Natural Disasters and Central Bank Asset Purchases*

Alessandro Cantelmo† Bank of Italy

Alessandro Lin‡ Bank of Italy

Francesco Zanetti§ University of Oxford

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Abstract

This paper evaluates the effectiveness of central bank asset purchases (APs) in mitigating the effects of the risk and the materialization of natural disasters on the distributions of inflation and output gap. The scope for the central bank's intervention via APs is given by the fact that a natural disaster strike may trigger, consistent with the empirical evidence provided, an over-reaction in financial markets captured by a sharp increase in the term premium. Post-disasters, APs effectively mitigate the negative effects of the supply-type shock by sustaining output and temporarily increasing inflation. Pre-disasters, APs counter the negative effects on aggregate demand ensuing the risk of natural disasters, thus sustaining economic activity while also increasing the likelihood of achieving the inflation target.

Keywords: rare disasters, natural disasters, climate change, DSGE, unconventional monetary policy, asset purchases, risk premium.

JEL Classification: E4, E5.

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†Bank of Italy, DG for Economics, Statistics and Research. Email: alessandro.cantelmo@bancaditalia.it

‡Bank of Italy, DG for Economics, Statistics and Research. Email: alessandro.lin@bancaditalia.it

§University of Oxford, Department of Economics. Email: francesco.zanetti@economics.ox.ac.uk

1 Introduction

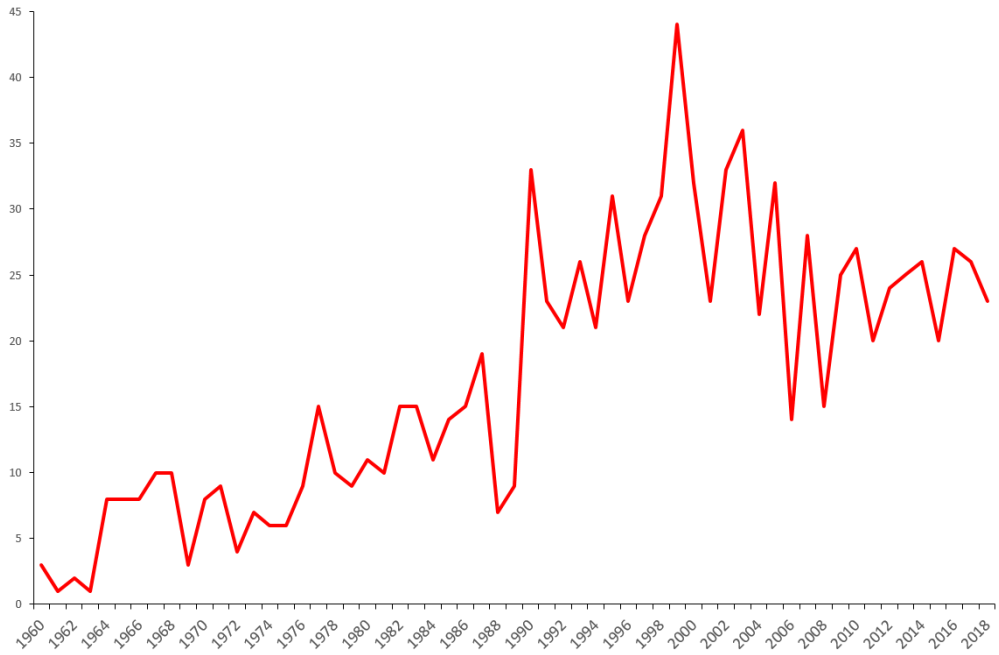
Since 2007, advanced economies have been hit by large shocks (i.e. the global financial crisis and the energy shock) and, some of them, of somewhat unprecedented nature (i.e. the Covid-19 pandemic). Starting from the the global financial crisis when policy rates have been brought to their effective lower bound (ELB), central banks have learned how to design, implement and maintain unconventional monetary policy tools. For instance, central bank's purchases of long-term government bonds have proved to be very effective at, first, ensuring the correct transmission of monetary policy by stabilizing financial markets turmoil, and second, at easing financing conditions for firms and households (see Schnabel, 2024b and references therein). While policy rates have been recently lifted from their ELB to tame the post-pandemic and energy-driven inflation surges, it is important to evaluate the properties of central bank's asset purchases away from the ELB and in response to shocks of different nature.

In this paper, we focus on natural disasters. While climate-related shocks such as severe storms, hurricanes, wildfires, floods, and the like, have become more frequent and more costly (see Figure 1), they are likely to further increase their occurrence and impact (see e.g. Intergovernmental Panel on Climate Change, 2022). It is therefore crucial for central banks to prepare how to respond to such events. In particular, we show that central bank asset purchases of long-term government bonds (APs) can be a useful tool to reduce the likelihood of hitting the ELB and increase the probability of achieving the inflation target while reducing output losses due to natural disasters.

Our interest on central banks asset purchases is motivated by three facts. First, the literature on natural disasters has thus far focused on standard monetary policy instruments (i.e. the short-term policy rate). Second, natural disasters events are associated with large physical capital disruptions and financial markets over-reactions in the form of higher term premia. Third, asset purchases have been established as a crucial tool for central banks when the policy rate is constrained by its effective lower bound but its potential role above it, with a few exceptions mentioned below, is somewhat unstudied.

The scope of the central bank's intervention via APs is given by the fact that a nat-

Figure 1: Number of natural disasters in OECD countries - 1960-2018



Notes: The figure reports the number of natural disasters occurred each year in OECD countries. Source: EM-DAT and authors' calculations.

ural disaster strike can trigger an overreaction in financial markets captured by a sharp increase in the term premium. We show that the long-term rate and the term premium increase following large natural disasters, while the policy rate remains overall constant. Given this change in the slope of the yield curve, it might be more effective to implement asses purchases by directly affecting long-term rates to stabilize macroeconomic and financial conditions while leaving room for maneuver of the policy rate away form the ELB.[1]

We consider the role of long-term government bond purchases programs (APP) from both the business cycle (related to natural disaster *strikes*) and long-term (related to natural disaster *risk*) perspectives. In fact, different aspects of natural disasters might have opposing effects. On the one hand, a disaster *strike* destroys the capital stock and decreases productivity, thus reducing production capacity and typically inducing inflationary pres-

[1] Considerations about the ELB are linked to the concept of the natural interest rate, r^*. Although climate-related risks posed by natural disasters tend to put downward pressure on r^* due to higher uncertainty and future lower productivity (see e.g. Mongelli et al., 2022 and Cantelmo, 2022), investment and technological advances enhanced by the green transition could tend to increase it (see e.g. Mongelli et al., 2022 and Schnabel, 2024a). Our framework is suited to account for only the first.

sures (see, for instance, Fratzscher et al., 2020, Parker, 2018 and Cantelmo et al., 2024). The resulting negative supply-side shocks imply the typical trade-off between stabilizing inflation and reducing output losses faced by central banks. On the other hand, the *risk* of future disaster realizations, associated with low and volatile future incomes, induces negative demand effects guided by precautionary savings. Moreover, as recently pointed out by Bolton et al. (2020), natural disasters could affect financial markets, potentially posing risks to financial and macroeconomic stability, such that traditional policy tools could not be effective, thus inducing policy makers to consider alternative instruments.

In this paper, we augment a New Keynesian model with rare disasters (as e.g. in Fernández-Villaverde and Levintal, 2018) to include: i) a segmented financial market à la Carlstrom et al. (2017); ii) financial markets over-reaction captured by a term premium shock; and iii) unconventional policy in the form of long-term government bond purchases by the central bank in response to the increase in the term premium when a disaster strikes.

The simulation exercises study a typical advanced economy. To calibrate natural disaster shocks, i.e. their frequency and average impact on GDP, we exploit the dataset constructed by Cantelmo (2022) on natural disasters occurred in OECD countries over 1960-2018, and define our baseline scenario as one in which they strike with an annual probability of 2.2% and an average impact on GDP of 2.95%. Starting from this historical perspective, we define two alternative (illustrative) scenarios aimed to capture the fact that climate change will likely make natural disasters more frequent and powerful.

We highlight how APs display their effects by both shifting the distributions of inflation and output and by changing their tails, despite being activated only in response to movements in the term premium following a disaster strike. In the long-run, i.e. in normal times, disaster risk depresses aggregate demand via higher precautionary savings thus exerting downward pressure on output and inflation. The expectation about the APP implementation affects the skewness of the output and inflation distributions, decreasing the likelihood that the former takes extremely negative values without significantly increasing the likelihood of inflation being above target. In the aftermath of disaster strikes, APs alleviate the central bank's trade-off due to the negative supply shock by shifting the

entire inflation and output distributions. Indeed, it counters the negative impact on output and temporarily moves the distribution of inflation rightward. Crucially, the higher likelihood of above-target inflation rates comes at the benefit of higher output and is nevertheless temporary. Moreover, the advantages of using APs become more evident with higher frequency or larger impact of natural disasters.

Literature Review Our paper speaks to a growing literature on rare events that began with the seminal work by Barro (2009) and more recently adapted to study natural disasters. To the best of our knowledge, we are the first to study the potential role of central bank asset purchases to mitigate the effects of natural disasters.

As regards the implications for monetary policy, empirical evidence reported by Fratzscher et al. (2020), Parker (2018), and Cantelmo et al. (2024), suggests that natural disaster strikes are typically inflationary, while theoretical analysis (see e.g. Cantelmo, 2022 and Cantelmo et al., 2024) focus on the role of conventional monetary policy, i.e. the short-term rate.[2]

Our work also relates to several contributions that document a connection between natural disasters and financial markets, in the form of higher risk-premia (Andreasen, 2012; Beirne et al., 2021; Cevik and Jalles, 2022; Painter, 2020; Mallucci, 2022; Cantelmo et al., 2023, among others), whereby we evaluate monetary policy options to address such over-reactions.[3]

[2] In a model without financial intermediaries and long-term bonds, Cantelmo (2022) studies the interactions between natural disasters and a range of Taylor rules, highlighting the importance of disentangling disaster strikes from disaster risk. From a normative perspective, Cantelmo et al. (2024) show that under recurrent natural disasters, it is optimal for central banks to ensure price stability while minimizing the impact on economic activity. Kim and Ruge-Murcia (2019) reach a similar conclusion using a model subject to extreme events in the form of realizations at the tails of standard business cycle shocks. However, they do not study natural disasters. These results are in line with Fratzscher et al. (2020), whose empirical evidence shows that countries adopting an inflation targeting regime experience lower inflation and smaller output losses in the aftermath of natural disasters relative to countries adopting alternative monetary policy regimes.

[3] Andreasen (2012) uses a DGSE model calibrated as in Barro (2009), to show that rare disasters increase the term premium on 10-year bonds by about 75 basis points on average. Beirne et al. (2021) and Cevik and Jalles (2022) estimate that higher vulnerability to climate change, including exposure to natural disasters, is associated with larger spreads in 10-year government bonds relative to the corresponding US benchmark. Similarly, Mallucci (2022) uses a model with long-term government debt and sovereign default, calibrated to Caribbean countries, to show the emergence of a term premium linked to disaster risk. Cantelmo et al. (2023) provide evidence that in Jamaica the interest rate paid on public debt increased on average by 315bps

Finally, our work is related to the several papers that explore the role of unconventional monetary policy as a tool to stabilize financial markets and preserve the correct transmission of monetary policy (Motto and Özen, 2022; BIS, 2023), its potential role in ensuring financial stability under climate change (Bolton et al., 2020), and its role above the effective lower bound on the policy rate (De Fiore and Tristani, 2019; Bigio and Sannikov, 2021; Vissing-Jorgensen, 2023; Bartocci et al., 2023).[4] Our results about the relevance of central bank asset purchases in a model without the ELB and the procyclical design of APP are in line with these contributions while adding a further angle to the literature related to natural disasters.

The remainder of the paper is organized as follows. In Section 2 we report empirical estimates of the effects of natural disasters on long-term rates and the term premium. Section 3 presents the model and discusses its calibration. Section 4 reports the results, Section 4.1 reports the dynamic impact of a disaster strike, while Section 4.2 shows the short- and long-run distributions of inflation and output. Section 5 concludes. The appendix reports the stationary equilibrium, the steady state and robustness checks.

in periods following natural disasters occurred in the last two decades. At a more granular level, Painter (2020) reports significant higher long-term borrowing costs for local governments in US counties exposed to climate risks.In particular, the annualized issuance cost of municipal bonds at long maturities is almost 24 basis point higher for a 1% increase in climate risk.

[4]The former refer to programs implemented by central banks in response to large shocks like the global financial crisis and the Covid-19 pandemic. For example, the ECB implemented the Pandemic Emergency Purchase Programme (PEPP) in March 2020 in response to the Covid-19 shock, and the Public Sector Purchase Programme (PSPP) in March 2015 in response to the sovereign debt crisis. For more details about central banks' use of unconventional tools in response to the pandemic, see BIS (2023). Motto and Özen (2022) show that unconventional policies aiming at ensuring financial stability are effective by compressing credit risk. Bolton et al. (2020) discuss the role of central banks in ensuring financial stability under climate change and recognize that physical risks posed by extreme weather events may lead to severe consequences for financial and price stability, such that traditional policy tools may be less effective at mitigating their effects. Without reference to natural disasters, few contributions explore the role of APs above the effective lower bound on the policy rate. De Fiore and Tristani (2019) emphasize that credit policies by the central bank can make the ELB constraint less likely to bind. The normative analysis of Bigio and Sannikov (2021) suggests that the central bank's balance sheet should be procyclical but non-zero during booms. Finally, Vissing-Jorgensen (2023) derives conditions that determine the size of the central bank's balance sheet above the ELB, which is nevertheless positive.

Table 1: Selected natural disasters.

Country	Date	Disaster type	Damages (% of GDP)
Canada	1977:Q1	Storm	1.5
Italy	1980:Q4	Earthquake	5.1
Luxembourg	1990:Q1	Storm	3.6
Japan	1995:Q1	Earthquake	2.1
Greece	1999:Q3	Earthquake	2.9
Czech Rep.	2002:Q3	Flood	3.5
Japan	2011:Q1	Earthquake	1.3

2 Natural disasters and the term premium: narrative and empirical evidence

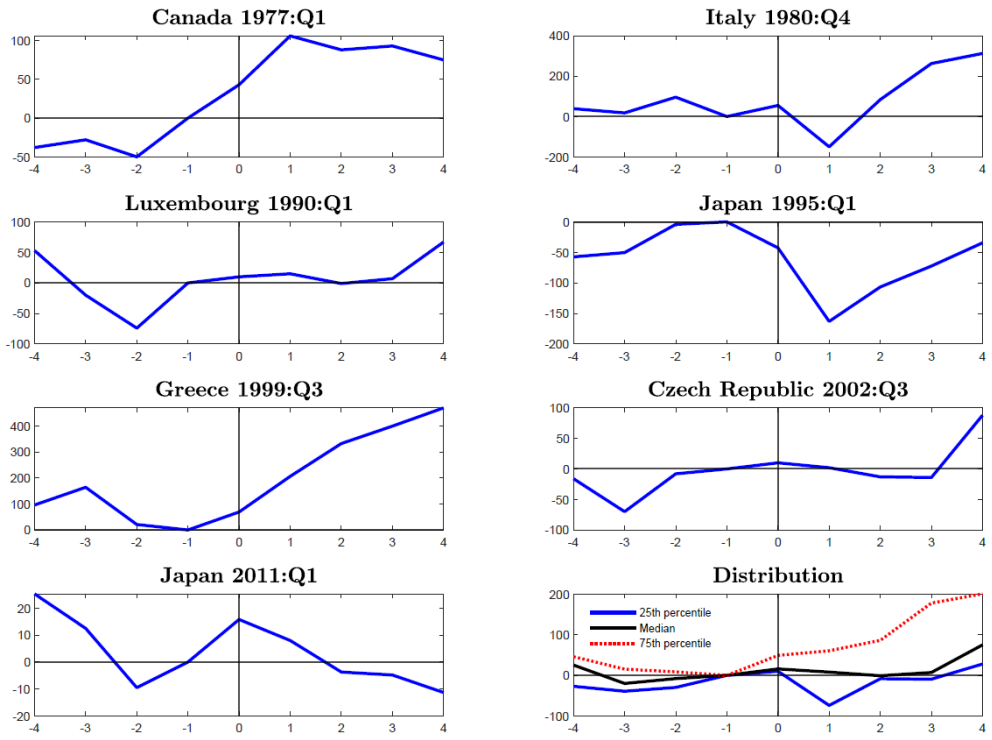
We start our analysis by studying the relationship between natural disasters and the term premium. As a first step, we look at the evolution of the term premium around selected natural disasters. To this end, we exploit the work and the dataset created by Fratzscher et al. (2020).[5] We select large natural disasters for which both the interest rate on the 10-year government bonds and the monetary policy rate are available and define the term premium as their difference. We then compute the differences between the term premium relative to the pre-disaster quarter.[6] Table 1 reports the list of the selected disasters and the damages computed as a percentage of the pre-disaster GDP, while Figure 2 shows the evolution of the term premium in a 1-year window around each selected disaster strike (time 0). In addition to the single disasters, the bottom-right panel reports the distribution of the term-premium implied by the selected disasters. We notice that the term premium often increases after a disaster strike, with magnitudes varying by country. Such evidence is suggestive of the impact of natural disasters on the term premium and the potential role of asset purchases at mitigating such variations.

