Why Does the Fed Move Markets so Much?

A Model of Monetary Policy and Time-Varying Risk Aversion

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Abstract

We build a new model integrating a work-horse New Keynesian model with investor risk aversion that moves with the business cycle. We show that the same habit preferences that explain the equity volatility puzzle in quarterly data also naturally explain the large high-frequency stock response to Federal Funds rate surprises. In the model, a surprise increase in the short-term interest rate lowers output and consumption relative to habit, thereby raising risk aversion and amplifying the fall in stocks. The model explains the positive correlation between changes in breakeven inflation and stock returns around monetary policy announcements with long-term inflation news.

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1 Introduction

It is well understood that cyclical variation in investors' capacity to bear risk is essential to understanding the link between the macroeconomy and financial markets (Cochrane (2017)). However, it is less clear how this time-varying link between the real economy and financial markets affects high-frequency stock and bond movements around monetary policy announcements, which are often used to assess the effectiveness of monetary policy for the real economy (Bernanke and Kuttner (2005)).

Our contribution is twofold. First, we integrate a small-scale New Keynesian model of monetary policy with the finance habit formation preferences of Campbell, Pflueger, and Viceira (2020), whereby investors become less willing to hold risky assets in times when output and consumption are low relative to a slowly-moving habit. These preferences have been shown to successfully reconcile the equity volatility puzzle of Shiller (1981), generate flight-to-safety in long-term Treasury bonds during the post-2001 period, and imply an exactly log-linear Euler equation typical of New Keynesian models. We fill a gap by departing from the reduced-form inflation and interest rate dynamics of Campbell, Pflueger, and Viceira (2020), and newly integrate finance habit preferences with a model of monetary policy.

Second, this new framework predicts how stocks and bonds should respond to monetary policy news, where news may be either about the short-term policy rate or long-term expected inflation. We show that our model, estimated to match quarterly macroeconomic moments, also matches the empirical high-frequency response of stock returns to monetary policy surprises around Federal Open Market Committee (FOMC) announcements. Further, the model implies that time-varying risk premia are quantitatively important for matching these responses.

We start by documenting empirically that stock returns around FOMC dates move differently with short-term interest rates and long-term breakeven inflation, building on the empirical literature that has documented that FOMC date surprises have at least two factors and reveal information about inflation and the macroeconomy.[1] Figure 1, Panel A plots the relationship between stock returns and short-term interest rate innovations

[1]See e.g. Romer and Romer (2000), Gürkaynak, Sack, and Swanson (2005b), Gürkaynak, Sack, and Swanson (2005a), Boyarchenko, Haddad, and Plosser (2015), Nakamura and Steinsson (2018). Figure 1, Panel A uses intraday changes in the Federal Funds rate from Gorodnichenko and Weber (2016) and in the S&P from TAQ. Panel B uses one-day changes in 10-year breakeven computed as the difference between Gürkaynak, Sack, and Wright (2007) nominal and Gürkaynak, Sack, and Wright (2010) Treasury Inflation-Protected Securities (TIPS) bond yields and one-day value-weighted stock returns from CRSP. Panel C uses one-day changes in 5-year TIPS yields from Gürkaynak, Sack, and Wright (2010) and the 6-month nominal yield from the St. Louis Fed. In Panel C, we measure monetary policy surprises with a somewhat longer bond maturity to match the empirical results in Nakamura and Steinsson (2018) during the zero-lower-bound period.

on FOMC dates, showing that a surprise decrease in the short-term Federal Funds rate is typically accompanied by a large increase in stock returns. This well-known result of Bernanke and Kuttner (2005) has been interpreted as evidence that the Fed can effectively stimulate the economy by temporarily lowering interest rates. Panel B shows that an increase in long-term breakeven inflation, which is defined as the difference between 10-year nominal and real interest rates and is often used as a measure of long-term inflation expectations, has the opposite correlation with stock returns on FOMC announcement dates, suggesting that FOMC dates reveal correlated news about the macroeconomy and inflation through a "Fed information effect". The comovement shown in Panel B provides additional information above and beyond the unconditional stock market beta of nominal bonds emphasized in Campbell, Pflueger, and Viceira (2020), because it zeros in on FOMC dates and hence captures monetary policy news.

We derive log-linear macroeconomic dynamics from consumers' intertemporal Euler equation and firms' profit optimization, and combine them with a log-linear Taylor-type rule for short-term interest rates. As in Campbell, Pflueger, and Viceira (2020) a representative consumer has habit preferences, whereby utility is determined by consumption in excess of a slowly moving habit, and surplus consumption dynamics take precisely the form needed to generate an exact log-linear consumption Euler equation. In order to link household and firm problems, we newly integrate leisure into these preferences by assuming that leisure is valued for its value in home production as in the classic model of Greenwood, Hercowitz, and Huffman (1988). This assumption separates wages from the intratemporal consumption-savings decision, thereby sidestepping the counterfactual labor implications that have previously affected models of asset pricing habits within production economies (Lettau and Uhlig (2000)). We derive a standard log-linearized Phillips curve, assuming that firms set prices optimally subject to standard Calvo (1983) staggered price setting with backwards indexation. Productivity features learning-by-doing (Lucas (1988)) to generate an endogenous stochastic output trend, and predictable productivity growth. Euler equation and Phillips curve shocks arise from shocks to habit and markups. All fundamental shocks are assumed to be conditionally homoskedastic, so time varying risk premia either at the quarterly frequency or around FOMC dates arise endogenously from preferences, rather than from auxiliary assumptions about time-varying quantities of risk.

We model monetary policy via a Taylor (1993)-type interest rate rule suited to study variation in short-term interest rates and breakeven around FOMC dates. The rule has two different types of shocks to match the multivariate stock return pattern documented in Figure 1. The first shock is a traditional short-term monetary policy shock that raises the the Federal Funds rate this quarter and lowers output and consumption through the

Euler equation. The second shock captures long-term economic news and is modeled via a shock to trend inflation. A decline in long-term inflation expectations acts like a costly disinflation similarly to Ball (1994) and Gürkaynak, Sack, and Swanson (2005b), moving the output gap and consumption expectations in the same direction as expected inflation. These effects are consistent with the effects of permanent interest rate shocks in Cochrane (2018), Uribe (2018), and Schmitt-Grohé and Uribe (2018). For simplicity, we model FOMC dates as occurring instantaneously and bearing no risk premium on average.

Our solution for asset prices preserves their full nonlinearity, following the best practices numerical solution of Wachter (2005). Nonlinear asset prices imply that after a sequence of bad shocks, when consumption is close to habit, required compensation for for holding risky assets – such as stocks – is high and required compensation for holding safe asses – such as nominal Treasury bonds – is low or even negative. The highly nonlinear nature of risk premia is necessary to generate high and volatile stock returns as in the data, and to ensure that the consumption Euler equation is log-linear. The main approximation we use in solving the model is a standard log-linearization procedure for the Phillips curve, since the Euler equation and monetary policy rule are already exactly log-linear.[2] By solving for log-linear macroeconomic dynamics, we keep the asset pricing solution tractable and focus on nonlinearities where they are most salient, namely in asset prices.

We estimate the model in two steps. We first calibrate the preference parameters, the parameters governing the firms' problem, and the monetary policy rule to standard values in the literature. In a second step, we use simulated method of moments (SMM) to estimate the volatilities of shocks. Our estimation targets reduced-form macroeconomic impulse responses for output, inflation, and the Federal Funds rate, and the volatility of quarterly changes in long-term breakeven, thereby matching basic volatilities and comovements in macroeconomic data. Despite the significant additional structure, our model is similarly successful in generating a low volatility of the output gap with a much higher volatility of stock returns as in Campbell and Cochrane (1999), and a negative stock market beta of long-term nominal Treasuries as in Campbell, Pflueger, and Viceira (2020). We obtain an equity Sharpe ratio of 0.50, an annualized equity premium of 6.82% and annualized equity return volatility of 13.55%. The model generates volatile excess returns for 10-year real bonds and breakeven, defined as the difference between nominal and real bond returns, though they are not as volatile in the data. Our model does not match the average risk premium in long-term nominal or real bonds, which is however

[2]Because we preserve the full nonlinearity of asset prices, our solution approach has the advantage of not mixing different orders of approximation.

hard to estimate reliably over a short sample of 20 years.

The model naturally explains the empirical evidence in Figure 1, Panel A, but only if the stock return response is amplified by countercyclical risk aversion. In the model, a positive shock to the short term nominal rate leads to declines in output and consumption. These model responses are hump-shaped, similarly to the data and to habit models with constant risk aversion (Fuhrer (2000), Boldrin, Christiano, and Fisher (2001)). As consumption declines towards habit, risk aversion and the return consumers require to hold risky stocks increase. Stock prices hence fall more than expected dividends, and our model attributes about one-half of the decline in stock prices to the higher required compensation for holding risk, in line with the empirical decomposition in Bernanke and Kuttner (2005).

The model ascribes the empirical evidence on breakeven inflation in Figure 1, Panel B, primarily to information about long-term inflation and output being revealed on FOMC dates. In the model, downward revisions to long-term inflation expectations tend to go along with lower expected output, as a permanent decline in inflation acts as a costly disinflation. In the model, the long-term monetary policy shock hence induces breakeven inflation and stock prices to rise and fall together, matching the positive comovement in the data. Risk premia again amplify the model decline in stock prices as consumption falls towards habit.

Finally, our model cautions against over-interpreting stock market responses to monetary policy during crisis periods. Our model predicts that when consumption is close to habit and risk bearing capacity is low, monetary policy may move stock markets significantly more than the real economy. This suggests that dramatic stock market responses to crisis monetary policy, such as during the Covid-19 crisis, may reflect volatile risk premia and need not indicate equally dramatic effectiveness for the real economy. This prediction follows naturally from the endogenous link between the business cycle and risk preferences in our model, and is in line with the higher volatility of stock returns around FOMC announcements in periods when the stock price-dividend ratio is low, such as during the financial crisis of 2008-09.

We contribute to a growing literature jointly modeling financial asset prices with New Keynesian macroeconomic dynamics. One strand of this literature uses long-run risks and Epstein-Zin preferences to understand asset pricing implications of macroeconomic channels (e.g. Van Binsbergen, Fernández-Villaverde, Koijen, and Rubio-Ramírez (2012), Kung (2015), Bretscher, Hsu, and Tamoni (2020), Gourio and Ngo (2020)). While these papers usually require an exogenously assumed link between the quantity of risk and other state variables, we generate an endogenous link between the macroeconomy and risk premia in financial markets. Prior research, including Uhlig (2007), Dew-Becker

(2014), Rudebusch and Swanson (2008), Lopez (2014), Stavrakeva and Tang (2019), and Bretscher, Hsu, and Tamoni (2019) has embedded simplified finance habit preferences into a New Keynesian model. By contrast, Campbell, Pflueger, and Viceira (2020) preserve the full non-linearity of Campbell and Cochrane (1999)'s consumption-based habit formation preferences, and thereby retain their favorable asset pricing properties generating volatile stock returns and stable short-term interest rates. We newly integrate these preferences with a model of monetary policy and use them to understand stock and bond responses to monetary policy news. This paper is complementary to theoretical work seeking to explain the strong stock return response to Federal Funds rate surprises. Lagos and Zhang (2020) present an explanation based on liquidity, and and Drechsler, Savov, and Schnabl (2018) and Kekre and Lenel (2020) propose models of of shifting wealth shares between agents with differing risk aversion. Our goal is complementary, in that we additionally match the two-dimensional shock structure around monetary policy announcements and the well-known equity volatility puzzle in lower-frequency data, thereby showing that high-frequency stock and bond movements around monetary policy announcements and the equity volatility puzzle are two sides of the same coin.

