Why Does the Fed Move Markets so Much?

A Model of Monetary Policy and Time-Varying Risk Aversion

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Abstract

The same habit preferences that explain the equity volatility puzzle in quarterly data also naturally explain large high-frequency stock responses to monetary policy news. To show this, we newly integrate a work-horse New Keynesian model with habit formation preferences. The model generates endogenously time-varying risk premia from level shocks to interest rates because a surprise increase in the short-term interest rate lowers output and consumption relative to habit, raising risk aversion and amplifying the fall in stocks. The model explains the positive comovement between long-term breakeven and stocks on FOMC dates with news about long-term inflation.

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1 Introduction

It is well understood that cyclical variation in investors' capacity to bear risk is essential to the link between the macroeconomy and financial markets (see e.g. Cochrane (2017)). However, much less is known how this time-varying link between the macroeconomy and financial markets drives the much-watched stock market responses to monetary policy announcements. Empirically, stocks fall sharply in response to a surprise increase in the Federal Funds rate, and a significant share of the stock response appears to reflect investors' changing risk bearing capacity (Bernanke and Kuttner (2005)). Does monetary policy drive the stock market by excessively calming or exciting investors' nerves, divorced from its real effects? Or, conversely, does the stock market provide high-frequency evidence that monetary policy is able to stimulate the real economy?

To answer these questions, we integrate a standard small-scale New Keynesian model of monetary policy with the finance habit preferences of Campbell, Pflueger, and Viceira (2020). In this model, monetary policy has large effects on stock risk premia precisely because it affects the real economy. Intuitively, if monetary policy news reduces output and consumption towards consumers' habit level, households become more risk averse, and stocks fall more than expected discounted dividends. Fitting this model to quarterly data we find that it naturally matches the large high-frequency stock return responses to two different types of monetary policy surprises on FOMC dates; a classic surprise increase in the Federal Funds rate, and a change in market-implied long-term breakeven inflation. For both surprises, the model attributes 50% of the stock return responses to changes in the risk discount that investors require for holding stocks and the remainder to changes in the present discounted value of expected dividends, matching closely the empirical decomposition in Bernanke and Kuttner (2005).

Figure 1, Panel A displays the empirical stock return response to the classic monetary policy shock of Bernanke and Kuttner (2005) and shows that a surprise decrease in the short-term Federal Funds rate around FOMC announcements is typically accompanied by a significant increase in stock prices in the same time interval.[1] This well-known result has often been interpreted as evidence that a decrease in the short-term monetary policy rate has the ability to boost output, consumption, and economic activity, as supported by a long literature that estimates impulse responses to innovations in short-term monetary

[1] Figure 1, Panel A uses intraday changes in the Federal Funds rate from Gorodnichenko and Weber (2016) and in the S&P from TAQ for the period from the start of 2001 to March 2019. 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. For a detailed description of the empirical results see Section 5.

policy rates (see Ramey (2016) for a review).[2] Panel B shows that an increase in long-term breakeven inflation, which is defined as the difference between 10-year nominal and real bond yields, has the opposite correlation with stock returns on FOMC announcement dates. This second finding echoes the recent empirical evidence by Jarociński and Karadi (2020) and Andrade and Ferroni (2020) and is often interpreted as evidence that Federal Reserve announcements reveal news about long-term inflation (e.g. Romer and Romer (2004)).

The model we construct departs in two ways from a standard small-scale New Keynesian model with Calvo (1978) price-setting frictions, backwards price indexation, and a Taylor (1993) type monetary policy rule. The first departure is that we assume finance habit preferences of the form proposed by Campbell, Pflueger, and Viceira (2020). The representative household's utility depends on consumption in excess of a slowly moving habit, implying that household risk aversion and risk premia increase when consumption falls close to habit. The goal of this paper is to study the stock risk premium implications of a well-understood model of monetary policy. It is therefore crucial that habit dynamics are such that the log-linear consumption Euler equation common in New Keynesian models holds exactly, and can be derived from the asset pricing Euler equation of the real risk-free bond. Different from simpler habit preferences, but similar to Campbell and Cochrane (1999), these preferences also have the advantage of explaining the equity volatility puzzle of Shiller (1981), generating volatile stock returns while avoiding excessive volatility in the risk-free rate.[3]

Different from Campbell, Pflueger, and Viceira (2020), we derive consumption within an economy with production, price-setting frictions, and monetary policy. To achieve this integration, we link the household and firm problems by integrating leisure into habit preferences. We assume that leisure is valued for its value in home production as in the classic model of Greenwood, Hercowitz, and Huffman (1988), thereby separating wages from the intratemporal consumption-savings decision, and sidestepping the counterfactual labor implications that can otherwise be challenging for models of asset pricing habits within production economies (Lettau and Uhlig (2000)). Productivity features learning-

[2]We consider classic shocks to short-term monetary policy rates, which a long empirical macroeconomic literature has shown to lead to decreases in economic activity. These shocks are different from the shocks to longer-term interest rates on monetary policy dates considered by Hanson and Stein (2015) and Nakamura and Steinsson (2018), which in addition may contain information about the economy's long-term growth potential, thereby confounding the direct effect of a change in the monetary policy rate.

[3]Simpler habit models are also common in macroeconomics and have been found to be useful to match empirical output responses to monetary policy shocks. Fuhrer (2000) includes habits within a macroeconomic model, while Boldrin, Christiano, and Fisher (2001) use habits that resolve the equity premium but not the smooth risk-free rate puzzle. Campbell, Pflueger, and Viceira (2020) do not study how stock returns responds to monetary policy announcements, which is the focus of this paper.

by-doing (Lucas (1988)) to generate an endogenous stochastic trend in consumption and output, while keeping the output gap stationary.

