Downward Nominal Rigidities and Term Premia[*]
Preliminary

François Gourio[†]
Phuong Ngo[‡]

October 4, 2022

Abstract

We develop a macro-finance asset pricing model with downward nominal rigidities and show that it helps explain both secular and cyclical movements in term premia. The asymmetry in nominal rigidities implies that when inflation is high, nominal rigidities are less relevant, leading to larger output and inflation responses to a productivity shock. As a result, when inflation is high, the consumption-inflation covariance is more negative, making the bond premium larger. This mechanism accounts for the downward trend in the term premium since the early 1980s due to the decline of inflation. Our model also generates substantial cyclical variation in term premia (i.e. the Campbell-Shiller or Fama-Bliss predictability of bond returns), as well as other compelling macroeconomic and finance properties, such as the negative skewness of output, positive skewness of inflation, and time variation in the covariance of stock and bond returns.

JEL classification: E31, E32, E43, E44, G12. **Keywords:** Term Premium, Risk Premium, Inflation, Asymmetry, Skewness.

[*]We thank participants in presentations at SED 2022, Midwest Macro 2022, and the Federal Reserve Bank of Chicago for comments. The views expressed here are those of the authors and do not necessarily represent those of the Federal Reserve Bank of Chicago or the Federal Reserve System.

[†]Federal Reserve Bank of Chicago; email: francois.gourio@chi.frb.org.

[‡]Cleveland State University; e mail p.ngo@csuohio.edu.

1 Introduction

Yields on long-term bonds have large secular and cyclical components. Understanding what drives yield changes is difficult, however. Notably, as is known at least since Fama and Bliss (1987) and Campbell and Shiller (1991), long-term yields are not simply expected future short rates, as assumed in the expectation hypothesis theory of the term structure. Rather, yields comprise a substantial, time-varying term premium, or bond premium, which represents the compensation required by investors to hold nominal long-term bonds over short-term bonds. But what are the economic mechanisms driving the variation in this bond premium?

In this paper, we develop a macro-finance asset pricing model with asymmetric nominal rigidities: prices are easier to raise than to cut. We show that this single, realistic ingredient can go some way towards understanding fluctuations in the bond premium. In particular, we show that our model, despite being highly stylized, can approximately reproduce the decline in the term premium since the 1980s, as documented in Wright (2011). Our model also generates substantial cyclical variation in term premia, consistent with Fama and Bliss (1987) and Campbell and Shiller (1991), as well as other compelling macroeconomic and finance properties, such as the asymmetry of output and inflation, and time variation in the covariance of stock and bond returns.

To understand the mechanism, note first that in our model, as in most New Keynesian models, a productivity shock leads to higher output and lower inflation, as real marginal costs falls. (This assumes that the central bank does not perfectly accommodate the productivity shock, perhaps because it does not observe productivity accurately in real-time.) When inflation is low, nominal rigidities become effectively more important, because prices are more likely to be cut in the future, which is more difficult or costly. And when prices are more rigid, the response of inflation is smaller, and the response of output is also smaller, making the covariance of the two smaller (in absolute value) and shrinking the risk premium of inflation, and hence of nominal bonds.[1] Overall, in our model, the *level* of inflation is one determinant of term premia. In contrast, we show that if nominal rigidities are symmetric, this effect disappears. The changes in inflation driving these change in term premia can arise both because of changes in trend inflation, or changes in cyclical inflation, and hence our model accounts for both changes through the same mechanism.

Our model is an extension of the canonical three-equation New Keynesian model (Gali

[1] Real term premia also fall, as they are determined by the autocovariance of consumption growth, which becomes smaller.

(2008), Woodford (2003)). To that model we make only two modifications: first, we incorporate asymmetric price adjustment (as in Kim and Ruge-Murcia (2009)), and second, we incorporate recursive preferences (as in Epstein and Zin (1989), Weil (1990)) with high risk aversion to match the level of bond premia. Two parameters - the level of risk aversion and the degree of asymmetry in price adjustment costs - govern the differences with the standard model and allow us to cleanly demonstrate its properties. Our model is deliberately kept stylized to allow a transparent numerical analysis. But of course, our model does not encompass many other mechanisms driving the yield curve.

Our contribution is to offer a simple economic mechanism to govern time-variation in covariances of macroeconomic quantities and asset returns, and term premia. We provide some evidence for time variation in these covariances in a manner consistent with the model. While much work in finance has documented variation in term premia, there are few models that provide an endogenous mechanism for this variation.[2] We find downward nominal rigidities compelling because there is strong empirical support for it. (See among many others, see Kahn (1997), Peltzman (2000), Basu and House (2016), Klenow and Malin (2010).) Asymmetry of nominal rigidities also has a long history in macroeconomics, dating back to Keynes; see also Tobin (1972) and Akerlof et al. (1996). More recent work, beside that of Kim and Ruge-Murcia (2009) that we follow, includes Schmitt-Grohé and Uribe (2016) and Daly and Hobijn (2014). To be sure, some of these papers emphasize asymmetric wage, rather than price, rigidities, for which the empirical support is even stronger. For our argument, it seems to make rather little difference how we model the asymmetry. (In the appendix, we set up and solve a model with both wage and price asymmetric rigidities, and show that it generates similar predictions.) While the relevance of the downward nominal rigidities is largely acknowledged by macroeconomists and policymakers, its implications for asset prices have been overlooked. One of our contributions is to close this gap.

The paper is organized as follows. The rest of the introduction reviews briefly the related literature. Section 2 presents some motivating evidence on the relation between term premia and inflation. Section 3 introduces a DSGE model with asymmetric nominal rigidities and Section 4 studies it quantitatively. Section 5 provides some additional results, comparative statics and robustness analysis. Section 6 concludes. An appendix describes additional quantitative results and our numerical method.

Related Literature

A huge finance literature studies the term structure of interest rates, so our literature

[2]Habit preferences offer an alternative way to endogenize time variation in risk premia, as in Pflueger (2022). See the literature review for a more detailed discussion.

review is necessarily highly selective. Much of this work use affine models (among many others, see Kim and Wright (2005), Christensen et al. (2011), Adrian et al. (2013a), D'Amico et al. (2018), Ang et al. (2008), Hordahl and Tristani (2014), Roussellet (2018).) We will use some of these estimates in Section 2. Representative agent endowment economy models have also been proposed, notably Piazzesi and Schneider (2006), David and Veronesi (2013), Bansal and Shaliastovich (2013), and Song (2017). Several of these papers also emphasize the "stagflation risk" that makes bonds risky, and some changes in regime over time. Our contribution relative to these papers is to endogenously generate the time-varying correlations between inflation and growth that are taken as primitives in these studies. More closely related to our work are studies that endogenize consumption and inflation using production models with nominal rigidities (a.k.a., "New Keynesian DSGE models"). Some key contributions include Rudebusch and Swanson (2008), Rudebusch and Swanson (2008), Li and Palomino (2014), Christiano et al. (2010), Palomino (2012), Swanson (2015a), Pflueger and Rinaldi (2022). In particular, most closely related some studies that also use a macro model to understand the variation in various macro-finance moments, notably Campbell et al. (2020), Branger et al. (2016), Pflueger (2022). These papers emphasize structural breaks in monetary policy rules and in the structure of shocks hitting the economy rather than endogenous time variation as in our model. Some work focuses on the role of the zero lower bound (ZLB), including our previous paper Gourio and Ngo (2020), Nakata and Tanaka (2016), Datta et al. (2018), and Bilal (2017), which is another mechanism for the changing covariance, with somewhat different implications, and which explains different periods and phenomena.

2 Motivating Evidence

This section presents some evidence on the association between the level of inflation and term premia. The key difficulty is that term premia are not directly observable, leading us to consider two types of proxies. First, we use term premia estimated by affine term structure models. Second, we use the covariance of inflation (or bond return) with consumption (or the index stock market return). The motivation for these proxies is that, in canonical asset pricing theory (the CAPM or the CCAPM) these covariances affect risk premia on bonds.

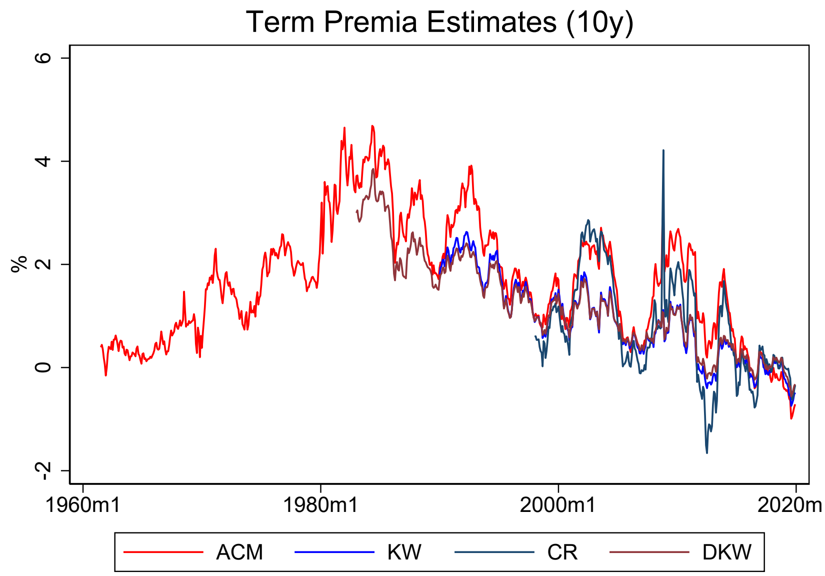

Figure 1: Estimates of 10-year term premia from affine term structure models. ACM denotes Adrian et al. (2013b), KW is Kim and Wright (2005), DKW is D'Amico et al. (2018), and CR is Christensen et al. (2011).

2.1 Term premia implied by affine models

A very large literature has developed sophisticated affine term structure models to infer term premia from bond prices and other observables. Figure 1 presents a variety of estimates, from Kim and Wright (2005), Christensen et al. (2011), Adrian et al. (2013a) (thereafter ACM), and D'Amico et al. (2018). Each estimates relies on a different statistical model and may use different data. Overall, these estimates move broadly similarly, both along the cyclical margin and along the secular margin. In particular, the low frequency movements appear to follow those of inflation or nominal interest rates during this period. To confirm this, we use the Adrian et al. (2013b) 10-year term premium estimate (thereafter ACM) since it has the longest available history. In figure 2 we depict the ACM estimate together with core inflation, and in table 1 we estimate

$$TPACM10Y_t = \beta_0 + \beta_1 \pi_t + \beta_2 t + \varepsilon_t,$$

where $TPACM10Y_t$ is the ACM estimate, π_t is either headline or core inflation (year-over-year), and we may include a linear trend as control. According to the table, a 1% decrease in inflation is associated with $0.11\% - 0.17\%$ decrease in the term premium, and that result is robust to introducing a linear trend.

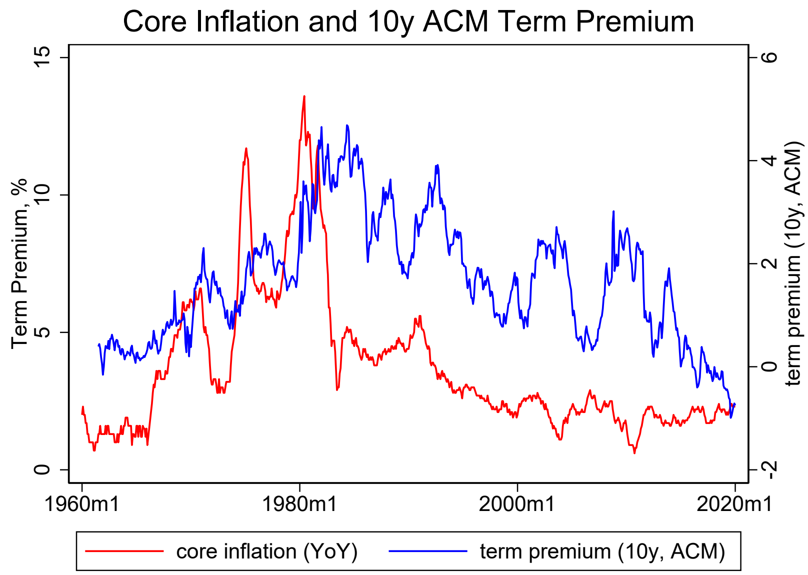

Figure 2: 10-year term premium by Adrian et al. (2013b) and realized year-over-year core CPI inflation.

	Dependent variable: 10-year ACM Term Premium			
Regressors	(1)	(2)	(3)	(4)
Core CPI inflation	0.164***		0.173***	
	(0.055)		(0.054)	
CPI inflation		0.107**		0.105**
		(0.049)		(0.053)
Time			0.000	-0.000
			(0.000)	(0.000)
Number of observations	716	716	716	716

Table 1: Association between Adrian et al. (2013b) 10-year term premium and inflation. Standard errors in parentheses are HAC with 36 lags. ***, **, * indicate statistical significance at 1%, 5%, and 10%, respectively.

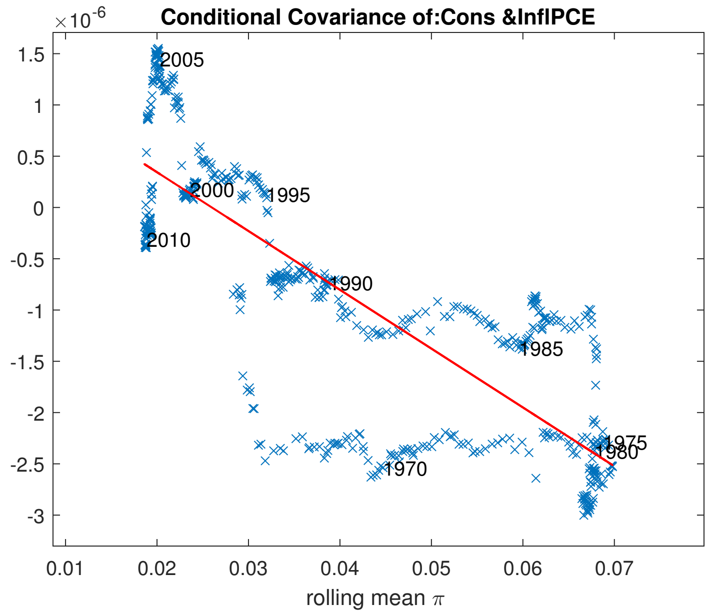

Figure 3: Conditional covariance of consumption growth and inflation against inflation. US monthly data, 1959-2019. The covariance is estimated as a 14-year rolling window covariance of the residuals from a VAR of consumption growth and inflation with 3 lags.

2.2 Time-varying Covariances

Another approach to measuring the riskiness of bonds is to estimate the covariance of inflation with macroeconomic proxies for marginal utility, such as consumption or the market stock return (corresponding to the consumption or market CAPM measure of riskiness). We estimate these covariance at each point in time by using the rolling covariance of residuals from a simple VAR model of the two monthly variables.[3] Figures 3 and 4 depict the estimated covariances against a rolling estimate of inflation. In both cases, there is a significant negative relationship: when inflation is higher, the covariance is more negative, corresponding to higher riskiness of inflation and hence bond returns. 5 verifies this by calculating directly the covariance of bond and stock returns, which is higher when inflation is higher. As the dates on the graphs show, these facts, which are not new,[4] are largely driven by the different behavior in the 1970s and early 1980s. All these time-varying covariances suggest a positive relation between inflation and bond premia, which is also intuitive.