The paper is organized as follows. Section 2 presents the model. Section 3 solves the model and discusses how individual modeling assumptions affect the equilibrium properties. Section 4 estimates the model and assesses its macroeconomic and asset pricing implications. Section 5 concludes.

2 Model

2.1 Summary

The model is specified such that households' and firms' first-order conditions imply the smallest scale New Keynesian work-horse model, i.e. a log-linear consumption Euler equation and Phillips curve:

$$x_t = f^x E_t x_{t+1} + \rho^x x_{t-1} - \psi\left(r_t - r_t^a\right) + v_{x,t}, \tag{1}$$

$$\pi_t = f^\pi E_t \pi_{t+1} + \rho^\pi \pi_{t-1} + \kappa x_t + v_{\pi,t}, \tag{2}$$

while nesting the asset pricing habit preferences of Campbell, Pflueger, and Viceira (2020), which, in turn, build on a long-standing literature of habits in finance (Constantinides (1990), Campbell and Cochrane (1999), Wachter (2006)).

Here, r_t denotes the log real risk-free interest rate that can be earned from time t to time $t+1$, the output gap, x_t, equals log real output minus log potential output at the

hypothetical equilibrium without price–setting frictions (Woodford (2003a), p.245), and π_t is log quarterly inflation. The rate r_t^a is the frictionless real rate related to expected productivity growth. The demand and Phillips curve shocks $v_{x,t}$ and $v_{\pi,t}$, and the positive coefficients f^x, ρ^x, ψ, f^π, ρ^π, κ arise from consumer preferences and the firm's problem. The consumption Euler equation is exact, and the Phillips curve is derived from the usual log-linearization. Both equations are specified up to a constant. We use lower-case letters to denote log variables throughout.

2.2 Preferences

2.2.1 Finance habit

There is a representative agent whose utility depends on the difference between consumption C_t and external habit H_t:

$$U_t = \frac{(C_t - H_t)^{1-\gamma} - 1}{1-\gamma} = \frac{(S_t C_t)^{1-\gamma} - 1}{1-\gamma}. \tag{3}$$

Here C_t is the quantity of market goods available for consumption, H_t is consumers' habit level for market-produced goods, and γ is a curvature parameter. The surplus consumption ratio

$$S_t = \frac{C_t - H_t}{C_t} \tag{4}$$

is the fraction of market consumption that is available to generate utility. Relative risk aversion varies inversely with the surplus consumption ratio: $-U_{CC}C/U_C = \gamma/S_t$.

The consumer first-order condition implies that the gross one-period real return $(1 + R_{t+1})$ on any asset satisfies

$$1 = \mathrm{E}_t \left[M_{t+1} \left(1 + R_{t+1} \right) \right], \tag{5}$$

where the stochastic discount factor is related to the log surplus consumption ratio s_{t+1} and log consumption c_{t+1} by

$$M_{t+1} = \frac{\beta U'_{t+1}}{U'_t} = \beta \exp\left(-\gamma (\Delta s_{t+1} + \Delta c_{t+1}) \right). \tag{6}$$

2.2.2 Surplus consumption dynamics

We model implicitly how habit adjusts to the history of consumption through the dynamics for log surplus consumption:

$$s_{t+1} = (1-\theta_0)\bar{s} + \theta_0 s_t + \theta_1 x_t + \theta_2 x_{t-1} + \varepsilon_{s,t} + \lambda(s_t)\varepsilon_{c,t+1}, \tag{7}$$

$$\varepsilon_{c,t+1} = c_{t+1} - \mathrm{E}_t c_{t+1}. \tag{8}$$

Here, $\bar{s}$ is steady-state log surplus consumption and $\varepsilon_{s,t}$ is a serially uncorrelated homoskedastic habit shock. The consumption shock $\varepsilon_{c,t}$ will be derived as a function of fundamental shocks in equilibrium. For now, we note that it is conditionally homoskedastic and serially uncorrelated with standard deviation σ_c.

The sensitivity function $\lambda(s_t)$ takes the form:

$$\lambda(s_t) = \begin{cases} \frac{1}{\bar{S}}\sqrt{1-2(s_t-\bar{s})}-1 & s_t \leq s_{max} \\ 0 & s_t > s_{max} \end{cases}, \tag{9}$$

$$\bar{S} = \sigma_c\sqrt{\frac{\gamma}{1-\theta_0}}, \tag{10}$$

$$\bar{s} = \log(\bar{S}), \tag{11}$$

$$s_{max} = \bar{s} + 0.5(1-\bar{S}^2). \tag{12}$$

The downward-sloping relation between $\lambda(s_t)$ and s_t has the intuitive implication that marginal consumption utility is particularly sensitive to consumption innovations when investors are close to their habit consumption level, as would be the case after a sequence of bad shocks. The particular non-linear form of $\lambda(s_t)$ implies that s_t drops out of the asset pricing Euler equation for the real risk-free rate, because the associated intertemporal substitution and precautionary savings terms cancel exactly. The terms $\theta_1 x_t$ and $\theta_2 x_{t-1}$ make habit depend on the output gap. Our model has no real investment, so it is intuitive to interpret the x_t terms as consumption relative to a frictionless level entering into surplus consumption. If $\theta_1 > 0$ and $\theta_2 < 0$, as in our empirical specification, the dependence of habit on the most recent consumption lag increases and its dependence on longer lags decreases relative to simple geometric weights. Up to this point, our only departure from Campbell, Pflueger, and Viceira (2020) is the habit shock $\varepsilon_{s,t}$, which captures independent fluctuations in habit and leads to a shock in the consumption Euler equation. A positive $\varepsilon_{s,t}$ lowers future expected habit and increases future expected surplus consumption, reducing risk aversion.[3]

2.2.3 Labor-leisure trade-off

Before describing the firm's problem we need to specify households' intratemporal labor-leisure trade-off, which is at the heart of wage determination. To achieve a standard functional form for the Phillips curve, we choose a labor disutility specification that ensures surplus consumption does not enter into the intratemporal labor-leisure trade-off.

[3] A similar intuition is captured by the reduced-form "moody investor" model of Bekaert, Engstrom, and Grenadier (2010) and Bekaert, Engstrom, and Xu (2019). We go beyond this prior literature by integrating preferences with typical New Keynesian microfoundations, and we separate habit shocks from heteroskedasticity in fundamentals.

Following the classic model of Greenwood, Hercowitz, and Huffman (1988), we assume that the representative household's total consumption, C_t^{tot}, is the sum of market consumption, C_t, and home production C_t^{home}:

$$C_t^{tot} = C_t + C_t^{home}, \tag{13}$$

$$C_t^{home} = A_t N_t \frac{\int_0^1 (1 - L_{i,t})^{1-\chi} \, di}{1 - \chi}. \tag{14}$$

Here, $L_{i,t}$ denotes the differentiated labor used for production by firm i and $(1 - L_{i,t})$ is labor used for home production. Home production has decreasing returns to scale, as in Campbell and Ludvigson (2001), and the parameter χ determines the elasticity of market labor supply. The differentiated labor assumption follows Woodford (2003, Chapter 3) and generates real rigidities from labor immobility across sectors (Ball and Romer (1990)).

The utility function (3) is specified in terms of market consumption C_t and habit H_t, which allows us to fit the model to data on market goods output. However, this basic utility function is clearly equivalent to a power utility function over the difference between total consumption and total habit, with total habit given by $H_t^{tot} = H_t + C_t^{home}$. Intuitively, home consumption drives up total habit one-for-one, and does not generate time-varying risk aversion over market goods consumption.

2.3 Firm Problem

2.3.1 Demand

Demand for the differentiated good i is downward-sloping in its product price $P_{i,t}$:

$$Y_{i,t} = Y_t \left(\frac{P_{i,t}}{P_t} \right)^{-\theta_t}. \tag{15}$$

Here, $P_t = \left[\int_0^1 P_{i,t}^{-(\theta_t - 1)} di \right]^{-\frac{1}{\theta_t - 1}}$ is the aggregate price level. The time-varying elasticity of substitution θ_t is assumed to be log-normally distributed around steady-state θ. Shocks to $\log \theta_t$ are denoted $\varepsilon_{\theta,t}$ and assumed to be serially uncorrelated and homoskedastic. Aggregate output and labor are Dixit-Stiglitz aggregates of differentiated goods $Y_{i,t}$ and labor $L_{i,t}$

$$Y_t \equiv \left[\int_0^1 Y_{i,t}^{\frac{\theta_t - 1}{\theta_t}} di \right]^{\frac{\theta_t}{\theta_t - 1}}, \; L_t \equiv \left[\int_0^1 L_{i,t}^{\frac{(\theta_t - 1)(1-\tau)}{\theta_t}} di \right]^{\frac{\theta_t}{(\theta_t - 1)(1-\tau)}}. \tag{16}$$

Because there is no time-varying real investment, consumption equals output $C_t = Y_t$.

2.3.2 Production

Firm i produces according to a Cobb-Douglas production function with capital share τ:

$$Y_{i,t} = A_t N_t L_{i,t}^{1-\tau}. \tag{17}$$

Productivity is the product of technology, A_t, and human capital, N_t. We incorporate predictable productivity growth in the simplest possible manner, assuming that A_t is predictable one period ahead, i.e. that the change in log technology Δa_{t+1} is known at time t. Following Lucas (1988), human capital depends on the average skill acquired by all agents, so agents do not internalize the effect of acquiring skills on aggregate production. We assume that for some constants $0 \leq \phi \leq 1$ and $\nu > 0$, changes in log human capital are driven by past market labor, l_{t-1}:

$$n_t = \nu + n_{t-1} + (1-\phi)(1-\tau) l_{t-1}. \tag{18}$$

Alternatively, the process (18) can be interpreted as a simple endogenous capital stock, similarly to Woodford (2003a) (Chapter 5), if a fixed proportion of employment each period is used as an input to produce investment goods. If real investment comes out of labor, this interpretation would leave the relationship between consumption and output unchanged and only the constants in the home production function (14) would change. The purpose of n_t is simply to detrend the output gap, so the specific interpretation is not central for us.