The second departure from the standard New Keynesian model is that we model two different types of monetary policy 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 reverts to steady-state relatively quickly. The second shock captures long-term economic news and is modeled via a shock to trend inflation. In addition to the two monetary policy shocks, the model features habit shocks and markup shocks. A positive shock to expected habit acts as a negative demand shock, increasing consumers' anticipated risk aversion, and generating an incentive to postpone consumption towards the future higher habit state. Shocks to the substitutability across goods generates shocks to firms' optimally desired markup. All four fundamental shocks are assumed to be conditionally homoskedastic, so time varying risk premia arise endogenously from preferences, rather than from auxiliary assumptions about time-varying quantities of risk.[4]

We model high-frequency stock returns and bond yield changes around FOMC dates by assuming that the quarterly fundamental shocks can be decomposed into independent pre-FOMC and FOMC components. This assumption captures that the well-identified surprises on FOMC dates plausibly represent only a relatively small portion of economic news, whereas most economic and even monetary policy news tend to be anticipated prior to the meeting announcement. We model stocks as a levered claim to aggregate consumption, while being careful to preserve the cointegration of consumption and dividends. All bonds are modeled as zero-coupon bonds.

We solve the model by deriving log-linear macroeconomic dynamics from consumers' intertemporal Euler equation, firms' profit optimization, and the log-linear monetary policy rule. Our solution for asset prices preserves their full nonlinearity, following the best practices of Wachter (2005).[5] Nonlinear asset prices imply that after a sequence of bad shocks, when consumption is close to habit, required compensation for holding risky assets – such as stocks – is high. The highly nonlinear nature of risk premia is crucial to match the high and volatile stock returns in the data. We solve for pre-FOMC

[4]Our focus on preferences is useful because it demonstrates that one does not need to assume that monetary policy shocks have a large effect on the quantity of macroeconomic risk, which would likely be hard to pin down in high-frequency data. If both time-varying risk aversion and time-varying quantity of risk, as in Jurado, Ludvigson, and Ng (2015), were present and both responded to monetary policy shocks, they would presumably amplify each other.

[5]By solving for log-linear macroeconomic dynamics, we keep the asset pricing solution tractable and comparable to a long-standing literature. As the consumption Euler equation and monetary policy rule are already exactly log-linear, and we preserve the full nonlinearity of asset prices, the main approximation we use in solving the model is a standard log-linearization for the Phillips curve. We therefore do not mix different orders of approximation.

asset prices at the expected state vector conditional on the pre-FOMC shock, and obtain post-FOMC asset prices at the state vector after both pre- and FOMC information have been revealed.

We 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 the output gap, 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 not being an explicit target, the model also generates empirically plausible consumption volatility. Even with the significant additional structure, our model is similarly successful at generating a low volatility of the output gap and a high 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 hard to estimate reliably over a short sample of 20 years.

The model naturally explains the large high-frequency stock responses to the monetary policy news in Figure 1, even though the model is fitted using no information from FOMC stock returns. While the model macroeconomic responses to monetary policy news are standard, the responses of stock risk premia are new and due to habit preferences. A surprise increase in the nominal short-term interest rate has the textbook contractionary effect on output and consumption (Woodford (2003), Gali and Monacelli (2005), Christiano, Eichenbaum, and Evans (2005)). Consistent with a long empirical literature (see Ramey (2016) for an overview), a hump-shaped contraction in output and consumption is followed by slow decline in inflation several quarters later. On the asset pricing side, investors require a larger price discount for holding risky stocks as consumption declines towards habits, and stocks fall more than expected discounted dividends. The short-term monetary policy shock in the model therefore explains the negative relationship between Federal Funds rate surprises and stock returns in Figure 1 Panel A.

A decline in long-term inflation expectations in the model acts like a costly disinflation and drives down real output and consumption similarly to Ball (1994) and Gürkaynak, Sack, and Swanson (2005). As long-term inflation expectations decline ahead of nominal interest rates, the implied real rate increases, leading households to postpone consumption. These effects are in line with permanent interest rate shocks in Cochrane (2018), Uribe (2018), and Schmitt-Grohé and Uribe (2018). The resulting fall in stocks is amplified by households' increased risk aversion as consumption declines towards habit. The long-term monetary policy shock in the model therefore explains the empirical relationship in Figure 1, Panel B, but only if the stock return response is amplified by countercyclical risk aversion.

Our model predicts that in bad times stocks react more strongly to monetary policy even if the real economy does not, potentially reconciling the observation that the stock response to monetary policy news is larger for some dates than others (Bernanke and Kuttner (2005)). This prediction arises naturally in our model from endogenous variation in risk bearing capacity. When consumption is close to habit, households' marginal utility is particularly sensitive to consumption. When risk bearing capacity is low, a monetary policy action that lifts the economy has an especially strong calming effect on household risk aversion, amplifying the risk premium effect on stocks. Consistent with this prediction, we find that stock return responses to monetary policy news were amplified after the financial crisis of 2008-09 (see also Paul (2020)).

The focus in this paper is to understand whether the sign and magnitude of stock responses to standard macroeconomic dynamics can be rationalized with simple preferences linked to the macroeconomy. We believe that this link is important for the broader research agenda to understand the interaction of monetary policy and financial markets (Schularick and Taylor (2012), Caballero and Simsek (2020), Pflueger, Siriwardane, and Sunderam (2020)). At the same time, time-varying demand for precautionary savings is incorporated into our exact Euler equation, and, together with time-varying intertemporal savings motive, generates the model's hump-shaped output response to monetary policy news.

This paper is also complementary to recent innovations in understanding heterogeneous consumer responses to monetary policy (Kaplan, Moll, and Violante (2018), McKay, Nakamura, and Steinsson (2016), Auclert, Rognlie, and Straub (2020)) and financial asset prices (Drechsler, Savov, and Schnabl (2018), Kekre and Lenel (2020)). We keep the representative agent assumption, but instead assume finance habit formation. The advantage of finance habits is that their quantitative implications for asset prices are well-understood. We thereby provide a parsimonious model that jointly explains a number of empirical findings: high-frequency stock return responses to both Federal Funds rate innovations and long-term inflation news, volatile aggregate stock returns and a smooth risk-free rate, and hump-shaped macroeconomic impulse responses. Finance habits and heterogeneous agents would likely lead to interesting interactions and amplify each other, though modeling these interactions is beyond the scope of this paper.