[3]We use 3 lags for the VAR, and the rolling window is centered and 14-year long. The sample is 1959m1 through 2019m12.

[4]These facts have been documented in extensive literature, for instance Piazzesi and Schneider (2006), Campbell et al. (2009), Gourio and Ngo (2020), and the references cited therein.

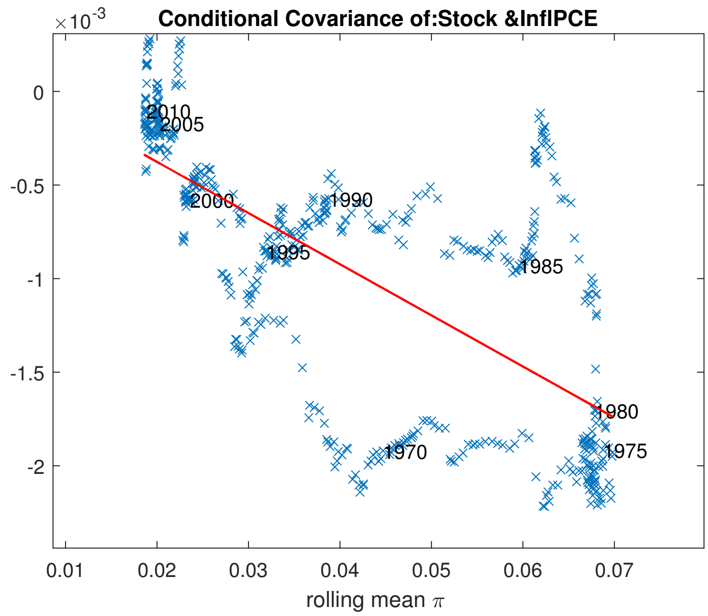

Figure 4: Conditional covariance of stock returns and inflation against inflation. US monthly data, 1959-2019. The covariance is estimated as a 14-year centered rolling window covariance of the residuals from a VAR of stock returns and inflation with 3 lags.

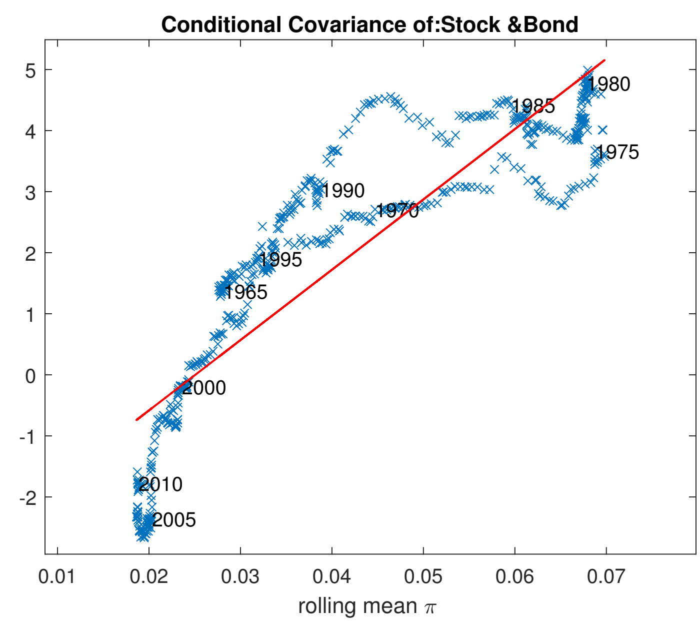

Figure 5: Conditional covariance of stock and bond returns against inflation. US monthly data, 1959-2019. The covariance is estimated using a 14-year centered rolling window.

3 Model

Our model builds on the standard New Keynesian model as outlined in Gali (2008) and Woodford (2003). We depart from this standard model in two ways. First, as many authors in the asset pricing literature, we use recursive preferences (Epstein and Zin (1989), Weil (1990)) with high risk aversion to match the observed level of risk premia. Second, we introduce asymmetric nominal rigidities following the work of Kim and Ruge-Murcia (2009).

3.1 Household

The representative household works, consumes, and decides how much to save in various assets. We will assume that these assets are in zero net supply (i.e. there is no capital, and the agents recognize that government debt is not a net asset, i.e. they are Ricardian). As a result, the equilibrium is not affected by the number and type of assets available, so we present here the household problem using only a risk-free bond. We discuss later in subsection 3.5 the various assets that we consider.

We use the formulation of recursive preferences introduced by Rudebusch and Swanson (2012). The flow utility of consumption is:

$$u\left(C_t, N_t\right) = \frac{C_t^{1-\sigma}}{1-\sigma} - \chi \frac{N_t^{1+\nu}}{1+\nu},$$

and the intertemporal utility is:[5]

$$V_t = \left(1-\beta\right) u(C_t, N_t) + \beta E_t \left(V_{t+1}^{1-\alpha}\right)^{\frac{1}{1-\alpha}}.$$

The household budget constraint is:

$$P_t C_t + \xi_t B_t = W_t N_t + H_t + R_{t-1} B_{t-1},$$

where B_t is the quantity of one-period risk-free assets bought, H_t are firms' profits, rebated to the household, P_t is the price level, and W_t is the wage rate. This budget constraint reflects our assumption that the household purchases risk-free assets at a discount ξ_t, which

[5]Note that, if the parameters lead to a negative flow utility $u(C_t, N_t)$, we define utility as:

$$V_t = \left(1-\beta\right) u(C_t, N_t) - \beta E_t \left(\left(-V_{t+1}\right)^{1-\alpha}\right)^{\frac{1}{1-\alpha}}.$$

is an exogenous stochastic process. We interpret this discount as reflecting the time-varying convenience yield of safe and liquid assets, which has been emphasized as an important factor in recent research (for instance, Krishnamurthy and Vissing-Jorgensen (2012)). This convenience yield could be motivated by introducing liquidity in the utility function as in Fisher (2015), but for simplicity we introduce it as a direct subsidy to risk-free assets. This shock will plays the same role in our model as the preference shock used in much of the New Keynesian literature. We will refer to ξ_t as "demand shock" or "liquidity shock" equivalently. We will assume that this convenience yield applies to all risk-free assets, regardless of their maturity, and whether they are nominal or real (inflation-indexed).[6] (Note that in our current calibration, demand shocks play a minuscule role.)

Labor supply is governed by the usual condition:

$$W_t = \frac{u_2\left(C_t, N_t\right)}{u_1\left(C_t, N_t\right)} = \chi C_t^{\sigma} N_t^{v}, \tag{1}$$

and optimal consumption is determined by the usual Euler equation linking the nominal short-term interest rate to the "marginal rate of substitution" a.k.a. nominal stochastic discount factor:

$$E_t\left[\xi_t^{-1} R_t M_{t+1}^{\$}\right] = 1, \tag{2}$$

where $R_t \equiv Y_t^{\$(1)}$ is the gross nominal yield on a one-period risk-free bond, and the nominal stochastic discount factor is

$$M_{t+1}^{\$} = \frac{M_{t+1}}{\Pi_{t+1}}, \tag{3}$$

where Π_{t+1} is gross inflation P_{t+1}/P_t, and the real stochastic discount factor is

$$M_{t+1} = \beta\left(\frac{C_{t+1}}{C_t}\right)^{-\sigma}\left(\frac{V_{t+1}}{E_t\left(V_{t+1}^{1-\alpha}\right)^{\frac{1}{1-\alpha}}}\right)^{-\alpha}. \tag{4}$$

[6] In reality, some government liabilities, such as T-bills, may provide more liquidity services.

3.2 Production and price-setting

There is a measure one of identical monopolistically competitive firms, each of which operates a constant return to scale, labor-only production function:

$$Y_{it} = Z_t N_{it}, \tag{5}$$

where Z_t is an exogenous stochastic productivity process, common to all firms. Each firm faces a downward-sloping demand curve coming from the Dixit-Stiglitz aggregator with elasticity of demand ε:

$$Y_{it} = Y_t \left(\frac{P_{it}}{P_t} \right)^{-\varepsilon}, \tag{6}$$

where P_t is the price aggregator:

$$P_t = \left(\int_0^1 P_{it}^{1-\varepsilon} di \right)^{\frac{1}{1-\varepsilon}}.$$

Following Rotemberg (1982) and Ireland (1997) we assume that each intermediate goods firm i faces costs of adjusting prices. These costs are measured in final goods. The adjustment cost is proportional to aggregate output, and a convex function of the price change:

$$AC_t = G\left(\frac{P_{i,t}}{P_{i,t-1}} \right) Y_t,$$

where G is an increasing and convex function.

The problem of firm i is to maximize the present discounted value of real profits, net of adjustment costs:

$$\max_{\{P_{i,t+j}\}} E_t \sum_{j=0}^{\infty} \left\{ M_{t,t+j} \left[\left(\frac{P_{i,t+j}}{P_{t+j}} - mc_{t+j} \right) Y_{i,t+j} - G\left(\frac{P_{i,t+j}}{P_{i,t+j-1}} \right) Y_{t+j} \right] \right\}$$

subject to its demand curve (6). Here mc_t denotes the real marginal cost, equal to W_t/Z_t. The first term in this expression reflects the real profit per unit sold, and the second term the cost of changing prices. In equilibrium, all firms will choose the same price and produce the same quantity (i.e., $P_{i,t} = P_t$ and $Y_{i,t} = Y_t$). Taking first-order conditions then yield the optimal pricing rule:

$$\left(1 - \varepsilon + \varepsilon \frac{w_t}{Z_t} - \Pi_t G'(\Pi_t) \right) Y_t + E_t \left[M_{t,t+1} G'(\Pi_{t+1}) \Pi_{t+1} Y_{t+1} \right] = 0. \tag{7}$$

If there are no costs to adjusting prices, this formula reduces to the Lerner rule. With adjustment costs, this equation yields a relation between inflation and current (and future) marginal costs, i.e. a Phillips curve. To a first-order, this Phillips curve is equivalent to that implied by a Calvo model.[7] Much of the literature assumes a symmetric, quadratic adjustment cost:

$$G\left(\frac{P_{i,t}}{P_{i,t-1}}\right) = \frac{\phi}{2}\left(\frac{P_{i,t}}{P_{i,t-1}} - \overline{\Pi}\right)^2, \tag{8}$$

where ϕ is the adjustment cost parameter which determines the degree of nominal price rigidity, and $\overline{\Pi}$ the degree of inflation which implies zero costs.

In contrast, we follow Kim and Ruge-Murcia (2009) (and Kim and Ruge-Murcia (2011)) who use a linex function to model adjustment costs:

$$G(x) = \frac{\phi}{\psi^2}\left(e^{-\psi(x-\overline{\Pi})} + \psi\left(x - \overline{\Pi}\right) - 1\right). \tag{9}$$

This function captures that reducing prices at a rate below $\overline{\Pi}$ is more costly than increasing prices at a rate above $\overline{\Pi}$. The parameter ϕ governs the magnitude of adjustment costs, while ψ governs the degree of asymmetry. Some intuition can be gained from a Taylor expansion:

$$G(x) \approx \frac{\phi}{2}\left(\left(x - \overline{\Pi}\right)^2 - \frac{\psi}{3}\left(x - \overline{\Pi}\right)^3\right), \tag{10}$$

which shows that a larger ψ makes the costs lower for positive adjustments (above $\overline{\Pi}$) and higher for negative adjustments (below $\overline{\Pi}$), while a larger ϕ increases adjustment costs for all adjustments. Moreover, when $\psi \to 0$, the specification converges to the usual quadratic one. This is an attractive property of this formulation, which allows to clearly demonstrate the role of asymmetry by varying ψ. Figure 6 contrasts the quadratic and linex adjustment costs. The dashed blue line is a quadratic function with $\varphi = 238$, while the solid red line is a linex function with $\phi = 238$ and $\psi = 300$.

Finally, following Miao and Ngo (2014), we assume that price adjustment costs are rebated to households.[8] Hence, the aggregate resource constraint is simply

$$C_t = Y_t. \tag{11}$$

[7]See Miao and Ngo (2016) for a detailed comparison of Rotemberg and Calvo models of price stickiness.
[8]We do so in the order to make the analysis more transparent, but this has little effect on our results.

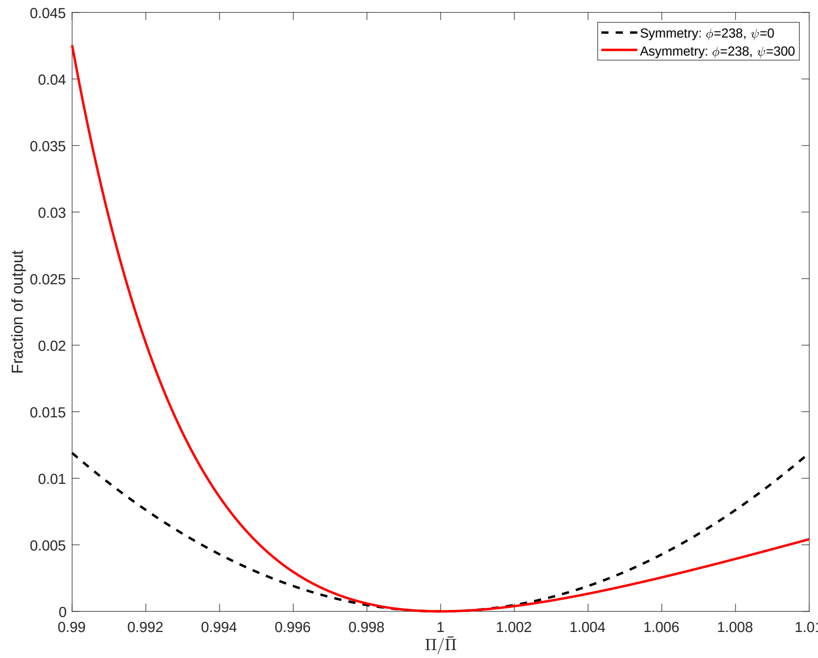

Figure 6: An example of symmetric quadratic and asymmetric linex cost functions.

3.3 Fundamental shocks

We assume that both the liquidity and the productivity shock follow independent AR(1) processes with normal innovations:

$$\log \xi_t = \rho_\xi \log \xi_{t-1} + \varepsilon_{\xi,t},$$

with $\varepsilon_{\xi,t}$ i.i.d $N(0, \sigma_\xi^2)$, and

$$\log Z_t = \rho_z \log Z_{t-1} + \varepsilon_{z,t},$$

with $\varepsilon_{z,t}$ i.i.d $N(0, \sigma_z^2)$. By imposing normal shocks, we force all skewness or higher moments to be generated endogenously through the model. Finally, a point of semantics: throughout the paper we use "liquidity shock" or "preference shock" or "demand shock" equivalently to refer to $\varepsilon_{\xi,t}$, and "supply shock" or "productivity shock" to refer to $\varepsilon_{z,t}$.

