances, g_t is per capita spending on public consumption, $0 < \beta < 1$ is the discount factor and $\mathbb{E}_0$ is the rational expectations operator. In our numerical simulations we use a log-linear utility function.

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

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

- There are N intermediate firms, each of which aims at maximizing profits with the following production function:

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

- Firms pay a carbon tax for using energy.

- We assume that $\widehat{A}_t \equiv e^{-\psi(T_t - T_0)} A_t$ is an adjusted TFP factor which incorporates the detrimental effects of climate change into the production function, and where $T_t - T_0$ can be interpreted as the temperature anomaly at time t relative to the pre-industrial period, and $e^{-\psi(T_t - T_0)}$ is a damage function defined in terms of the temperature anomaly.
- Tthe temperature anomaly can be written as

$$\begin{aligned} T_t - T_0 &= \Lambda Q_t, \\ Q_t &= (1 - \delta^e) \sum_{s=0}^{t-1} E_s + E_t. \end{aligned}$$

- Each intermediate firm does not internalize, when making its decisions, the aforementioned detrimental effect, hence it takes the environmental externality as given. Internalization (partial) is obtained by the carbon tax.

We allow the nominal interest rate R_t to follow a standard Taylor rule, meaning that it can react to inflation as a deviation from a policy target and to output growth.

$$R_t = \widetilde{R} + \phi^{\pi}(\pi_t - \widetilde{\pi}) + \phi^{y}(y_t - y_{t-1}),$$

where $\widetilde{R}$ and $\widetilde{\pi}$ denote target values, and ϕ^{π} and ϕ^{y} are feedback monetary policy coefficients.

- A positive temporary TFP shock produces an increase in output, which in turn increases inflation. Thus the policy question is how the nominal interest rate – which, in our case, follows a simple Taylor rule – should react to deviations from targets, when the targets are given for instance by the long-run solution.
- In the standard new Keynesian setup, this would require an increase in the nominal interest rate so as to offset the tendency of prices to increase above the target after the positive TFP shock.
- Note that the energy (produced by fossil fuels) affects productivity in two opposite ways. On the one hand, energy increases output since it enters the production function as a separate factor, and on the other hand the more the energy used, the higher the adverse effect on climate (through the increase in temperature) and therefore the higher the detrimental effect on TFP productivity through the damage function.

- The economy is hit by a negative TFP shock (namely, a 1% decrease in A_t which returns gradually to its initial value). In order to study the effects of climate change we examine the impact of the TFP shock for $\psi = (0.1, 0.2, 0.3, 0.4, 0.5, 0.6)$.
- Notice that what is crucial here is not the path of TFP, A_t, itself, but rather the path of the adjusted TFP component, $\widehat{A}_t \equiv e^{-\psi \Lambda Q_t} A_t$.

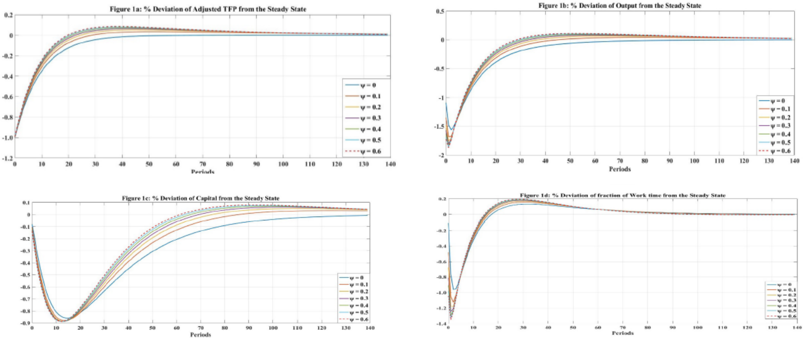


Figure 1a: % Deviation of Adjusted TFP from the Steady State
Periods
Figure 1b: % Deviation of Output from the Steady State
Periods
Figure 1c: % Deviation of Capital from the Steady State
Periods
Figure 1d: % Deviation of fraction of Work time from the Steady State
Periods
ψ = 0
ψ = 0.1
ψ = 0.2
ψ = 0.3
ψ = 0.4
ψ = 0.5
ψ = 0.6