We similarly view our model as complementary to the liquidity-based model of stock responses to Federal Funds rate innovations of Lagos and Zhang (2020). Our work is also complementary to Wachter and Zhu (2020), who provide a disasters-based model of a different but related empirical finding, namely average stock returns around macroeconomic announcements.

We also contribute to a growing literature jointly modeling stocks and bonds with endogenous macroeconomic dynamics. Bianchi, Lettau, and Ludvigson (2020) argue within a New Keynesian model with learning that changes in monetary policy regimes can explain the secular movements in the real risk-free rate. Prior work has used ambiguity aversion (Bianchi, Ilut, and Schneider (2018)), disaster risks (Gourio (2012), Kilic and Wachter (2018)) and long-run risks (e.g. Kung (2015), Gourio and Ngo (2020)) to understand asset pricing implications within models of the macroeconomy. A portion of this literature, such as Rudebusch and Swanson (2012), has focused on bond term premia within DSGE models, but in contrast to us has not modeled stocks. While most of this literature assumes an exogenous link between uncertainty and other state variables in their models, our model with endogenous risk aversion is ideally suited to study the question at hand, namely how much stock risk premia respond to level shocks in monetary policy. Some previous 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. Following Campbell, Pflueger, and Viceira (2020), we build on the full non-linearity of Campbell and Cochrane (1999)'s consumption-based habit formation preferences, and thereby generate endogenously time-varying risk premia and a well-behaved real risk-free rate within a model of monetary policy.

The paper is organized as follows. Section 2 presents the model. Section 3 presents the solution method and discusses model assumptions. Section 4 solves and discusses the model. Section 5 presents stock responses to monetary policy surprises in the model and in the data. Section 6 concludes.

2 Model

This section describes the problems faced by households and firms. It also describes the behavior of monetary policy, and defines stocks and bonds. There are four fundamental sources of uncertainty: shocks to habits, markups, and short-term and long-term monetary policy shocks. All four shocks are homoskedastic and serially uncorrelated. We use lower-case letters for logs throughout.

2.1 Households

2.1.1 Consumption and preferences

Following the classic model of Greenwood, Hercowitz, and Huffman (1988), we assume that consumption consists of market consumption and home produced goods. Labor not used in the market is used for home production, such as cooking at home instead of eating out. We assume that the representative household's total consumption is the sum of market consumption, C_t, and home production C_t^{home}:

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

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.[6] Utility equals

$$U_t = \frac{\left((C_t - H_t) + (C_t^{home} - H_t^{home})\right)^{1-\gamma} - 1}{1 - \gamma} \tag{2}$$

Both market and home consumption are assumed to give rise to habits, H_t and H_t^{home}. Habits are external, meaning that they are shaped by aggregate consumption and households do not internalize how habits might respond to their personal consumption choices. The parameter γ is a curvature parameter.

2.1.2 Habit dynamics

For simplicity we assume that home good habit follows the average household's home goods consumption, i.e. $H_t^{home} = C_t^{home}$. Because habit is external, equation (2) then implies that relative risk aversion increases as market consumption falls towards market habit. In particular, relative risk aversion over payoffs in market goods equals $-U_{CC}C/U_C = \gamma/S_t$, where surplus consumption is the share of market consumption available to generate utility:

$$S_t = \frac{C_t - H_t}{C_t}. \tag{3}$$

As equation (3) makes clear, a model for market habit implies a model for surplus consumption and vice versa. Following Campbell, Pflueger, and Viceira (2020), we model

[6] The differentiated labor assumption follows Woodford (2003, Chapter 3) and generates real rigidities from labor immobility across sectors (Ball and Romer (1990)).

market habit implicitly by assuming that log surplus consumption, s_t, satisfies:

$$s_{t+1} = (1-\theta_0)\bar{s} + \theta_0 s_t + \theta_1 x_t + \theta_2 x_{t-1} + \varepsilon_{s,t} + \lambda(s_t)\varepsilon_{c,t+1}, \tag{4}$$

$$\varepsilon_{c,t+1} = c_{t+1} - \mathrm{E}_t c_{t+1}. \tag{5}$$

Here, x_t is the log output gap relative to the flexible-price equilibrium. As we abstract from real investment dynamics, x_t can also be interpreted as market consumption relative to a frictionless benchmark. The constant $\bar{s}$ is steady-state log surplus consumption and $\varepsilon_{s,t}$ is the habit shock. The sensitivity function $\lambda(s_t)$ takes the form of Campbell and Cochrane (1999):

$$\lambda(s_t) = \begin{cases} \frac{1}{\bar{S}}\sqrt{1-2(s_t-\bar{s})} - 1 & s_t \leq s_{max} \\ 0 & s_t > s_{max} \end{cases}, \tag{6}$$

$$\bar{S} = \sigma_c \sqrt{\frac{\gamma}{1-\theta_0}}, \tag{7}$$

$$\bar{s} = \log(\bar{S}), \tag{8}$$

$$s_{max} = \bar{s} + 0.5(1-\bar{S}^2). \tag{9}$$

Here, σ_c denotes the standard deviation of the consumption surprise $\varepsilon_{c,t+1}$. This consumption surprise is an equilibrium object depending on fundamental shocks, and we will verify in our solution that it is conditionally homoskedastic. Implied log market habit implied follows approximately a weighted average of past log market consumption and log market consumption relative to a frictionless benchmark, see Appendix A.