Obviously, many factors may be behind these variations, that is why we next turn to a more structural empirical approach and estimate the responses of the interest rate on 10-year government bonds, the policy rate and the term premium in the aftermath of natural disasters. To this end, we again exploit the work by Fratzscher et al. (2020)

[5] We are heavily indebted with the authors of the paper for sharing their codes and data.

[6] Therefore, by construction the difference is zero at time t-1.

Figure 2: Evolution of the term premium around selected natural disasters.



Notes: The figure reports the basis points variations in the annualized term premium around selected natural disaster strikes, relative to the pre-disaster (time -1) term premium. Time 0 is the quarter of the event. The term premium is defined as the difference between the interest rate on the 10-year government bonds and the monetary policy rate. Source: Fratzscher et al. (2020) and authors' calculations.

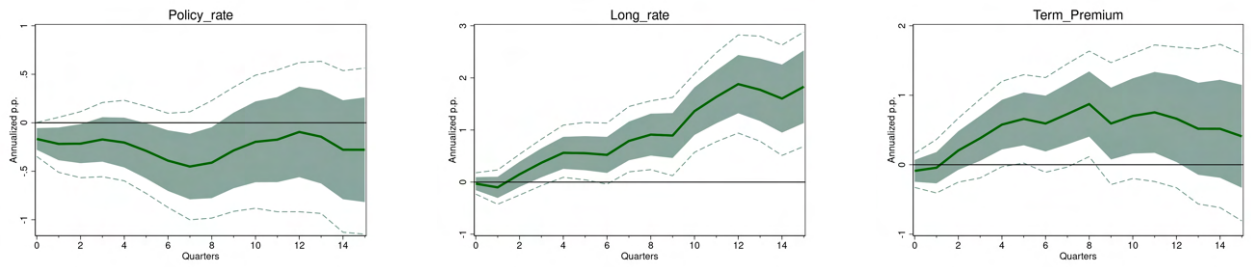
and their dataset. The dataset compiled by Fratzscher et al. (2020) includes a natural disaster shock variable which is constructed from the EM-DAT database and essentially represents damages as a percentage of the pre-disaster GDP.[7] The data covers the period 1980Q1-2015Q4 and includes 605 natural disasters throughout 76 countries, covering both advanced and emerging and developing economies.

To evaluate the dynamic responses of our variables of interest to natural disaster shocks, we estimate the following equation:

$$\Delta y_{i,t} = c + \sum_{j=0}^{J} \left[\beta_j S_{i,t-j} + \vartheta_j GDPpc_{i,t-j} S_{i,t-j} \right] + \nu_i + \nu_Y + \phi X_{i,t-1} + \sum_{l=1}^{L} \mu_l \Delta y_{i,t-l} + \varepsilon_{i,t}. \quad (1)$$

[7] This is consistent with the data we use for calibrating the model, which we retrieve from the same database, see Section 3.9.

Figure 3: Cumulative effects of large natural disasters.



(a) Policy rate (b) Long-term rate (c) Term premium

Notes: The figure shows the cumulated response of the policy rate, the long-term rate and the term premium to large natural disasters over the period 1980Q1-2015Q4. Confidence bands refer to the 90% level (dashed lines) and a one standard deviation interval (shaded area), based on 500 Monte-Carlo draws.

Differently from Fratzscher et al. (2020) we are not interested in computing the differential effects of natural disasters between inflation- and non-inflation targeting countries, therefore equation (1) is a reduced specification of their model. This allows us to compute the dynamic response of the dependent variable $\Delta y_{i,t}$ to a natural disaster shock $S_{i,t}$. The model by Fratzscher et al. (2020) includes several control variables that we keep in our analysis.

Figure 3 shows the cumulative impulse responses of the three variables to large natural disasters. Starting from panel (a), the policy rate displays a mild negative response, whereas the long-term rate (panel (b)) shows a sizable and persistent increase following large natural disasters. By applying the expectation hypothesis to the term structure, the long-term rate reflects movements in the short-term rate plus the term premium. Since the policy rate is stable, the increase in the log-term rate is consistent with a higher term premium. To confirm this conjecture, we construct the term premium as the difference between the long- and short-term rates and plot its response in panel (c). The term premium increases persistently over the projected horizon.

Overall, we find evidence of higher returns on long-term rates and higher term premia following large natural disasters, such that it might be desirable for central banks to intervene. We assess this options by means of the theoretical model described below.

3 Model

We set up a New-Keynesian model with disaster shocks and recursive preferences following Fernández-Villaverde and Levintal (2018).[8] Relative to the related literature, we add financial intermediaries and market segmentation as in Carlstrom et al. (2017) and study the role of APP, determined by a feedback rule linked to excessive movements in the term premium due to disaster strikes.

3.1 Disasters

We start by describing the channels by which disaster shocks propagate through the economy. First, they hit the capital stock. Denote k^*_{t-1} as the optimal capital chosen at time $t-1$, the time-t initial capital stock, k_t, may be lower due to disasters:

$$k_t = k^*_{t-1} e^{-d_t \theta_t}. \tag{2}$$

Given adjustment costs $S(\cdot)$ to private investment x_t, the optimal capital stock follows the law of motion:

$$k^*_t = (1-\delta)\, k_t + \left(1 - S\left[\frac{x_t}{x_{t-1}}\right]\right) x_t. \tag{3}$$

The dummy variable d_t takes a value of 1 with probability p_d in case of disaster and 0 otherwise, thus determining the frequency of disasters. When a disaster occurs, the capital stock falls by θ_t, which is time-varying:

$$\log \theta_t = (1-\rho_\theta) \log \bar{\theta} + \rho_\theta \log \theta_{t-1} + \sigma_\theta \epsilon_{\theta,t}, \quad \epsilon_{\theta,t} \sim \mathcal{N}(0,1). \tag{4}$$

The random variable θ_t takes a log-normal distribution with average disaster size $\bar{\theta}$ and stochastic volatility as specified by the term σ_θ. Disasters therefore entail two sources of uncertainty, the first related to the timing of the strikes and the second related to the actual size of each realization.

Disasters also hit total factor productivity. Following Gourio (2012), Cantelmo (2022) and Cantelmo et al. (2024), we assume that aggregate TFP (A^{agg}_t) has both a permanent

[8] Other similar models are used, for example, by Gourio (2012), Isoré and Szczerbowicz (2017), Cantelmo (2022), and Cantelmo et al. (2024).

(A_t) and a stationary (A_t^T) component. The former is defined as a random walk with a drift while the latter follows an AR(1) process. The equations governing the TFP processes are:

$$\log A_t^{\text{agg}} = \log A_t + \log A_t^T, \tag{5}$$

$$\log A_t = \log A_{t-1} + \Lambda_A - \omega(1-\alpha)\, d_t \theta_t, \tag{6}$$

$$\log A_t^T = \rho_a \log A_{t-1}^T - (1-\omega)(1-\alpha)\, d_t \theta_t, \tag{7}$$

where Λ_A is the steady-state TFP growth. Disasters affect the two components of TFP differently, with $\omega \in [0,1]$ governing the relative impact. Whenever $0 < \omega < 1$, disaster realizations generate a permanent loss in TFP followed by a partial recovery, i.e. after the disaster, the economy experiences temporarily higher growth rate relative to the pre-disaster growth rate.[9] Note that, following Fernández-Villaverde and Levintal (2018), the impact of the disaster shock on TFP is normalized by $1-\alpha$, with α being the capital share in the production function.

3.2 Households

Households have access to two assets: short-term deposits (B_t) in financial intermediaries (FIs henceforth) and physical capital (k_t).[10]

Market segmentation arises because all the investment, x_t, needs to be financed by issuing long-term bonds purchased by FIs. As in Carlstrom et al. (2017), these are assumed to be perpetual bonds with cash flows 1, κ_L, κ_L^2, ... In other words, if $P_{L,t}$ is the time-t price of a new issue, $\kappa_L P_{L,t}$ is the time-t price of the perpetuity issued in period $t-1$ and so on. The duration of these bonds is defined by $(1-\kappa_L)^{-1}$ and their gross yield to maturity by $P_{L,t}^{-1} + \kappa_L$. Define CI_t as the number of perpetuities issued at time t to finance investment, then the representative household's overall nominal liability is:

$$F_{t-1} = CI_{t-1} + \kappa_L CI_{t-2} + \kappa_L^2 CI_{t-3} + ..., \tag{8}$$

[9] Empirical estimates of Hsiang and Jina (2014) and Nakamura et al. (2013) support this modeling approach, see also discussion in Cantelmo (2022) and Cantelmo et al. (2024) for more details.

[10] They may also hold short-term government bonds and short-term debt issued by the central bank to finance its asset purchase program, but since these are perfect substitute with deposits and move endogenously to hit the central bank's short term interest rate target, B_t can be treated as the households' net resource flow into FIs.

with the time-t new issue of perpetuities defined as

$$CI_t = F_t - \kappa_L F_{t-1}. \tag{9}$$

Following the literature on rare disasters, households' preferences are assumed to be recursive (i.e. as in Epstein and Zin, 1989) and defined as:

$$V_t^{1-\psi} = U_t^{1-\psi} + \beta E_t \left(V_{t+1}^{1-\gamma} \right)^{\frac{1-\psi}{1-\gamma}}, \tag{10}$$

where the period-t utility U_t is defined over consumption c_t and labor l_t, $U_t = c_t(1-l_t)^{\nu}$, while V_{t+1} is its continuation value, with discount factor $\beta \in (0,1)$. Parameter γ governs risk aversion while $1/\hat{\psi}$ is the inter-temporal elasticity of substitution, where $\hat{\psi} = 1 - (1+\nu)(1-\psi)$ is its inverse. Each period, households choose consumption, labor supply, capital, deposits and liabilities to maximize (10) subject to the following constraints (in real terms):

$$\begin{aligned}
c_t + q_t x_t + \frac{B_t}{P_t} + \frac{F_{t-1}}{P_t} &\leq w_t l_t + R_{t-1}\frac{B_{t-1}}{P_t} + r_t^k k_t + P_{L,t}\frac{F_t - \kappa_L F_{t-1}}{P_t} - \tau_t + \mathcal{P}_t, && (11)\\
k_t^* &\leq (1-\delta) k_{t-1}^* e^{-d_t \theta_t} + x_t, && (12)\\
q_t x_t &\leq \frac{P_{L,t}(F_t - \kappa_L F_{t-1})}{P_t} = \frac{P_{L,t} CI_t}{P_t}, && (13)\\
q_t k_t^* &\geq \frac{P_{L,t} F_t}{P_t}, && (14)
\end{aligned}$$

where q_t is the real price of capital while r_t^k is its real rental rate; R_{t-1} is the gross nominal interest rate on deposits; w_t is the real wage; τ_t is a lump-sum tax; and $\mathcal{P}_t$ are profits from all financial and non-financial firms. Equation (11) is the households' budget constraint, equation (12) represents the capital accumulation equation, while equation (13) is a "loan-in-advance" constraint, which increases the cost of purchasing investment goods.[11]

The first-order conditions of the representative household read as follows:

[11] All investment projects must be financed by issuing perpetuities purchased by FIs, therefore the total expenditure on investment cannot exceed the total value of perpetuities.

$$1 = M_{t+1}E_t\left[\frac{R_t}{\Pi_{t+1}}\right], \tag{15}$$

$$w_t = \nu\frac{c_t}{(1-l_t)}, \tag{16}$$

$$\Theta_t P_{L,t} = E_t M_{t+1}\left[\frac{1+\Theta_{t+1}\kappa_L P_{L,t+1}}{\Pi_{t+1}}\right], \tag{17}$$

$$\Theta_t q_t = E_t M_{t+1}\left[e^{-d_{t+1}\theta_{t+1}}\left(r^k_{t+1}+q_{t+1}\Theta_{t+1}(1-\delta)\right)\right]. \tag{18}$$

Equation (15) is a standard Euler Equation of consumption, where $M_{t+1} \equiv \beta\frac{\lambda_{t+1}}{\lambda_t}\frac{V_{t+1}^{\psi-\gamma}}{E_t\left(V_{t+1}^{1-\gamma}\right)^{\frac{\psi-\gamma}{1-\gamma}}}$ is the stochastic discount factor with Epstein-Zin preferences, with λ_t being the Lagrange multiplier on the budget constraint (11). Equation (16) represents the marginal rate of substitution between consumption and leisure. Equations (17) and (18) are asset prices equations, with $\Theta_t \equiv \left(1+\frac{\vartheta_t}{\lambda_t}\right)$ being a dynamic distortion caused by market segmentation, and ϑ_t being the multiplier attached to the constraint (13).

3.3 Financial Intermediaries

We model financial intermediaries as in Carlstrom et al. (2017). They are the sole buyers of investment bonds F_t and long-term government bonds B_t^{FI}, which for simplicity are assumed to be perfect substitutes and are sold at the same price of a time-t issue $P_{L,t}$.[12]

FIs collect deposits B_t from households and accumulate net worth N_t. Let $\bar{F}_t = \frac{F_t}{P_t}P_{L,t}$ and $\bar{B}_t^{FI} = \frac{B_t^{FI}}{P_t}P_{L,t}$ denote the real values of investment and long-term government bonds, respectively. Then, the FI's balance sheet reads as:

$$\bar{B}_t^{FI} + \bar{F}_t = \frac{B_t}{P_t} + N_t = L_t N_t, \tag{19}$$

where L_t is leverage. The spread between the lending rate $R_t^L \equiv \left(\frac{1+\kappa_L P_{L,t}}{P_{L,t-1}}\right)$ and borrowing rate R_t determines the FI's profits. A share of the profits are then distributed to households as dividends while the rest is retained as net worth.[13] FIs make these choices using

[12] Long-term government bonds have exactly the same structure as investment bonds, hence they are modeled as perpetuities with maturity $(1-\kappa_L)^{-1}$.