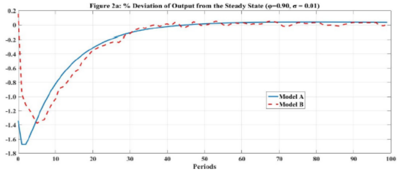


Figure 2a: % Deviation of Output from the Steady State (φ=0.90, σ = 0.01)
Model A
Model B
Periods

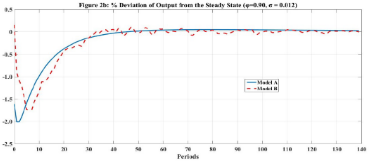


Figure 2b: % Deviation of Output from the Steady State (φ=0.90, σ = 0.012)
Model A
Model B
Periods

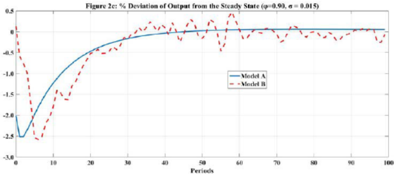


Figure 2c: % Deviation of Output from the Steady State (φ=0.90, σ = 0.015)
Model A
Model B
Periods

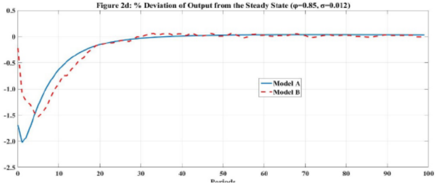


Figure 2d: % Deviation of Output from the Steady State (φ=0.85, σ=0.012)
Model A
Model B

- In the presence of the detrimental effects of climate change on the economy's productivity, the effect of a negative TFP shock – as can be seen in Figure 1 through the path of the adjusted TFP component – is gradually mitigated, although in the impact period the output decreases more relative to the case in which there is no climate change.
- This happens because the negative TFP shock, apart from capital and labour, also decreases the demand for energy which requires a decrease in the use of fossil fuels. The decrease in the use of fossil fuels in turn slows down the temperature rise, a development which positively affects the productivity of the economy.
- In other words, we have two opposite, conflicting effects: a direct negative effect through the negative shock in A_t, and an indirect positive effect through the mitigation of the detrimental impact of climate change. The former tends to decrease the adjusted TFP component, whereas the latter tends to increase it.

- Initially it is the former effect that dominates, but over time this is reversed, and as a result the adjusted TFP component rises above its steady-state value before eventually converging to it.
- The strength of the indirect positive effect on the adjusted TFP component depends on the magnitude of ψ. However, the qualitative nature of our results does not depend on the value of ψ, although the effect of the TFP shock is mitigated faster, the higher ψ is, which affects only the size of the distance between the paths for $\psi = 0$ and $\psi > 0$ at each point in time. The higher the parameter ψ is, the larger the distance is between the paths for $\psi = 0$ and $\psi > 0$ at each point in time.

- If the Central Bank does not internalize the detrimental effects of climate change on the economy's productivity, output exhibits increased volatility relative to the case in which the Central Bank takes into account these effects (Fig. 2).
- The adjustments after the TFP shock are non-monotonic even when the CB is forward-looking and internalizes climate change damages. When the CB is myopic it fails to adress the non-monotonic behavior and this increases fluctuations. In a sense forward-looking behavior smooths out fluctuations but can not entirely extinguish them.

- The results are robust to parameter changes.
- Our 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 behavior of an economy. As Cœuré (2018) points out, more intense climate-related shocks in the future may erode Central Banks' conventional policy space, and more importantly, may raise uncertainties regarding the transition towards a low-carbon economy.
- So it is time for action!