To economize on state variables, we assume that productivity growth is perfectly predictable and is a linear function of existing state variables, and in particular the real risk-free rate

$$\Delta a_{t+1} = \rho^a r_t \tag{19}$$

This relationship captures the intuition that the central bank may try to set the real risk-free rate following variation in the natural rate due to variation in expected growth rates (Nakamura and Steinsson (2018)). We use the notation

$$r_t^a = \gamma \Delta a_{t+1} \tag{20}$$

for the natural real rate due to expected productivity growth.[4]

[4]The purpose of time-varying expected productivity growth is simply to generate volatility in real bonds, and to drive down the real bond return correlation with output and stock returns. The assumption of predictable productivity growth does not affect the stock return responses to Federal Funds rate surprises or long-term inflation innovations, which are the focus of our analysis (Appendix Table 5).

2.3.3 Price setting

When a firm can update its product price, it maximizes the discounted sum of current and future expected profits discounted at the stochastic discount factor while the price remains in place. Firm profits equal output minus the cost of labor, subject to the production function (17), demand for differentiated goods (15), and taking wages from consumers' labor-leisure trade-off as given.

Firms face price-setting frictions in the manner of Calvo (1983), where fraction $1-\alpha$ of firms can change prices every period with equal probabilities across firms. When firms cannot update, their prices are indexed to lagged inflation (Smets and Wouters, 2003; Christiano, Eichenbaum, and Evans, 2005). A firm that last reset its price at time t to $\tilde{P}_t$, charges a nominal time $t+j$ price $\tilde{P}_t \left(\frac{P_{t-1+j}}{P_{t-1}}\right)$.

2.4 Monetary Policy

Motivated by the empirical evidence in Figure 1, we choose the simplest Taylor-type rule with a two factor shock structure (ignoring constants):

$$
\begin{aligned}
i_t &= \rho^i i_{t-1} + \left(1-\rho^i\right) i_t^* + v_{ST,t}, && (21)\\
v_t^* &= v_{t-1}^* + v_{LT,t} && (22)\\
i_t^* &= \gamma^x x_t + \gamma^\pi \pi_t + \left(1-\gamma^\pi\right) v_t^* && (23)
\end{aligned}
$$

The first shock, $v_{ST,t}$, is a short-term monetary policy shock and represents a standard innovation to the short-term nominal interest rate. The second shock, v_{LT}^*, is a long-term monetary policy shock and shifts the random walk component of inflation expectations, v_t^*, thereby moving the entire term structure of nominal interest rates.[5] We assume that short-term and long-term monetary policy shocks are uncorrelated, motivated by the empirical correlation between Fed Funds rate and breakeven innovations on FOMC dates in our sample being close to zero. Here, i_t^* denotes the central bank's interest rate target, to which it adjusts slowly with a smoothing coefficient ρ^i.

To keep the macroeconomic dynamics tractable and log-linear we use the common log-linear approximation for the nominal log short-term interest rate

$$
i_t = r_t + E_t \pi_{t+1}. \qquad (24)
$$

Note that the frictionless real rate, more broadly defined, would encompass both r_t^a and shocks to preferences (Woodford (2003b)).

[5] We do not explicitly model the zero-lower-bound (ZLB) for simplicity, leaving this application for future research. One simple way to incorporate the ZLB explicitly into the model would be through a Markov regime switching model, which would preserve the tractability of the model.

The approximation error stemming from (24) in our estimated model is small and within the range of measurement error of bond yields. We do not approximate longer-term bond prices, instead solving for time-varying risk premia numerically.

2.5 Stocks

We model stocks as a levered claim on consumption, as in Abel (1990) and Campbell (2003), while preserving the cointegration of consumption and dividends. Let P_t^c denote the price of a claim to the entire future consumption stream C_{t+1}, C_{t+2},... At time t the aggregate firm buys P_t^c and sells equity worth δP_t^c, with the remainder of the firm's position financed by one-period risk-free debt worth $(1-\delta)P_t^c$. Stocks in our model should therefore simply be interpreted as a financial asset with pro-cyclical dividends, rather than a financial claim tied specifically to firm cash flows.[6]

3 Model Solution and Discussion

3.1 Steady-State and Output Gap

We log-linearize output, consumption, and labor around the steady-state with $\bar{Y}_t = A_t \bar{L}^{1-\tau}$, where $\bar{L}$ is the labor supply consistent with flexible prices and steady-state markups. We use hats to denote log deviations from this steady-state. In a flexible-price equilibrium, each firm wishes to charge a markup $\frac{\theta_t}{\theta_t - 1}$ over real marginal cost.

The log output gap x_t is the deviation of log output from the flexible-price equilibrium (up to a constant):

$$x_t \;=\; y_t - n_t - a_t = c_t - (1-\phi)\sum_{j=0}^{\infty}\phi^j c_{t-1-j} - \sum_{j=0}^{\infty}\phi^j \Delta a_{t-j}. \tag{25}$$

Here, we have used the resource constraint $y_t = c_t$ and the process for human capital (18). Equation (25) has the appealing feature that the empirical output gap from the Bureau of Economic Analysis closely resembles stochastically detrended consumption (Campbell, Pflueger, and Viceira (2020)). Inverting equation (25) gives an intuitive expression for consumption growth in terms of the output gap and productivity growth:

$$\Delta c_{t+1} \;=\; x_{t+1} - \phi x_t + \Delta a_{t+1}. \tag{26}$$

[6] Alternatively, one could models stocks as a claim on firm profits rather than consumption. However, this would require modeling infrequent wage setting to match the cyclical behavior of dividends (Favilukis and Lin (2016)). Since our goal is to understand the implications of a time-varying price of risk in response to monetary policy more generally, it is not crucial for us whether stocks represent a claim on profits.

3.2 Euler Equation

We obtain the *exact* log-linear Euler equation (1) in terms of preference parameters:

$$x_t = \underbrace{\frac{1}{\phi - \theta_1}}_{f^x} \mathrm{E}_t x_{t+1} + \underbrace{\frac{\theta_2}{\phi - \theta_1}}_{\rho^x} x_{t-1} - \underbrace{\frac{1}{\gamma(\phi - \theta_1)}}_{\psi} (r_t - r_t^a) + \underbrace{\frac{1}{\phi - \theta_1}}_{v_{x,t}} \varepsilon_{s,t}. \tag{27}$$

This expression is the no-arbitrage condition (5) for the one-period real risk-free bond, substituting in the stochastic discount factor (6), log surplus consumption dynamics (7), and the updating equation for consumption growth (26). The log-linear Euler equation (27) does not depend on the specific microfoundations for consumption and output, provided that consumption is homoskedastic and satisfies the updating equation (26).

Our modeling choices simplify the no-arbitrage condition for the one-period real risk-free bond, and ensure that it takes exactly the form of a New-Keynesian consumption Euler equation. The specific nonlinear form of the sensitivity function $\lambda(s_t)$ has the unique advantage that the precautionary savings and intertemporal substitution terms from s_t cancel, and s_t is not a state variable for macroeconomic dynamics. Surplus consumption dynamics are of course linked to the consumption Euler equation (27) through consumption and habit shocks.

The Euler equation (27) shows that $\theta_2 > 0$ generates a lagged output gap term. As a lagged output gap term is known to be crucial for matching hump-shaped output gap responses to monetary policy shocks (Boldrin, Christiano, and Fisher (2001) and Fuhrer (2000)), this parameter is essential for linking the finance and monetary policy sides of our model. In our estimation, we constrain the parameter θ_1 so that the forward- and backward-looking terms in the consumption Euler equation sum to one.

The habit shock microfounds risk-centric demand shocks in the Euler equation, and shows that preference shocks enter into macroeconomic dynamics in line with a growing literature including Christiano, Motto, and Rostagno (2014), Caballero and Simsek (2020), Pflueger, Siriwardane, and Sunderam (2020), and Kekre and Lenel (2020). Demand shocks from other microfoundations, such as a gap between interest earned by consumers relative to the interest rate controlled by the central bank (Smets and Wouters (2007)), or a shock to the rate of time preference (e.g. Justiniano and Primiceri (2008), Albuquerque, Eichenbaum, Luo, and Rebelo (2016)), would lead to similar macroeconomic dynamics but different asset pricing implications. Demand shocks microfounded from habit allow us to use a single stochastic discount factor to price all assets, and drive bonds and stocks in opposite directions similarly to the data.

3.3 Phillips Curve

Combining the labor-leisure choice (14) with external habit preferences (3) and log-linearizing around a steady-state with $\bar{L}_{i,t} = \bar{L}$ gives a standard expression for the log-linearized real wage in terms of labor supply (up to a constant):

$$\hat{w}_{i,t} = \underbrace{\left(\chi \frac{\bar{L}}{1-\bar{L}}\right)}_{\text{Inverse Frisch } \eta} \hat{l}_{i,t}. \tag{28}$$

Equation (28) makes clear that the log-linearized real wage takes a standard form independent of habit, thereby sidestepping the issue noted by Lettau and Uhlig (2000) that habit may affect labor supply decisions in a production economy. Comparing to standard New Keynesian models (e.g. Galí (2008)) our log real wage is even somewhat simpler because it does not depend on aggregate consumption.[7] When consumption is close to habit the marginal utility from both market and home consumption is high, leaving the wage unaffected. In practice, this might capture that after an adverse shock consumers shift from eating out to cooking at home, as documented in Aguiar, Hurst, and Karabarbounis (2013). The assumption that home production increases with aggregate productivity, $A_t N_t$, ensures that the labor-leisure trade-off does not become irrelevant over time (Kehoe, Lopez, Midrigan, and Pastorino (2019)), consistent with empirical evidence (Chodorow-Reich and Karabarbounis (2016)).

We then proceed with standard log-linearization of the firms' price-setting problem around the random walk component v_t^* (Cogley and Sbordone (2008)) to obtain the log-linearized Phillips curve:

$$\pi_t = \underbrace{\frac{\beta_g}{1+\beta_g}}_{f^\pi} E_t \pi_{t+1} + \underbrace{\frac{1}{1+\beta_g}}_{\rho^\pi} \pi_{t-1} + \kappa x_t + \underbrace{\left(-\frac{\kappa}{\omega(\theta-1)}\right)}_{v_{\pi,t}} \varepsilon_{\theta,t}. \tag{29}$$

Here, $\beta_g = \beta exp\left(-(\gamma-1)g\right)$ is the growth-adjusted time discount rate, and the slope of the Phillips curve equals $\kappa = \frac{1-\alpha}{\alpha}\frac{1-\beta_g\alpha}{1+\beta_g}\frac{\omega}{1+\omega\theta}$. The parameter $\omega = (\tau+\eta)/(1-\tau)$ captures the steady-state elasticity of real marginal cost vs. own-firm output.

A complementary approach to separate wages from consumption habit would be to introduce separate habits for consumption and leisure combined with labor market frictions, though matching asset pricing moments can be challenging in such a setup (Uhlig (2007), Rudebusch and Swanson (2008), Lopez (2014)). Our formulation is more parsimonious and requires only one parameter, closely related to the Frisch elasticity of labor

[7] Because labor supply and consumption are linked in equilibrium, this has no effect on the qualitative nature of the log-linearized Phillips curve and a negligible quantitative effect.

supply, to describe preferences over leisure (χ). Because of this parsimony we consider our model a useful template to study the interaction between labor market frictions and habits in future research.