[13] This is necessary to prevent FIs from infinitely accumulating net worth, which would eliminate their need to borrow.

the discount factor $\beta\zeta < \beta$ which implies that they are more impatient than households.[14] When optimally deciding their net worth, FIs are subject to portfolio adjustment costs, which in the stationary equilibrium are $f\left(\tilde{N}_t\right) = \frac{\psi_n}{2}\left(\frac{\tilde{N}_t}{\tilde{N}_{t-1}}\hat{z}_t - \hat{z}\right)^2$, thus preventing them from fully adjusting its assets side of the balance sheet in response to shocks, as governed by parameter $\psi_n \in [0, \infty)$.[15] Financial frictions are introduced via a simple hold-up problem. Each period, before aggregate shocks realize, FIs can default on their debt toward depositors and retain a fraction $\Psi_t < 1$ of the assets. It follows that, in order for optimizing households to be willing to lend to FIs, the following incentive compatibility constraint (ICC) must hold:

$$E_t V_{t+1}^{FI} \geq \Psi_t L_t N_t E_t \frac{\lambda_{t+1}}{\Pi_{t+1}} R_{t+1}^L, \tag{20}$$

according to which the expected value of the FI, V_{t+1}^{FI}, needs to be at least as great as the amount it can divert and is limited by net worth. Assuming that the ICC is binding, equation (20) can be explicitly defined as

$$L_t = \frac{E_t\left(\frac{\lambda_{t+1}}{\Pi_{t+1}}\right)}{E_t\left(\frac{\lambda_{t+1}}{\Pi_{t+1}}\right) + \left(e^{\phi} - 1\right) E_t\left(\frac{\lambda_{t+1}}{\Pi_{t+1}}\right)\frac{R_{t+1}^L}{R_t}}, \tag{21}$$

where e^{ϕ} is a financial wedge that helps pin down leverage in steady state.[16] Maximizing the FI's value yields the following optimal accumulation of net worth:

$$1 + N_t f'(N_t) + f(N_t) = E_t \frac{\zeta M_{t+1}}{\Pi_{t+1}}\left[R_t + L_t\left(R_{t+1}^L - R_t\right)\right]. \tag{22}$$

Financial frictions have real affects because of a limit to arbitrage between the return on long-term bonds R_{t+1}^L and the deposit rate R_t due to the adjustment costs in net worth. This will determine the real impact of central bank's asset purchases, as detailed in Section 3.7.

[14] This assumption is necessary to induce FIs to borrow in equilibrium from households.

[15] This functional form is slightly different from that employed by Carlstrom et al. (2017) which features deviations of net worth from the deterministic steady state. Analogously to investment adjustment costs, we made the growth in net worth costly because our model features permanent deviations from the initial steady state hence we allow for adjustment costs to be zero in the stochastic steady state.

[16] In Carlstrom et al. (2017) this is a stochastic object representing a financial shock. We keep this term constant because we are not interested in such shocks but we exploit it to pin down leverage in steady state.

The introduction of long-term bonds entails the presence of a term premium in the economy. Consider a ten-year bond, with its yield to maturity defined as:

$$R_t^{10} = \kappa_L + \frac{1}{P_{L,t}}. \tag{23}$$

Then the term premium is defined as the difference between its observed yield and the corresponding yield under the expectation hypothesis (EH, see Carlstrom et al., 2017). Let the yield on the ten-year bond under EH be

$$R_t^{10,EH} = \kappa_L + \frac{1}{P_{L,t}^{EH}}, \tag{24}$$

with its price satisfying

$$R_t = \frac{1 + \kappa_L P_{L,t+1}^{EH}}{P_{L,t}^{EH}}. \tag{25}$$

Then, in gross terms, the term premium is defined as

$$TP_t = 1 + R_t^{10} - R_t^{10,EH}. \tag{26}$$

3.4 Non-financial Firms

The firms' side of the economy is standard. Perfectly competitive final good producers combine i intermediate goods according to

$$y_t = \left(\int_0^1 y_{i,t}^{\frac{\epsilon-1}{\epsilon}} di \right)^{\frac{\epsilon}{\epsilon-1}}, \tag{27}$$

where ϵ is the elasticity of substitution.

Intermediate goods producers combine labor and capital according to a Cobb-Douglas production function:

$$y_{i,t} = A_t^{\text{agg}} k_{i,t}^{\alpha} l_{i,t}^{1-\alpha}, \tag{28}$$

where $\alpha \in [0,1]$ is the capital share of income. They choose inputs and prices to maximize profits $F_{i,t} = y_{i,t} - w_{i,t} l_{i,t} - r_{i,t}^k k_{i,t}$ subject to the production function (28) and a Dixit-Stiglitz

demand function $y_{i,t} = \left(\frac{P_{i,t}}{P_t}\right)^{-\epsilon} y_t$. Prices are sticky as in Calvo (1983). At the symmetric equilibrium all i firms are equal hence the first-order conditions read as:

$$g_t^1 = mc_t y_t + \theta_p E_t M_{t+1} \left(\frac{\Pi_t^{\chi}}{\Pi_{t+1}}\right)^{-\epsilon} g_{t+1}^1, \tag{29}$$

$$g_t^2 = \Pi_t^* y_t + \theta_p E_t M_{t+1} \left(\frac{\Pi_t^{\chi}}{\Pi_{t+1}}\right)^{1-\epsilon} \left(\frac{\Pi_t^*}{\Pi_{t+1}^*}\right) g_{t+1}^2, \tag{30}$$

$$\epsilon g_t^1 = (\epsilon - 1) g_t^2, \tag{31}$$

$$1 = \theta_p \left(\frac{\Pi_{t-1}^{\chi}}{\Pi_t}\right)^{1-\epsilon} + \left(1 - \theta_p\right) (\Pi_t^*)^{1-\epsilon}, \tag{32}$$

$$mc_t = \left(\frac{1}{1-\alpha}\right)^{1-\alpha} \left(\frac{1}{\alpha}\right)^{\alpha} \frac{w^{1-\alpha} \left(r_t^k\right)^{\alpha}}{A_t^{\text{agg}}}, \tag{33}$$

$$\frac{k_t}{l_t} = \frac{\alpha}{1-\alpha} \frac{w_t}{r_t^k}, \tag{34}$$

$$v_t^p = \theta_p \left(\frac{\Pi_{t-1}^{\chi}}{\Pi_t}\right)^{1-\epsilon} v_{t-1}^p + \left(1 - \theta_p\right) (\Pi_t^*)^{1-\epsilon}, \tag{35}$$

where $\theta_p \in [0,1]$ denotes the per-period probability of not resetting the price, while $\chi \in [0,1]$ governs the degree of indexation to past inflation, $\Pi_t = \frac{p_t}{p_{t-1}}$ is the gross inflation rate, $\Pi_t^* = \frac{p_t^*}{p_t}$ is the ratio of the optimal reset price and the price of the final good, mc_t is the marginal cost, g^1 and g^2 are auxiliary variables, and finally v_t^p denotes price dispersion.

3.5 New capital producers

New capital is produced by firms that take investment goods x_t and convert them into units of new capital goods. These firms are owned by households and maximize the following profit function:

$$q_t \left[1 - S\left(\frac{x_t}{x_{t-1}}\right)\right] x_t - x_t, \tag{36}$$

where $S\left(\frac{x_t}{x_{t-1}}\right) \equiv \frac{\kappa}{2}\left(\frac{x_t}{x_{t-1}} - 1\right)^2$ represents the investment adjustment costs as governed by parameter κ.[17] Maximizing (36) with respect to x_t yields the following asset price equa-

[17] As in Christiano et al. (2005), the adjustment costs function $S(\cdot)$ satisfies $S(1) = S'(1) = 0$ and $S''(1) > 0$. In the stationary equilibrium, the function reads as $S\left[\frac{\bar{x}_t}{\bar{x}_{t-1}} \hat{z}_t\right] = \frac{\kappa}{2}\left(\frac{\bar{x}_t}{\bar{x}_{t-1}} \hat{z}_t - \hat{z}\right)^2$.

tion for investment:

$$1 = q_t \left[1 - S\left[\frac{x_t}{x_{t-1}} \right] - S'\left[\frac{x_t}{x_{t-1}} \right] \frac{x_t}{x_{t-1}} \right] + E_t M_{t+1} q_{t+1} S'\left[\frac{x_{t+1}}{x_t} \right] \left(\frac{x_{t+1}}{x_t} \right)^2. \tag{37}$$

3.6 Financial market over-reaction

The model assumes that long-term bonds bear a form of long-run risk due to the permanent technology process. While the response of the long-term rate is endogenous and depends on the optimal decisions of households and financial intermediaries, financial markets might over-react to a disaster strike thus increasing long-term rates and, consequently, the term premium. This would give the scope for central bank intervention via asset purchases to restore efficiency in the bonds market and preserve the correct transmission of monetary policy, as for instance happened during the recent pandemic, see e.g. Motto and Özen (2022).[18]

We therefore assume that the return on 10-year bonds is subject to a risk premium linked to the disaster. This is similar to what Barro (2006), Gourio (2012), Isoré and Szczerbowicz (2017) and Cantelmo (2022) do on the short-term rate.

We therefore replace R_t^{10} with $R_t^{10} e^{\eta \tau_t}$ where the exogenous variable τ_t follows an AR(1) process linked to a disaster strike:

$$\log\left(\frac{\tau_t}{\tau}\right) = \rho_\tau \log\left(\frac{\tau_{t-1}}{\tau}\right) + d_t \theta_t. \tag{38}$$

When a disaster strikes, the 10-year rate and hence the term premium increase because of the financial market over-reaction. The impact of the disaster strike is determined by η.[19]

3.7 Monetary policy instruments

The central bank can employ two instruments to achieve its inflation target and stabilize the economy. The first is the traditional short-term interest rate, set according to a Taylor rule. For the sake of comparison with other policy instruments, we also consider a rule

[18] In the long-run, the term premium is higher than in an economy without disaster risk, with the magnitude depending on the distribution of disaster shocks. However, we let the central bank react only to the large deviations of the term premium from its long-run level triggered by a disaster strike because these are the cases of over-reaction we capture.

[19] See Section 3.9 for details about the calibration of η and the process (38).

that responds to inflation and output growth, as well as to the term premium in case of a disaster strike. The Taylor rule is then specified as follows:

$$\frac{R_t}{R} = \left(\frac{R_{t-1}}{R}\right)^{\gamma_R} \left(\left(\frac{\Pi_t}{\bar{\Pi}}\right)^{\gamma_\Pi} \left(\frac{\frac{y_t}{y_{t-1}}}{\exp\left(\Lambda_y\right)} \right)^{\gamma_y} \exp\left(-\frac{d_t TP_t}{dTP} \right)^{\gamma_{TP}} \right)^{1-\gamma_R}. \tag{39}$$

In addition to setting the short-term rate, the central bank can engage in purchases of long-term government bonds in order to reduce the long-term rate and hence the term premium. Indeed, asset purchases consist of a reduction in the supply of long-term bonds which increases their price and reduces the return. As a consequence, financial intermediaries increase the supply of investment bonds which, in turn, stimulates private investment.[20] We assume that the central bank sets asset purchases based on a feedback rule that responds to movements in the term premium in the period a natural disaster strikes:

$$\frac{\bar{B}_t^{CB}}{\bar{B}^{CB}} = \left(\frac{\bar{B}_{t-1}^{CB}}{\bar{B}^{CB}}\right)^{\gamma_b} \exp\left(\frac{d_t TP_t}{dTP}\right)^{\gamma_{bTP}}. \tag{40}$$

According to (40), the central bank purchases long-term government bonds when a disaster strikes, it keeps its balance sheet higher due to the persistence parameter γ_b, and in the long run it reverts back to the pre-disaster balance sheet, i.e. the central bank sells its assets over time.

3.8 Market clearing and stationary equilibrium

In equilibrium all markets clear hence the aggregate resource constraint reads as:

$$y_t = c_t + x_t. \tag{41}$$

The model exhibits a stochastic trend growth rate hence it is detrended before finding the solution. In general, variables are detrended by $z_t = A_t^{\frac{1}{1-\alpha}}$ unless otherwise stated. The full detrended system is reported in Appendix A.

[20] For simplicity, we also assumed that the supply of government bonds is held fixed, as in Carlstrom et al. (2017), so that we avoid modeling the evolution of public debt and of fiscal rules (e.g. on government spending and taxes) thus having a clean evaluation of the effects of asset purchases.

3.9 Baseline calibration and solution method

The model is calibrated to a representative advanced economy at quarterly frequency. Most of the parameter values are borrowed from Cantelmo (2022) and the literature, as reported in Table 2. Here we discuss some crucial parameter values.

Parameters related to natural disasters are taken from the data. As specified in Cantelmo (2022), we set $p_d = 0.0055$ and $\bar{\theta} = 0.0299$ to match the annual probability of 2.2% and the average impact on GDP of 2.95% featured in data on natural disasters in OECD countries from 1960 to 2018. Moreover, the parameters of the disaster risk shock, ρ_θ and σ_θ, approximate the observed distribution of damages to GDP.[21] The parameters governing the impact of disasters on TFP (ω and ρ_a) capture the evidence of a partial recovery following a disaster strike, as discussed in Section 3.1.[22]

The calibration of the financial markets over-reaction due to disaster strikes is illustrative. We set $\eta = 0.75$ and $\rho_\tau = 0.7$ such that under an average disaster strike, the term premium suddenly increases by 0.5 annualized percentage points and returns to its pre-disaster level in 4 quarters.

Parameters and targets related to FIs are borrowed from Carlstrom et al. (2017), except for the adjustment cost of net worth. Indeed, we calibrate ψ_n to replicate the impulse responses of macroeconomic variables to an exogenous APs shock as in Carlstrom et al. (2017). The difference from the value they estimate for the US economy is dictated by the different functional form of net worth adjustment costs that we employ, see discussion in Section 3.3.[23]

[21] The source of data on natural disasters is the EM-DAT, The Emergency Events Database - Universite Catholique de Louvain (UCL) - CRED, D. Guha-Sapir - www.emdat.be, Brussels, Belgium. The EM-DAT database is compiled from various sources including UN, governmental and non-governmental agencies, insurance companies, research institutes and press agencies. Natural disasters are recorded if they meet at least one of the following criteria: (a) 10 or more people reported killed; (b) 100 or more people reported affected; (c) declaration of a state of emergency; (d) call for international assistance. Economic damages cover both direct and indirect losses related to the disaster. They include the amount of damage to property, crops, and livestock. For each disaster, the registered figure corresponds to the damage value at the moment of the event. The choice of 1960 as the starting data is dictated by the availability of GDP series for all countries from the World Bank's World Development Indicators.

[22] Our results are qualitatively unchanged when setting higher or lower values of ω. Quantitatively, higher (lower) values of ω slightly increases (decreases) the stabilization properties of APs, see Section C.1 of the Appendix.

[23] Batini et al. (2021) estimate similar values to Carlstrom et al. (2017) for the Euro Area, Germany, France

Table 2: Baseline values of calibrated parameters.