3.4 Monetary policy

We assume that monetary policy follows the following rule, in the spirit of Taylor (1993):

$$\log R_t = \log R^* + \phi_\pi(\log \Pi_t - \log \Pi^*) + \phi_y(\log Y_t - \log Y^*), \quad (12)$$

where R_t is the gross nominal interest rate on a one-period risk-free bond; ϕ_π and ϕ_y are the responsiveness to inflation and GDP respectively; and R^*, Π^* and Y^* are constants.We abstract from the zero lower bound, which we studied in detail in Gourio and Ngo (2020), and from unconventional policies.

Taylor's original rule (1993) assumes that the central bank responds to the deviation of GDP from potential GDP, i.e. the level of GDP that would prevail in an economy without price stickiness; in contrast, we assume (as in Fernandez-Villaverde et al. (2015) and Swanson (2015a)) that the central bank responds to the deviation of GDP from "trend". Given that our model abstracts from long-run growth, actual GDP and potential GDP are both stationary, and potential GDP equals $Y^* Z_t^{\frac{1+v}{\sigma+v}}$. Trend GDP is simply Y^*. This assumption can be motivated by the difficulty of measuring potential GDP, in particular in real time. We discuss in section 5.6 the (un)importance of this assumption for our results.

3.5 Asset prices

This section describes the various asset prices that we calculate in the model. While our model description only considered a short-term bond, we can allow the household to hold any other asset in zero net supply and calculate its value, since this does not affect the equilibrium of the model.

We use the standard recursions to calculate real and nominal zero-coupon bond prices (see, e.g., Cochrane (2009)). The price $P_t^{(n)}$ of a n-maturity bond satisfies

$$P_t^{(n)} = E_t \left[M_{t+1} P_{t+1}^{(n-1)} \right], \tag{13}$$

with $P_t^{(0)} = 1$. For nominal bonds, we have similarly

$$P_t^{\$(n)} = E_t \left[M_{t+1}^{\$} P_{t+1}^{\$(n-1)} \right], \tag{14}$$

with $P_t^{\$(0)} = 1$. From these prices, we deduce log gross real yield as

$$y_t^{(n)} = \log Y_t^{(n)} = -\frac{1}{n} \log P_t^{(n)}, \tag{15}$$

and similarly for nominal bonds. The log gross real (1-period) forward rate at horizon n is the rate that can be locked in at time t to lend/borrow at time $t+n$ for one period, i.e.

$$f_t^{(n)} = n y_t^{(n)} - (n-1) y_t^{(n-1)}. \tag{16}$$

and similarly for nominal forward rates. The one-period log (gross) return (a.k.a. holding period return) for real bonds is

$$r_{t+1}^{(n)} = \log P_{t+1}^{(n-1)} - \log P_t^{(n)}, \tag{17}$$
$$= ny_t^{(n)} - (n-1)y_{t+1}^{(n-1)}. \tag{18}$$

Similarly, the log gross real holding period return for nominal bonds:

$$r_{t+1}^{\$(n)} = ny_t^{\$(n)} - (n-1)y_{t+1}^{\$(n-1)} - \log \Pi_{t+1}. \tag{19}$$

Next, we can define inflation compensation (a.k.a. breakevens) as the difference between the log nominal yield and the log real yield at a given maturity:

$$IC_t^n = \log Y_t^{\$,(n)} - \log Y_t^{(n)}. \tag{20}$$

We define the risk-neutral real (resp. nominal) log yield as the average expected future short-term log real (nominal) yields over the remaining lifetime of a bond.[9] With this in hand, the (log) term premium of a bond at maturity n is the difference between actual and risk-neutral yields, or for a real bond:

$$tp_t^{(n)} = y_t^{(n)} - y_t^{rn(n)},$$

and similarly for a nominal bond. The term premium measures the expected return per year on a bond of maturity n if it is held to maturity, over holding short-term bonds. Term premia and holding period returns are two related ways to measure the riskiness of bonds - the term premium smoothes out the average excess returns over the remaining maturities. We can also break out the nominal term premium into the real term premium and the inflation term premium.

Finally, we also price a stock, which we define, following Abel (1999), as an asset with payoff $D_t = C_t^\lambda$, where $\lambda \geq 1$ reflects leverage.[10] The real stock price P_t^s satisfies the usual

[9]Formally, we define the risk-neutral price through the recursion

$$P_t^{rn(n)} = E_t\left[M_{t+1}\right] E_t\left[P_{t+1}^{rn(n-1)}\right],$$

then define the risk-neutral yield using

$$y_t^{rn(n)} = -\frac{1}{n}\log P_t^{rn(n)},$$

and similarly for nominal bonds.

[10]We do not define a stock as a claim to profits, because profits tend to be countercylical in this model. A

recursion

$$P_t^s = E_t\left[M_{t+1}\left(P_{t+1}^s + D_{t+1}\right)\right],$$

and the gross stock return is $R_{t+1}^s = (P_{t+1}^s + D_{t+1})/P_t^s$.

Under the assumption of conditional log-normality (which is approximately true in our model if the standard deviations of the innovations are not too large), the log excess return of any asset i satisfies the usual condition:

$$\log E_t\left[\frac{R_{it+1}}{R_{ft}}\right] = E_t(r_{it+1} - r_{ft}) + \frac{1}{2}Var_t(r_{it+1}) = -Cov_t(m_{t+1}, r_{it+1}),$$

where r_{it+1} is the log real return on asset i, r_{ft} is the real risk-free rate, and m_{t+1} is the real SDF. Assets which returns covary negatively with the SDF have positive excess returns.[11]

4 Quantitative results

This section studies the quantitative implications of the model presented in the previous section. We first discuss our choice of parameters. We then explain the key economic mechanisms by showing how the response of the economy to either supply (productivity) or demand (liquidity) disturbances changes when the adjustment cost is asymmetric, and how this response depends on the level of inflation. We then discuss the ability of the model to match some basic moments. Finally, we discuss how a change in "trend" inflation affects risk premia and other features. We leave for the next section a discussion of additional model implications.

4.1 Parametrization and solution method

Table 2 presents the baseline parameters that we use for our quantitative analysis; section 5.5 provides comparative statics. Most of the parameters are taken from the New Keynesian literature. The time period is one quarter. The time discount factor β is 0.992, in line with Woodford (2003, 2011), generating an average annualized real interest rate of 2.9%.[12] We set the intertemporal elasticity of substitution (IES) of consumption $1/\sigma$ to

number of extensions have been proposed to explain this cyclicality, for instance fixed costs, sticky wages, or financial leverage (see, for instance, Li and Palomino (2014)). We do not incorporate these extensions in the interest of simplicity.

[11] This formula also holds in nominal terms, with a nominal returns $r_{it+1}^{\$}$, the log nominal risk-free rate (the policy rate) r_t, and the log nominal SDF $m_{t+1}^{\$}$.

[12] Note that this average is less than the nonstochastic steady state value of 3.3% due to precautionary savings.

Parameter	Description and source	Value
β	Subjective discount factor	0.992
α	Curvature with respect to next period value (note: CRRA=136)	-110.00
σ	IES is 0.5	2.00
υ	Frisch labor supply elasticity is 0.66	1.50
χ	Calibrated to achieve the steady state labor of 1/3	40.66
ε	Gross markup is 1.15	7.66
ϕ_π	Weight on inflation in the Taylor rule	2.00
ϕ_y	Weight on output in the Taylor rule	0.125
R^*	Intercept of Taylor Rule	1.05
Π^*	Inflation target of 2% per year	1.005
$\overline{\Pi}$	Inflation to be indexed, 2% per year	1.005
ϕ	Adjustment cost, corresponding to the Calvo parameter of 0.85	238
ψ	Asymmetry parameter	0;1000
ρ_z	Persistence of technology shock	0.99
ρ_ξ	Persistence of demand shock	0.90
σ_z	Std. dev. of the technology innovations (%)	1.07
σ_ξ	Std. dev. of the preference innovations (%)	0.13

Table 2: Model parameters.

0.5, and the Frisch elasticity of labor supply to 2/3, again in line with the literature. We also set the gross markup to 1.15, corresponding to the the demand elasticity parameter $\varepsilon = 7.66$. The adjustment cost of changing prices is $\phi = 238$, which maps in a Calvo model to a probability of keeping price unchanged of 0.85 per quarter. This value is consistent with the estimates of Del Negro et al. (2015) and lower than those of Leeper et al. (2017). For the asymmetry parameter, ψ, we use two values: 0 and 1000. When $\psi = 0$ the adjustment cost is symmetric. We will conduct more comparative analysis with respect to this parameter in a subsection below.

Our monetary policy rule builds on recent empirical estimates by Gust et al. (2017) and Arouba et al. (2018); the weight on inflation in the Taylor rule is $\phi_\pi = 2$ and the weight on output gap is ϕ_y equal to 0.13 (which translates into the usual 0.5 response once the interest rate is annualized).

We set Π^* (the so-called target inflation rate) to the conventional value of 2% ($\Pi^* = 1.02$) and adjust the intercept of the Taylor rule, R^* to match the average inflation rate in the model to 2%, leading to $R^* = 1.012$. We also set $\overline{\Pi} = \Pi^*$ as standard.

Finally, the shock process we choose is also in line with the New Keynesian literature: both productivity and liquidity shocks play an important role and both are fairly transitory (in contrast to the asset pricing literature which largely focuses on shocks that have very persistent effects). The persistence of technology shocks is 0.99 and the standard deviation of the innovation is 1.07%, in line with Anzoategui et al. (2017). The persistence of the liquidity shock is 0.90 and the standard deviation of the innovation is 0.13%, in line with Gust et al. (2017) and Arouba et al. (2018). Overall, these shock processes help match the volatilities of consumption growth and inflation for the 1985q1-2015q4.

We diverge strongly from the New Keynesian consensus on one parameter: risk aversion, which is related to the parameter α which measures the curvature with respect to next period value in the recursive preference. Given our shock process, consumption volatility is fairly low. As a result, the model requires a high risk aversion to generate sizeable risk premia. We set α to -110, which corresponds to a relative risk aversion to consumption (CRRA) of 79 once we take into account the curvature parameters on consumption and labor in the flow utility (see Rudebusch and Swanson (2012), Swanson (2015b)). Clearly, this parameter does not reflect the preferences of any single individual. Rather, it captures the aversion of the macroeconomy to fairly small fluctuations in aggregate consumption, as inferred from asset prices. The value we use is actually relatively modest; for instance Swanson (2015b) requires α to be -338, or CRRA to be 600, to generate the equity premium of only 1.5% per annum. Rudebusch and Swanson (2012) require α to be -396, or CRRA to be 200, to generate a term premium of 1.06% in line with the U.S. data.[13] We will discuss below in detail how this risk aversion affects macroeconomic dynamics and other model features.

Due to the presence of asymmetric adjustment costs, we need to solve the model using nonlinear methods. This is especially important because asset prices can be sensitive to nonlinearities. We use projection methods with cubic spline, similar to Fernandez-Villaverde et al. (2015), Miao and Ngo (2014), and Ngo (2018). Our solution method is detailed in the appendix.

4.2 State-Dependent Impulse Response Functions

The case of symmetric adjustment costs

Figure 7 presents impulse responses to a one-standard deviation of liquidity shock (left column) and productivity shock (right column) when the economy is at a state with low inflation (0.8% inflation per year; red line) vs. at a state with higher inflation (3.2%

[13] From Swanson (2015b), to generate the equity premium of 1.5%, which is smaller than the value estimated by US data, α and CRRA are required to be around -338 and 600, respectively, based on figure 1. According to Rudebusch and Swanson (2012), to generate the value of term premia of 1.06%, which is in line with US data, the CRRA is required to be approximately 200 based on figure 1. This means α is approximately -396, based on the formula in footnote 23 of this paper. Note that the IES and Frisch values in our paper are the same as those in their paper.

inflation per year; black dashed line) for the case of symmetric price adjustment costs. Impulse response at a state is calculated as the difference between two paths: (1) a path with only initial shocks that result in low/high inflation, and (2) a path with the same shocks, plus an additional on-standard-deviation shock, either liquidity or TFP. Note that in this subsection, we use an initial liquidity shock to cause lower/higher inflation. In the appendix, we use TFP shocks as initial shocks to cause lower/higher inflation. The results are basically the same regardless of which shock is used as initial shock.

It is not surprising that regardless of the state of the economy (with low inflation or higher inflation) the responses of inflation and GDP under a positive shock (either liquidity or TFP) are the same. This is due to the fact that the adjustment cost is symmetric. We will also investigate if there are symmetric responses to a negative and to a positive shock in a section below.

The case of asymmetric adjustment costs

Figure 20 shows impulse responses to a one-standard deviation of liquidity shock (left column) and productivity shock (right column) when the economy is at a state with low inflation (0.8% inflation per year; red line) vs. at a state with higher inflation (3.2% inflation per year; black dashed line) for the case of asymmetric adjustment costs. Again, impulse response at a state is calculated as the difference between two paths: (1) a path with only initial shocks that result in low/high inflation, and (2) a path with the same shocks, plus an additional on-standard-deviation shock, either liquidity or TFP. Note that in this subsection, we use an initial liquidity shock to cause lower/higher inflation. In the appendix, we use TFP shocks as initial shocks to cause lower/higher inflation. The results are basically the same regardless of which shock is used as initial shock.

Unlike the case with symmetric adjustment costs, it is evident in this case that the impulse responses are dependent on the state of the economy, whether inflation is high or low initially. From column 2, when inflation is low relatively to its target and the economy is hit by a positive TFP shock, downward nominal rigidities prevent firms from cutting their prices as much as they would otherwise when inflation is above its target, leading to a smaller increase in output and consumption than there would otherwise be when firms can adjust their prices more freely.

In addition, when inflation is relatively low firms are not able to lower their prices under an adverse demand shock (a positive liquidity shock) as much as they would otherwise when inflation is high, causing larger decrease in consumption associated with smaller change in prices.