3.4 Macroeconomic Equilibrium Dynamics

We first solve for log-linear macroeconomic dynamics, and second for highly nonlinear asset prices. This tractability is achieved because the surplus consumption ratio does not appear directly in the Euler equation or the Phillips curve, though finance and macroeconomics are connected through habit and consumption shocks. Equilibrium macroeconomic dynamics are determined by the real rate Euler equation (27), the log-linearized Phillips curve (29), and the monetary policy rule (21) through (23). The macroeconomic state vector is:

$$Y_t \quad = \quad [x_t, \pi_t - v_t^*, i_t - v_t^*]', \tag{30}$$

and the vector of structural shocks is

$$v_t \quad = \quad [v_{x,t}, v_{\pi,t}, v_{ST,t}, v_{LT,t}]'. \tag{31}$$

The vector of shocks v_t is assumed to be homoskedastic with a time-invariant diagonal variance-covariance matrix. Further, v_t is assumed to be serially uncorrelated and multivariate normal. We denote the standard deviations σ_x, σ_π, σ_{ST}, and σ_{LT}. We solve for a minimum state variable equilibrium of the form:

$$Y_t = BY_{t-1} + \Sigma v_t, \tag{32}$$

where B and Σ are [3×3] and [3×4] matrices, respectively. We solve for the matrix B using Uhlig (1999) formulation of the Blanchard and Kahn (1980) method. For our estimation, we choose a monetary policy rule that raises real rates in response to an increase in inflation ($\gamma^\pi > 1$), so there exists a unique equilibrium of the form (32) in which all eigenvalues of B are less than one in absolute value. However, New Keynesian models are subject to well-known equilibrium multiplicity issues and equilibria with additional state variables or sunspots may exist (Cochrane (2011)), and resolving these issues is beyond this paper.

3.5 Solving for Asset Prices

We use numerical best practices to preserve the full nonlinearity of asset prices (Wachter (2005)). We use the following recursion to solve for the price-consumption ratio of an n-period zero-coupon consumption claim:

$$\frac{P_{nt}^c}{C_t} = \mathrm{E}_t\left[M_{t+1}\frac{C_{t+1}}{C_t}\frac{P_{n-1,t+1}^c}{C_{t+1}}\right]. \tag{33}$$

The price-consumption ratio for a claim to aggregate consumption is equal to the infinite sum of zero-coupon consumption claims:

$$\frac{P_t^c}{C_t} = \sum_{n=1}^{\infty}\frac{P_{nt}^c}{C_t}. \tag{34}$$

The price of the levered equity claim equals $P_t^\delta = \delta P_t^c$. Leverage hence scales stock returns roughly proportionally, increasing stock return volatility but leaving the Sharpe ratio unchanged. We initialize the recursions for real and nominal zero coupon bond prices:

$$P_{1,t} = \exp\left(-r_t\right), \tag{35}$$
$$P_{1,t}^{\$} = \exp(-i_t). \tag{36}$$

The n-period zero coupon prices follow the recursions:

$$P_{n,t} = \mathrm{E}_t\left[M_{t+1}P_{n-1,t+1}\right], \tag{37}$$
$$P_{n,t}^{\$} = \mathrm{E}_t\left[M_{t+1}\exp(-\pi_{t+1})P_{n-1,t+1}^{\$}\right]. \tag{38}$$

Log bond yields for real and nominal zero coupon bonds with maturity n are defined by $y_{n,t} = -\log\left(P_{n,t}\right)/n$ and $y_{n,t}^{\$} = -\log\left(P_{n,t}^{\$}\right)/n$.

The model generates an intuitive flight-to-safety effect, driving up safe asset prices and decreasing risky asset prices when surplus consumption is low. To gain intuition, we solve analytically for the risk premium of a one-period consumption claim. This claim pays aggregate consumption in period $t+1$ and pays nothing in all other periods, thereby sharing the cyclical properties of stocks but having a shorter horizon. We denote the log return on the one-period consumption claim by $r_{1,t+1}^c$. The risk premium, adjusted for a standard Jensen's inequality term, equals the conditional covariance between the negative

log SDF and and log output:

$$\begin{aligned} E_t\left[r^c_{1,t+1} - r_t\right] + \frac{1}{2}Var\left(r^c_{1,t+1}\right) &= \mathrm{Cov}_t\left(-m_{t+1}, x_{t+1}\right), \\ &= \gamma\left(1+\lambda\left(s_t\right)\right)\sigma_c^2. \end{aligned} \tag{39}$$

Equation (39) shows that risk premia are time-varying and increase with the sensitivity function $\lambda(s_t)$. Investors require a higher expected return for holding risky assets when surplus consumption is highly sensitive to consumption, as is the case when surplus consumption is low. The relationship between risk premia and surplus consumption has the reverse sign for safe assets that comove positively with SDF.

We solve for asset prices numerically on a four-dimensional grid consisting of the macroeconomic state vector $\hat{Y}_t$ and the surplus consumption ratio s_t. Iterating along a grid, as opposed to local approximation or global solution methods, is the best practice for this type of numerical problem because it imposes the least structure (Wachter (2005)). By contrast, approximation with polynomials would miss the particularly strong non-linearity of the sensitivity function as the log surplus consumption ratio becomes small, distorting numerical asset prices even around the steady-state. Grid iteration is facilitated in our framework because macroeconomic dynamics are log-linear. For details of the numerical solution see the Appendix.

3.6 Modeling FOMC Date Shocks

We assume that the quarterly fundamental shock vector v_t consists of independent pre-FOMC and FOMC shocks:

$$v_t = v_t^{pre} + v_t^{FOMC}.$$

The vector of FOMC shocks is assumed to have a diagonal variance-covariance matrix with standard deviations σ_x^{FOMC}, σ_π^{FOMC}, σ_{ST}^{FOMC}, and σ_{LT}^{FOMC}. We solve for the variance-covariance matrix of v_t^{pre} such that the standard deviations of v_t are as described in section 3.4. We model FOMC announcements as occurring instantaneously, so no dividends are paid and the aggregate price level is constant during the short FOMC interval. We solve for pre-FOMC prices of stocks, real and nominal bonds by setting the FOMC shock to its mean (i.e. $v_t^{FOMC} = 0$), whereas the post-FOMC price is computed at random realizations of v_t^{FOMC}.

4 Estimated Model

We estimate the model in two steps. In a first step, we set preference parameters, firm parameters, and monetary policy parameters to standard values from the literature. In a second step, we use a Simulated Method of Moments (SMM) procedure to estimate the standard deviations of shocks.

4.1 Calibrated Parameters

Table 1, Panel A lists the calibrated parameters. The consumption growth rate, utility curvature, steady-state real risk free rate, persistence of surplus consumption, and the learning-by-doing parameter ϕ responsible for detrending output are taken from Campbell, Pflueger, and Viceira (2020). We choose the preference parameters θ_1 and θ_2 to match the macroeconomics literature. We choose $\theta_2 = 0.6$ in line with the habit parameters in Fuhrer (2000), Smets and Wouters (2007), Christiano, Eichenbaum, and Evans (2005). The parameter θ_1 is set to ensure that the forward- and backward-looking parameters in the real rate Euler equation sum to one.

On the firm side, we follow Galí (2008). We set the price-stickiness parameter to 0.67, meaning that the average price duration is three-quarters. The capital share of production is set to a standard value of $\tau = 1/3$. The cross-goods substitutability is set to $\theta = 6$, implying a steady-state markup of 20%. The steady-state Frisch elasticity of labor supply, which in our model equals $\left(\chi \frac{\bar{L}}{1-\bar{L}}\right)^{-1}$, is set to one. We set the leverage parameter to 0.4. We interpret this leverage parameter broadly, to include operational leverage. The main purpose of this parameter is to match the volatility of equity returns, while leaving the equity Sharpe ratio unchanged.

We also choose conventional monetary policy parameters. The reaction coefficients for inflation and output fluctuations are from Taylor (1993) and equal $\gamma_x = 0.5$ and $\gamma_\pi = 1.5$. The monetary policy smoothing parameter is set to 0.9 to match the larger root in interest rates estimated by Nakamura and Steinsson (2018). We set ρ^a determining the relationship between expected growth and the real rate to $0.34 = 0.68/\gamma$ to match the relationship between the frictionless real rate embedded in growth expectations and the actual real rate in Nakamura and Steinsson (2018).

4.2 SMM Estimation

Having calibrated this initial set of parameters, we estimate the vector of standard deviations $\sigma = [\sigma_x, \sigma_\pi, \sigma_{ST}, \sigma_{LT}]$ by minimizing the objective function

$$J(\sigma) = (\Psi(\sigma) - \hat{\Psi})' V(\hat{\Psi})^{-1} (\Psi(\sigma) - \hat{\Psi}).$$

Following Christiano, Eichenbaum, and Evans (2005), the vector $\hat{\Psi}$ collects empirical macroeconomic impulse responses, and we weight each moment by the inverse of its bootstrapped variance. Our sample begins in 2001Q2, when the relationship between inflation and empirical output gap measures displays a structural change (Campbell, Pflueger, and Viceira, 2020), and ends in 2019Q2. The vector $\Psi(\sigma)$ collects the corresponding model moments, obtained by applying the same procedure to simulated data of the same length. Our moments are from a one lag VAR in the log output gap, the one-quarter change in inflation, and the difference between the nominal Federal Funds rate and inflation, thereby respecting the joint unit root in inflation and nominal interest rates in the model.[8] Impulse responses are orthogonalized so shocks to the Fed Funds rate do not contemporaneously affect inflation or output, and inflation innovations do not enter into the same period output. This orthogonalization does not directly identify the structural shocks in our model, and merely defines a unique set of empirical macroeconomic moments that are comparable to the literature. We target the output gap, inflation, and Fed Funds rate responses in periods 0, 1, 2 , 4, 8, and 12 quarters after the initial shock giving us $3 \times 6 = 18$ moments. Since σ_{LT} is not well identified from the reduced-form macroeconomic impulse responses, we additionally target the standard deviation of quarterly changes in inflation swap rates for 10-year inflation starting 10 years from now, which we estimate to equal 0.26% over our sample.[9] For details of the SMM procedure see the Appendix.

The estimated standard deviations of shocks are shown in Table 1, Panel B. The Phillips curve shock is somewhat more volatile than the demand and short-term monetary policy shocks. The long-term monetary policy shock is the least volatile, and its volatility of 0.22% closely matches the standard deviation of quarterly changes in 10 on 10-year breakeven inflation in the model, which equals 0.26% just like in the data.