Parameter		Value	Source/target
Disaster probability	p_d	0.0055	EMDAT
Mean disaster size	$\bar{\theta}$	0.0299	EMDAT
Persistence of disaster risk shock	ρ_θ	0.95	Damages distribution
Std. of disaster risk shock	σ_θ	0.22	Damages distribution
Weight of disasters on permanent TFP	ω	0.50	Partial recovery
Persistence of stationary TFP	ρ_a	0.10	Partial recovery
Elasticity of long-term rate to disasters	η	0.75	
Persistence of long-term rate shock	ρ_τ	0.7	
Leisure preference	ν	1.55	$L = 0.33$
Risk aversion	γ	**7**	$R^n_{RSS} \approx 1.6\%$
Inverse IES	$\hat{\psi}$	0.5	Gourio (2012)
Trend growth of technology	Λ_A	0.0026	Coenen et al. (2018)
Discount factor	β	0.999	Coenen et al. (2018)
Capital share of income	α	0.30	Smets and Wouters (2003)
Capital depreciation rate	δ	0.025	Coenen et al. (2018)
Investment adjustment cost parameter	κ	6.92	Smets and Wouters (2003)
Calvo price stickiness parameter	θ_p	0.905	Smets and Wouters (2003)
Automatic price adjustment	χ	0.472	Smets and Wouters (2003)
Elasticity of substitution	ϵ	6	Villa (2016)
Duration of long-term bonds	$(1-\kappa_L)^{-1}$	40	10 years maturity
FI additional discount factor	ζ	0.9854	$\bar{TP}$=100 ann. b.p., Carlstrom et al. (2017)
Financial wedge	e^ϕ	0.1687	$L = 6$, Carlstrom et al. (2017)
Net worth adjustment cost parameter	ψ_n	3000	IRFs APs shock Carlstrom et al. (2017)
Inflation target	$\bar{\Pi}$	1.005	2% inflation target
Inflation parameter in Taylor rule	γ_Π	1.69	Smets and Wouters (2003)
Output growth parameter in Taylor rule	γ_y	0.095	Smets and Wouters (2003)
Interest rate smoothness in Taylor rule	γ_R	0.95	Smets and Wouters (2003)
Term premium parameter in Taylor rule	γ_{TP}	0.27	
Persistence of asset purchases	γ_b	0.99	
Asset purchases reaction to term premium	γ_{bTP}	50	

As far as monetary policy is concerned, parameters of the Taylor rule are borrowed from Smets and Wouters (2003) and in line with the literature. When we allow the Taylor rule to respond to the term premium, we set $\gamma_{TP} = 0.27$ so that the output loss to an average disaster is the same when the central bank implements APP to make the two policies comparable (see discussion in Section 4.1). When we activate APs, we set $\gamma_b =$

and Italy. Again, their specification of the net worth adjustment costs is different from ours.

0.99 and $\gamma_{bTP} = 50$, implying that the central bank's balance increases by about 1% of GDP in response to an average disaster and is then slowly decreased, see Section 4.1 for a more detailed discussion.

In Appendix C we perform robustness checks about the calibration of some key parameters, i.e. ω, γ_{Π} and ψ_n.

Finally, we solve the model with a third-order Taylor projection, a solution method proposed by Fernández-Villaverde and Levintal (2018) to accurately and efficiently solve DSGE models with rare disasters.[24]

4 Results

In this section we report the results of our simulations. We begin by exploring the transmission of a natural disaster under three possible monetary policy strategies as described above: 1) a standard interest rate rule responding to inflation and output gap; 2) an augmented interest rate rule that also aims at stabilizing the term premium; 3) a standard interest rate rule accompanied by asset purchases.

Second, we move to a longer horizon analysis of the three policies, by studying the implied distributions of inflation and output gap under our *baseline calibration*, which reflects historical frequency and impact of disasters in OECD countries. This exercise sheds some light on both the short- and long-run effects of the policies, under the assumption that the underlying process for natural disasters remains constant.

Finally, we relax the last assumption by considering two alternative scenarios for the disaster process, meant to capture, in an illustrative way, the effects of climate change. In the first scenario, we increase the annual disaster probability p_d from 2% to 8%, implying an event every 12 years on average, as opposed to one every 50 years. This scenario of *higher frequency of disasters* captures the idea that, under climate change, the occurrence of natural disasters is bound to increase significantly. In the second scenario, we double the average impact of natural disasters on GDP, $\bar{\theta}$, increasing it from 2.95% to 6%. This scenario of *larger disasters* accounts for the fact that natural disasters are likely to become

[24] See also Cantelmo (2022), Cantelmo et al. (2023), Dietrich et al. (2021) and Cantelmo et al. (2024) for further applications of this solution method.

more sizable over time.

4.1 Dynamic impact of a disaster strike

We begin by showing how the dynamics post-disaster are affected by whether the central bank responds to an increase in the term premium or not, and by the instrument employed, i.e. asset purchases or the short-term rate.

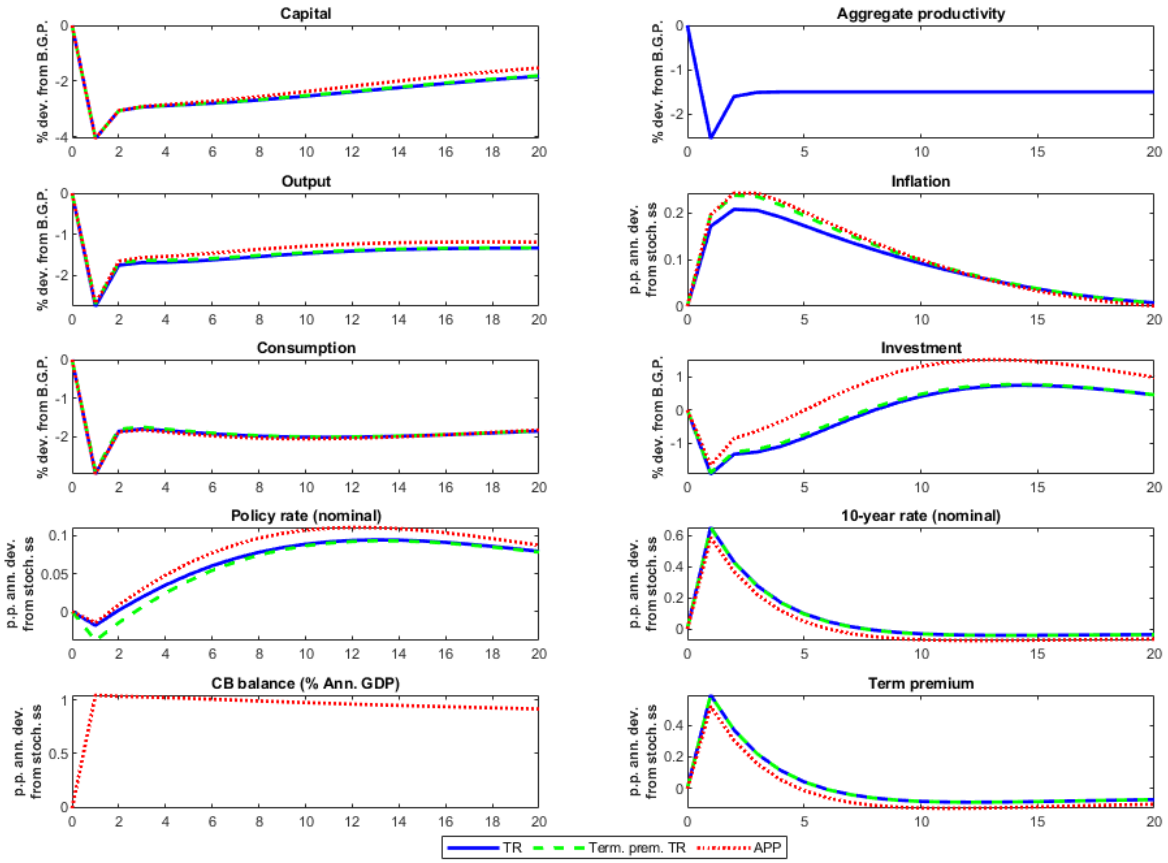
Figure 4 reports the impulse response functions of selected macroeconomic variables to an average disaster shock, i.e. a shock causing a GDP loss of almost 3% under the standard Taylor rule.[25] Blue-solid lines report the responses under the standard Taylor rule. The shock hits the supply-side of the economy by destroying capital and causing a productivity loss.[26] The latter only partially recovers its pre-disaster level because of the assumption about the propagation of a disaster shock to the permanent and temporary components of TFP (see equations (5)-(7)). Following the dynamics of productivity, also output and consumption fall on impact and only partly recover their pre-disaster level in the long-run. Investment overshoots its pre-disaster level because of the endogenous response to the capital destruction. Given the contraction in aggregate supply, annualized inflation increases with a peak response of 0.2 percentage points (pp) and sluggishly decreases toward the central bank's target. On impact the policy rate is mildly decreased because of the GDP loss but then increased in response to higher inflation. As regards financial markets, the 10-year rate increases on impact to capture a case of distress following the disaster strike (see eq. (38)), such that the term premium peaks by about 0.5 pp.

We now turn to analyzing the role of central bank policies in response to a disaster strike. Red-dotted lines in Figure 4 show the dynamics when the central bank purchases long-term government bonds in order to reduce the impact of the disaster on the term premium. According to the rule defined in equation (40), the central bank's balance sheet is immediately increased in response to the disaster strike and then slowly decreases. The bottom-left panel of Figure 4 shows that the central bank balance as a fraction of annu-

[25] Impulse responses under an extreme disaster are qualitatively identical and are available upon request.

[26] The path of productivity is affected only by the disaster shocks and not by the other endogenous variables, including those related to monetary policy. That is why Figure 4 displays only one line for TFP.

Figure 4: Impulse responses to an average disaster shock



Notes: Impulse responses to an average disaster shock equal to 2.95% of GDP. Output, consumption, investment, capital and productivity are expressed in percent deviations from the pre-disaster balanced growth path. Inflation, interest rates, term premium and the central bank balance to annual GDP ratio are in annualized terms and in percentage points deviations from the risky steady state. The risky steady state is calculated by simulating the model for 100 periods without shocks.

alized GDP increases on impact by about 1 pp and slowly decays.[27] Asset purchases by the central bank directly decrease long-term yields and hence the term premium, which is equivalent to relaxing FI's leverage constraint, thus stimulating investment and mitigating the output loss. Indeed, while the impact response of GDP is mildly reduced, over the longer horizon the level of output is higher than without APs. Given the boost to

[27] This is somewhat conservative. For example, in March 2020 in response to the Covid shock, a shock comparable in size to natural disasters studied in our paper, the ECB announced the implementation of the Pandemic Emergency Purchase Programme (PEPP). The cumulative net purchases at the end of 2020Q2 amounted to about 14% of the EA (annualized) GDP. In this sense, our results could be interpreted as conservative. See BIS (2023) for more details about asset purchase programs implemented throughout the world.

aggregate demand, inflation increases by a further 0.1 pp. The dynamics of inflation in this case are driven by three factors: the supply reduction due to the shock, the boost to aggregate demand given by APs, and by the systematic response of the short-term interest rate to higher inflation. Moreover, we note that the effects of APP on inflation might look contained because first, we implement it away from the ELB, second, because of the systematic response of the policy rate, and third we simulate a conservative response of asset purchases.

We then consider an alternative policy, in which the central bank decides to move the short-term rate in response to the term premium instead of implementing asset purchases. To make this *term premium Taylor rule* comparable with APs, we calibrate it such that the impact response of output is the same (by setting $\gamma_{TP} = 0.27$ in eq.(39)). An alternative criterion to compare the two policies would be to obtain the same reduction in the term premium. However, the large policy rate cut that would be needed would bring it below the ELB. Since we do not explicitly account for the ELB, we prefer to target the same output loss. Green-dashed lines report the impulse responses. The policy rate is further decreased on impact and is kept at a lower level than under APs. Therefore, while this policy is only mildly less inflationary than asset purchases, it also has a much less positive effect on output. In fact, lowering the short-term rate does not affect the slope of the yield curve as much as APs hence it provides a smaller stimulus on investment. We therefore infer that asset purchases are more effective at sustaining economic activity in response to a disaster shock than lowering the policy rate, while inflation is only mildly and temporarily higher.[28] In other words, by using the additional instrument of asset purchases improves the typical inflation-output trade-off, by boosting output at contained inflation costs.

The dynamics analyzed in this section describe the effects of a disaster realization and the implications of different monetary policies. We find that, compared to only using the short-term rate, adding asset purchases incentivizes investments and sustains aggregate demand, allowing the central bank to attenuate the negative effects of disaster strikes and

[28] This result is in line with the welfare analysis of Carlstrom et al. (2017), who show that a balance sheet policy brings about higher welfare gains than using the short-term rate.

the financial market over-reactions. In the next section, we consider a longer horizon perspective by analyzing the distributions of inflation and the output gap under alternative assumptions about the process governing disaster shocks.

4.2 Distributions of inflation and output

We now turn to analyzing how APs affect the distributions of inflation and output gap. We simulate the model over a long sample and select a two-years window around each disaster to distinguish between pre- and post-disaster periods.[29] In particular, the pre-disaster distributions include simulated data two years before a disaster strike thus representing the long-run, while the post-disaster distributions include the quarter of a disaster occurrence and the following seven quarters, thus capturing short-run effects.[30] Consistently with the construction of the impulse responses reported in Figure 4, we define the output gap as the difference between the actual level of output and the level that would have occurred without the disaster strike.

As described above, we consider the baseline calibration and two alternative scenarios for the disaster process meant to capture the effects of climate change.

Figures 5-7 display four panels reporting the pre- and post-disaster distributions of inflation and output gap under each monetary policy rule considered in each scenario. Each panel also reports the fifth, fiftieth and ninety-fifth percentiles and the mean of each distribution. Those values, along the skewness, are shown in Tables 3-5.

Under the baseline calibration (Figure 5 and Table 3), the pre-disaster distributions of inflation and output gap are almost identical regardless of the monetary policy implemented. This is due to the low frequency and relatively small average impact on output. While, pre-disaster, the distribution of inflation is narrowly centered around the 2% target, that of the output gap is somewhat wide. Nevertheless, APs increase the positive skewness of inflation and decrease the negative skewness of output, making less likely realizations of inflation below target and extreme negative realizations of output. Cru-

[29] The model is simulated for 10000 periods of which the first 1500 are discarded as burn-in.

[30] Whenever two or more disasters occur less than eight quarters apart, we consider them as a single disaster and all the periods between the first occurrence and the eighth quarter after the last strike are used to construct the post-disaster distributions.

cially, these effects materialize without the occurrence of a disaster, therefore APP can mitigate natural disaster risk to an extent by affecting the tails of the inflation and output gap distributions. Moreover, pre-disaster periods follow times in which the central bank reduced its balance sheet, thus providing less support to aggregate demand. However, the expectation that APs will be implemented once a disaster occurs suffices to make it effective also after long periods without disasters. Turning to the post-disaster distributions, given the supply-type impact of disaster strikes, that of inflation is wider and farther to the right, while that of the output gap moves further to the left, compared to their pre-disaster counterparts. Under APs, both the distributions of inflation and output are farther to the right relative to the two alternative Taylor rules meaning that it more effectively sustains output by accepting larger realizations of inflation, as also witnessed by its larger skewness. Both pre- and post- disasters, using the short-term rate to respond to the term premium (i.e. using the *term premium Taylor rule*) has qualitatively the same effects but smaller. While these results already point toward an important role of APs at mitigating the effects of natural disasters, the magnitude of the effects are somewhat contained because of the low frequency and relatively small average impact on output based on historical data. However, moving toward a world subject to more frequent and powerful natural disasters might make the use of APs more relevant. We study this aspect in the next two scenarios.