2.2 Firms

2.2.1 Final good

A final consumption good is produced by a representative perfectly competitive firm from a continuum of differentiated goods $Y_{i,t}$:

$$Y_t \equiv \left[\int_0^1 Y_{i,t}^{\frac{\theta_t-1}{\theta_t}} di\right]^{\frac{\theta_t}{\theta_t-1}}. \tag{10}$$

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

$$Y_{i,t} = Y_t \left(\frac{P_{i,t}}{P_t}\right)^{-\theta_t}. \tag{11}$$

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. We assume that the $\log\theta_t = \log\theta + \varepsilon_{\theta,t}$, where $\varepsilon_{\theta,t}$ is homoskedastic and independently and identically distributed.

2.2.2 Intermediate good

Intermediate goods firm i produces according to a Cobb-Douglas production function with capital share τ:

$$Y_{i,t} = A_t N_t L_{i,t}^{1-\tau}. \quad (12)$$

Productivity is the product of technology, A_t, and human capital, N_t. With (10), aggregate output then satisfies

$$Y_t = A_t N_t L_t^{1-\tau}, \quad (13)$$

where aggregate labor is defined:

$$L_t \equiv \left[\int_0^1 L_{i,t}^{\frac{(\theta_t-1)(1-\tau)}{\theta_t}} di\right]^{\frac{\theta_t}{(\theta_t-1)(1-\tau)}}. \quad (14)$$

The aggregate resource constraint in this economy is simple. Because there is no time-varying real investment, consumption equals output $C_t = Y_t$.

Following Lucas (1988), we assume that human capital depends on the average skill acquired by all agents, and that changes in log human capital are driven by past market labor, l_{t-1}:

$$n_t = \nu + n_{t-1} + (1-\phi)(1-\tau)l_{t-1}. \quad (15)$$

Here, $0 \leq \phi \leq 1$ and $\nu > 0$ are constants.

Predictability in technology growth takes a very simple form. We assume that A_t is predictable one period ahead, or that the change in log technology Δa_{t+1} is known at time t. To economize on state variables, we assume that productivity growth is a linear function of existing state variables, and in particular the real risk-free rate deviation from the frictionless steady-state as in Nakamura and Steinsson (2018)[7]

$$\mathrm{E}_t \Delta a_{t+1} = \rho^a (r_t - \bar{r}). \quad (16)$$

[7]Predictable productivity growth is not crucial to our central model implications, as can be seen by setting $\rho^a = 0$, see Appendix F.1. Time-varying expected productivity growth helps quantitatively to generate volatility in real bond returns, and to drive down the real bond return correlation with output and stock returns.

Intermediate firm profit equals output minus the cost of labor, subject to the production function (12), demand for differentiated goods (11), and taking wages from consumers' labor-leisure trade-off as given.

2.2.3 Price setting

Intermediate 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 (2007), 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 $\tilde{P}_t\left(\frac{P_{t-1+j}}{P_{t-1}}\right)$. A firm that can update its product price maximizes the discounted sum of current and future expected profits while the price is expected to remain in place, discounted at the households' stochastic discount factor.

2.3 Monetary policy

Let i_t denote the log nominal risk-free rate available from time t to $t+1$. Monetary policy is described by the following rule (ignoring constants):

$$i_t = \rho^i i_{t-1} + \left(1-\rho^i\right) i_t^* + v_{ST,t}, \tag{17}$$

$$i_t^* = \gamma^x x_t + \gamma^\pi \pi_t + (1-\gamma^\pi)\, v_t^* \tag{18}$$

$$v_t^* = v_{t-1}^* + v_{LT,t} \tag{19}$$

Here, i_t^* denotes the central bank's interest rate target, to which it adjusts slowly with a lag coefficient ρ^i, and v_t^* represents a random walk component in long-term inflation expectations. 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.[8] We assume that short-term and long-term monetary policy shocks are uncorrelated, motivated by the economically and statistically insignificant correlation between Fed Funds rate and breakeven innovations on FOMC dates in our sample.

[8]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.

2.4 Stocks and bonds

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 $(1-\delta)P_t^c$. Nominal bonds in the model represent zero-coupon claims to one dollar n periods in the future, while real bonds represent zero-coupon claims to one unit of market consumption.

3 Model Solution and Discussion

3.1 Steady-state and output gap

The steady-state is given by $\bar{Y}_t = A_t N_t \bar{L}^{1-\tau}$, where $\bar{L}$ is the labor supply consistent with flexible prices and steady-state markups. The log output gap, x_t, defined as the log deviation of output from steady-state, equals (up to a constant):

$$x_t \;=\; y_t - n_t - a_t = c_t - (1-\phi)\sum_{j=0}^{\infty}\phi^j c_{t-1-j} - \sum_{j=0}^{\infty}\phi^j \Delta a_{t-j}. \tag{20}$$

Here, we have used the resource constraint $y_t = c_t$ and the process for human capital (15). Equation (20) has the appealing feature that the empirical output gap from the Bureau of Economic Analysis matches this consumption-output gap relation well (Campbell, Pflueger, and Viceira (2020)). Inverting equation (20) gives the equilibrium consumption dynamics from the output gap and productivity growth:

$$\Delta c_{t+1} \;=\; x_{t+1} - \phi x_t + \Delta a_{t+1}. \tag{21}$$

3.2 Household intertemporal first-order condition

The log real risk-free rate that can be earned from time t to time $t+1$ satisfies households' intertemporal first-order condition

$$1 = \mathrm{E}_t\left[M_{t+1} exp(r_t)\right]. \tag{22}$$

Here, the stochastic discount factor (SDF) M_{t+1} follows from households' habit utility

$$M_{t+1} = \beta\frac{\frac{\partial U_{t+1}}{\partial C}}{\frac{\partial U_t}{\partial C}} = \beta\exp\left(-\gamma(\Delta s_{t+1} + \Delta c_{t+1})\right). \tag{23}$$