4.3 Model Fit

4.3.1 Macroeconomic Dynamics

Figure 2 shows that the model matches the empirical volatilities of the output gap, inflation, and Fed Funds rate, their persistence over time, and their comovements. It is

[8] Quarterly real GDP, real potential GDP, and the GDP deflator in 2012 chained dollars are from the FRED database at the St. Louis Federal Reserve. Since output, unlike asset prices, is a flow over a quarter, it can be treated either as occurring at the beginning or end of a quarter. We follow Campbell (2003) and align output reported for quarter t with interest rates and stock prices measured at the end of quarter $t-1$. The log output gap is in percent units. We use the Federal Funds rate averaged over the last week of the quarter from the Federal Reserve's H.15 publication. Interest rates and inflation are in annualized percent.

[9] Inflation swap rates, in annualized percent, are from Bloomberg.

important to keep in mind that the impulse responses shown in Figure 2 are not structural, only a statistical decomposition, and that each innovation reflects a combination of the underlying structural shocks. We turn to structural impulse responses in section 4.4.1.

Both in the model and in the data the output gap, inflation, and the Federal Funds rate tend to move together in response to all innovations, with the exception of the interest rate innovation. The interest rate innovation has a negative but quantitatively small output gap response both in the model and in the data. The overall positive inflation-output gap comovement in Figure 2 is consistent with prior literature, which documents that the output gap-inflation correlation is positive and long-term nominal bonds are hedges for the post-2001 period (Baele, Bekaert, and Inghelbrecht (2010), Campbell, Sunderam, Viceira, et al. (2017), Song (2017), Campbell, Pflueger, and Viceira (2020), Gourio and Ngo (2020)).

4.3.2 Asset Prices

Table 2 shows that our model also generates volatile stock returns with an empirically plausible equity Sharpe ratio of 0.50, an equity premium of 6.57%, and annualized equity return volatility of 13.02%. This high stock return volatility is achieved through time-varying risk premia of the form (39).[10] The model fits the negative breakeven beta with respect to the stock market, which Campbell, Pflueger, and Viceira (2020) have argued is important to generate endogenous flight-to-safety towards nominal bonds when equity risk premia rise. The real bond-stock beta in the model is slightly positive, compared to a slightly negative real bond beta in the data. Breakeven excess returns are volatile at 5.01% similarly to the data, and real bond excess returns in the model have substantial volatility at 1.56%. The empirical volatility of 10-year TIPS excess returns exceeds the real bond return volatility in the model at 6.82%. However, this empirical volatility is likely overestimated because TIPS contain large and time-varying liquidity premium (Gürkaynak, Sack, and Wright (2010), Fleckenstein, Longstaff, and Lustig (2014), Pflueger and Viceira (2016)).

While the model matches the data well along many dimensions, it misses realized excess bond returns over our sample period. We face a choice between fitting betas or term premia and we prefer to fit second moments, which are measured more precisely

[10]To compute the empirical asset pricing moments, we use value-weighted combined NYSE/AMEX/-Nasdaq stock returns including dividends from CRSP. The dividend-price ratio is constructed using data for real S&P 500 dividends and the S&P 500 real price from Robert Shiller's website. For both bonds and stocks, we consider log returns in excess of the log T-bill rate, where the end-of-quarter three-month T-bill is from the CRSP monthly Treasury risk-free rate file. Log bond returns are derived from changes in yields in the data. End-of-quarter bond yields for both nominal Treasuries and TIPS are from the daily zero coupon curves of Gürkaynak, Sack, and Swanson (2005b) and Gürkaynak, Sack, and Wright (2010). All yields and returns are continuously compounded.

over short samples. The fundamental tension between matching a positive term premium and a negative bond beta is not specific to our model and arises for most single-factor models. For example, the seminal contribution of Wachter (2005) obtains a positive term premium from a positive bond-stock beta, which however has turned negative in our more recent sample. Regime switches in monetary policy can potentially resolve this tension (Song (2017)), and although exploring them is beyond this current paper we believe that the convenient log-linear macroeconomic dynamics would make our model a tractable building block.

4.4 Model Drivers

To better understand the model mechanisms, we show impulse responses to the structural innovations $v_{x,t}$, $v_{\pi,t}$, $v_{ST,t}$ and $v_{LT,t}$.

4.4.1 Structural Macroeconomic Responses

Figure 3 confirms that the macroeconomic side of our model behaves like a standard three-equation New Keynesian model. A habit shock acts as a demand shock and leads to a temporary increase in output, and a smaller temporary increase in inflation. A positive Phillips curve shock, due to an increase in markups, leads to a decline in output and an increase in inflation. A short-term increase in the short-term interest rate causes a decline in output through consumers' consumption-savings decision, and lower inflation through the Phillips curve. Finally, a negative long-term monetary policy shock leads to a costly disinflation, lowering inflation expectations ahead of nominal interest rates, and thereby raising the real rate and contracting output. The backward-looking component in the consumption Euler equation ensures a hump-shaped output gap responses as in Fuhrer (2000) and Boldrin, Christiano, and Fisher (2001).

4.4.2 Structural Asset Price Responses

Figure 4 shows that the structural impulse responses for stocks and bonds follow naturally from the macroeconomic impulse responses. The first row shows cumulative equity returns in excess of the steady-state return, and the subsequent rows show yields on 10-year nominal and real bonds. Because bond yields are inversely related to prices, an increase in the 10-year yield implies a decrease in the corresponding bond price.

Comparing the first rows across Figures 3 and 4 shows that stock prices move in the same direction as output gap responses, with the overall stock response quantitatively dominated by time-varying risk premia.[11] The second row of Figure 4 shows that long-

[11]The risk neutral response for all asset prices is computed as if assets were priced by a risk neutral

term nominal bond yields respond in the same direction as the Federal Funds rate in Figure 3. The third row of Figure 4 shows that 10-year real bond yields respond in the same direction as the short-term real rate and are almost exclusively driven by the risk-neutral component.

The first column of Figure 4 helps understand the habit shock, and shows that it affects asset prices through both intertemporal substitution and risk aversion. The expected increase in surplus consumption generates an incentive for intertemporal substitution, driving down risk-neutral prices of both real bonds and stocks. Because bond yields move inversely with prices, risk-neutral long-term real bond yields increase. Higher expected surplus consumption also affects risk premia, because it leads to higher consumption today through the consumption Euler equation, raising surplus consumption and driving up stock prices. The risk premium effect dominates the stock price response, whereas the risk-neutral component dominates the real bond yield response. The demand shock therefore has the unique ability to drive down the real bond-stock beta towards zero.

4.5 Equity returns on FOMC dates

Having seen that time-varying risk premia amplify stock return responses to macroeconomic shocks, we now turn to stock price changes around FOMC dates. In this Section, we first expand on the motivating evidence reported in Figure 1 and then show how the model can account for these empirical patterns.

In Table 3, we establish the relationships described in Figure 1 more formally. Column (1) corresponds to the left panel of Figure 1, and replicates the classic result of Bernanke and Kuttner (2005). We find that a 25 bps surprise increase in the Federal Funds rate empirically leads to around one percentage point drop in the stock price on average.[12] Column (2) mirrors the right panel of Figure 1 and shows that breakeven changes on FOMC dates have a statistically significant and economically meaningful positive relationship with stock returns around FOMC announcements. In contrast to column (1), a 25 bps surprise increase in 10-year breakeven tends to be associated with a 1.5 percentage point increase in stock returns.

agent, holding macroeconomic dynamic fixed. The risk premium component is the difference between the total and the risk neutral responses.

[12]We collect the release date of FOMC statements from January 1st 2001 until Dec 31st 2019 from the Federal Reserve's website. To construct an empirical counterpart to the short term monetary policy shock in our model, we collect one-hour changes in Federal Funds rate around scheduled FOMC announcements from the updated data of Gorodnichenko and Weber (2016), while for the long term monetary shock we use one-day changes in zero coupon nominal Treasury yields and TIPS yields are from Gürkaynak, Sack, and Swanson (2005b) and Gürkaynak, Sack, and Wright (2010). We are unable to construct higher frequency proxies for this shock due to data availability for long-term bond yields. The equity return outcome variable is measured using S&P 500 returns in the same one-hour windows around FOMC announcement constructed from Trade and Quote data, accessed through WRDS.

To establish that the two relationships of columns (1) and (2) indeed reflect two separate shocks, we report multivariate regression results in column (3). Both coefficients are statistically significant and quantitatively similar to the univariate regressions in columns (1) and (2). Column (4) further shows that FOMC day changes in 10-year breakeven inflation do not load significantly onto Federal Funds rate surprises over our sample, further supporting the presence of two independent shocks to monetary policy.

Table 4 shows the corresponding model regressions. We use post- minus pre-FOMC asset prices to compute model stock returns, short-term interest rate changes, and 10-year breakeven changes from, where we split aggregate quarterly shocks into pre-FOMC and FOMC components as described in Section 3.6. As in the data, we assume that FOMC date monetary policy shocks represent only a portion of the quarterly volatility of monetary policy shocks. To match the volatilities of Federal Funds and 10-year breakeven changes around FOMC dates and their lack of a significant relationship in our sample, we assume that the FOMC date short-term monetary policy shock has a standard deviation of $\sigma_{ST}^{FOMC} = 4.3$ bps, the FOMC date long-term monetary policy shock has a standard deviation of $\sigma_{LT}^{FOMC} = 3.3$ bps, and the two shocks on FOMC dates are uncorrelated.[13]

Table 4, column (2) shows that the model matches the empirical regression results in Table 3, column (3). Table 4, column (3) replaces the change in 10-year breakeven by its risk-neutral counterpart. Both regression coefficients remain unchanged, showing that 10-year breakeven changes proxy for a shock to long-term inflation expectations in these regressions, and therefore capture long-term monetary policy shocks in the model.

In column (4) we highlight the amplification effect from countercyclical risk-aversion, showing that the model attributes roughly half of the stock market's response to both monetary policy shocks to time-varying risk premia. This large risk premium component for the stock market response to monetary policy news is quantitatively in line with the empirical decomposition into cash flow news versus discount rate news by Bernanke and Kuttner (2005).

Why do stock returns move so much in response to short term monetary policy news? The macroeconomic and asset pricing responses to a short-term interest rate increase in Figures 3 and 4 show that such a shock leads to a hump-shaped decrease in output and consumption. As surplus consumption declines towards habit, investors require higher compensation for holding risky stocks. The fall in stocks due to lower expected consumption is therefore compounded by risk premia. Because time-varying risk premia in our model are quantitatively important in equilibrium, they are similarly quantitatively important around monetary policy shocks, helping to explain why stock returns decrease so

[13] We show in Appendix Figure 6 that the model regression slope coefficients are not sensitive to this choice for the volatilities of FOMC monetary policy shocks.

much in response to a surprise increase in the Federal Funds rate in the data. Similarly, Figures 3 and 4 also show that long-term monetary policy shocks move long-term inflation expectations and the output gap in the same direction, but have little immediate impact on short-term interest rates. As output and consumption decline, investors become more risk averse, amplifying the fall in stocks in response to a negative long-term monetary policy shock. Because breakeven returns have a stock market beta that is much smaller than one in magnitude, the risk premium component in the breakeven response is small, and changes in breakeven are a good proxy for long-term monetary policy shocks.[14]

Appendix Table 5, Panel A shows that the strong relationship between equity returns and monetary policy surprises on FOMC dates remains a robust feature of the model when we switch off individual model components, while Panel B shows that the same is true for the quantitative importance of risk premia.