The important implication of these asymmetries is that the conditional covariance between inflation and consumption growth is dampened at a state with relatively low infla-

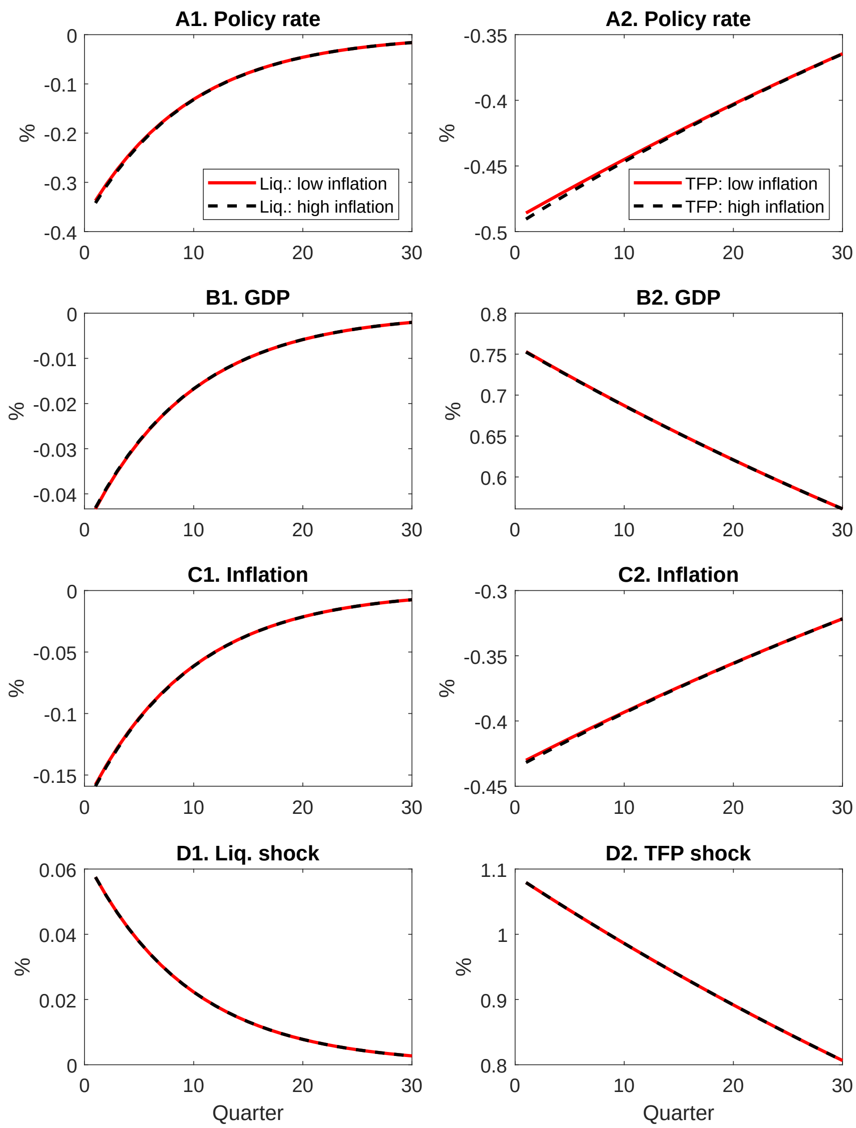

Figure 7: **Impulse response functions with symmetric price adjustment costs.** IRF to a one-standard deviation liquidity shock (left column) and productivity shock (right column) at a state with 0.8% inflation (red line) vs. at a state with 3.2% inflation (black dashed line). Impulse response at a state is calculated as the difference between two paths: (1) a path with only initial shocks that result in low/high inflation, and (2) a path with the same shocks, plus an additional on-standard-deviation shock. Note that we use an initial liquidity shock to cause lower/higher inflation in this case. In the appendix, we use TFP shocks as initial shocks to cause lower/higher inflation.

	Data		Full sample		$\pi \leq 2\%$	$\pi \geq 4\%$
	Mean	Sd	Mean	Sd	Mean	Mean
$D.lnY$	0.00	2.40	-0.00	2.23	0.09	-0.36
π	1.80	1.48	1.79	1.72	0.91	5.60
$y^{n(1)}$	3.60	2.60	3.72	1.69	2.92	7.62
$y^{n(40)}$	5.50	2.30	5.66	1.98	4.63	9.61
$y^{r(1)}$	NaN	NaN	1.82	0.55	1.93	1.94
$y^{r(40)}$	3.30	0.90	1.84	0.20	1.79	2.15
Real term premium	NaN	NaN	-0.05	0.25	-0.19	0.35
Nominal term premium	NaN	NaN	1.79	0.82	1.40	2.97

Table 3: Data and model moments. Columns 2 and 3 give the mean and standard deviation from U.S. Data over the sample 1985q1-2021q4. Columns 4 and 5 give the mean and standard deviation using simulated data from the model. Columns 6 and 7 give the mean and standard deviation by subsamples. $D.lnY$ is the first difference in natural logarithm of output.

tion, leading to smaller inflation term premia.

4.3 Moments

Table 3 presents the moments of some interested variables for both the full sample and for subsamples, where the subsamples are defined based on simulated inflation.

Consider first the full sample moments. The model generates a reasonable volatility for the otuput gap. The volatilities of ouput gap in the data and in the full sample are the same (2.4%). The sample mean and volatility of inflation are in line with the data, around 1.8% and 1.5%, respectively. While our model can generates an upward sloping yield curve on average (105bps), it is flatter than in the data. The 10-year nominal term premium is substantial in the model (108bps on average), the real term premium is lower at 46bps, so our model implies an inflation term premium of 63bps. Hence the average breakeven, at 2.2% per year, is higher than average inflation, reflecting that on average agents fear inflation.

Now, we turn to the change in the term premia associated with average inflation in the two subsamples. When inflation is 0.91% on average in the first subsample, the average nominal term and inflation term premia are 101bps and 59bps, respectively. The premia increase to 132bps and 0.78bps in the second subsample when the average inflation is about 5.18%. The increases are 31bps and 19bps with respect to a abount 4.2% increase inflation, slightly smaller than what we documented in the data: 1% increase ininflation

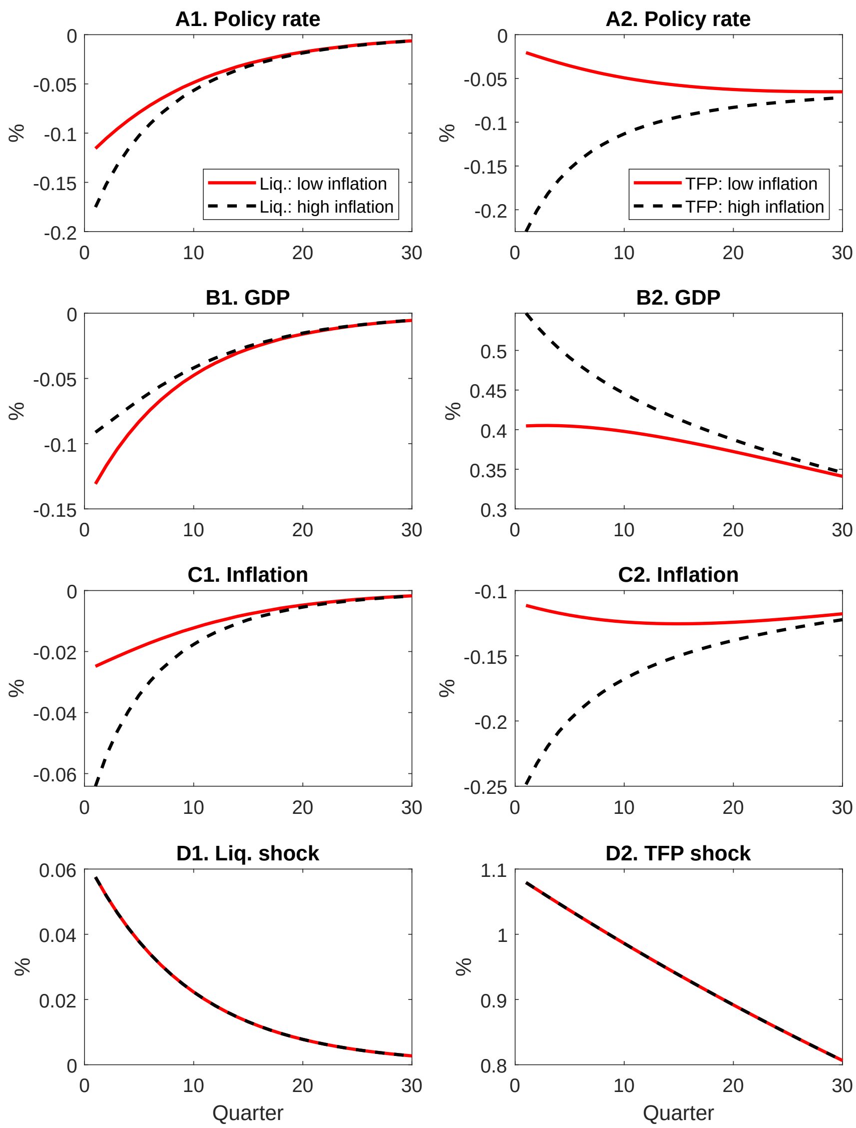

Figure 8: **Impulse response functions with asymmetric price adjustment costs.** IRF to a one-standard deviation liquidity shock (left column) and productivity shock (right column) at a state with 0.8% inflation (red line) vs. at a state with 3.2% inflation (black dashed line). Impulse response at a state is calculated as the difference between two paths: (1) a path with only initial shocks that result in low/high inflation, and (2) a path with the same shocks, plus an additional on-standard-deviation shock. Note that we use an initial liquidity shock to cause lower/higher inflation in this case. In the appendix, we use TFP shocks as initial shocks to cause lower/higher inflation.

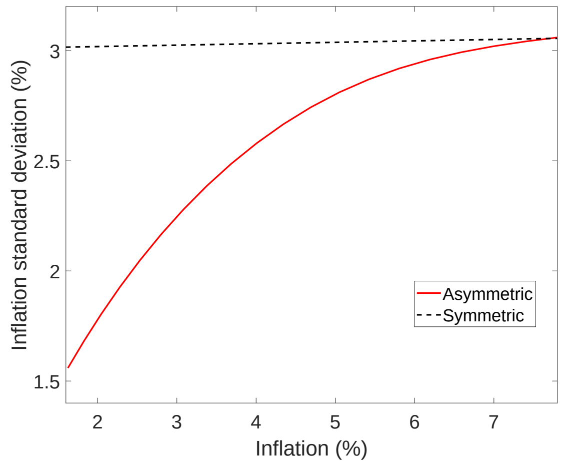

Figure 9: Inflation standard deviation vs long run inflation in the model

is associated with 10-17bps increase in the nominal term premium.

4.4 Effect of Trend Inflation on Macro Dynamics and Risk Premia

Figures 9 and 10 illustrate that the volatility and skewness of inflation are positively related to the level of inflation in the model.

Figures 11, 12 and 13 illustrate that the model broadly reproduces the correlations between the level of inflation and the covariances shown in section 2.

We vary the intercept of the Taylor rule to obtain different long-run inflation. Table 4 presents the moments of selected variables for full sample.

From this table, when the long-run inflation increases from 1.82% to 3.24%, the term premium increases from 109bps to 124bps. In other words, a 1% decrease in the long-run inflation is associated with 11bps decrease in the term premium of the 10-year bonds, which is in line with the data. ***More to be added.***

5 Additional Implications

This section first discusses some additional implications of the model, in particular regarding asymmetry, before presenting some comparative statics and robustness.

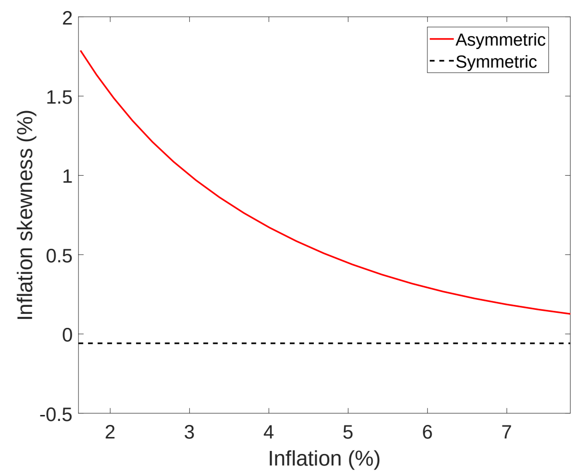

Figure 10: Inflation skewness vs long run inflation in the model

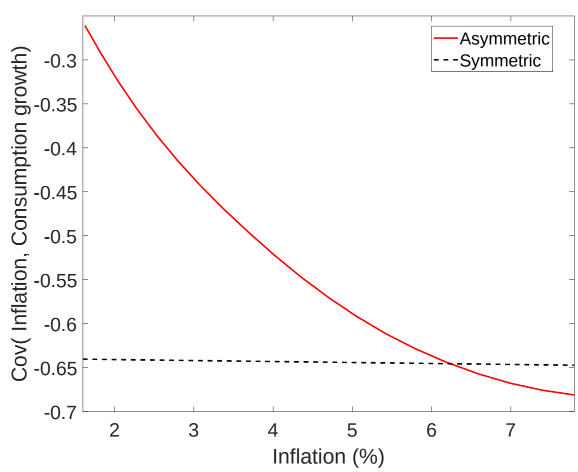

Figure 11: Covariance of consumption growth and inflation, as a function of inflation, in the model.

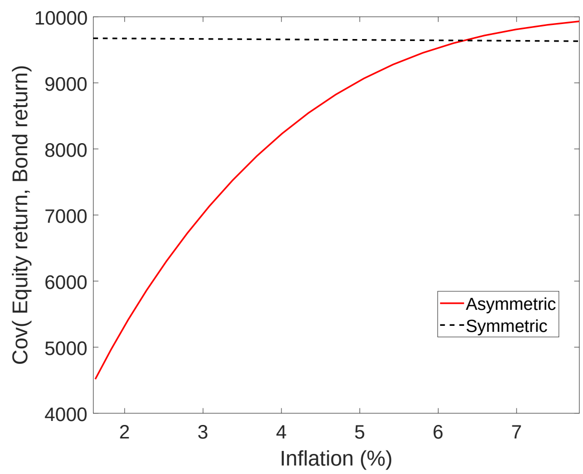

Figure 12: Covariance of stock return and bond return, as a function of inflation, in the model.

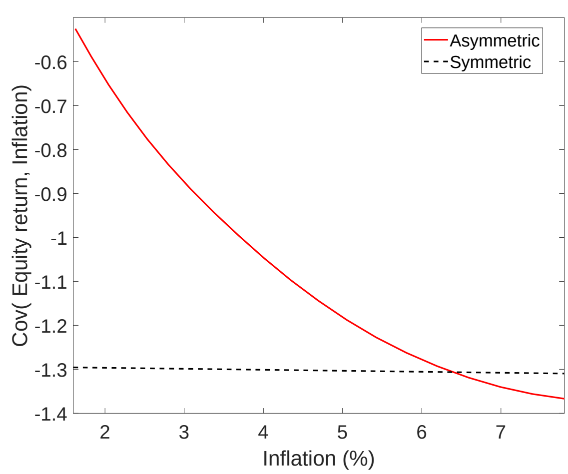

Figure 13: Covariance of stock return and inflation, as a function of inflation, in the model.

	Data		Benchmark		Varying Taylor Intercepts			
			$R^* = 1.0124$		$R^* = 1.0080$		$R^* = 1.0029$	
	Mean	Std	Mean	Std	Mean	Std	Mean	Std
D.lnY	0.00	2.40	-0.00	2.23	0.00	2.55	0.00	2.83
π	1.80	1.48	1.79	1.72	2.80	2.16	4.34	2.67
$y^{n(1)}$	3.60	2.60	3.72	1.69	4.43	2.24	5.73	2.91
$y^{n(40)}$	5.50	2.30	5.66	1.98	6.89	2.31	8.63	2.62
$y^{r(1)}$	NaN	NaN	1.82	0.55	1.49	0.55	1.24	0.57
$y^{r(40)}$	3.30	0.90	1.84	0.20	1.68	0.23	1.59	0.30
Real TP	NaN	NaN	-0.05	0.25	0.09	0.25	0.24	0.19
Nominal TP	NaN	NaN	1.79	0.82	2.29	0.71	2.72	0.49

Table 4: Comparative analysis with long-run inflation (or Taylor rule intercept). $D.lnY$ is the first difference in natural logarithm of output.