Figure 6 and Table 4 report the distributions and statistics in the case of *higher frequency of natural disasters*. Differences about the effects of the three policies become more visible. Pre-disaster, under APs the distribution of inflation displays a fatter right-tail although the mean is identical to that under the standard Taylor rule and the Term premium Taylor rule. This implies a larger positive skewness under APs. Again, this makes inflation to be more likely close to target. APs also keep the distribution of the output gap toward less negative values and lower its negative skewness. This is due to the fact that, under APs, higher investment in post-disaster periods increases the capital stock in the long-run hence sustaining output. The effects of APs are even larger post-disasters. The distribution of inflation entails a likely overshoot of the target and an increase in the positive skewness, that are more pronounced than using the short-term rate to respond to the

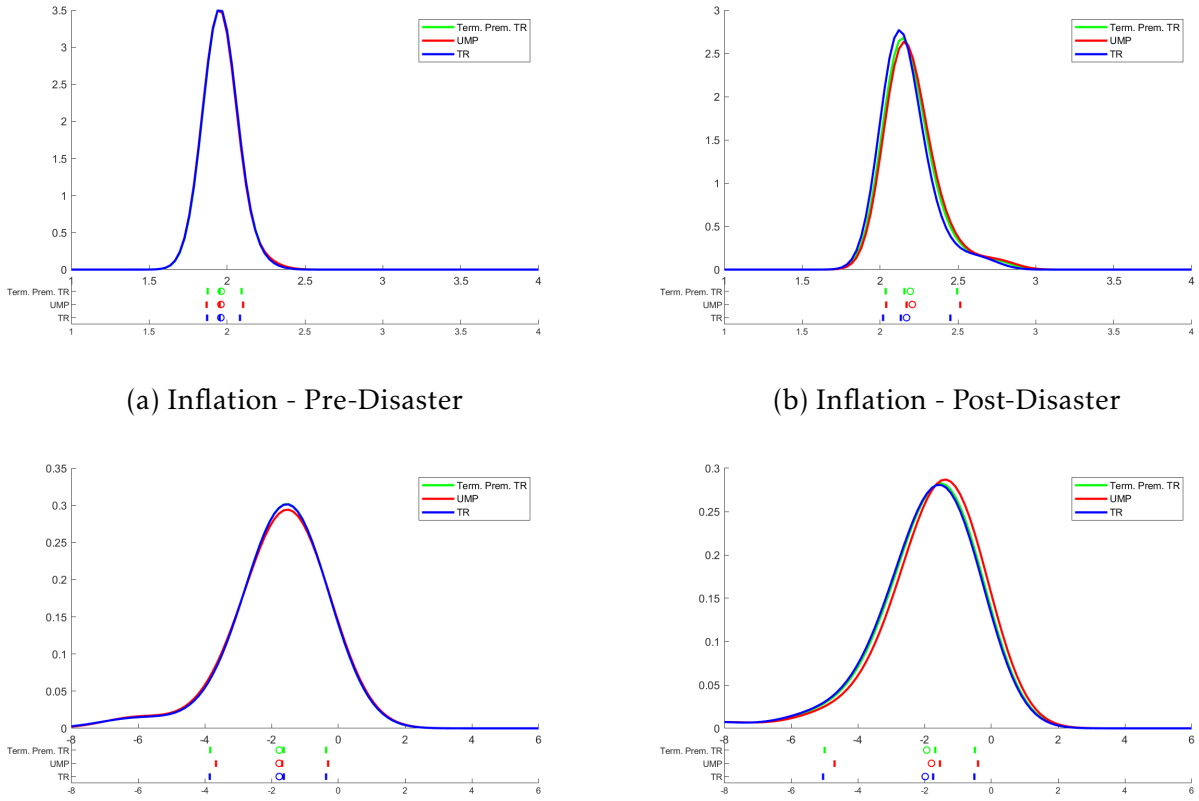
term premium. Crucially, as witnessed by the impulse responses and by the pre-disaster distribution, the overshooting of the inflation target is temporary. Accepting temporarily higher inflation comes at the benefit of significantly reducing the output losses. In fact, under APs the distribution of the output gap is shifted rightward although there is no reduction in the negative skewness. APs therefore do not make the left tail thinner but move the entire distribution toward less negative values.[31]

A similar picture arises under the *larger disaster* scenario (Figure 7 and Table 5), in which the frequency of natural disasters is exactly the same as under the baseline calibration, but on average disasters are twofold larger. This implies that, relative to the baseline calibration, the post-disaster distributions of inflation and output gap are centered around higher and lower values, respectively. Crucially, the ability of APs at reducing the effects of natural disasters, both pre- and post-disaster, is confirmed.

To sum up, we establish that APs can be an effective tool to mitigate the effects of natural disasters, both in short- and the long-run, especially under scenarios that envisage more frequent or more powerful natural disasters. APs prove more effective than using the short-term rate to respond to fluctuations in the term premium caused by disaster strikes. In pre-disaster periods, APs counter the negative inflation outcomes ensuing the increased risk of natural disasters, thus increasing the likelihood of achieving the inflation target. Moreover, they also keep the distribution of the output gap around less negative values. Post-disaster, APs are very effective at sustaining the entire distribution of output while moving that of inflation rightward and increasing its positive skewness. However, the larger overshoot of the inflation target under APs is only temporary.

[31] With more frequent disasters, financial markets might over-react to a lesser extent because agents learn about the higher frequency. However, lower values of η qualitatively leave the results unaltered.

Figure 5: Distributions Pre/Post-Disaster - Baseline Calibration



(a) Inflation - Pre-Disaster

(b) Inflation - Post-Disaster

(c) Output Gap - Pre-Disaster

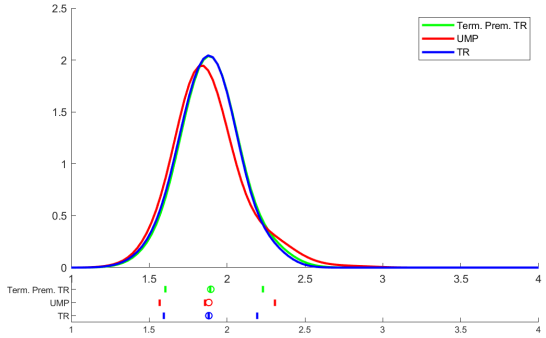
(d) Output Gap - Post-Disaster

Notes: Solid lines report the distributions under the standard Taylor rule (blues), APs (red) and the Term-premium Taylor rule (green). Below the distributions, vertical lines report the 5$^{\text{th}}$, 50$^{\text{th}}$ and 95$^{\text{th}}$ percentiles, while circle report the mean. Inflation is in annualized terms. The output gap is defined as the difference between the actual level of output and the level that would have occurred without the disaster strike.

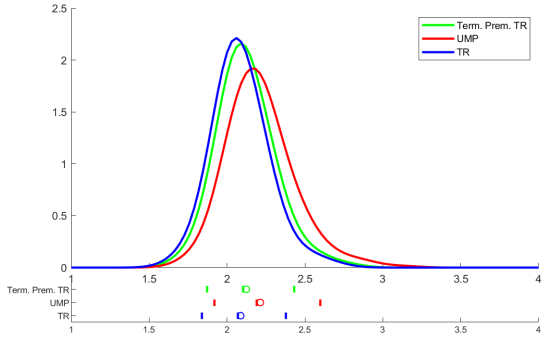
Table 3: Summary statistics: baseline calibration of natural disasters

	Summary statistics														
	Baseline calibration (p_d^{ann} = 2.2%; Average damages to GDP = 2.95%)														
	TR					APs					Term. prem. TR				
	5^{th}	50^{th}	Mean	95^{th}	Skewness	5^{th}	50^{th}	Mean	95^{th}	Skewness	5^{th}	50^{th}	Mean	95^{th}	Skewness
	(i) Post-disaster														
Inflation	2.02	2.13	2.17	2.45	1.72	2.04	2.17	2.21	2.52	1.70	2.03	2.16	2.19	2.49	1.70
Output gap	-5.03	-1.74	-1.98	-0.51	-2.23	-4.70	-1.54	-1.79	-0.40	-2.32	-4.99	-1.67	-1.93	-0.49	-2.24
	(ii) Pre-disaster														
Inflation	1.87	1.95	1.96	2.08	1.44	1.87	1.95	1.96	2.10	1.91	1.87	1.95	1.96	2.09	1.79
Output gap	-3.84	-1.63	-1.77	-0.37	-1.89	-3.67	-1.69	-1.77	-0.31	-1.71	-3.84	-1.63	-1.77	-0.37	-1.90

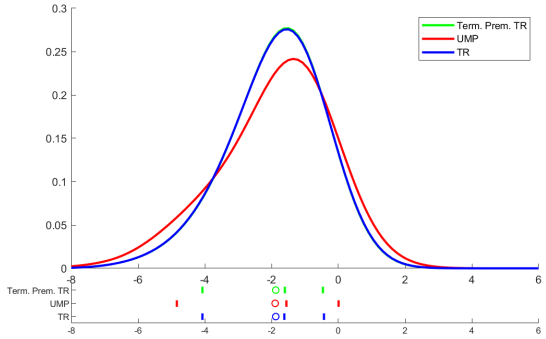
Figure 6: Distributions Pre/Post-Disaster - Higher Frequency of Disasters



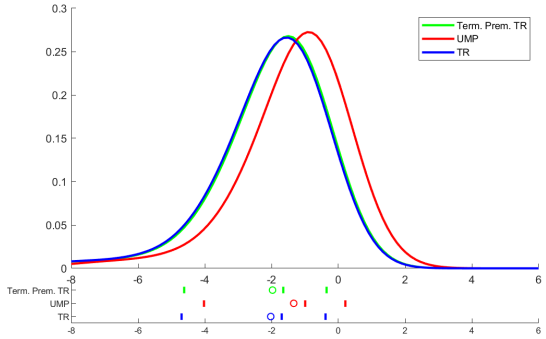
(a) Inflation - Pre-Disaster



(b) Inflation - Post-Disaster



(c) Output Gap - Pre-Disaster



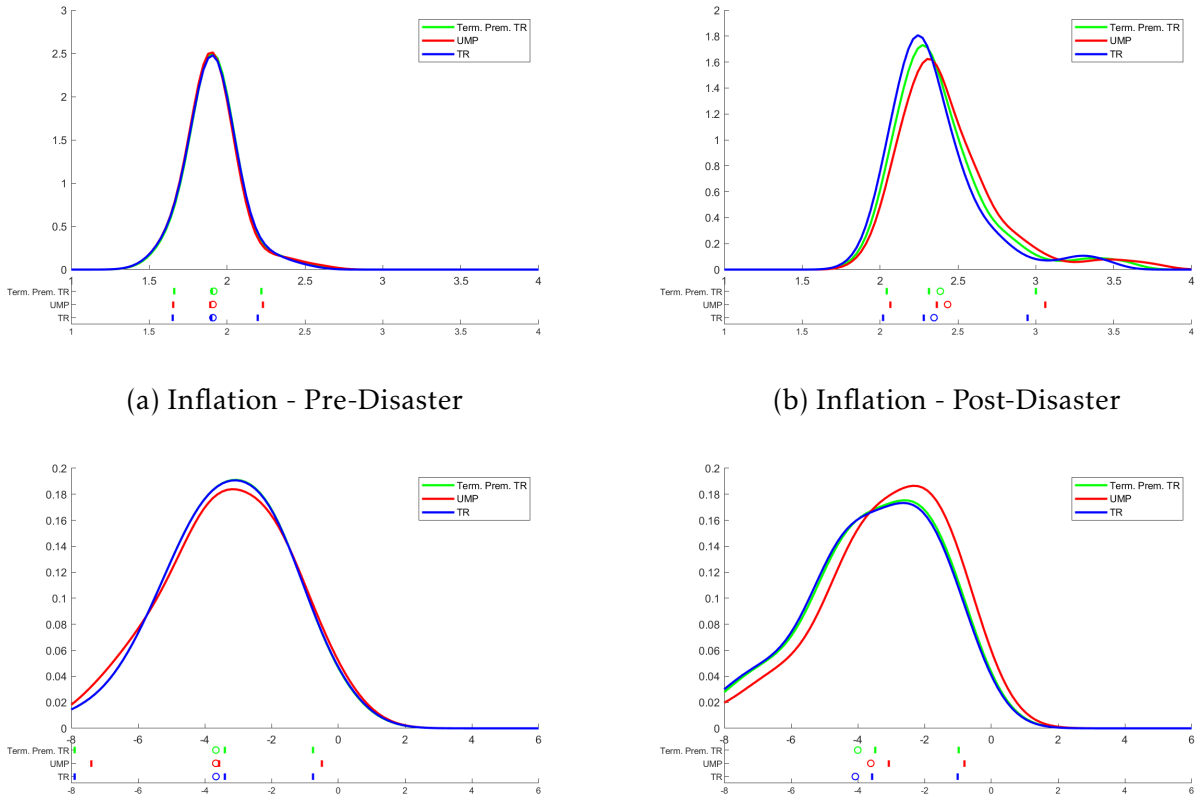
(d) Output Gap - Post-Disaster

Notes: Solid lines report the distributions under the standard Taylor rule (blues), APs (red) and the Term-premium Taylor rule (green). Below the distributions, vertical lines report the 5$^{\text{th}}$, 50$^{\text{th}}$ and 95$^{\text{th}}$ percentiles, while circle report the mean. Inflation is in annualized terms. The output gap is defined as the difference between the actual level of output and the level that would have occurred without the disaster strike.

Table 4: Summary statistics: Higher frequency of disasters

Summary statistics															
Higher frequency of disasters (p_d^{ann} = 8%; Average damages to GDP = 2.95%)															
	TR					APs					Term. prem. TR				
	5^{th}	50^{th}	Mean	95^{th}	Skewness	5^{th}	50^{th}	Mean	95^{th}	Skewness	5^{th}	50^{th}	Mean	95^{th}	Skewness
(i) Post-disaster															
Inflation	1.84	2.07	2.09	2.38	0.60	1.92	2.19	2.21	2.60	0.88	1.87	2.10	2.12	2.43	0.66
Output gap	-4.70	-1.69	-2.02	-0.39	-1.80	-4.02	-1.00	-1.34	0.21	-1.80	-4.62	-1.64	-1.97	-0.36	-1.82
(ii) Pre-disaster															
Inflation	1.59	1.88	1.88	2.19	0.07	1.57	1.86	1.88	2.30	0.88	1.61	1.89	1.90	2.23	0.23
Output gap	-4.07	-1.62	-1.87	-0.43	-0.96	-4.84	-1.55	-1.89	0.00	-0.81	-4.07	-1.59	-1.87	-0.46	-0.98

Figure 7: Distributions Pre/Post-Disaster - Larger Disasters



(a) Inflation - Pre-Disaster

(b) Inflation - Post-Disaster

(c) Output Gap - Pre-Disaster

(d) Output Gap - Post-Disaster

Notes: Solid lines report the distributions under the standard Taylor rule (blues), APs (red) and the Term-premium Taylor rule (green). Below the distributions, vertical lines report the 5$^{\text{th}}$, 50$^{\text{th}}$ and 95$^{\text{th}}$ percentiles, while circle report the mean. Inflation is in annualized terms. The output gap is defined as the difference between the actual level of output and the level that would have occurred without the disaster strike.

Table 5: Summary statistics: Larger disasters

Summary statistics															
Larger disasters (p_d^{ann} = 2.2%; Average damages to GDP = 6%)															
	TR					APs					Term. prem. TR				
	5^{th}	50^{th}	Mean	95^{th}	Skewness	5^{th}	50^{th}	Mean	95^{th}	Skewness	5^{th}	50^{th}	Mean	95^{th}	Skewness
(i) Post-disaster															
Inflation	2.02	2.28	2.35	2.95	1.63	2.06	2.36	2.43	3.06	1.64	2.04	2.31	2.39	3.00	1.63
Output gap	-10.2	-3.57	-4.07	-1.01	-2.17	-9.30	-3.07	-3.61	-0.80	-2.32	-10.1	-3.48	-4.00	-0.98	-2.19
(ii) Pre-disaster															
Inflation	1.65	1.90	1.91	2.20	0.58	1.65	1.89	1.91	2.23	1.04	1.66	1.90	1.91	2.22	0.83
Output gap	-7.90	-3.40	-3.66	-0.76	-1.72	-7.40	-3.58	-3.67	-0.50	-1.53	-7.90	-3.41	-3.67	-0.76	-1.73

5 Conclusions

In this paper we highlight the potentially important role of central bank purchases of long-term government bonds to mitigate the negative effects of natural disasters on inflation and economic activity. Our focus is not only on average outcomes, but on the entire distributions of inflation and output, both in the aftermath of disasters and in normal times.