The average model monetary policy effects in Table 4 conceal substantial heterogeneity with respect to the level of surplus consumption. In Figure 5 we estimate the multivariate model regressions in ten different sub-samples, one for each decile of the pre-FOMC surplus consumption ratio. The figure shows that the overall effect (solid lines) of both long and short term monetary policy shocks increases in magnitude when surplus consumption is low. Since the macroeconomic consequences of the shocks reported in Figure 3 are invariant to the level of surplus consumption, the risk neutral component (dashed lines) is flat. The variation in stock return responses to short- and long-term monetary policy shocks is driven by more volatile risk premia (dotted lines) when consumption is low relative to habit.

In line with this model prediction, we confirm that during the height of the financial crisis (defined as October 2008 through December 2009), stock returns on FOMC dates were fifty percent more volatile than in the rest of our sample even though Federal Funds rate surprises and breakeven changes were no more volatile.[15] The model prediction of greater stock return sensitivity to announcements during recessions is also consistent with the empirical evidence from macroeconomic announcements by Law, Song, and Yaron (2019).

[14]While our results support the notion that FOMC dates reveal news about long-term inflation, we cannot speak to whether specific tools and or communications move investors' long-term inflation expectations, which may very well be time-varying (Goodfriend and King (2005)), context-specific (Coibion, Gorodnichenko, and Weber (2020)), and depend on behavioral channels (Orphanides and Williams (2004), Gabaix (2019), Zhao (2020)).

[15]In unreported results, we find that the point estimates from our benchmark regression in Table 3 also increase in magnitude for this crisis subsample, though the coefficients are not statistically significant due the small number of observations.

5 Conclusion

We integrate a small-scale New Keynesian model of monetary policy with countercyclical risk premia in asset prices using the habit formation preferences of Campbell and Cochrane (1999) and Campbell, Pflueger, and Viceira (2020), and apply it to understand asset price movements around monetary policy announcements. The model easily matches the large stock return response to traditional monetary policy shocks, but only if stock responses are amplified time-varying compensation for risk. Our model attributes the large and positive empirical relationship between breakeven inflation innovations and stock returns around monetary policy announcements to correlated news about long-term inflation and output, supporting the notion that monetary policy announcements reveal news about the economy in a "Fed information effect".

Taken together, our analysis suggests that volatile stock returns in lower frequency data and quantitatively large stock return responses to monetary policy announcements are internally consistent and two sides of the same coin. This has important implications for interpreting asset price reactions to monetary policy. Greater sensitivity of risk bearing capacity in times of low surplus consumption suggests that policy makers, economists, and market observers need to be careful to not extrapolate from average relationships, as during crises stock markets may react a lot even to monetary policy announcement with modest real effects.

Our framework is tractable and portable towards broader macroeconomic models. We anticipate that our framework will be useful to interpret macroeconomic drivers of asset price fluctuations beyond the channels considered in this basic macroeconomic model, such as wage rigidities or heterogeneity in price-setting frictions (Weber (2015)). We also believe that the framework will be useful to understand the role of time-varying risk premia in other empirical puzzles, such as the empirical finding that equity returns are typically high prior to FOMC dates (Lucca and Moench (2015), Cieslak, Morse, and Vissing-Jorgensen (2019), Cieslak and Pang (2019), Laarits (2019)).

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Table 1: Model Parameters

Panel A: Calibrated Parameters		
Consumption Growth Rate	g	1.89
Utility Curvature	γ	2.00
Steady-State Riskfree Rate	$\bar{r}$	0.94
Persistence Surplus Consumption Ratio	θ_0	0.87
Dependence Output Gap	θ_1	-0.67
Dependence Lagged Output Gap	θ_2	0.60
Capital Share of Production	τ	0.33
Learning-by-Doing	ϕ	0.93
Frisch Elasticity	$\chi\frac{\bar{L}}{1-\bar{L}}$	1.00
Price Stickiness	α	0.67
Cross-Goods Substitutability	θ	6.00
Productivity Growth - Real Rate	ρ^a	0.34
Leverage	δ	0.40
MP Coefficient Output	γ^x	0.50
MP Coefficient Inflation	γ^π	1.50
MP Persistence	ρ^i	0.90
Panel B: Estimated Parameters		
Std. Demand Shock (%)	σ_x	0.37
Std. PC Shock (%)	σ_π	0.49
Std. Short-Term MP (%)	σ_{ST}	0.37
Std. Long-Term MP (%)	σ_{LT}	0.22
Panel C: Implied Parameters		
Discount Rate	β	0.90
Steady-State Surplus Consumption Ratio	$\bar{S}$	0.04
Maximum Surplus Consumption Ratio	S^{max}	0.07
Euler Equation Lag Coefficient	ρ^x	0.37
Euler Equation Forward Coefficient	f^x	0.63
Euler Equation Real Rate Slope	ψ	0.08
Phillips Curve Lag Coefficient	ρ^π	0.51
Phillips Curve Forward Coefficient	f^π	0.49
Phillips Curve Slope	κ	0.06

Note: Panel A shows the parameters we calibrate following previous literature, as detailed in Section 4.1. Panel B displays the parameters we estimate by matching the empirical impulse response functions and the volatility of long-term breakeven as described in Section 4.2. Panel C reports moments implied by the other parameters listed above. Consumption growth and the steady-state risk-free rate are in annualized percent. The discount rate and the persistence of surplus consumption are annualized. The monetary policy coefficients and the Phillips curve slope are reported in units corresponding to our empirical variables, i.e. the de-trended log output is in percent, and inflation, the Fed Funds rate are in annualized percent. The implied Euler equation real rate slope is hence reported as $\frac{1}{4}\psi$ and the implied Phillips curve slope is reported as 4κ. We report quarterly standard deviations of shocks to percent output gap, annualized percent inflation, the annualized percent Fed Funds rate, and the annualized percent long-term monetary policy target.

Table 2: Asset Prices

		Model	Data
Stocks			
	Volatility	13.55	16.96
	Equity Premium	6.82	7.41
	Sharpe Ratio	0.50	0.44
10Y Breakeven			
	Volatility	5.10	7.01
	Breakeven-Stock Beta	-0.13	-0.23
	Excess Returns	-0.67	0.55
	Sharpe Ratio	-0.14	0.08
10Y Real Bonds			
	Volatility	1.56	6.83
	Real Bond-Stock Beta	0.03	-0.08
	Sharpe Ratio	0.05	0.55
	Excess Returns	0.07	3.76

Note: This table reports the unconditional asset pricing moments both empirically and in model simulated data. The equity premium is computed as the quarterly log return on the value-weighted combined NYSE/AMEX/Nasdaq stock return including dividends from CRSP in excess of the log 3-month Treasury bill plus one-half times the log excess return variance to adjust for Jensen's inequality. Breakeven excess returns are defined as nominal minus real bond excess returns. Real bond excess returns are quarterly log returns on 10-year real Treasury bonds in excess of the log nominal 3-month Treasury bill return. We compute empirical log returns on the 10-year nominal Treasury bond and inflation-indexed bond (TIPS) from log bond yields: $r^{\$}_{n,t} = -(n-1)y^{\$}_{n-1,t} + ny^{\$}_{n,t}$ and $r^{TIPS}_{n,t} = -(n-1)y^{TIPS}_{n-1,t} + ny^{TIPS}_{n,t} + \pi_t$. We obtain continuously compounded 10-year zero-coupon yields from Gürkaynak, Sack, and Wright (2007, 2010). Breakeven and real bond term premia are average excess nominal bond and breakeven log returns plus one-half times the log excess return variance. Excess returns, term premia, and volatilities are in annualized percent. Our sample period is from 2001Q2 until 2019Q2, except for TIPS data which begins in 2003Q1. Model moments follows the same procedures as above on simulated data and are averaged over 2 simulations of length 10000.

Table 3: Empirical Equity Returns and Monetary Policy Surprises

	Dependent variable:			
	S&P 500 Return			10Y Breakeven
	(1)	(2)	(3)	(4)
FF Shock	-4.89^{***}		-4.11^{***}	-0.15
	(1.64)		(1.50)	(0.11)
10Y Breakeven		5.90^{**}	5.05^{*}	
		(2.54)	(2.60)	
Constant	0.07	0.06	0.05	0.004
	(0.05)	(0.06)	(0.06)	(0.003)
Observations	146	146	146	146
R^2	0.08	0.09	0.14	0.03
Adjusted R^2	0.07	0.08	0.13	0.03