5.1 Asymmetric Impulse Responses

We illustrate here that the model produces asymmetric responses to positive and negative shocks. In the appendix, we verify that these asymmetric responses disappear when the adjustment cost is symmetric.

Figure 14 shows impulse responses to a three-standard deviation of liquidity shock (left column) and productivity shock (right column) when the shock is negative (red full line) vs. positive (black dashed line). The responses to positive shocks are displayed with the reverse sign. Again, the economy is initially at the deterministic steady state.

When hit by a negative supply shock, firms respond more aggressively than when they are hit by a positive shock. Under a negative TFP shock, the marginal cost increases and firms would like to raise their prices. On the contrary, firms would lower their prices under a positive TFP. However, the magnitude of price increase is about three times larger than that of price cut. This happens due to downward nominal rigidities embedded in our model prevent firms from cutting the prices. This asymmetry occurs to GDP and consumption too.

The asymmetric responses implies that the covariance between inflation and consumption growth is more negative under a negative TFP shock than under a positive TFP shock. This means that the inflation term premium is more positive under a negative TFP shock than under positive TFP shock, leading to the distribution of inflation term premium being skewed to the right.

Overall, the inflation term premium is smaller in the asymmetric case than in the symmetric case because the covariance between inflation and consumption growth is less negative on average. In addition, in the asymmetric case the inflation term premium is more skewed to the right. Thus, the slope of the yield curve is steeper in the case of downward nominal rigidities.

5.2 Asymmetry of macroeconomic variables

We now illustrate that this simple model generates negative skewness in economic activity, and positive skewness in output, consistent with the data. Figure 15 depicts the histogram of outcomes in the model. The distributions of policy rates and inflation are skewed to the right, while the distribution of output gap is skewed to the left.

5.3 Asymmetry versus symmetry

This subsection examines the difference between asymmetry and symmetry. The results are presented in table 5.

Table 5 shows that in the symmetric world, 1% decrease in inflation is associated with only 2.8bps decrease in the term premium, which is very small relative to 7.3bps in the case of asymmetry. Note that the level of asymmetry in the exercise is very modest, $\psi = 300$. In the next subsection we show that when we raise the asymmetry level, the decrease in term premium becomes much bigger. ***More to be added.***

5.4 The role of asymmetry due to downward nominal rigidity

This subsection investigates the role of asymmetry by varying the asymmetry parameter, ψ. The results are presented in table 6.

As seen from this table, the higher level of asymmetry, the larger the decrease in term premia associated with 1% decrease in inflation across the subsamples. Specifically, the decrease is 7.3bps in the benchmark with $\psi = 300$, while it is 10.3bps in the case $\psi = 2500$. ***More to be added.***

5.5 Downward nominal price rigidity versus downward nominal wage rigidity

In this subsection, we examine a model with both wage and price rigidities. The model is described in detail in Appendix A. ***More to be added.***

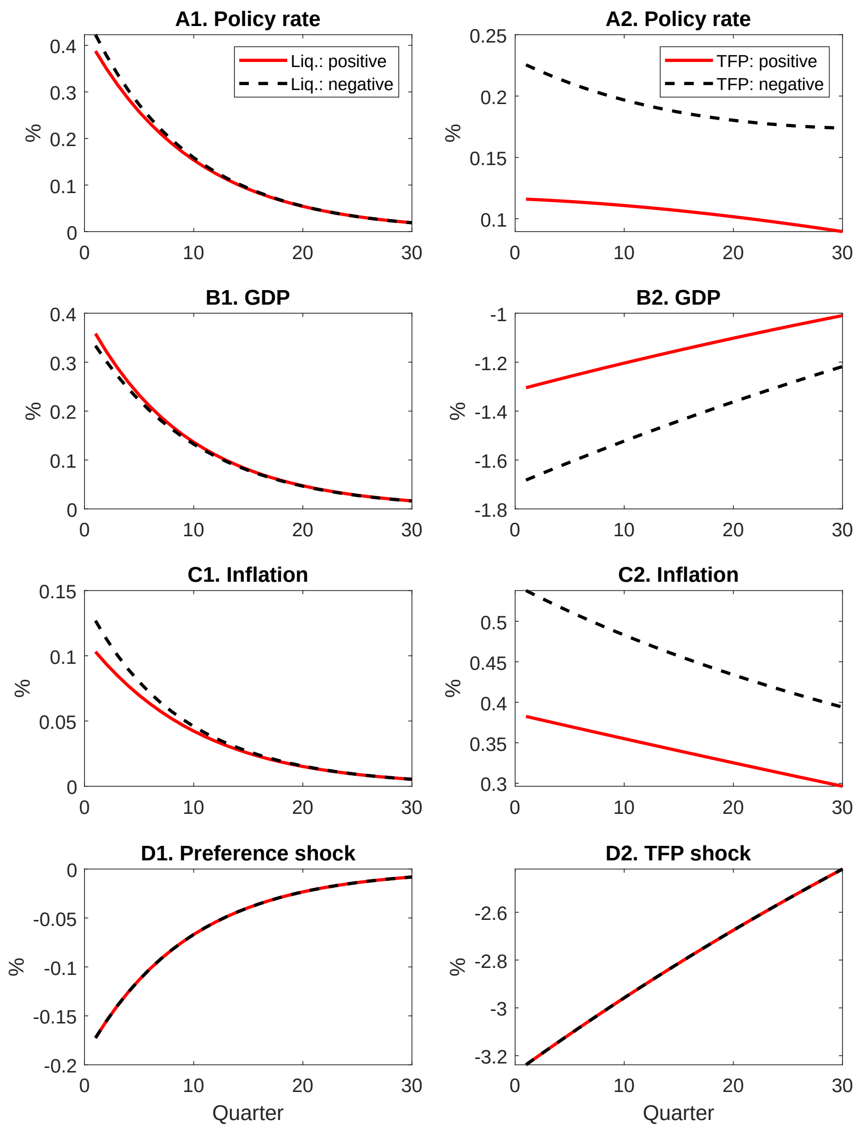

Figure 14: **Impulse response functions to positive and negative shocks with asymmetric price adjustment costs.** Impulse response to a three-standard deviation of liquidity shock (left column) and productivity shock (right column) when the shock is negative (red full line) vs. positive (black dashed line). The responses to positive shocks are displayed with the reverse sign. The economy is initially at the deterministic steady state. The case of asymmetric adjustment costs.

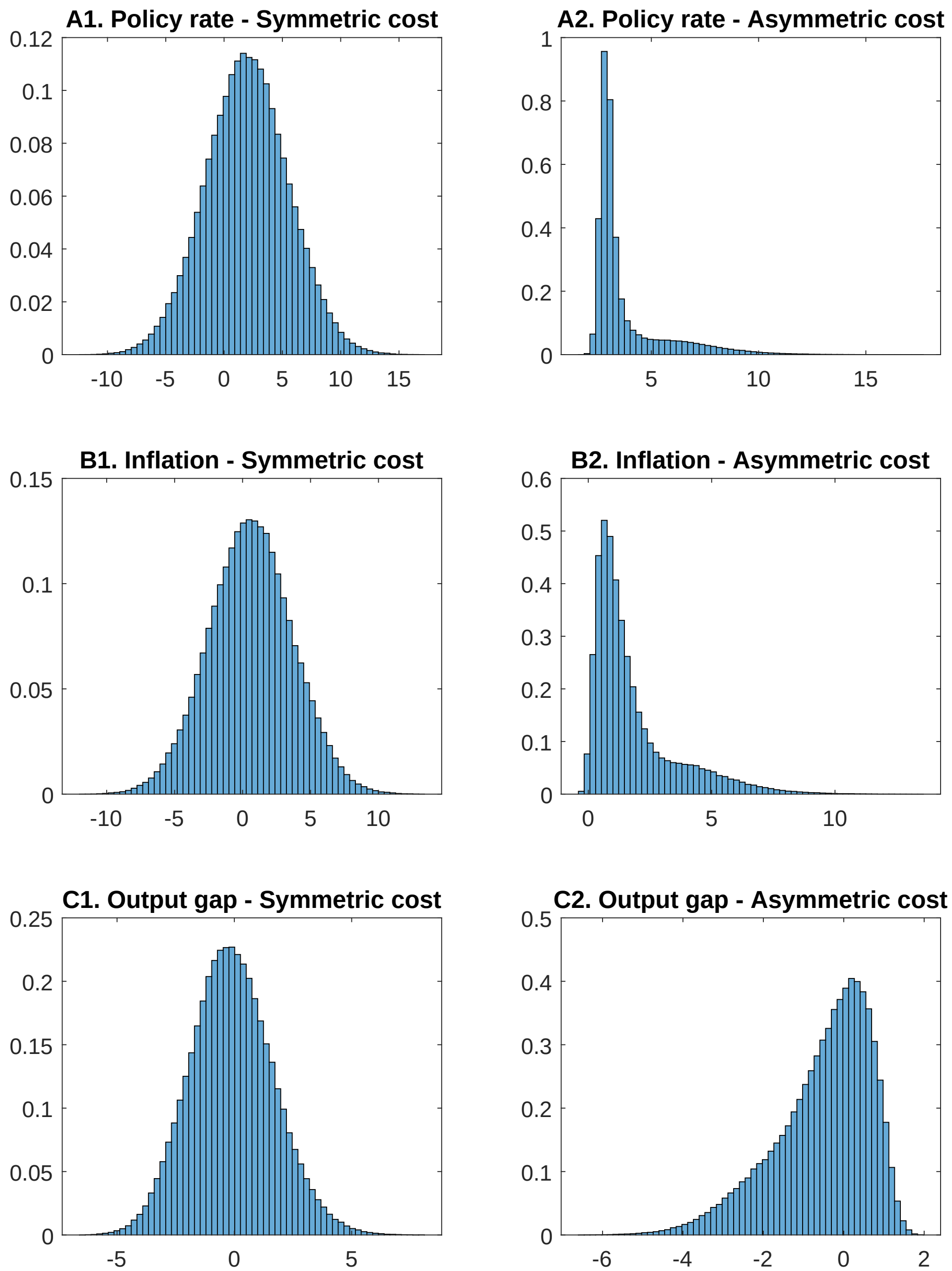

Figure 15: Probability density functions of macroeconomic variables based on 500,000 periods simulation.

A. All observations

	Data		Symmetric		Benchmark	
	Mean	Std	Mean	Std	Mean	Std
D.lnY	0.00	2.40	0.00	3.03	-0.00	2.23
π	1.80	1.48	0.61	3.08	1.79	1.72
$y^{n(1)}$	3.60	2.60	1.96	3.53	3.72	1.69
$y^{n(40)}$	5.50	2.30	5.00	2.87	5.66	1.98
$y^{r(1)}$	NaN	NaN	1.19	0.61	1.82	0.55
$y^{r(40)}$	3.30	0.90	1.58	0.37	1.84	0.20
Real TP	NaN	NaN	0.39	0.00	-0.05	0.25
Nominal TP	NaN	NaN	3.03	0.02	1.79	0.82

B. Subsample

	Data		Symmetric		Benchmark	
	Mean	Std	$\pi < 2\%$	$\pi > 4\%$	$\pi < 2\%$	$\pi > 4\%$
D.lnY	0.00	2.40	0.11	-0.33	0.09	-0.36
π	1.80	1.48	-1.02	5.58	0.91	5.60
$y^{n(1)}$	3.60	2.60	0.10	7.60	2.92	7.62
$y^{n(40)}$	5.50	2.30	3.49	9.60	4.63	9.61
$y^{r(1)}$	NaN	NaN	0.94	1.94	1.93	1.94
$y^{r(40)}$	3.30	0.90	1.39	2.16	1.79	2.15
Real TP	NaN	NaN	0.39	0.39	-0.19	0.35
Nominal TP	NaN	NaN	3.02	3.05	1.40	2.97

Table 5: Asymmetry versus symmetry. $D.lnY$ is the first difference in natural logarithm of output.

A. All observations

	Data		Benchmark		$\psi = 500$		$\psi = 1500$	
	Mean	Std	Mean	Std	Mean	Std	Mean	Std
D.lnY	0.00	2.40	-0.00	2.23	-0.00	2.41	-0.00	2.19
π	1.80	1.48	1.79	1.72	1.54	1.99	2.00	1.61
$y^{n(1)}$	3.60	2.60	3.72	1.69	3.31	2.00	3.98	1.59
$y^{n(40)}$	5.50	2.30	5.66	1.98	5.55	2.16	5.83	1.89
$y^{r(1)}$	NaN	NaN	1.82	0.55	1.64	0.44	1.87	0.60
$y^{r(40)}$	3.30	0.90	1.84	0.20	1.78	0.19	1.87	0.21
Real TP	NaN	NaN	-0.05	0.25	0.05	0.20	-0.09	0.27
Nominal TP	NaN	NaN	1.79	0.82	2.11	0.64	1.70	0.87

B. Subsample

	Data		Benchmark		$\psi = 500$		$\psi = 1500$	
	Mean	Std	$\pi < 2\%$	$\pi > 4\%$	$\pi < 2\%$	$\pi > 4\%$	$\pi < 2\%$	$\pi > 4\%$
D.lnY	0.00	2.40	0.09	-0.36	0.10	-0.37	0.09	-0.38
π	1.80	1.48	0.91	5.60	0.42	5.56	1.17	5.53
$y^{n(1)}$	3.60	2.60	2.92	7.62	2.21	7.54	3.25	7.54
$y^{n(40)}$	5.50	2.30	4.63	9.61	4.35	9.60	4.82	9.55
$y^{r(1)}$	NaN	NaN	1.93	1.94	1.67	1.88	2.01	1.92
$y^{r(40)}$	3.30	0.90	1.79	2.15	1.69	2.15	1.83	2.14
Real TP	NaN	NaN	-0.19	0.35	-0.06	0.36	-0.23	0.34
Nominal TP	NaN	NaN	1.40	2.97	1.78	2.99	1.27	2.95

Table 6: Comparative analysis with the asymmetry parameter. $D.lnY$ is the first difference in natural logarithm of output.

5.6 The role of monetary policy

Now that we have learned the implication of downward nominal rigidities on macroeconomy and asset prices, it is important to know what kind of policy we would implement to address the problem of high premiums and skewness.

A potential solution is to increase the agressiveness of monetary policy toward stabilizing inflation. In other words, if the central bank is able to stabilize inflation around its target, there won't be much low or high inflation that trigger the working of downward nominal rigidities. Figure 16 shows the distributions of inflation, policy rates, and output gap when monetary policy is more aggressive toward stabilizing inflation, i.e. the coefficient on inflation gap in the Taylor rule is raised to 3 from 2. It can be seen from the figure that the skewness of the distributions of macroeconomic variables almost disappears.

6 Conclusion (TBA)

This paper develops a macro-finance asset pricing model with downward nominal rigidities. When inflation is low, nominal rigidities are more important, leading to a smaller response of output and inflation to a productivity shock, and dampening the magnitude of the covariance between inflation and consumption, resulting in a smaller inflation term premium. We argue that this feature helps account for the secular change in term premia.