Substituting the SDF and the surplus consumption dynamics into (22) gives up to a constant

$$
\begin{aligned}
r_t &= \gamma \mathrm{E}_t \Delta c_{t+1} + \gamma \mathrm{E}_t \Delta s_{t+1} - \frac{\gamma^2}{2}\left(1+\lambda(s_t)\right)^2 \sigma_c^2, && (24)\\
&= \gamma \mathrm{E}_t \Delta c_{t+1} + \gamma\theta_1 x_{t-1} + \gamma\theta_2 x_{t-2} + \gamma\varepsilon_{s,t} + \underbrace{\gamma(\theta_0-1)s_t - \frac{\gamma^2}{2}\left(1+\lambda(s_t)\right)^2 \sigma_c^2}_{=0}. && (25)
\end{aligned}
$$

Here, we use that for the sensitivity function given by equations (6) through (9) the last two terms in equation (25) exactly cancel. Using the equilibrium consumption-output gap link (21) and rearranging gives an *exactly* log-linear consumption Euler equation:

$$
x_t = \frac{1}{\phi-\theta_1}\mathrm{E}_t x_{t+1} + \frac{\theta_2}{\phi-\theta_1}x_{t-1} - \frac{1}{\gamma(\phi-\theta_1)}r_t + \frac{1}{\phi-\theta_1}\mathrm{E}_t\Delta a_{t+1} + \underbrace{\frac{1}{\phi-\theta_1}\varepsilon_{s,t}}_{v_{x,t}}. \qquad (26)
$$

Note that so far we have not used any approximations. Expected growth $\mathrm{E}_t\Delta a_{t+1}$ and the scaled habit shock $v_{x,t}$ here reflect fluctuations in the natural risk-free rate.

To simplify the solution for macroeconomic dynamics we use the common log-linear approximation for the nominal log short-term interest rate

$$
i_t = r_t + E_t\pi_{t+1}. \qquad (27)
$$

The approximation error stemming from (27) 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.

3.3 Profit first-order condition

An intermediate firm that gets the chance to reset its price at time t equates the expected discounted sum of the marginal change in revenue with the expected discounted sum of the marginal change in cost of producing the quantity demanded

$$
\begin{aligned}
&\frac{\tilde{P}_t}{P_t}\mathrm{E}_t\sum_{j=0}^{\infty}\alpha^j M_{t,t+j}Y_{t+j}(\theta_{t+j}-1)\left(\frac{P_{t-1+j}/P_{t-1}}{P_{t+j}/P_t}\right)^{1-\theta_{t+j}}\\
=\;&\mathrm{E}_t\sum_{j=0}^{\infty}\alpha^j M_{t,t+j}Y_{t+j}\theta_{t+j}\left(\frac{P_{t-1+j}/P_{t-1}}{P_{t+j}/P_t}\right)^{-\theta_{t+j}} MC_{i,t+j}. \qquad (28)
\end{aligned}
$$

Here, $\tilde{P}_t$ denotes the optimal price chosen by an intermediate firm that gets to re-set its price at time t, $M_{t,t+j} = M_{t+1}M_{t+2}...M_{t+j}$ is the households' SDF for discounting time

$t+j$ cash flows back to time t, and $MC_{i,t+j}$ denotes intermediate firm i's marginal cost of producing at time $t+j$.

The real wage for labor of type i satisfies the household's intratemporal first-order condition for difference habit utility with home production

$$W_{i,t} = \frac{\frac{\partial U}{\partial L_{i,t}}}{\frac{\partial U}{\partial C_t}} = A_t N_t (1 - L_{i,t})^{-\chi}. \tag{29}$$

Note in particular that the real wage does not depend on habit, thereby sidestepping the issue noted by Lettau and Uhlig (2000) that habit may affect labor supply decisions in a production economy.

We log-linearize the firms' profit first-order condition, so as to study the risk premium implications for well-understood macroeconomic responses to monetary policy shocks.[9] Substituting the log real wage into firm i's marginal cost of production, we follow a standard log-linearization procedure for the profit first-order condition, being careful to log-linearize inflation around its random walk component v_t^* (Cogley and Sbordone (2008)). This gives the log-linearized inflation Phillips curve

$$\pi_t = \frac{\beta_g}{1+\beta_g} E_t \pi_{t+1} + \frac{1}{1+\beta_g} \pi_{t-1} + \kappa x_t + \underbrace{\left(-\frac{\kappa}{\omega(\theta-1)}\right) \varepsilon_{\theta,t}}_{v_{\pi,t}}. \tag{30}$$

Here, π_t denotes log inflation, $\beta_g = \beta exp\left(-(\gamma-1)g\right)$ 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 $\omega = (\tau+\eta)/(1-\tau)$ is the steady-state elasticity of real marginal cost with respect to own-firm output. For a detailed derivation of equation (30) see Appendix B.

3.4 Macroeconomic equilibrium dynamics

We solve for the dynamics of the log-linear state vector

$$Y_t = [x_t, \pi_t - v_t^*, i_t - v_t^*]'. \tag{31}$$

Equilibrium macroeconomic dynamics are determined by the consumption Euler equation (26), the log-linearized Phillips curve (30), and the monetary policy rule (17) through (18). We collect the structural macroeconomic shocks in the vector

$$v_t = [v_{x,t}, v_{\pi,t}, v_{ST,t}, v_{LT,t}]', \tag{32}$$

[9] In that sense our work is complementary to Bianchi, Kung, and Tirskikh (2018), who present a model of price-setting dynamics with higher-order moments.

which is assumed to be serially uncorrelated and homoskedastic with a time-invariant diagonal variance-covariance matrix. 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:

$$Y_t = BY_{t-1} + \Sigma v_t, \tag{33}$$

where B and Σ are [3×3] and [3×4] matrices, respectively. We solve for the matrix B using Uhlig (1999)'s formulation of the Blanchard and Kahn (1980) method. Having solved for the state vector Y_t, equilibrium consumption dynamics follow from the relationship (21).