The scope for the central bank's intervention via asset purchases is given by the fact that a natural disaster strike may trigger an over-reaction in financial markets captured by a sharp increase in the term premium. We first empirically estimate that long-term rates and the term premium increase after large natural disasters. Then we use a theoretical model to assess the use of asset purchases.

We highlight that, by directly affecting long-term rates and hence investment decisions, using APs in response to movements in the term premium is more effective at stabilizing inflation and output than employing the standard monetary policy instrument, i.e. the short-term policy rate, both in normal times and in the aftermath of disaster strikes, especially if natural disasters become more frequent and intense. Indeed, APs significantly affect the distribution and skewness of inflation and output. Post-disaster, APs alleviate the central bank's trade-off posed by the negative supply shock by sustaining output and accepting temporarily higher inflation. In the long-run, they make less likely extremely negative output realizations and would counter the negative inflation outcomes ensuing the increased risk of natural disasters, thus increasing the likelihood of achieving the inflation target.

Importantly, we abstract entirely from fiscal and macroprudential policies considerations, as well as other relevant channels, e.g. via asymmetric effects across sectors and labor market. We leave these issues for future research.

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Appendix

A Stationary equilibrium

The model exhibits a stochastic trend growth rate hence it is detrended before finding the solution. In general, variables are detrended by $z_t = A_t^{\frac{1}{1-\alpha}}$ unless otherwise stated. I denote the detrended variable with a $\ll\tilde{}\gg$, i.e. $\tilde{x}_t = \frac{x_t}{z_t}$, while growth rates are denoted by a $\ll\hat{}\gg$, i.e. $\hat{x}_t = \frac{x_t}{x_{t-1}}$. The full detrended system is the following:

$$d_{t+1} = \mu^d + \left(\epsilon_{d,t+1} - \mu^d\right) \tag{42}$$

$$\log\theta_{t+1} = (1-\rho_\theta)\log\bar{\theta} + \rho_\theta \log\theta_t + \sigma_\theta \epsilon_{\theta,t+1} \tag{43}$$

$$\log\hat{A}_t = \Lambda_A - \omega(1-\alpha)\, d_t \theta_t \tag{44}$$

$$\log A_t^{\text{agg}} = \log A_t + \log A_t^T \tag{45}$$

$$\log A_t^T = \rho_a \log A_{t-1}^T - (1-\omega)(1-\alpha)\, d_t \theta_t \tag{46}$$

$$\log\hat{z}_t = \frac{1}{1-\alpha}\log\hat{A}_t \tag{47}$$

$$\left(\frac{\tilde{V}_t}{\tilde{V}}\right)^{1-\psi} = \left(\frac{\tilde{U}_t}{\tilde{U}}\right)^{1-\psi}\left(\frac{\tilde{U}}{\tilde{V}}\right)^{1-\psi} + \beta E_t\left(\left(\frac{\tilde{V}_{t+1}}{\tilde{V}}\right)^{1-\gamma}\hat{z}_{t+1}^{1-\gamma}\right)^{\frac{1-\psi}{1-\gamma}} \tag{48}$$

$$\tilde{U}_t = \tilde{c}_t(1-l_t)^\nu \tag{49}$$

$$U_{c,t} = (1-l_t)^\nu \tag{50}$$

$$\tilde{U}_{l,t} = -\nu\tilde{c}_t(1-l_t)^{\nu-1} \tag{51}$$

$$\tilde{\lambda}_t = (1-\psi)\,\tilde{U}_t^{-\psi} U_{c,t} \tag{52}$$

$$-\tilde{\lambda}_t\tilde{w}_t = (1-\psi)\,\tilde{U}_t^{-\psi}\tilde{U}_{l,t} \tag{53}$$

$$M_{t+1} = \beta\frac{\tilde{\lambda}_{t+1}}{\tilde{\lambda}_t}\hat{z}_{t+1}^{-\psi}\frac{\left(\frac{\tilde{V}_{t+1}}{\tilde{V}^{ss}}\right)^{\psi-\gamma}\hat{z}_{t+1}^{\psi-\gamma}}{E_t\left(\left(\frac{\tilde{V}_{t+1}}{\tilde{V}^{ss}}\right)^{1-\gamma}\hat{z}_{t+1}^{1-\gamma}\right)^{\frac{\psi-\gamma}{1-\gamma}}} \tag{54}$$

$$1 = E_t M_{t+1}\frac{R_t}{\Pi_{t+1}} \tag{55}$$

$$\Theta_t P_{L,t} = E_t M_{t+1}\left[\frac{1+\Theta_{t+1}\kappa_L P_{L,t+1}}{\Pi_{t+1}}\right] \tag{56}$$

$$\Theta_t q_t = E_t M_{t+1} \exp\left(-d_{t+1}\theta_{t+1}\right)\left[r^k_{t+1} + q_{t+1}\Theta_{t+1}\left(1-\delta\right)\right] \tag{57}$$

$$\tilde{k}^*_t = \left(1-\delta\right)\tilde{k}_t + \left(1 - S\left[\frac{\tilde{x}_t}{\tilde{x}_{t-1}}\hat{z}_t\right]\right)\tilde{x}_t \tag{58}$$

$$\tilde{k}_t = \frac{\tilde{k}^*_{t-1}}{\hat{z}_t}\exp\left(-d_t\theta_t\right) \tag{59}$$

$$\tilde{N}_t L_t = \bar{B}_t^{FI} + \bar{F}_t \tag{60}$$

$$L_t = \frac{1}{1 + \left(e^{\phi} - 1\right)E_t\frac{R^L_{t+1}}{R_t}} \tag{61}$$

$$q_t\tilde{x}_t = \bar{F}_t - \frac{\kappa_L \bar{F}_{t-1}}{\hat{z}_t\Pi_t}\frac{P_{L,t}}{P_{L,t-1}} \tag{62}$$

$$1 = E_t\frac{\zeta M_{t+1}}{\Pi_{t+1}}\left[R_t + L_t\left(R^L_{t+1} - R_t\right) + f'\left(\tilde{N}_{t+1}\right)\left(\frac{\tilde{N}_{t+1}}{\tilde{N}_t}\hat{z}_{t+1}\right)^2\right]\left[1 + \frac{\tilde{N}_t}{\tilde{N}_{t-1}}f'\left(\tilde{N}_t\right)\hat{z}_t + f\left(\tilde{N}_t\right)\right]^{-1} \tag{63}$$

$$f\left(\tilde{N}_t\right) = \frac{\psi_n}{2}\left(\frac{\tilde{N}_t}{\tilde{N}_{t-1}}\hat{z}_t - \hat{z}\right)^2 \tag{64}$$

$$f'\left(\tilde{N}_t\right) = \psi_n\left(\frac{\tilde{N}_t}{\tilde{N}_{t-1}}\hat{z}_t - \hat{z}\right)\frac{1}{\tilde{N}_{t-1}} \tag{65}$$

$$R^L_{t+1} = \frac{1 + \kappa_L P_{L,t+1}}{P_{L,t}} \tag{66}$$

$$R^{10}_t e^{\eta\tau_t} = \kappa_L + \frac{1}{P_{L,t}} \tag{67}$$

$$R_t = \frac{1 + \kappa_L P^{EH}_{L,t+1}}{P^{EH}_{L,t}} \tag{68}$$

$$R^{10,EH}_t = \kappa_L + \frac{1}{P^{EH}_{L,t}} \tag{69}$$

$$TP_t = 1 + R^{10}_t - R^{10,EH}_t \tag{70}$$

$$\begin{aligned} 1 = {} & q_t\left[1 - S\left[\frac{\tilde{x}_t}{\tilde{x}_{t-1}}\hat{z}_t\right] - S'\left[\frac{\tilde{x}_t}{\tilde{x}_{t-1}}\hat{z}_t\right]\frac{\tilde{x}_t}{\tilde{x}_{t-1}}\hat{z}_t\right] + \\ & + E_t M_{t+1} q_{t+1} S'\left[\frac{\tilde{x}_{t+1}}{\tilde{x}_t}\hat{z}_{t+1}\right]\left(\frac{\tilde{x}_{t+1}}{\tilde{x}_t}\hat{z}_{t+1}\right)^2 \end{aligned} \tag{71}$$

$$S\left[\frac{\tilde{x}_t}{\tilde{x}_{t-1}}\hat{z}_t\right] = \frac{\kappa}{2}\left(\frac{\tilde{x}_t}{\tilde{x}_{t-1}}\hat{z}_t - \hat{z}\right)^2 \tag{72}$$

$$S'\left[\frac{\tilde{x}_t}{\tilde{x}_{t-1}}\hat{z}_t\right] = \kappa\left(\frac{\tilde{x}_t}{\tilde{x}_{t-1}}\hat{z}_t - \hat{z}\right) \tag{73}$$

$$\tilde{g}_t^1 = mc_t \tilde{y}_t + \theta_p E_t M_{t+1} \left(\frac{\Pi_t^{\chi}}{\Pi_{t+1}} \right)^{-\epsilon} \tilde{g}_{t+1}^1 \hat{z}_{t+1} \tag{74}$$

$$\tilde{g}_t^2 = \Pi_t^* \tilde{y}_t + \theta_p E_t M_{t+1} \left(\frac{\Pi_t^{\chi}}{\Pi_{t+1}} \right)^{1-\epsilon} \left(\frac{\Pi_t^*}{\Pi_{t+1}^*} \right) \tilde{g}_{t+1}^2 \hat{z}_{t+1} \tag{75}$$

$$\epsilon \tilde{g}_t^1 = (\epsilon - 1) \tilde{g}_t^2 \tag{76}$$

$$1 = \theta_p \left(\frac{\Pi_{t-1}^{\chi}}{\Pi_t} \right)^{1-\epsilon} + \left(1 - \theta_p\right) (\Pi_t^*)^{1-\epsilon} \tag{77}$$

$$mc_t = \left(\frac{1}{1-\alpha} \right)^{1-\alpha} \left(\frac{1}{\alpha} \right)^{\alpha} \tilde{w}_t{}^{1-\alpha} \left(r_t^k \right)^{\alpha} \tag{78}$$

$$\frac{\tilde{k}_t}{l_t} = \frac{\alpha}{1-\alpha} \frac{\tilde{w}_t}{r_t^k} \tag{79}$$

$$\tilde{y}_t = \frac{\frac{\hat{A}_t}{\hat{z}_t} A_t^T \left[\tilde{k}_{t-1}^* \exp\left(-d_t \theta_t\right) \right]^{\alpha} l_t^{1-\alpha}}{v_t^p} \tag{80}$$

$$v_t^p = \theta_p \left(\frac{\Pi_{t-1}^{\chi}}{\Pi_t} \right)^{-\epsilon} v_{t-1}^p + \left(1 - \theta_p\right) (\Pi_t^*)^{-\epsilon} \tag{81}$$

$$\frac{R_t}{R} = \left(\frac{R_{t-1}}{R} \right)^{\gamma_R} \left(\left(\frac{\Pi_t}{\bar{\Pi}} \right)^{\gamma_{\Pi}} \left(\frac{\frac{y_t}{y_{t-1}}}{\exp\left(\Lambda_y\right)} \right)^{\gamma_y} \left(\exp\left(- \frac{d_t TP_t}{dTP} \right)^{\gamma_{TP}} \right) \right)^{1-\gamma_R} \tag{82}$$

$$\frac{\bar{B}_t^{CB}}{\bar{B}^{CB}} = \left(\frac{\bar{B}_{t-1}^{CB}}{\bar{B}^{CB}} \right)^{\gamma_b} \left(\exp\left(- \frac{d_t TP_t}{dTP} \right)^{\gamma_{bTP}} \right) \tag{83}$$

$$\tilde{y}_t = \tilde{c}_t + \tilde{x}_t \tag{84}$$

B Steady state

To solve the steady state, the real wage $\tilde{w}$ solves equation $-\tilde{\lambda}_t \tilde{w}_t = (1-\psi) \tilde{U}_t^{-\psi} \tilde{U}_{l,t}$, while remaining variables are found recursively as follows:

$$d = \mu^d \tag{85}$$

$$\theta = \bar{\theta} \tag{86}$$

$$\Pi = \bar{\Pi} \tag{87}$$

$$L = \bar{L} \tag{88}$$

$$TP = \bar{TP} \tag{89}$$

$$\log \hat{A} = \Lambda_A - \omega(1-\alpha)\, d\theta \tag{90}$$

$$\log \hat{z} = \frac{1}{1-\alpha} \log \hat{A} \tag{91}$$

$$S = 0 \tag{92}$$

$$S^{'} = 0 \tag{93}$$

$$f = 0 \tag{94}$$

$$f' = 0 \tag{95}$$

$$q = 1 \tag{96}$$

$$M = \beta \hat{z}^{-\psi} \tag{97}$$

$$R = \frac{\Pi}{M} \tag{98}$$

$$v^p = \frac{\left(1-\theta_p\right)(\Pi^*)^{-\epsilon}}{1-\theta_p\left(\frac{\Pi^{\chi}}{\Pi}\right)^{-\epsilon}} \tag{99}$$

$$P_L^{EH} = (R-\kappa_L)^{-1} \tag{100}$$

$$R^{10,EH} = \kappa_L + \frac{1}{P_L^{EH}} \tag{101}$$

$$R^{10} = TP + R^{10,EH} - 1 \tag{102}$$

$$P_L = \left(R^{10} - \kappa_L\right)^{-1} \tag{103}$$

$$R^L = \kappa_L + \frac{1}{P_L} \tag{104}$$

$$e^{\phi} = \frac{1-L}{L}\frac{R}{R^L} + 1 \tag{105}$$

$$\zeta = \frac{\Pi}{M\left[R + L\left(R^L - R\right)\right]} \tag{106}$$

$$\Theta = \frac{M}{\Pi}\left[P_L\left(1 - \frac{M\kappa_L}{\Pi}\right)\right]^{-1} \tag{107}$$

$$r^k = \Theta q\left[\frac{1}{M\exp(-d\theta)} - (1-\delta)\right] \tag{108}$$

$$\frac{\tilde{k}}{l} = \frac{\alpha}{1-\alpha}\frac{\tilde{w}}{r^k} \tag{109}$$

$$\frac{\tilde{k}^*}{l} = \frac{\tilde{k}}{l}\exp(d_t\theta_t)\,\hat{z} \tag{110}$$

$$l = \frac{1}{1-g_y}\frac{\tilde{w}}{\nu}v^p\left[\frac{\hat{A}}{\hat{z}}\left(\frac{\tilde{k}^*}{l}\exp\left(-d\theta\right)\right)^{\alpha} + \frac{1}{1-g_y}\frac{\tilde{w}}{\nu}v^p - \frac{1}{1-g_y}\frac{\tilde{k}^*}{l}\left(1 - \frac{(1-\delta)}{\hat{z}}\exp\left(-d\theta\right)v^p\right)\right]^{-1} \tag{111}$$

$$\tilde{k}^* = \frac{\tilde{k}^*}{l}l \tag{112}$$

$$\tilde{k} = \frac{\tilde{k}^*}{\hat{z}}\exp\left(-d\theta\right) \tag{113}$$

$$\tilde{x} = \tilde{k}^* - (1-\delta)\tilde{k} \tag{114}$$

$$\tilde{c} = \frac{(1-l)\tilde{w}}{\nu} \tag{115}$$

$$\tilde{y} = \frac{\tilde{c}+\tilde{x}}{1-g_y} \tag{116}$$

$$\tilde{U} = \tilde{c}(1-l)^{\nu} \tag{117}$$

$$U_c = (1-l)^{\nu} \tag{118}$$

$$\tilde{U}_l = -\nu\tilde{c}(1-l)^{\nu-1} \tag{119}$$

$$\tilde{\lambda} = (1-\psi)\tilde{U}^{-\psi}U_c \tag{120}$$

$$mc = \left(\frac{1}{1-\alpha}\right)^{1-\alpha}\left(\frac{1}{\alpha}\right)^{\alpha}\tilde{w}^{1-\alpha}\left(r^k\right)^{\alpha} \tag{121}$$

$$\tilde{g}^1 = \frac{mc\tilde{y}}{1-\theta_p M\left(\frac{\Pi^x}{\Pi}\right)^{-\epsilon}\hat{z}} \tag{122}$$

$$\tilde{g}^2 = \frac{\epsilon}{\epsilon-1}\tilde{g}^1 \tag{123}$$

$$\Pi^* = \tilde{g}^2\frac{1-\theta_p M\left(\frac{\Pi^x}{\Pi}\right)^{1-\epsilon}\hat{z}}{\tilde{y}} \tag{124}$$

$$\bar{B} = b_y 4\tilde{y} \tag{125}$$

$$\bar{B}^{CB} = b_{cb}4\tilde{y} \tag{126}$$

$$\bar{B}^{FI} = \bar{B} - \bar{B}^{CB} \tag{127}$$

$$\bar{F} = q\tilde{x}\left(1 - \frac{\kappa}{\hat{z}\Pi}\right)^{-1} \tag{128}$$

$$N = \frac{\bar{B}^{FI}+\bar{F}}{L} \tag{129}$$

C Robustness checks

In this section we verify that our results still hold under alternative assumptions about: i) the impact of disasters on the components of TFP; ii) stricter inflation targeting, i.e. higher responsiveness of the central bank toward inflation deviations from target; and iii) lower FI's net worth adjustment costs. For each case, we report both impulse responses to an average disaster strike and the distributions of inflation and output gap under our baseline calibration.