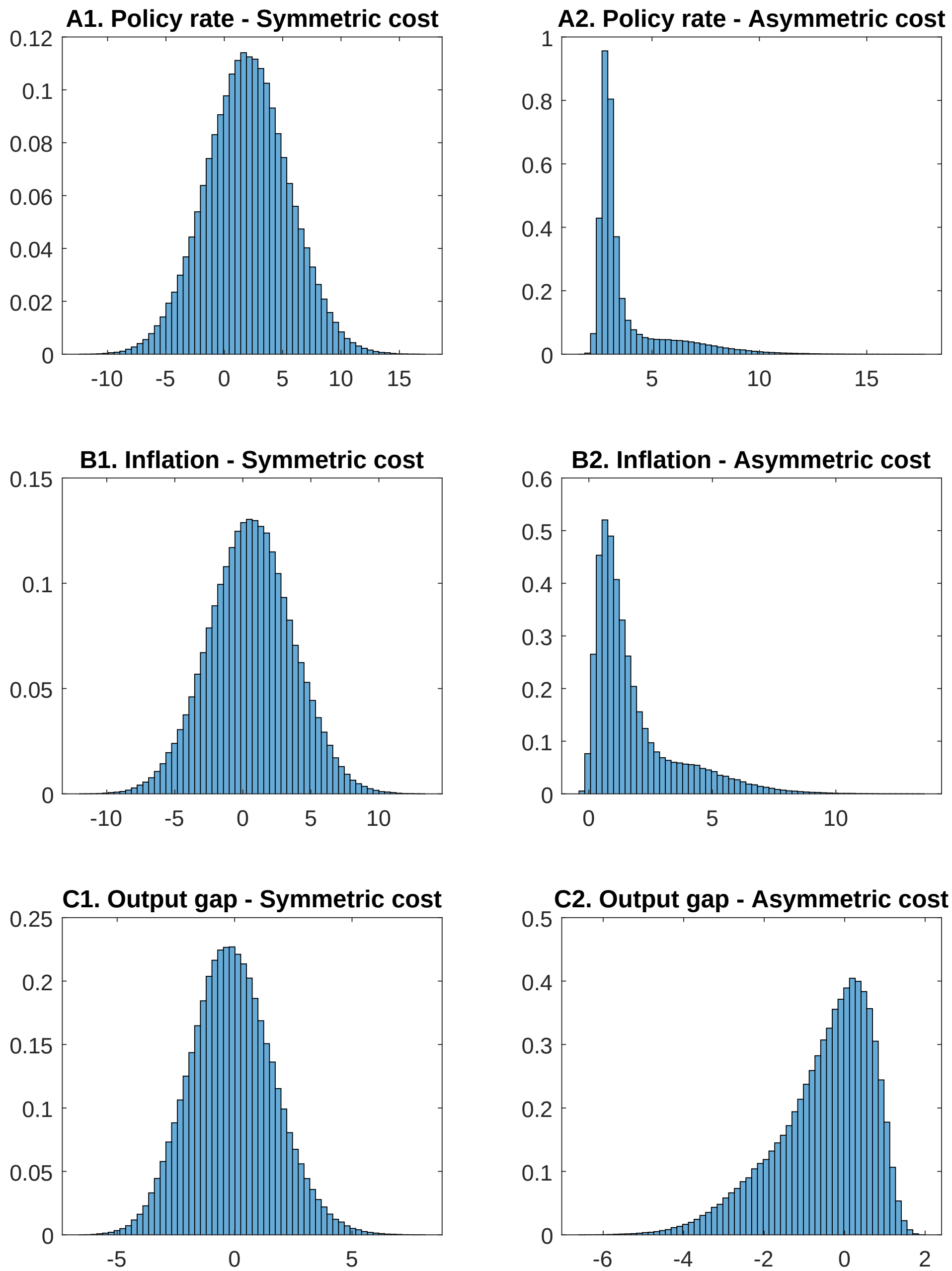

Figure 16: Probability density functions of macroeconomic variables with more inflation-stabilizing monetary policy, i.e. $\phi_\pi = 3$. The result is computed based 500,000 periods simulation.

References

Adrian, T., Crump, R. K., Moench, E., 2013a. Pricing the term structure with linear regressions. Journal of Financial Economics 110(1), 110–138.

Adrian, T., Crump, R. K., Moench, E., 2013b. Pricing the term structure with linear regressions. Journal of Financial Economics 110 (1), 110–138.

Akerlof, G. A., Dickens, W. T., Perry, G. L., Gordon, R. J., Mankiw, N. G., 1996. The macroeconomics of low inflation. Brookings papers on economic activity 1996 (1), 1–76.

Ang, A., Bekaert, G., Wei, M., 2008. The term structure of real rates and expected inflation. Journal of Finance 63 (2), 797–849.

Anzoategui, D., Comin, D., Gertler, M., Martinez, J., 2017. Endogenous technology adoption and r&d as sourses of business cycle persistence. NBER Working Paper.

Arouba, B., Cuba-Borda, P., Schorfheide, F., 2018. Macroeconomic dynamics near the zlb: A tale of two countries. The Review of Economic Studies 85 (1), 87–118.

Bansal, R., Shaliastovich, I., 2013. A long-run risks explanation of predictability puzzles in bond and currency markets. The Review of Financial Studies 26(1), 1–33.

Basu, S., House, C. L., 2016. Allocative and remitted wages: New facts and challenges for keynesian models. In: Handbook of macroeconomics. Vol. 2. Elsevier, pp. 297–354.

Bilal, M., 2017. Zeroing in: Asset pricing near the zero lower bound. Available at SSRN 2897926.

Branger, N., Schlag, C., Shaliastovich, I., Song, D., 2016. Macroeconomic bond risks at the zero lower bound. Available at SSRN 2820207.

Campbell, J., Pflueger, C., Viceira, L. M., 2020. Macroeconomic drivers of bond and equity risks",. Journal of Political Economy 128, 3148–3185.

Campbell, J. Y., Shiller, R. J., 1991. Yield spreads and interest rate movements: A bird's eye view. The Review of Economic Studies 58 (3), 495–514.

Campbell, J. Y., Sunderam, A., Viceira, L. M., 2009. Inflation bets or deflation hedges? the changing risks of nominal bonds. National Bureau of Economic Research Working Paper.

Christensen, J. H., Diebold, F. X., Rudebusch, G. D., 2011. The affine arbitrage-free class of nelson–siegel term structure models. Journal of Econometrics 164 (1), 4–20.

Christiano, L., Eichenbaum, M., Rebelo, S., 2010. When is the government spending multiplier is large? Northwestern University Working Paper.

Cochrane, J. H., 2009. Asset pricing: Revised edition. Princeton university press.

Daly, M. C., Hobijn, B., 2014. Downward nominal wage rigidities bend the phillips curve. Journal of Money, Credit and Banking 46 (S2), 51–93.

D'Amico, S., Kim, D. H., Wei, M., 2018. Tips from tips: the informational content of treasury inflation-protected security prices. Journal of Financial and Quantitative Analysis 53 (1), 395–436.

Datta, D., Johannsen, B. K., Kwon, H., Vigfusson, R. J., 2018. Oil, equities, and the zero lower bound. FEDS Working paper.

David, A., Veronesi, P., 2013. What ties return volatilities to price valuations and fundamentals?",. Journal of Political Economy 121 (4), 682–746.

Del Negro, M., Giannoni, M. P., Schorfheide, F., 2015. Inflation in the great recession and new keynesian models. American Economic Journal: Macroeconomics 7(1), 168–196.

Epstein, L. G., Zin, S. E., 1989. Substitution, risk aversion, and the temporal behavior of consumption and asset returns: A theoretical framework. Econometrica 57(4), 937–969.

Fama, E. F., Bliss, R. R., 1987. The information in long-maturity forward rates. The American Economic Review, 680–692.

Fernandez-Villaverde, J., Gordon, G., Guerron-Quintana, P., Rubio-Ramirez, J., 2015. Nonlinear adventures at the zero lower bound. Journal of Economic Dynamics and Control 57, 182 –204.

Fisher, J. D., 2015. On the structural interpretation of the smets–wouters risk premium shock. Journal of Money, Credit and Banking 47 (2-3), 511–516.

Gali, J., 2008. Monetary Policy, Inflation, and the Business Cycle: An Introduction to the New Keynesian Framework. Princeton University Press.

Gourio, F., Ngo, P. V., 2020. Risk premia at the zlb: A macroeconomic interpretation. FRB of Chicago Working Paper No. WP-2020-01.

Gust, C., Herbst, E. Lopez-Salido, D., Smith, M., 2017. The emperical implications of the interest-rate lower bound. American Economic Review 107(7), 1971–2006.

Hordahl, P., Tristani, O., 2014. Inflation risk premia in the euro area and the united states. International Journal of Central Banking 2014(3), 1–47.

Ireland, N. P., 1997. A small, structural, quarterly model for monetary policy evaluation. Carnegie-Rochester Conference Series on Public Policy 47, 83–108.

Kahn, S., 1997. Evidence of nominal wage stickiness from microdata. The American Economic Review 87 (5), 993–1008.

Kim, D. H., Wright, J. H., 2005. An arbitrage-free three-factor term structure model and the recent behavior of long-term yields and distant-horizon forward rates.

Kim, J., Ruge-Murcia, F. J., 2009. How much inflation is necessary to grease the wheels? Journal of Monetary Economics 56, 365–377.

Kim, J., Ruge-Murcia, F. J., 2011. Monetary policy when wages are downwardly rigid: Friedman meets tobin. Journal of Economic Dynamics & Control 35, 2064–2077.

Klenow, P. J., Malin, B. A., 2010. Microeconomic evidence on price-setting. In: Handbook of monetary economics. Vol. 3. Elsevier, pp. 231–284.

Krishnamurthy, A., Vissing-Jorgensen, A., 2012. The aggregate demand for treasury debt. Journal of Political Economy 120(2), 233–267.

Leeper, E. M., Traum, N., Walker, T. B., 2017. Clearing up the fiscal multiplier morass. American Economic Review 107(8), 2409 – 2454.

Li, E., Palomino, F., 2014. Nominal rigidities, asset returns, and monetary policy. Journal of Monetary Economics 66, 210–225.

Miao, J., Ngo, P., 2016. Does calvo meet rotemberg at the zero lower bound? Working Paper.

Miao, J., Ngo, P. V., 2014. Does calvo meet rotemberg at the zero lower bound?". Working Paper, Boston Univerisity and Cleveland State University.

Nakata, T., Tanaka, H., 2016. Equilibrium yield curves and the zero lower bound. Working Paper, Federal Reserve Board.

Ngo, V. P., 2018. The risk of hitting the zero lower bound and the optimal inflation target. Macroeconomic Dynamics (Published online by Cambridge University Press: 02 May 2017) 22 (2), 402–425.

Palomino, F., 2012. Bond risk premiums and optimal monetary policy. Review of Economic Dynamics 15(1), 19–40.

Peltzman, S., 2000. Prices rise faster than they fall. Journal of Political Economy 108(3), 466–502.

Pflueger, C., Rinaldi, G., 2022. Why does the fed move markets so much? a model of monetary policy and time-varying risk aversion. Journal of Financial Economics 146 (1), 71–89.

Pflueger, C. E., 2022. What do treasury bond risks say about supply and demand shocks? University of Chicago, Becker Friedman Institute for Economics Working Paper (102).

Piazzesi, M., Schneider, M., 2006. Equilibrium yield curves. NBER Working Paper.

Rotemberg, J., 1982. Sticky prices in the united states. Journal of Political Economy 90, 1187–211.

Roussellet, G., 2018. The term structure of macroeconomic risks at the zero lower bound. Available at SSRN 2863271.

Rudebusch, G., Swanson, E., 2008. Examining the bond premium puzzle with a dsge model. Journal of Monetary Economics 55, S111–S126.

Rudebusch, G., Swanson, E., 2012. The bond premium in a dsge model with long-run real and nominal risks. American Economic Journal: Macroeconomics 4(1), 105–143.

Schmitt-Grohé, S., Uribe, M., 2016. Downward nominal wage rigidity, currency pegs, and involuntary unemployment. Journal of Political Economy 124 (5), 1466–1514.

Song, D., 2017. Bond market exposures to macroeconomic and monetary policy risks. The Review of Financial Studies 30 (8), 2761–2817.

Swanson, E., 2015a. A macroeconomic model of equities and real, nominal, and defaultable debt. Working Paper, UC Irvine.

Swanson, E., 2015b. Risk aversion, risk premia, and the labor margin with generalized recursive preferences. Working Paper, Federal Reserve Bank of San Francisco.

Taylor, B., 1993. Discretion versus policy rules in practice. Carnegie-Rochester Conference Series on Public Policy 39, 195–214.

Tobin, J., 1972. Inflation and employment. American Economic Review 62, 1–18.

Weil, P., 1990. Nonexpected utility in macroeconomics. The Quarterly Journal of Economics 105 (1), 29–42.

Woodford, M., 2003. Interest and Prices: Foundations of a Theory of Monetary Policy. Princeton University Press.

Woodford, M., 2011. Simple analytics of the government expenditure multiplier. American Economic Journal: Macroeconomics 3, 1–35.

Wright, J. H., 2011. Term premia and inflation uncertainty: Empirical evidence from an international panel dataset. American Economic Review 101 (4), 1514–34.

7 Appendix A: Model with downward nominal wage rigidities

7.1 Composite labor

Firms need to use composite labor to produce intermdediate differentiated goods. Composite labor can be created by aggregating a variety of differentiated labor indexed by $h \in [0, 1]$ using a CES technology

$$N_t = \left(\int_0^1 N_t^{h \, \frac{\epsilon_w - 1}{\epsilon_w}} dh \right)^{\frac{\epsilon_w}{\epsilon_w - 1}}, \tag{21}$$

where ε_w determines the elasticity of substitution among differentiated types of labor. The profit maximization problem is given by

$$\max \; W_t N_t - \int_0^1 W_t^h N_t^h dh,$$

where W_t^h and N_t^h are the wage and quantity of differentiated labor of type h.

Profit maximization and the zero-profit condition give the demand for labor of type h

$$N_t^h = \left(\frac{W_t^h}{W_t} \right)^{-\epsilon_w} N_t, \tag{22}$$

and the aggregate wage level

$$W_t = \left(\int \left(W_t^h \right)^{1-\epsilon_w} dh \right)^{\frac{1}{1-\epsilon_w}}. \tag{23}$$

7.2 Final consumption goods

To produce consumption goods, households buy and aggregate a variety of differentiated intermediate goods indexed by $i \in [0, 1]$ using a CES technology

$$Y_t = \left(\int_0^1 Y_t\,(i)^{\frac{\epsilon - 1}{\epsilon}} di \right)^{\frac{\epsilon}{\epsilon - 1}},$$

where ε determines the elasticity of substitution among intermediate goods. The profit maximization problem is given by

$$\max \; P_t Y_t - \int_0^1 P_t(i) \, Y_t(i) \, di,$$

where $P_t(i)$ and $Y_t(i)$ are the price and quantity of intermediate good i.