In our empirical specification, there exists a unique equilibrium of the form (33) with non-explosive eigenvalues, since we have a monetary policy rule that raises real rates in response to an increase in inflation ($\gamma^\pi > 1$). However, as in most New Keynesian models, there may be further equilibria with additional state variables or sunspots (Cochrane (2011)), but resolving these issues is beyond this paper.

3.5 Solving for asset prices

Having solved for log-linear macroeconomic dynamics, we next use numerical methods to solve for highly nonlinear asset prices. The tractability of this two step solution method is achieved because the surplus consumption ratio does not appear directly in the consumer first-order condition or the log-linearized profit first-order conditions.

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:

$$\frac{P^c_{nt}}{C_t} = \mathrm{E}_t \left[M_{t+1} \frac{C_{t+1}}{C_t} \frac{P^c_{n-1,t+1}}{C_{t+1}} \right]. \tag{34}$$

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

$$\frac{P^c_t}{C_t} = \sum_{n=1}^{\infty} \frac{P^c_{nt}}{C_t}. \tag{35}$$

The price of the levered equity claim equals $P^\delta_t = \delta P^c_t$. 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:

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

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 $y^{\$}_{n,t} = -\log\left(P^{\$}_{n,t}\right)/n$.

An analytic solution exists for the one-period consumption claim, the first claim in the infinite sum (35). Denoting the log return on the one-period consumption claim by $r^c_{1,t+1}$, the risk premium – adjusted for a standard Jensen's inequality term – equals the conditional covariance between the negative log SDF and and log consumption:

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

This equation shows that investors require a higher expected return, or risk premium, for holding the one-period consumption claim when surplus consumption is highly sensitive to consumption, as is the case when consumption has fallen close to habit. The relationship between risk premia and surplus consumption has the reverse sign for safe assets that comove positively with SDF. Because asset prices are inversely related with expected returns this can be interpreted as a flight-to-safety effect, whereby risky asset prices fall and safe asset prices rise in times of low risk bearing capacity.

We solve the asset pricing recursions recursively along 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 Appendix D.

3.6 FOMC announcement returns

We make the simplifying assumption that FOMC dates occur at the end of the quarter, so post-FOMC asset prices correspond to end-of-quarter asset prices.[10] In order to model the discrete arrival of news on FOMC dates, we assume that the quarterly fundamental

[10]Given that our results are robust to varying the volatility of news released on FOMC dates (Appendix C.7), modeling FOMC dates as occurring every six weeks is unlikely to change our findings.

shock vector v_t consists of independent pre-FOMC v_t^{pre} and FOMC v_T^{FOMC} components

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

The vector of FOMC shocks v_t^{FOMC} is assumed to have a diagonal variance-covariance matrix with standard deviations $\sigma_x^{FOMC} = 0$, $\sigma_\pi^{FOMC} = 0$, $\sigma_{ST}^{FOMC} < \sigma_{ST}$, and $\sigma_{LT}^{FOMC} < \sigma_{LT}$, so a portion of the monetary policy news shock is revealed on FOMC dates.

Pre-FOMC asset prices in our model differ from quarter $t-1$ asset prices because they also reflect information encoded in v_t^{pre}. We compute quarter t pre-FOMC asset prices at the expected quarter t state vector conditional on information available at the end of period $t-1$ and v_t^{pre}. We model FOMC announcements as occurring instantaneously, so no dividends are paid and the aggregate price level is constant during the short FOMC interval. The model high-frequency log stock return around monetary policy news then equals the post- minus the pre-FOMC log price for the levered consumption claim. The model high-frequency change in breakeven around monetary policy news equals post- minus pre-FOMC log 10-year breakeven. For details of model high-frequency asset price changes see Appendix C.7.

3.7 Discussion

Habit dynamics in this model are the minimal combination to reconcile volatile risk bearing capacity with a stable risk-free rate, and the achievements of habits within a standard small-scale New Keynesian model. The advantage of the specification (4) through (5) and the the sensitivity function (6) through (9) is to generate higher risk aversion after a sequence of bad shocks, while avoiding excessive volatility in the risk-free rate (Campbell and Cochrane (1999)), and ensuring that the household's intertemporal first-order condition takes exactly the form of a New-Keynesian consumption Euler equation (Campbell, Pflueger, and Viceira (2020)).

The downward-sloping relation between $\lambda(s_t)$ and s_t implies 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 specific nonlinear form for $\lambda(s_t)$ has the unique advantage that the precautionary savings and intertemporal substitution terms from surplus consumption cancel, and s_t is not a state variable for macroeconomic dynamics. Intuitively, when surplus consumption is low, the precautionary savings motive drives down the risk-free rate, but the motive to consume at a time of high marginal utility drives up the risk-free rate. The competing intertemporal substitution and precautionary savings motives result in a risk-free rate that depends only on expected consumption growth, two lags of the output gap, and the habit shock $\varepsilon_{s,t}$. Since surplus consumption depends on the same consumption and habit shocks as consumption and output, risk premia and macroeconomic dynamics are linked.

A few terms in the implied habit dynamics are particularly relevant for macroeconomic dynamics. Setting $\theta_1 > 0$ and $\theta_2 < 0$, as in our empirical specification, increases the dependence of habit on the most recent consumption lag, and makes habits more similar to the typical assumption in macroeconomic models where habit often equals lagged consumption (Christiano, Eichenbaum, and Evans (2005), Boldrin, Christiano, and Fisher (2001)). We therefore generate hump-shaped output responses to monetary policy shocks as in those macroeconomic models. This can also be seen from the intertemporal first-order condition (26), where $\theta_2 > 0$ generates a lagged output gap term. In our empirical specification, we constrain the parameter θ_1 so that the forward- and backward-looking terms in the consumption Euler equation sum to one for comparability with prior work.