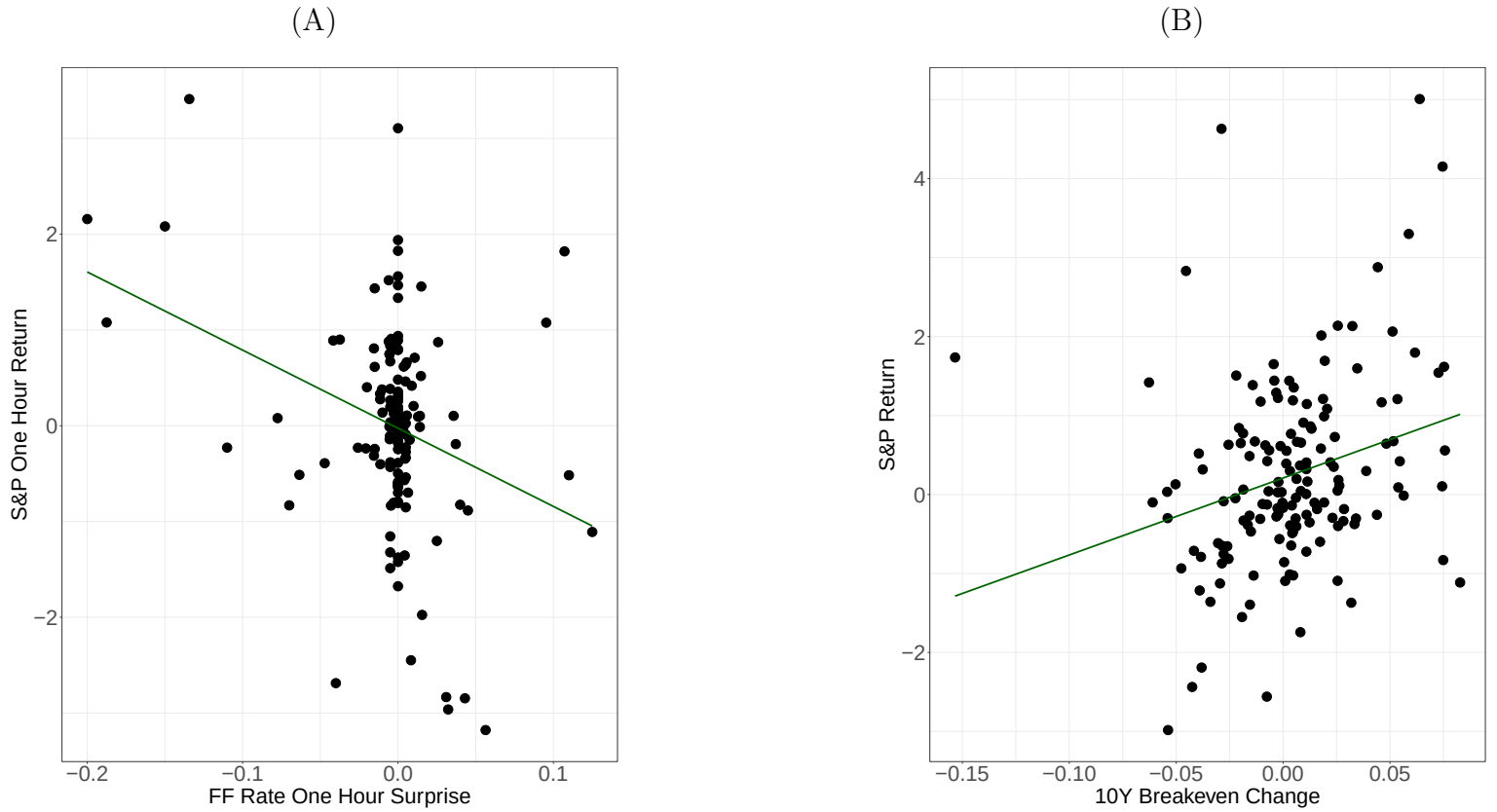
Note: This table reports regression estimates of the impact of monetary policy shocks on equity returns. For columns (1) to (3), we estimate regressions of the form: $r_t^{\delta,FOMC} = b_0 + b_1 \Delta^{FOMC} i_t + b_2 \Delta^{FOMC} b_{10,t} + \varepsilon_t$. $\Delta^{FOMC} i_{n,t}$ is the change in the Federal Funds rate in the one hour around FOMC announcements and $\Delta^{FOMC} b_{10,t}$ is the daily change in the 10-year breakeven rate, defined as the difference between 10-year nominal and 10-year real bond yields. We include these variables separately in columns (1) and (2), and jointly in column (3). The data on Federal Fund rate surprises is from Gorodnichenko and Weber (2016), breakeven rate changes are constructed using the data of Gürkaynak, Sack, and Wright (2007) and Gürkaynak, Sack, and Wright (2010), and one hour S&P 500 returns are from TAQ data. Column (4) reports estimates from a regression of the form $\Delta^{FOMC} b_{10,t} = b_0 + b_1 \Delta^{FOMC} b_{n,t} + \varepsilon_t$. Our sample consists of scheduled FOMC days from January 2001 up to March 2019. Heteroskedasticity adjusted standard errors are reported in parentheses below the estimates. *p<0.1; **p<0.05; ***p<0.01

Table 4: Model Equity Returns and Monetary Policy Surprises

	Dependent variable:				
	S&P 500 Return				
	Data	Overall		Risk Premium	
	(1)	(2)	(3)	(4)	(5)
FF Shock	-4.11^{***}	-5.27	-5.35	-2.54	-2.58
	(1.50)				
10Y Breakeven	5.05^{*}	5.89		2.70	
	(2.50)				
10Y Breakeven RN			5.96		2.73

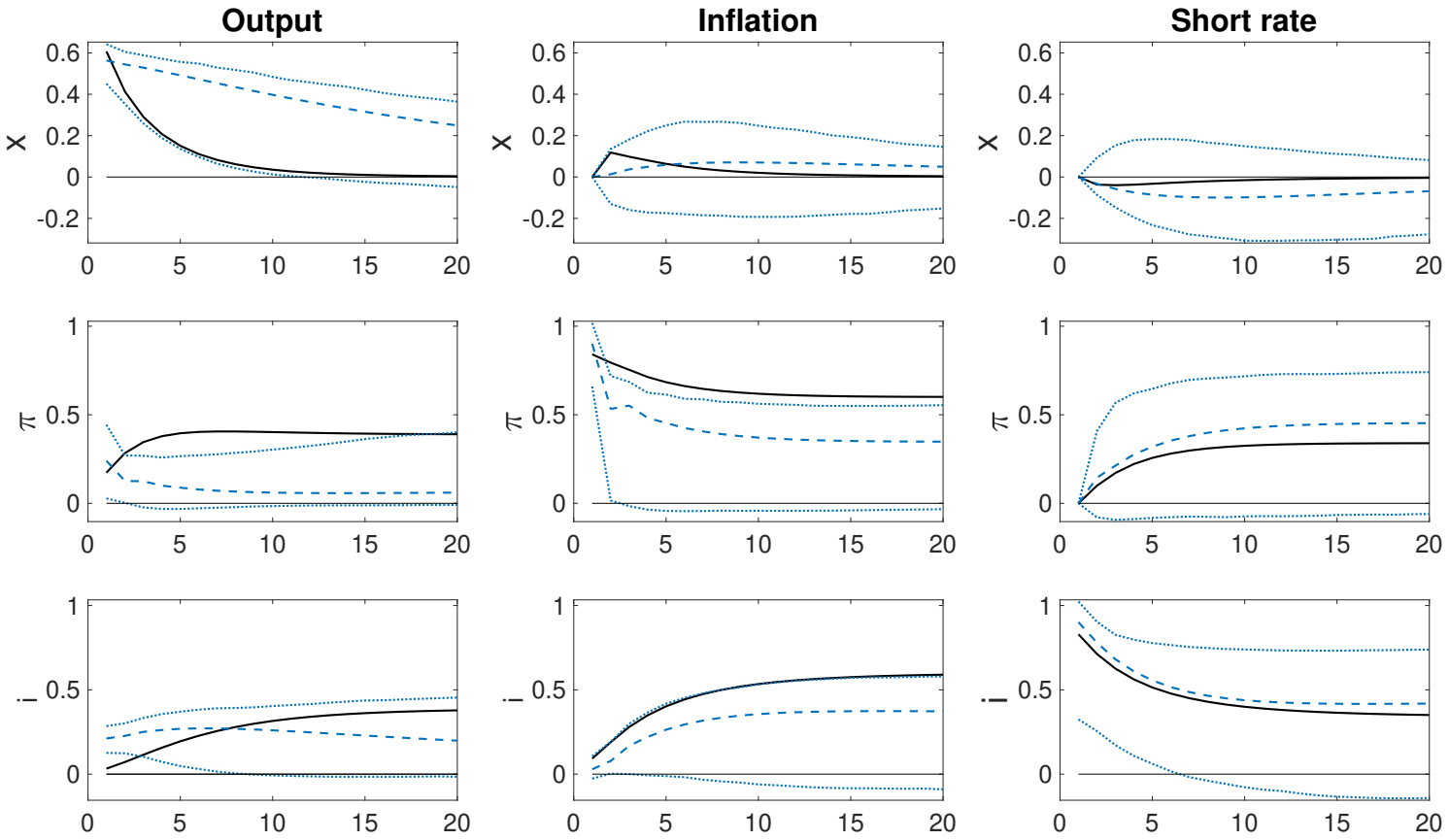
Note: This table compares the asset price reactions around monetary policy news in the model and in the data. Column (1) repeats the empirical estimates from Table 3, column (3). Column (2) estimates the analogous regression on model simulated data, assuming that FOMC dates are subject to uncorrelated long-term and short-term monetary policy shocks. The standard deviations of the ST and LT monetary policy shocks are set to 4.3 bps and 3.3 bps to match the volatilities of one-hour Fed Funds surprises and breakeven changes on FOMC dates in the data. Column (3) uses the risk neutral component of the 10-year breakeven change on the right-hand-side instead. Columns (4) and (5) report model regressions, with the component of stock returns due to time-varying risk premia as the left-hand-side variable. For details of model FOMC asset prices see Section 3.6. Risk neutral asset prices are the asset prices that would obtain under a risk neutral investor taking macroeconomic dynamics as given. The risk premium component of stock returns is the difference between the overall return minus the risk neutral return. Heteroskedasticity adjusted standard errors are reported in parentheses below the empirical estimates. *p<0.1; **p<0.05; ***p<0.01

Figure 1: Stocks and Bonds on FOMC Dates



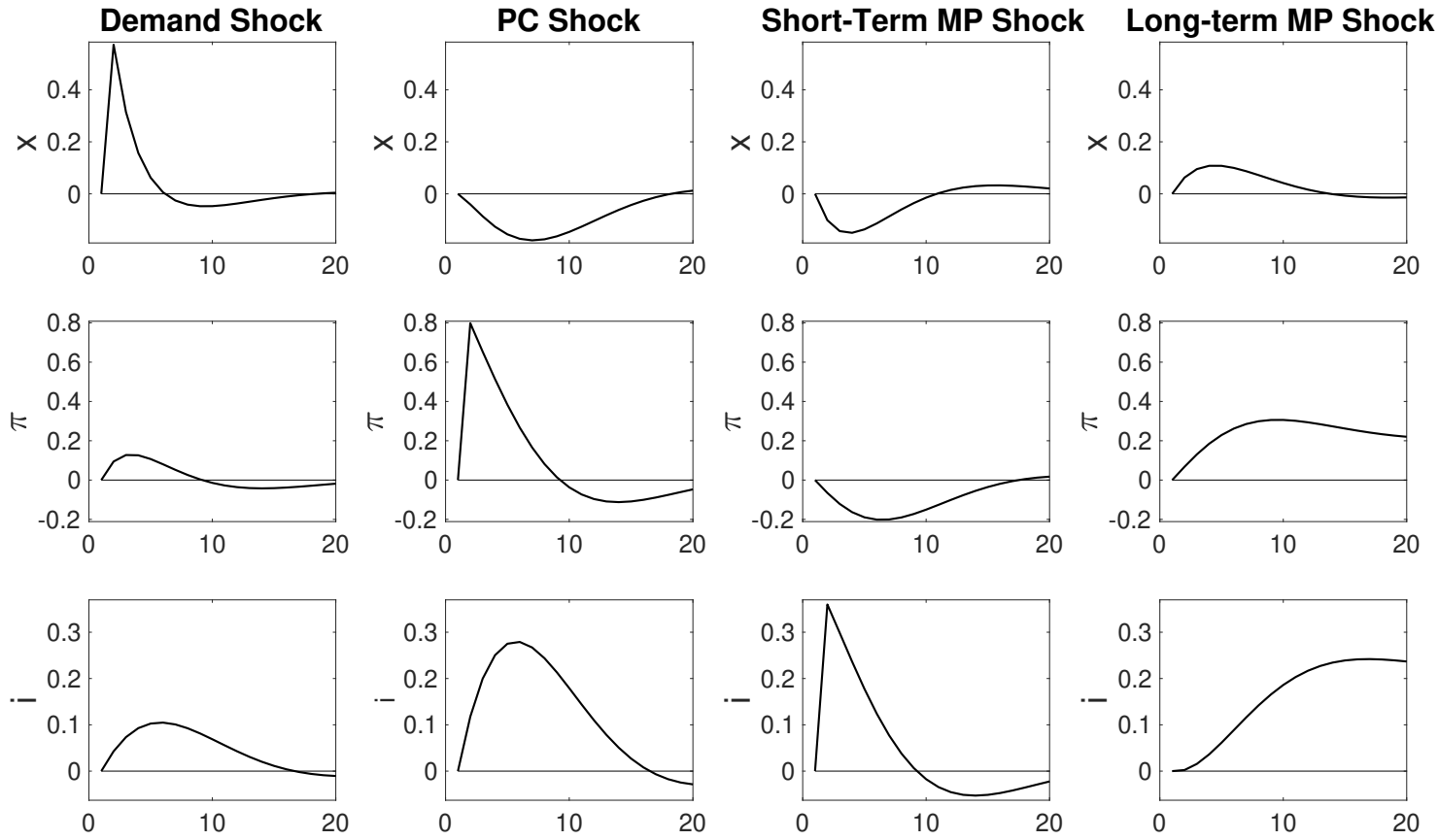
Note: Panel A shows the relationship of Federal Funds rates surprises in an hourly window around FOMC announcements from Gorodnichenko and Weber (2016) and S&P 500 returns in the same window constructed from TAQ data, where each data point corresponds to a FOMC meeting day. Panel B shows the relationship of the daily change in 10-year breakeven inflation rates and daily S&P 500 returns where again each data point corresponds to a FOMC meeting day. The breakeven rate is the difference between the 10-year nominal Treasury yield and 10-year TIPS yield from Gürkaynak, Sack, and Wright (2007, 2010). The green lines are linear regression best fit lines. The sample of FOMC days is from the start of 2001 until end of 2019, excluding the QE episodes of 16th of December 2008 and the 18th of March 2009. For Panels B and C, the data begins from the start of 2003 since this is when the TIPS data start.