Profit maximization and the zero-profit condition give the demand for differentiated intermediate good i

$$Y_t(i) = \left(\frac{P_t(i)}{P_t} \right)^{-\epsilon} Y_t, \tag{24}$$

and the aggregate price level

$$P_t = \left(\int P_t(i)^{1-\epsilon} \, di \right)^{\frac{1}{1-\epsilon}}. \tag{25}$$

7.3 Household h's problem

There is a unit mass of households. Each household indexed by $h \in [0,1]$ provides type-h labor and is competitively monopolistic in the labor market. It is costly to adjust wages. Without loss of generality, we assume that households pay wage adjustment costs which have a general form

$$\Phi_t^h = \Phi \left(\frac{W_t^h}{W_{t-1}^h} \right) W_t^h N_t^h,$$

where $\Phi'(\cdot) > 0$ and $\Phi''(\cdot) > 0$.

In this paper, we follow Kim and Ruge-Murcia (2009) and use the linex function to model wage adjustment costs. Specifically,

$$\Phi_{t+\tau}^h = \Phi \left(\frac{W_{t+\tau}^h}{W_{t+\tau-1}^h} \right) = \phi \left(\frac{\exp\left(-\psi \left(\frac{W_{t+\tau}^h}{W_{t+\tau-1}^h} - \overline{\Pi} \right) \right) + \psi \left(\frac{W_{t+\tau}^h}{W_{t+\tau-1}^h} - \overline{\Pi} \right) - 1}{\psi^2} \right), \tag{26}$$

where ϕ_w is the level parameter and ψ_w is the asymmetry parameter. If $\psi_w > 0$, the wage adjustment cost is asymmetric. In particular, the cost to lower a wage is higher than to increase it by the same amount. When ψ_w approaches 0, this function becomes a symmetric quadratic function

$$\Phi\left(x\right)=\frac{\phi_{w}}{2}\left(x-\overline{\Pi}\right)^{2}.$$

Household h choose $\left\{C^{h}_{t+\tau},N^{h}_{t+\tau},W^{h}_{t+\tau},B^{h}_{t+\tau}\right\}_{\tau=0}^{\infty}$ to maximize the inter-temporal utility

$$V_{t}^{h}=\left(1-\beta\right)u(C_{t}^{h},N_{t}^{h})+\beta E_{t}\left((V_{t+1}^{h})^{1-\alpha}\right)^{\frac{1}{1-\alpha}}$$

with the flow utility

$$u\left(C_{t},N_{t}\right)=\frac{C_{t}^{1-\sigma}}{1-\sigma}-\frac{\chi N_{t}^{1+\nu}}{1+\nu},$$

subject to the labor demand (22) and the budget constraint as described below.

If the parameters we use lead to a negative flow utility $u(C_t,N_t)$, we define utility as:

$$V_{t}^{h}=\left(1-\beta\right)u(C_{t}^{h},N_{t}^{h})-\beta E_{t}\left(\left(-V_{t+1}^{h}\right)^{1-\alpha}\right)^{\frac{1}{1-\alpha}}.$$

The budget constraint is:

$$P_{t+\tau}C^{h}_{t+\tau}+\xi_{t+\tau}B^{h}_{t+\tau}=W^{h}_{t+\tau}N^{h}_{t+\tau}\left(1-\Phi^{h}_{t+\tau}\right)+R_{t+\tau}B^{h}_{t+\tau-1}+D^{h}_{t+\tau}+T^{h}_{t+\tau}, \tag{27}$$

where the liquidity shock, $\xi_{t+\tau}$, follows an AR(1) process,

$$\begin{aligned}\ln\left(\xi_{t+\tau}\right) &= \rho_{\beta}\ln\left(\xi_{t+\tau-1}\right)+\varepsilon_{\xi,t+\tau}, \\ \varepsilon_{\xi,t} &\sim i.i.d\ N\left(0,\sigma_{\xi}^{2}\right).\end{aligned} \tag{28}$$

A symmetric solution to this optimization problem, i.e. $W_t^h=W_t$ and $N_t^h=N_t$, implies a New Keynesian Phillips curve for wages and the Euler equation (see Appendices for our derivation):

$$\left(1-\varepsilon_{w}\right)\left(1-\Phi\left(\Pi_{t}^{w}\right)\right)N_{t}-\Phi'\left(\Pi_{t}^{w}\right)\Pi^{w}N_{t}+\varepsilon_{w}\chi\frac{N_{t}^{\eta+1}}{w_{t}C_{t}^{-\gamma}}+E_{t}\left[M_{t,t+1}\frac{\Phi'\left(\Pi_{t+1}^{w}\right)\left(\Pi^{w}\right)^{2}}{\Pi_{t+1}}N_{t+1}\right]=0, \tag{29}$$

$$E_{t}\left[M_{t,t+1}\left(\frac{\beta_{t}^{-1}R_{t}}{\Pi_{t+1}}\right)\right]=1, \tag{30}$$

where $w_t = W_t / P_t$ is the real wage; $\Pi_t = P_t / P_{t-1}$ is gross inflation; $\Pi_t^w = W_t / W_{t-1}$ is gross wage inflation. Wage inflation and and the stochastic discount factor are given by

$$\Pi_t^w = \frac{w_t}{w_{t-1}} \Pi_t, \tag{31}$$

$$M_{t,t+1} = \beta \left(\frac{C_{t+1}}{C_t} \right)^{-\sigma} \left(\frac{V_{t+1}}{E_t \left(V_{t+1}^{1-\alpha} \right)^{\frac{1}{1-\alpha}}} \right)^{-\alpha}, \tag{32}$$

Note that when $\phi = 0$ and $\varepsilon_w \to \infty$, equation (29) becomes a standard marginal rate of substitution between labor and consumption

$$\frac{\chi N_t^\eta}{C_t^{-\gamma}} = w_t.$$

7.4 Intermediate goods producer $i's$ problem

There is a unit mass of intermediate goods producers that are monopolistic competitors. Suppose that each intermediate good $i \in [0, 1]$ is produced by one producer using the technology

$$Y_t^i = Z_t \left(N_t^i \right)^\alpha, \tag{33}$$

where $\alpha \geq 0$; N_t^i is composite labor input used by firm i; and

$$\begin{aligned} \ln (Z_t) &= \rho_A \ln (Z_{t-1}) + \varepsilon_{Z,t}, \\ \varepsilon_{Z,t} &\sim i.i.d\ N \left(0, \sigma_Z^2 \right). \end{aligned} \tag{34}$$

Following Rotemberg (1982), we assume that each intermediate goods firm i faces costs of adjusting prices in terms of final goods. The adjustment cost function is in a general form

$$\Gamma_t = \Gamma \left(\frac{P_t^i}{P_{t-1}^i} \right) Y_t,$$

where $\Gamma' (\cdot) > 0$ and $\Gamma'' (\cdot) > 0$.

We also use the linex function to model price adjustment costs. Specifically,

$$\Gamma (x) = \phi_p \left(\frac{\exp \left(-\psi_p \left(x - \overline{\Pi} \right) \right) + \psi_p \left(x - \overline{\Pi} \right) - 1}{\psi_p^2} \right), \tag{35}$$

where ϕ_p, ψ_p are parameters that determines the level and the asymmetry of price adjustment costs. If $\psi_p > 0$, the price adjustment cost is asymmetric. Particularly, the cost to lower a price is higher than to increase it by the same amount. The linex function nests the symmetric quadratic cost when ψ_p approaches 0, i.e. it becomes a quadratic function

$$\Gamma\left(x\right) = \frac{\phi_p}{2}\left(x - \overline{\Pi}\right)^2,$$

which is popularly used in the ZLB literature.

The problem of firm i is given by

$$\max_{\{Y^i_{t+j}, N_{t+j}, P^i_{t+j}\}_{j=0}^{\infty}} E_t \sum_{j=0}^{\infty} \left\{ M_{t,t+j} \left[\left(\frac{P^i_{t+j}}{P_{t+j}} Y^i_{t+j} - w_t N^i_t \right) - \Gamma\left(\frac{P^i_{t+j}}{P^i_{t+j-1}} \right) Y_{t+j} \right] \right\} \tag{36}$$

subject to its demand (24) and production function (33). In a symmetric equilibrium where all firms choose the same price and produce the same quantity (i.e., $P^i_t = P_t$ and $Y^i_t = Y_t$). The optimal pricing rule then implies a New Keynesian Phillips curve,

$$(1-\varepsilon) Y_t - \Pi_t \Gamma'\left(\Pi_t\right) Y_t + \frac{\varepsilon w_t}{\alpha} \left(\frac{Y_t}{A_t} \right)^{\frac{1}{\alpha}} + E_t \left(M_{t,t+1} \Pi_{t+1} \Gamma'\left(\Pi_{t+1}\right) Y_{t+1} \right) = 0. \tag{37}$$

When the production is linear, i.e. $\alpha = 1$, the NKP become the popular one:

$$\left(1 - \varepsilon + \varepsilon \frac{w_t}{A_t} - \Pi_t \Gamma'\left(\Pi_t\right) \right) Y_t + E_t \left(M_{t,t+1} \Pi_{t+1} \Gamma'\left(\Pi_{t+1}\right) Y_{t+1} \right) = 0.$$

7.5 Monetary policy

The central bank conducts monetary policy by setting the interest rate using a simple Taylor rule:

$$R_t = R^* \left(\frac{GDP_t}{GDP^*} \right)^{\phi_y} \left(\frac{\Pi_t}{\Pi^*} \right)^{\phi_\pi} \exp\left(\zeta_t\right), \tag{38}$$

where $GDP_t \equiv C_t$ denotes the gross domestic product (GDP); GDP^* and Π^* denote the target GDP and inflation, respectively; R^* denotes the intercept of the Taylor rule. The monetary shock, ζ, follows an AR(1) process.

$$\begin{aligned} \ln\left(\zeta_t\right) &= \rho_\zeta \ln\left(\zeta_{t-1}\right) + \varepsilon_{\zeta,t}, \\ \varepsilon_{\zeta,t} &\sim i.i.d\ N\left(0, \sigma^2_\zeta\right). \end{aligned} \tag{39}$$

Parameter	Description and source	Value
β	Subjective discount factor	0.992
α	Curvature with respect to next period value (note: CRRA=136)	-300.00
σ	IES is 0.5	2.00
v	Frisch labor supply elasticity is 0.66	1.50
χ	Calibrated to achieve the steady state labor of 1/3	33.91
ε	Gross markup is 1.15	7.66
ϕ_π	Weight on inflation in the Taylor rule	1.50
ϕ_y	Weight on output in the Taylor rule	0.13
Π^*	Inflation target	1.040
R^*	Taylor rule intercept	1.074
ϕ_p	Price adjustment cost, corresponding to the Calvo parameter of 0.85	60.00
ψ_p	Price adjustment asymmetry parameter	1.00
ϕ_w	Wage adjustment cost, Kim and Ruge-Murcia (2011)	300.00
ψ_w	Wage adjustment asymmetry parameter, Kim and Ruge-Murcia (2011)	160.00
ρ_z	Persistence of technology shock	0.92
ρ_ξ	Persistence of demand shock	0.85
σ_z	Std. dev. of the technology innovations (%)	0.14
σ_ξ	Std. dev. of the preference innovations (%)	0.09

Table 7: Parameter calibration with downward nominal wage rigidities

7.6 Equilibrium systems

With the Rotemberg price setting, the aggregate output satisfies

$$Y_t = A_t N_t^\alpha, \tag{40}$$

The resource constraint is given by

$$C_t = (1 - \Gamma(\Pi_t)) Y_t - w_t N_t \Phi(\Pi_t^w). \tag{41}$$

The equilibrium system for the model consists of a system of six nonlinear difference equations (29), (30), (31), (37), (38), (40), (41) for six variables w_t, C_t, i_t, π_t, π_t^w, N_t, and Y_t.

7.7 Parameter calibration

The parameters are calibrated and presented in table 7.

7.8 Impulse responses

Impulse responses to liquidity and TFP shocks are presented in Figures 17 and 18.

8 Appendix B: Additional graphs and tables

8.1 No asymmetric responses with symmetric adjustment costs

Figure 21 presents impulse responses to a three-standard deviation of liquidity shock (left column) and productivity shock (right column) when the shock is negative (red full line) vs. positive (black dashed line) for the case of symmetric price adjustment costs. The responses to positive shocks are displayed with the reverse sign. The economy is initially at the deterministic steady state.

It is evident from this figure that even the shocks are quite large, the responses of policy rate, GDP, inflation to a negative shock (either liquidity shock or TFP shock) are almost identical to the responses to a positive shock except the signs of the responses. In other words, the responses to a negative shock and to a positive shock are symmetric.

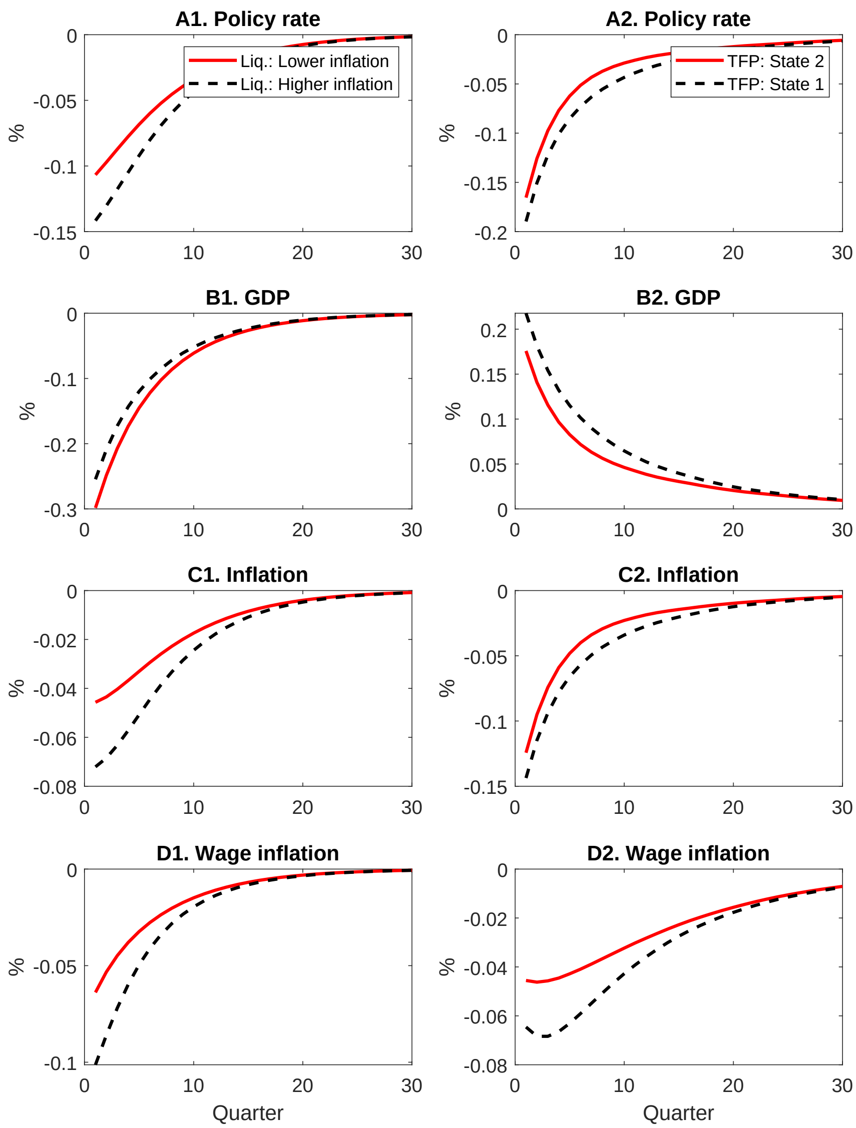

Figure 17: Impulse response to a one-standard deviation of liquidity shock (left column) and productivity shock (right column) at a state with ...% inflation (red line) vs. at a state with ...% inflation (black dashed line). Impulse response at a state is calculated as the difference between two paths: (1) a path with only initial shocks that result in low/high inflation, and (2) a path with the same shocks, plus an additional on-standard-deviation shock. The case of asymmetric wage adjustment costs.