The new habit shock $\varepsilon_{s,t}$ captures independent fluctuations in habit and leads to risk-centric demand shocks in the Euler equation. A positive $\varepsilon_{s,t}$ lowers future expected habit and increases future expected surplus consumption, reducing risk aversion.[11] We interpret this shock 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 microfounded from habit allow us to use a single stochastic discount factor to price all assets, and drive real bonds and stocks in opposite directions similarly to the data.

Home production and habit over home-produced goods are new compared to prior finance habit models, though they are in line with classic research by Greenwood, Hercowitz, and Huffman (1988). By separating the intratemporal labor-leisure choice from the intertemporal consumption-savings decision, this assumption ensures that intermediate firms face a standard first-order profit condition. When market consumption is close to habit consumers perceive high marginal utility not just from market- but also from home-produced goods, leaving the trade-off between working in the market versus at home unchanged, and thereby separating fluctuations in asset price risk premia from firms' profit optimization. Concretely, after an adverse shock consumers shift from eating out to cooking at home, as documented in Aguiar, Hurst, and Karabarbounis (2013). The assumption that productivity in the home increases with aggregate productivity, $A_t N_t$, ensures that the labor-leisure trade-off does not become irrelevant over time consistent with empirical evidence (Kehoe, Lopez, Midrigan, and Pastorino (2019), Chodorow-Reich and Karabarbounis (2016)). A complementary approach to separate

[11] 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.

wages from consumption habit would be to introduce separate slow-moving 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, χ, closely related to the Frisch elasticity of labor supply. Because of this parsimony we consider our model a useful template to study the interaction between labor market frictions and habits in future research.

In order to present the simplest possible model of monetary policy and finance habits we do not explicitly model real investment. However, the process (15) can equivalently be interpreted as a simple endogenous capital stock, similarly to (Woodford, 2003, Chapter 5), if a fixed proportion of market labor each period is used to produce investment goods and we scale the total amount of labor available accordingly. Our analysis is therefore complementary to the classic paper of Jermann (1998), which studies a real business cycle model with habit formation preferences.

We choose to model stocks as a consumption claim to capture the properties of a generic pro-cyclical risky asset. It is well-known that consumption and profits diverge in simple New Keynesian models without wage-setting frictions such as ours (Romer (2006)). The simplest way to reconcile the gap between firm profits and stock dividends in our model is if the government charges intermediate goods producers a lump-sum tax equal to this gap, that is rebated again lump-sum to households. Because the macroeconomic dynamics in our model are exactly equivalent to the standard New Keynesian model, a different route at the cost of additional state variables would be to add standard wage setting frictions, which are well-known to resolve the gap between firm profits and consumption (Favilukis and Lin (2016)).

4 Econometric Methodology

We take the model to the data in two steps. In a first step, we set preference parameters, firm parameters, and monetary policy parameters to standard values from the literature.[12] In a second step, we estimate the standard deviations of shocks using a Simulated Method of Moments (SMM) procedure to fit moments from quarterly macroeconomic data. This procedure ensures that parameters are set without regard to the high-frequency moments around monetary policy announcements.

[12] We check in Appendix Table A2 that the particular values of the calibrated parameters are not crucial for our main results. We choose the current procedure because it ensures that, for example, firm parameters reflect intuition from outside our specific data set and to avoid overfitting.

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 $\tau = 1/3$. 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 $\gamma_\pi = 1.5$. We set the monetary policy smoothing parameter to $\rho^i = 0.9$ to match the larger root in interest rates, and $\rho^a = 0.34 = 0.68/\gamma$ to match the relationship between the frictionless real rate embedded in growth expectations and the actual real rate from 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

$$J(\sigma) = (\Psi(\sigma) - \hat{\Psi})'\hat{W}(\Psi(\sigma) - \hat{\Psi}). \tag{40}$$

Following Christiano, Eichenbaum, and Evans (2005), the vector $\hat{\Psi}$ collects empirical macroeconomic impulse responses, and we weight the moments by a diagonal matrix $\hat{W}$ with the inverses of the bootstrapped variances along the diagonal. 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.[13] 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. 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.[14] For details of the SMM procedure see Appendix E.

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 empirical macroeconomic impulse responses well. Because all impulse responses are to one-standard deviation innovations, the initial impulse responses show that the model matches the volatilities of innovations to the log output gap, log inflation, and log Federal Funds rate. It is 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. Impulse responses to structural model shocks are described in Section 5.3.

Both in the model and in the data the output gap, inflation, and the Federal Funds rate

[13]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.

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

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 has documented 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)).

Even though our estimation does not match consumption dynamics directly, they are also well-approximated by the model. The standard deviation of annual consumption growth is 1.24% in the model, compared to 1.26% in the data over our sample. The consumption-output gap relationship also fits well. In the model, a regression of annual log consumption growth onto the annual log output gap change yields a coefficient of 1.05 (correlation 0.96) compared to a coefficient of 0.89 (correlation 0.75) in the data. While we slightly undershoot the standard deviation of annual output gap changes (1.13% model vs. 1.51% data), we are not concerned about this slight gap for two reasons. First, Figure 2 shows that the model output gap dynamics are clearly within reasonable confidence intervals. Second, a lower output gap volatility should, if anything, lead to conservative model risk premium responses.

4.3.2 Asset prices

Table 2 shows quarterly asset prices and shows that despite the additional structure our model replicates the successes of Campbell, Pflueger, and Viceira (2020). The model generates volatile stock returns with an empirically plausible equity Sharpe ratio of 0.50, an equity premium of 6.82%, and annualized equity return volatility of 13.55%. This high stock return volatility is achieved through time-varying risk premia.[15] The model fits the negative breakeven beta with respect to the stock market.[16] The real bond-stock beta in the model is slightly positive, compared to a slightly negative real bond beta in

[15]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 (2005) and Gürkaynak, Sack, and Wright (2010). All yields and returns are continuously compounded.