Figure 2: Reduced Form Macro Impulse Responses



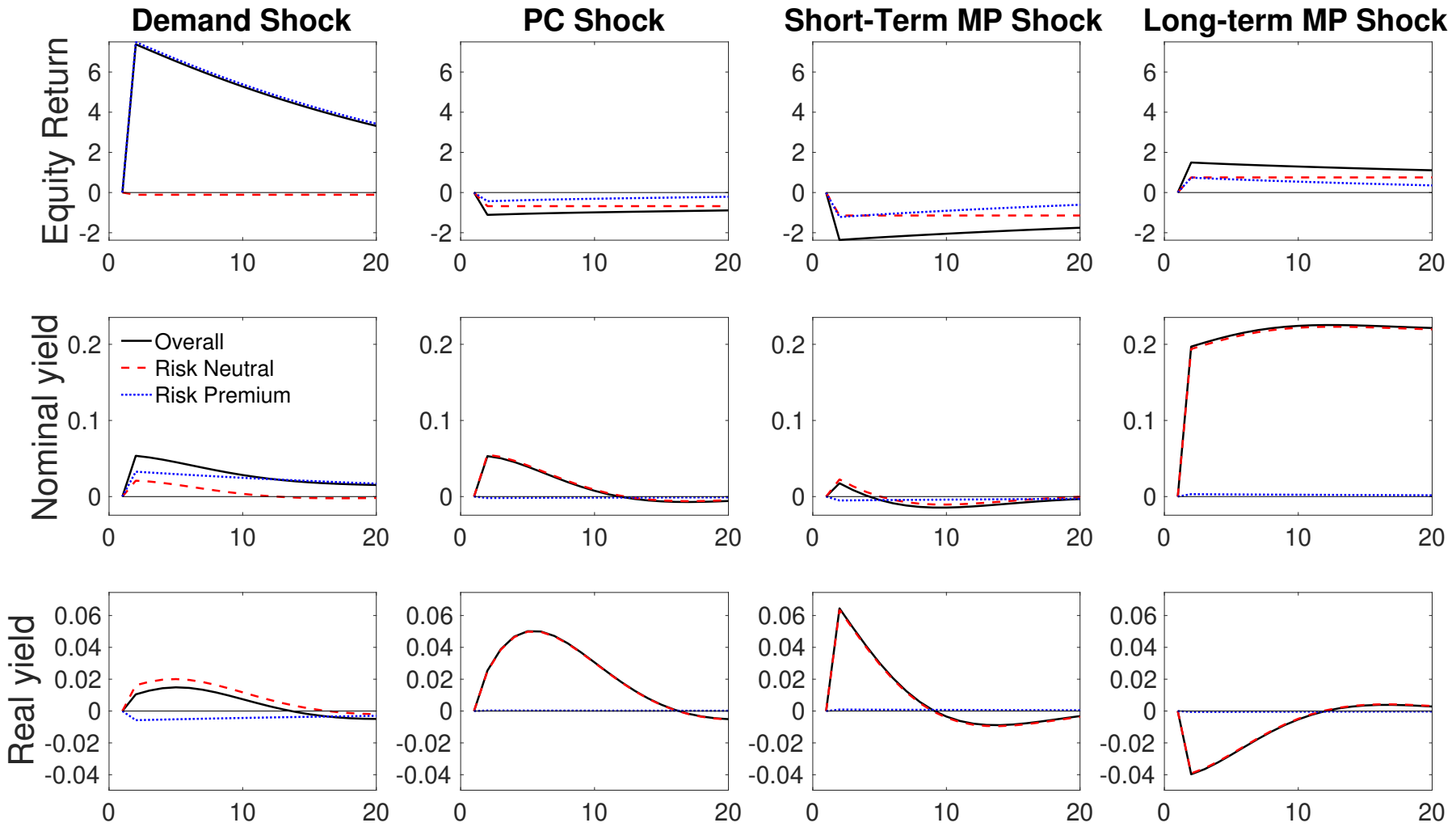
Note: This figure shows macroeconomic impulse responses to reduced-form output gap, inflation, and Federal Funds rate innovations in the model and in the data. The estimation of impulse responses is identical on actual and simulated data and is described in detail in Section 4.2. All impulses are one-standard deviation shocks and are orthogonalized so shocks to the Fed Funds rate do not contemporaneously affect inflation or the output gap, and inflation innovations do not enter into the same period output gap. The first row shows the response of output in percent, the second row shows the response of inflation in percent. The third row shows the response of the Federal Funds rate in percent. The horizontal axis of each panel shows the number of quarters after the shock.

Figure 3: Structural Macro Impulse Responses



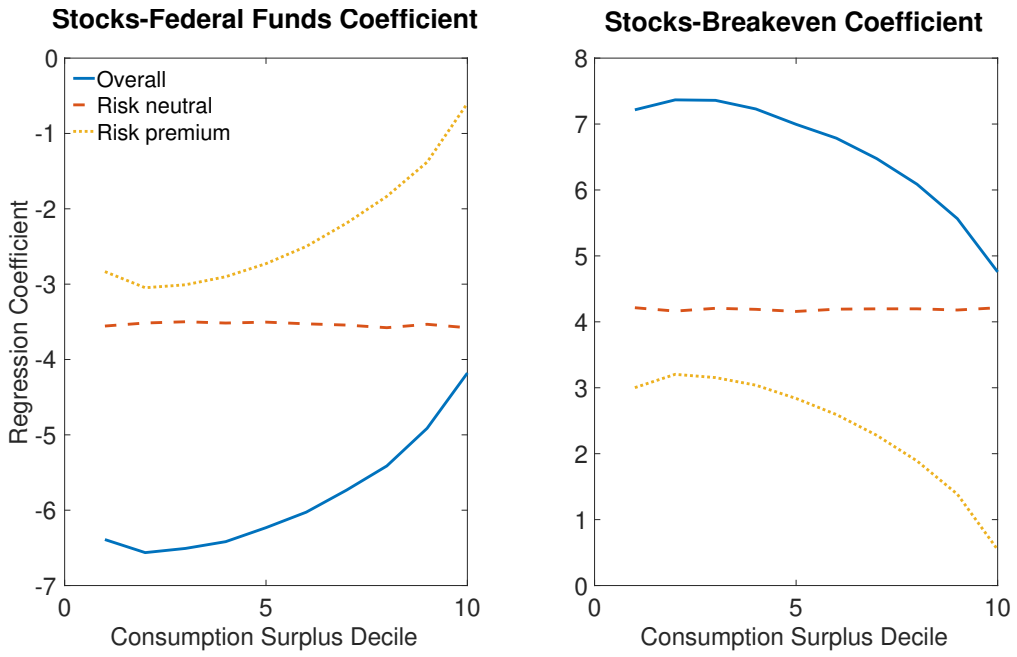
Note: Each column of this figure shows the macroeconomic impulse responses to one of the structural shocks, namely the demand shock, the Phillips Curve (PC) shock, the short-term monetary policy shock, and the long-term monetary policy shock. All impulses are one-standard deviation shocks. The first row shows the response of the output gap in percent, the second row shows the response of inflation in percent. The third row shows the response of the Federal Funds rate in percent. The horizontal axis of each panel shows the number of quarters after the shock.

Figure 4: Structural Asset Price Impulse Responses



Note: Each column of this figure shows the impulse responses of asset prices to one of the structural shocks, namely the demand shock, the Phillips Curve (PC) shock, the short-term monetary policy shock, and the long-term monetary policy shock. All impulses are one-standard deviation shocks. The first row shows the response of unexpected equity returns in percent, the second row shows the response of nominal yield in annualized percent. The third row shows the response of the real yield in annualized percent. The horizontal axis of each panel shows the number of quarters after the shock. Responses are decomposed into the risk neutral component, which is computed as if assets were priced by a risk neutral agent, and the risk premium component. The risk neutral and risk premium components add up to the total response. Unexpected equity returns are computed subtracting from each quarter's return the steady state equity return in the absence of shocks.

Figure 5: Heterogeneity in Model Stock Response to Monetary Policy Surprises



Note: This figure shows model regressions of the same form as in Tables 3 and 4 conditional on the model surplus consumption ratio: $r_t^{\delta,FOMC} = b_0 + b_1 \Delta^{FOMC} i_t + b_2 \Delta^{FOMC} b_{10,t} + \varepsilon_t$. The left and right panels correspond to estimates of b_1 and b_2, respectively. Δ^{FOMC} is the change in the short term interest rate around the FOMC date, $\Delta^{FOMC} b_{10,t}$ is the change in the breakeven rate around in the same time period and $r_t^{\delta,FOMC}$ is the equity return. The simulated data is split into ten sub samples according to the deciles of the surplus consumption ration $\hat{s}$ so a lower decile corresponds higher effective risk aversion. We plot the coefficients obtained by running the regression separately within each of these ten subsamples. Solid lines use overall equity returns as the left-hand-side variable, dashed lines use risk neutral stock returns, and dotted lines use the risk premium component of stock returns. The overall coefficient is the sum of risk neutral and risk premium coefficients. Risk neutral and risk premium coefficients add up to the overall coefficient. For details of model FOMC asset prices see Section 3.6 and for details of the decomposition into risk neutral and risk premium returns see Table 4. The results are obtained by averaging over 5 model simulations of length 30000.