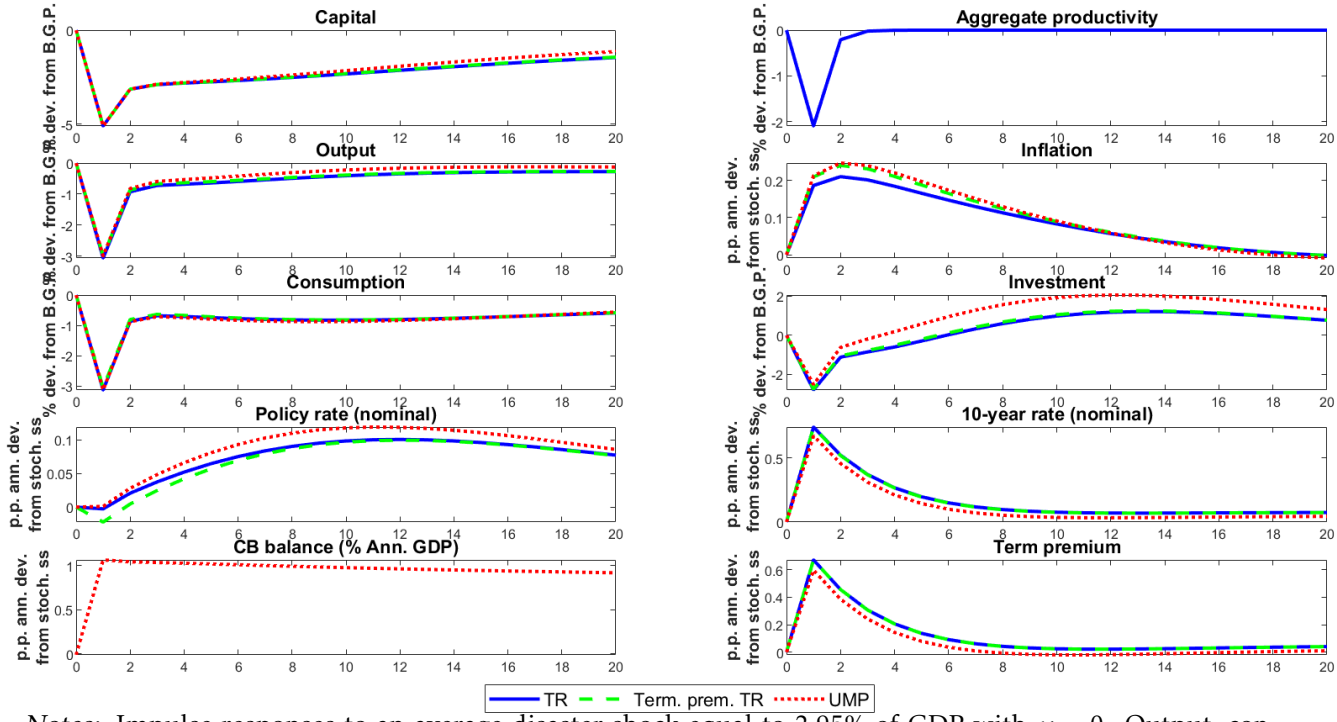
C.1 The impact of disasters on TFP

We start by assessing the role of the impact of disasters on TFP. In the baseline calibration, we set $\omega = 0.5$ meaning that disasters equally affect the permanent and stationary components of TFP. Here we alternatively set $\omega = 0$ and $\omega = 1$, i.e. we let disasters have only temporary or permanent effects, respectively. Figures 8 and 9 show the impulse responses following an average disaster shocks with $\omega = 0$ and $\omega = 1$, respectively. The main differences relative to the baseline case (Figure 4 regard the dynamics of aggregate productivity and trended variables (i.e. capital, output, consumption and investment). When disasters have only temporary effects ($\omega = 0$, Figure 8), TFP quickly recovers to the pre-disaster balanced-growth-path. Trended variables also recover their pre-disaster level although at a slower pace. Conversely, when disasters have only permanent effects ($\omega = 1$, Figure 9), TFP, as well as trended variables, never go back to their pre-disaster balanced-growth-path.

Crucially, in both cases the relative effects of the three policies at study do not change. APs still deliver better output outcomes at little higher inflation.

Turning to the pre- and post-disaster distributions of inflation and output, Figures 10 and 11 show that our main findings are still valid under the two alternative specifications of the impact of disasters on TFP, although some differences arise especially in the distribution of the output gap. This is due to the fact that the output gap depends on the growth rate of the economy which in turn depends on TFP. Compared to the baseline calibration (Figure 5), when disasters have only temporary effects (Figure 10) the pre- and

Figure 8: Impulse responses to an average disaster shock: only temporary effects on TFP.



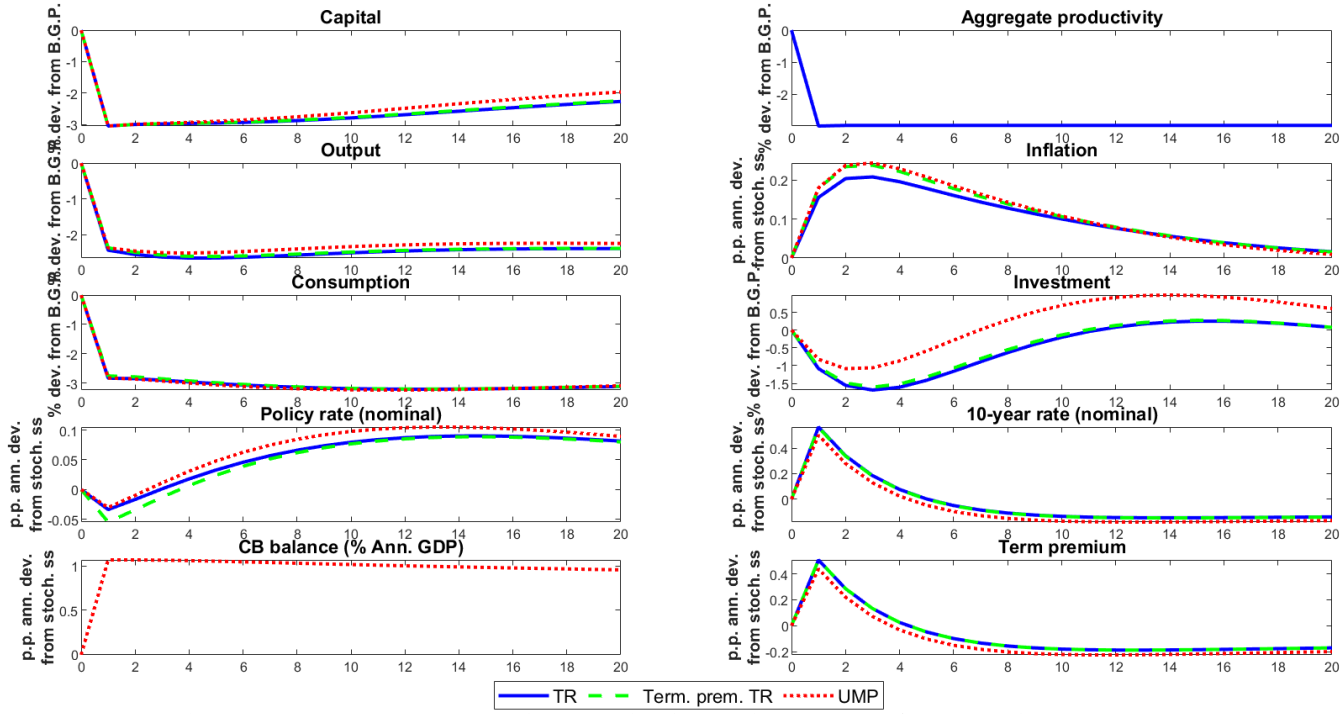
Notes: Impulse responses to an average disaster shock equal to 2.95% of GDP with $\omega = 0$. Output, consumption, investment, capital and productivity are expressed in percent deviations from the pre-disaster balanced growth path. Inflation, interest rates, term premium and the central bank balance to annual GDP ratio are in annualized terms and in percentage points deviations from the risky steady state. The risky steady state is calculated by simulating the model for 100 periods without shocks.

post- disasters distributions of output are slightly more to the right and display thinner left tails because disaster strikes have purely temporary effects. Conversely, when disasters have only permanent effects on TFP (Figure 11) the output distributions move toward more negative values and the left tails are fatter. Nevertheless, in both cases the relative effects of the three policies are the same as under the baseline calibration.

C.2 Stricter inflation targeting

We now explore the case in which the central bank is further concerned with inflation development by setting $\gamma_\Pi = 3$ rather than setting $\gamma_\Pi = 1.69$ as in the baseline calibration. The rationale for this robustness is that central banks may want to avoid looking through inflationary shocks that may potentially be very large. the impulse responses to an average disaster shock (Figure 12) reveal similar dynamics as in the baseline case, with the only

Figure 9: Impulse responses to an average disaster shock: only permanent effects on TFP.



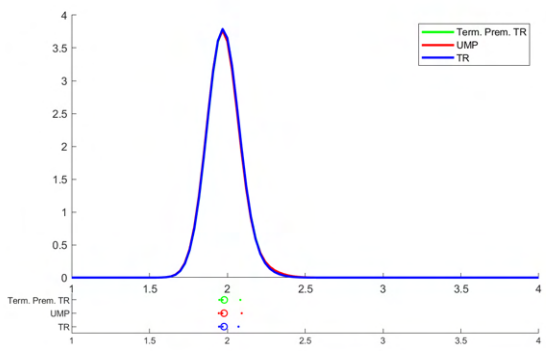
Notes: Impulse responses to an average disaster shock equal to 2.95% of GDP with $\omega = 1$. Output, consumption, investment, capital and productivity are expressed in percent deviations from the pre-disaster balanced growth path. Inflation, interest rates, term premium and the central bank balance to annual GDP ratio are in annualized terms and in percentage points deviations from the risky steady state. The risky steady state is calculated by simulating the model for 100 periods without shocks.

difference that the inflationary effects of the shock are curbed with some additional output loss. Importantly, the relative effects of the three policies do not change. Moreover, the pre- and post-disaster distributions reported in Figure 13 show that, as expected, the main impact of stricter inflation targeting is on inflation. In particular, both pre- and post-disasters the distributions display thinner tails and are more centered around the 2% target. However, the effect of APs on the distributions is unaltered.

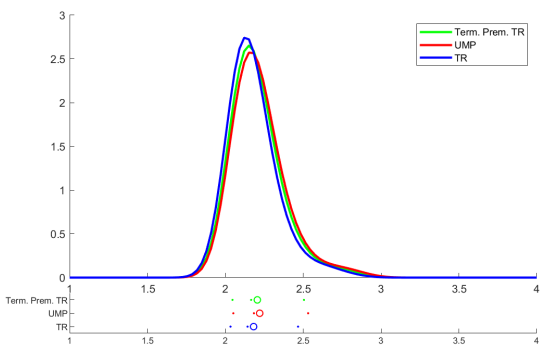
C.3 The role of financial frictions

We then evaluate the role of financial frictions by changing the calibration of the portfolio adjustment cost parameter ψ_n from 3000 to 300. The reason is that high adjustment costs prevent financial intermediaries from adjusting their portfolio thus amplifying both the effects of aggregate shocks and the real impact of asset purchases. Figures 14 and

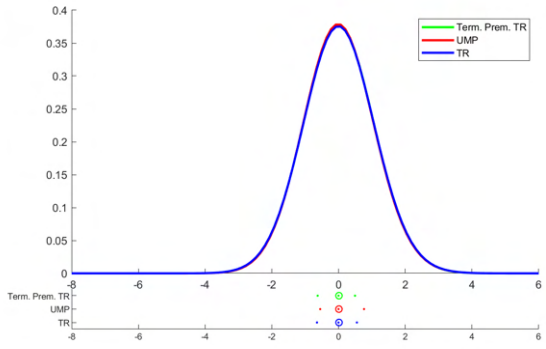
Figure 10: Distributions Pre/Post-Disaster: only temporary effects on TFP.



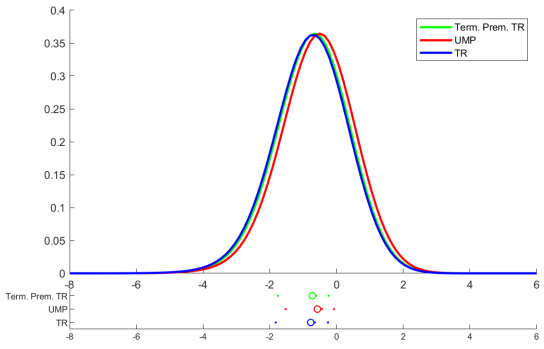
(a) Inflation - Pre-Disaster



(b) Inflation - Post-Disaster



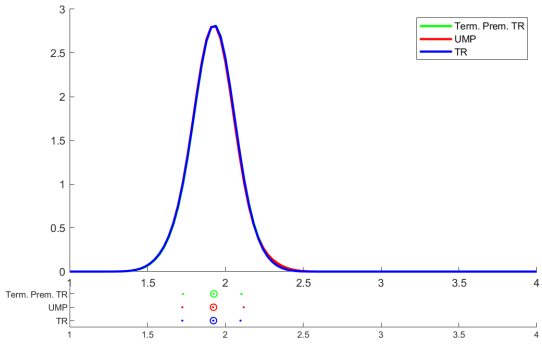
(c) Output Gap - Pre-Disaster



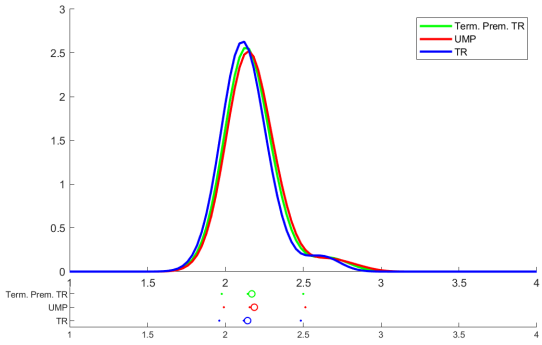
(d) Output Gap - Post-Disaster

Notes: Solid lines report the distributions under the standard Taylor rule (blues), APs (red) and the Term-premium Taylor rule (green). Below the distributions, vertical lines report the 5^{th}, 50^{th} and 95^{th} percentiles, while circle report the mean. Inflation is in annualized terms. The output gap is defined as the difference between the actual level of output and the level that would have occurred without the disaster strike.