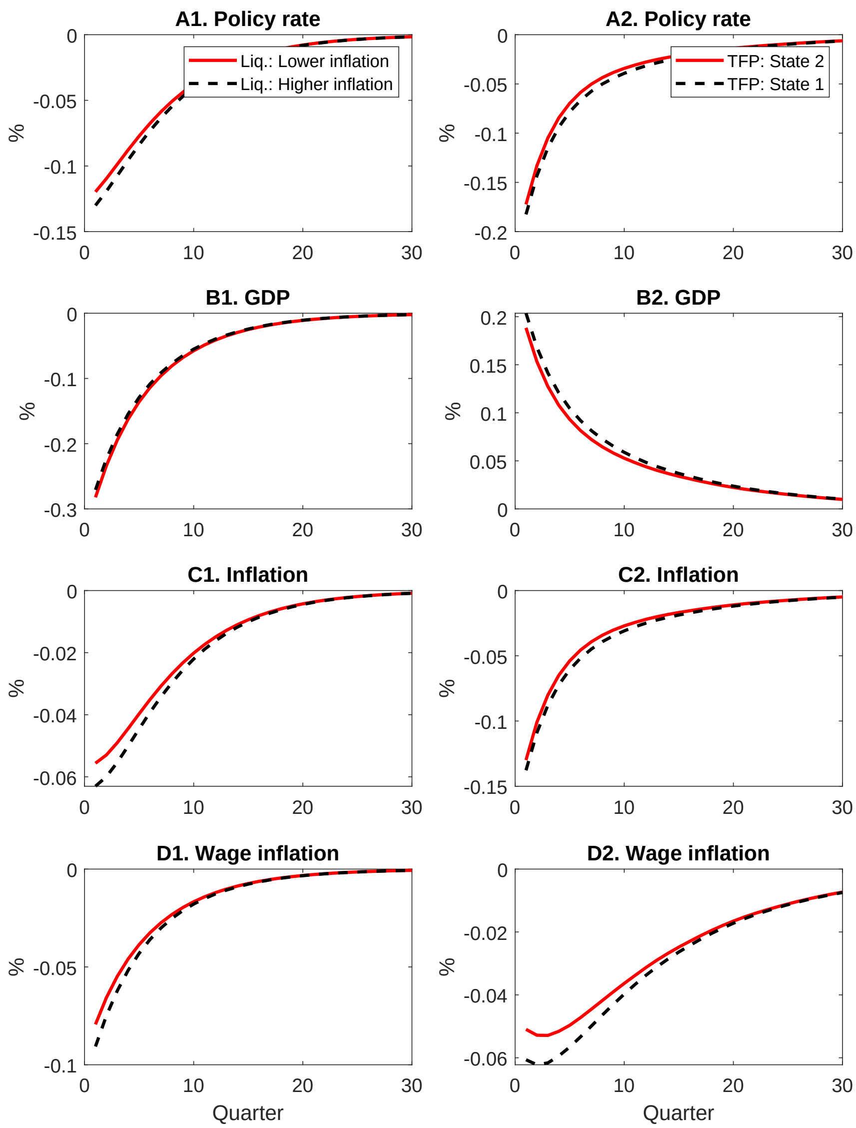

Figure 18: Impulse response to a one-standard deviation of liquidity shock (left column) and productivity shock (right column) at a state with ...% inflation (red line) vs. at a state with ...% inflation (black dashed line). Impulse response at a state is calculated as the difference between two paths: (1) a path with only initial shocks that result in low/high inflation, and (2) a path with the same shocks, plus an additional on-standard-deviation shock. The case of symmetric wage adjustment costs.

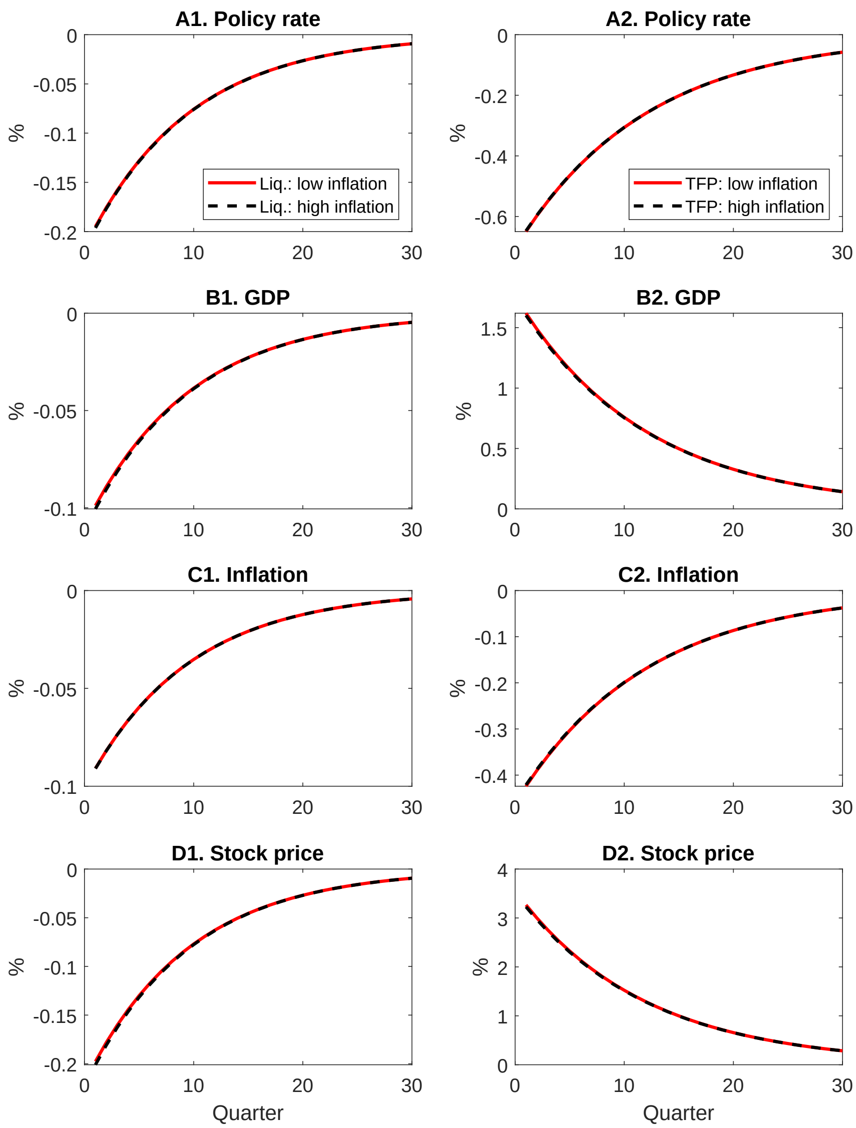

Figure 19: Impulse response to a one-standard deviation of liquidity shock (left column) and productivity shock (right column) at a state with 0.8% inflation (red line) vs. at a state with 3.2% inflation (black dashed line). Impulse response at a state is calculated as the difference between two paths: (1) a path with only initial shocks that result in low/high inflation, and (2) a path with the same shocks, plus an additional on-standard-deviation shock. The case of asymmetric price adjustment costs. Note that we use an initial TFP shock to cause lower/higher inflation in this case. In the main analysis, we use liquidity shocks as initial shocks to cause lower/higher inflation.

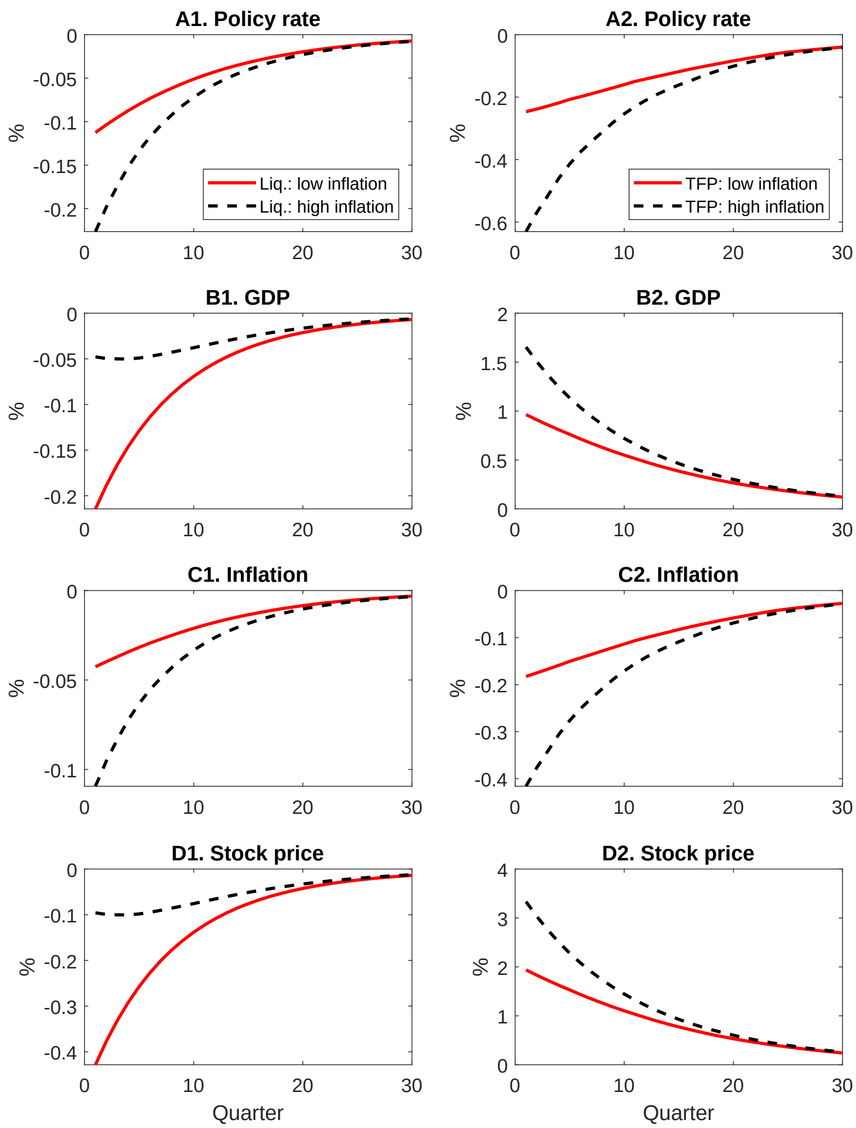

Figure 20: Impulse response to a one-standard deviation of liquidity shock (left column) and productivity shock (right column) at a state with 0.8% inflation (red line) vs. at a state with 3.2% inflation (black dashed line). Impulse response at a state is calculated as the difference between two paths: (1) a path with only initial shocks that result in low/high inflation, and (2) a path with the same shocks, plus an additional on-standard-deviation shock. The case of asymmetric price adjustment costs. Note that we use an initial TFP shock to cause lower/higher inflation in this case. In the main analysis, we use liquidity shocks as initial shocks to cause lower/higher inflation.

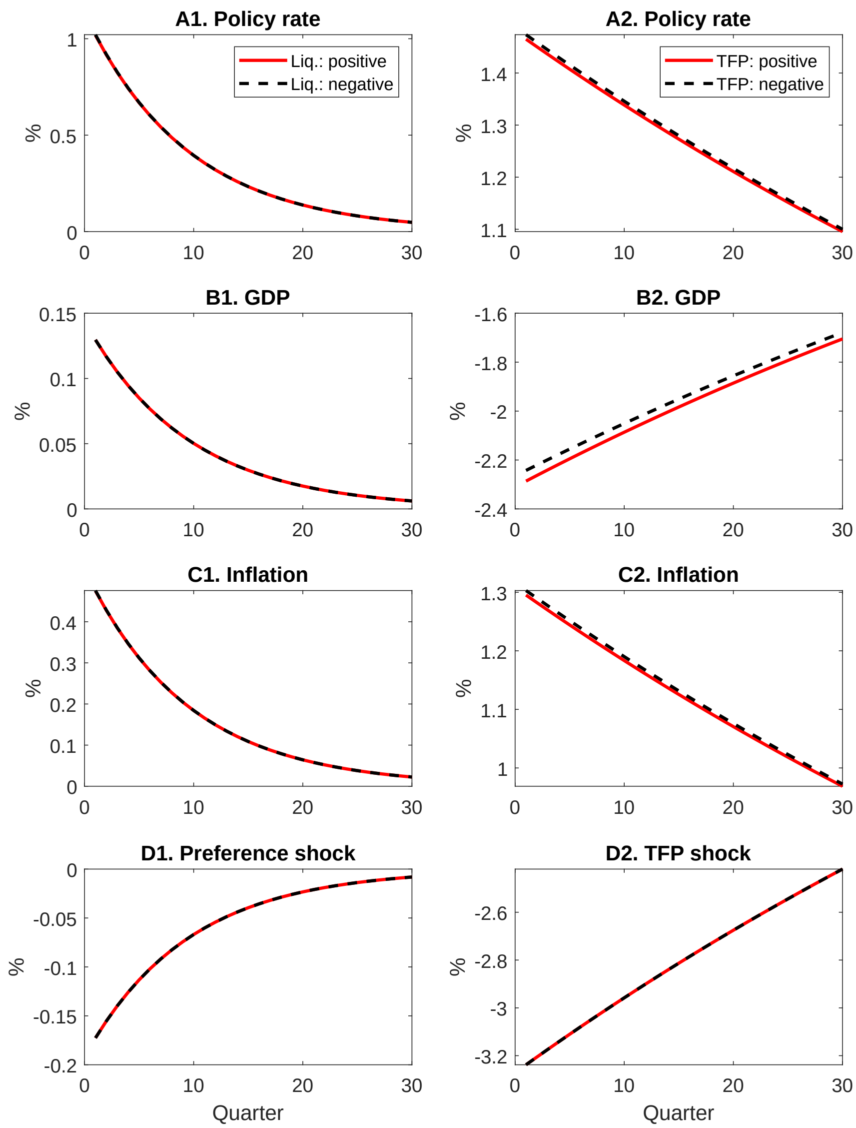

Figure 21: **Impulse response functions to positive and negative shocks with symmetric price adjustment costs.** Impulse response to a three-standard deviation of liquidity shock (left column) and productivity shock (right column) when the shock is negative (red full line) vs. positive (black dashed line). The responses to positive shocks are displayed with the reverse sign. The economy is initially at the deterministic steady state. The case of symmetric adjustment costs.