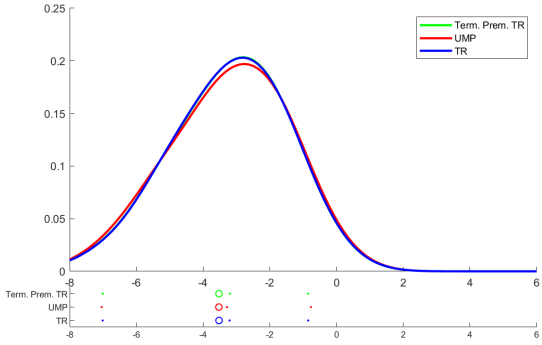
Figure 11: Distributions Pre/Post-Disaster: only permanent effects on TFP.



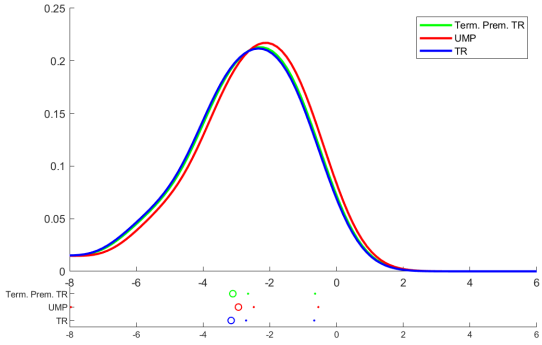
(a) Inflation - Pre-Disaster



(b) Inflation - Post-Disaster



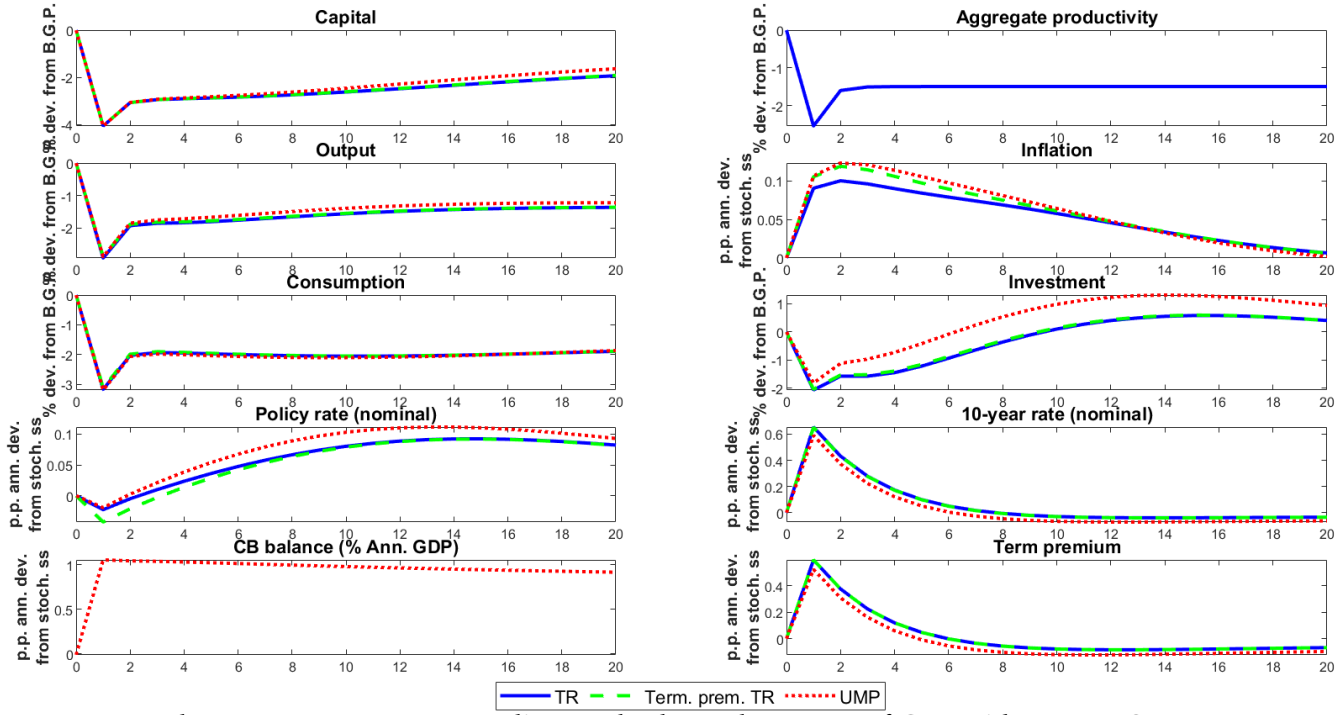
(c) Output Gap - Pre-Disaster



(d) Output Gap - Post-Disaster

Notes: Solid lines report the distributions under the standard Taylor rule (blues), APs (red) and the Term-premium Taylor rule (green). Below the distributions, vertical lines report the 5^{th}, 50^{th} and 95^{th} percentiles, while circle report the mean. Inflation is in annualized terms. The output gap is defined as the difference between the actual level of output and the level that would have occurred without the disaster strike.

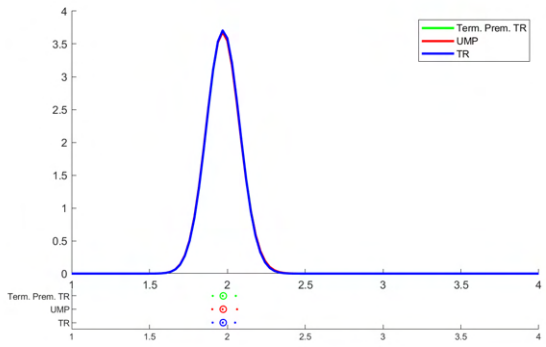
Figure 12: Impulse responses to an average disaster shock: stricter inflation targeting.



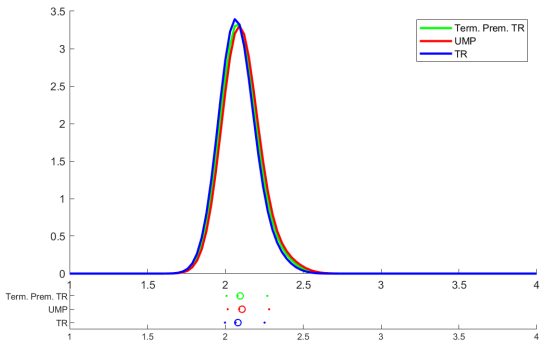
Notes: Impulse responses to an average disaster shock equal to 2.95% of GDP with $\gamma_{\Pi} = 3$. Output, consumption, investment, capital and productivity are expressed in percent deviations from the pre-disaster balanced growth path. Inflation, interest rates, term premium and the central bank balance to annual GDP ratio are in annualized terms and in percentage points deviations from the risky steady state. The risky steady state is calculated by simulating the model for 100 periods without shocks.

15 report the impulse responses and the distributions under lower portfolio adjustment costs. One difference relative to the baseline results is the slightly lower real impact of asset purchases which nevertheless still provides better output outcomes at little inflation costs.

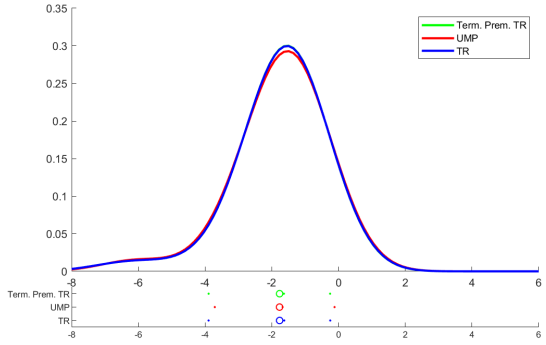
Figure 13: Distributions Pre/Post-Disaster: stricter inflation targeting.



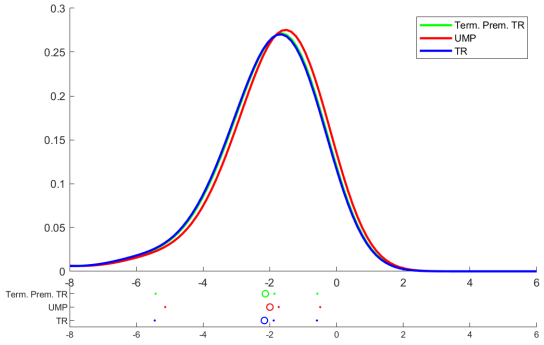
(a) Inflation - Pre-Disaster



(b) Inflation - Post-Disaster



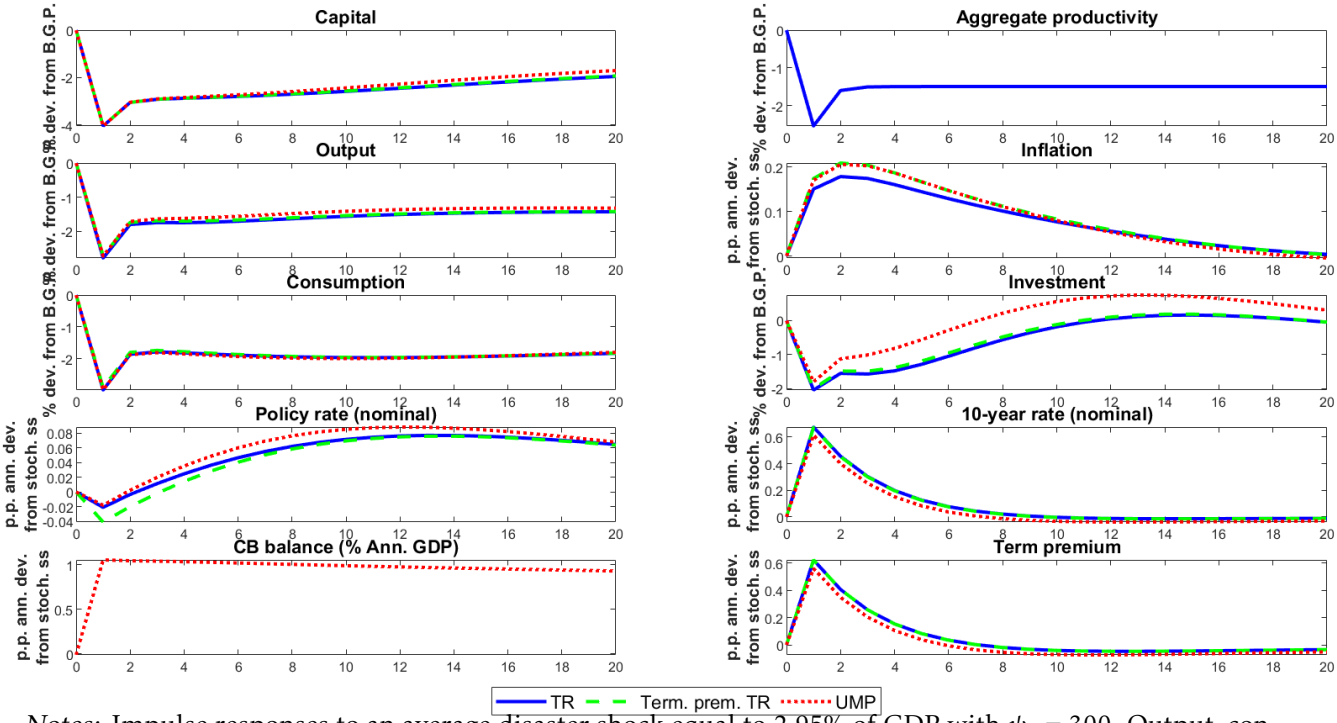
(c) Output Gap - Pre-Disaster



(d) Output Gap - Post-Disaster

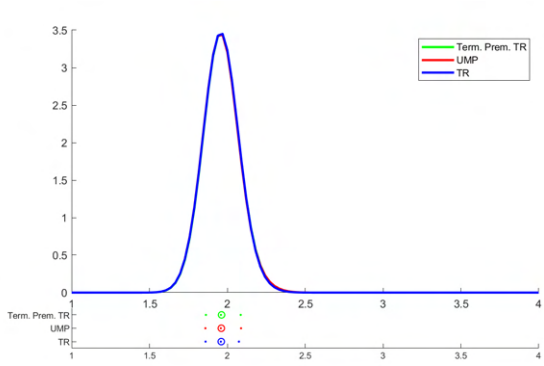
Notes: Solid lines report the distributions under the standard Taylor rule (blues), APs (red) and the Term-premium Taylor rule (green). Below the distributions, vertical lines report the 5^{th}, 50^{th} and 95^{th} percentiles, while circle report the mean. Inflation is in annualized terms. The output gap is defined as the difference between the actual level of output and the level that would have occurred without the disaster strike.

Figure 14: Impulse responses to an average disaster shock: lower financial frictions.

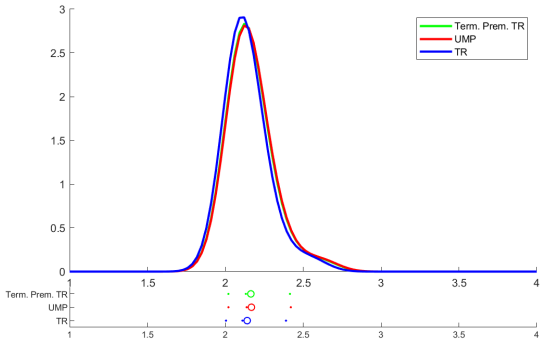


Notes: Impulse responses to an average disaster shock equal to 2.95% of GDP with $\psi_n = 300$. Output, consumption, investment, capital and productivity are expressed in percent deviations from the pre-disaster balanced growth path. Inflation, interest rates, term premium and the central bank balance to annual GDP ratio are in annualized terms and in percentage points deviations from the risky steady state. The risky steady state is calculated by simulating the model for 100 periods without shocks.

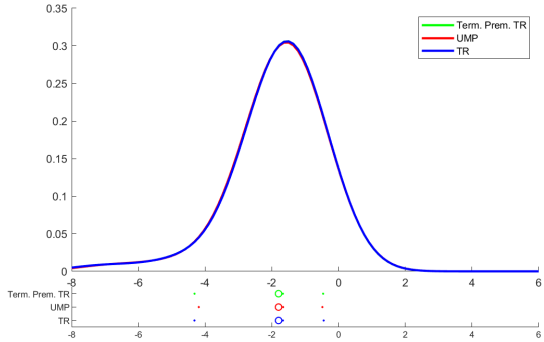
Figure 15: Distributions Pre/Post-Disaster: lower financial frictions.



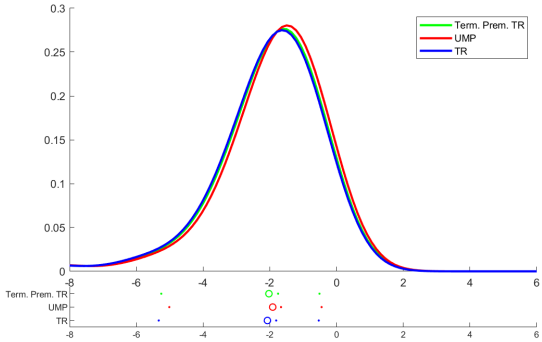
(a) Inflation - Pre-Disaster



(b) Inflation - Post-Disaster



(c) Output Gap - Pre-Disaster



(d) Output Gap - Post-Disaster

Notes: Solid lines report the distributions under the standard Taylor rule (blues), APs (red) and the Term-premium Taylor rule (green). Below the distributions, vertical lines report the 5^{th}, 50^{th} and 95^{th} percentiles, while circle report the mean. Inflation is in annualized terms. The output gap is defined as the difference between the actual level of output and the level that would have occurred without the disaster strike.