[16]Breakeven returns are defined as the log returns on 10-year nominal bonds in excess of 10-year inflation indexed bonds. Because yields move inversely with prices, a negative breakeven return beta as documented in Table 2 is consistent with a positive comovement between changes in breakeven inflation and stock returns.

the data. Breakeven excess returns are volatile at 4.76% 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 prefer to fit second moments, which are measured more precisely 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 the convenient log-linear macroeconomic dynamics would make our model a tractable building block for such an analysis.

5 Stock Returns around Monetary Policy News

We now turn to the new implications for high-frequency stock price changes around monetary policy announcements. In this section, we first expand on the motivating evidence reported in Figure 1, we then show that the model can account for these empirical patterns, and finally demonstrate the economic mechanism through structural impulse responses. Appendix F.2 shows that the model also matches the comovement between the short-term policy rate and long-term real bond yields on FOMC dates.

5.1 Empirical stocks returns on FOMC dates

In Table 3, we formally establish the empirical relationships described in Figure 1. Column (1) corresponds to the left panel of Figure 1, and replicates the classic result of Bernanke and Kuttner (2005) for our more recent sample. We find that a 25 bps surprise increase in the Federal Funds rate leads to a one percentage point drop in the stock price on average. 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.[17] To establish that FOMC dates reveal separate information about short-term interest rates and long-term breakeven, 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 changes in 10-year breakeven on FOMC dates are uncorrelated with Federal Funds rate surprises over our sample period.

The relationship between S&P 500 returns and 10-year breakeven changes on FOMC days is not driven by changes in liquidity premia. We verify this in Appendix Section G. First, in Figure A3 we show that the relationship is essentially unchanged if one uses inflation swap rate changes instead of breakeven changes. More directly, in Appendix Table A4, we show that, different from breakeven changes, changes in the Treasury-TIPS basis are not significantly related to stock returns on FOMC dates. We also repeat the analysis with intraday changes in inflation swap rates for a shorter sample in Appendix Table A5.

5.2 Model stock returns on FOMC dates

Table 4 shows estimates from model regressions corresponding to the empirical ones in Table 3. 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. We compute high-frequency model stock returns, short-term interest rate changes, and 10-year breakeven changes using post- minus pre-FOMC asset prices as described in Section 3.6.[18]

Table 4, column (2) shows that the model matches the baseline empirical regression in Table 3, column (3). A 25 bps surprise increase in the short-term nominal risk-free rate in the model leads on average to a 1.3 percentage point fall in the stock market. On the other hand, a 25 bps surprise increase in 10-year breakeven on a monetary policy news event is associated with a 1.5 percentage point increase in stock returns in the model. Of course,

[17]We collect the release date of FOMC statements from January 1st 2001 until March 31st 2019 from the Federal Reserve's website. One-hour changes in the Federal Funds rate around scheduled FOMC announcements are from the updated data of Gorodnichenko and Weber (2016) and Neuhierl and Weber (2030). The equity return 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. For the long-term monetary shock we use one-day changes in zero coupon nominal Treasury yields minus TIPS yields from Gürkaynak, Sack, and Swanson (2005) and Gürkaynak, Sack, and Wright (2010).

[18]We show in Appendix Figure A1 that the model regression slope coefficients are not sensitive to reasonable variation in the volatilities of FOMC date news.

breakeven inflation may reflect both the risk-neutral long-term inflation expectations and risk premia and our model allows us to decompose these effects. Table 4 column (3) shows that the stock return regression remains unchanged compared to column (2) when we replace 10-year breakeven in the model by a version that is stripped of all risk premia, showing that the model attributes the empirical relationship between breakeven and stock returns to surprises in long-term inflation expectations.

Column (4) reveals the power of endogenously time-varying risk premia in response to monetary policy. This column isolates the stock return component due to time-varying risk premia on the left-hand side, stripping out the risk neutral component of stock returns. In the model, a 25 bps increase in the short-term nominal rate on monetary policy news days is associated with a 64 bps decrease in stock prices due to changes in risk premia.[19] A 25 bps increase in model 10-year breakeven (or long-term expected inflation in column (5)) on monetary policy news days is associated with a 68 bps increase in stock prices due to risk premia alone. Columns (4) and (5) hence show that monetary policy has an economically meaningful impact on investors' willingness to hold risky assets. This channel in the model significantly amplifies the stock return response to monetary policy news, compared to a world where monetary policy affects asset prices only through its impact on the discounted sum of future expected dividends. The large risk premium response in our model to monetary policy news is quantitatively very similar to the empirical decomposition of Bernanke and Kuttner (2005), which attributes about 60% of the overall high-frequency stock response to time-varying risk premia. Appendix Table A1 shows that the results in Table 4 are robust to switching off various model components.

5.3 Economic mechanism

Why do stock returns move so much in response to short-term monetary policy news? To better understand the model mechanisms, we show impulse responses to the structural shocks $v_{x,t}$, $v_{\pi,t}$, $v_{ST,t}$ and $v_{LT,t}$. Figure 3 shows macroeconomic impulse responses, with each column corresponding to a different shock and the rows showing responses for the log output gap, log inflation, and the log short-term nominal interest rate. Figure 4 shows cumulative equity returns in excess of the steady-state return, yields on 10-year nominal, and 10-year real bonds. Because bond yields are inversely related to prices, an increase

[19]Given the nonlinearity of risk premia in the model, one might expect that contractionary shocks would display a larger response than surprise reductions in interest rates. Appendix Figure A2 shows that the model relationship between monetary policy surprises and FOMC stock returns displays no clear asymmetry between positive and negative monetary policy surprises for small monetary policy surprises. This is because the FOMC shocks are relatively small.

in the 10-year yield implies a decrease in the corresponding bond price.[20]

The impulse responses to a short-term monetary policy shock illustrate why model stock returns decline so much with a short-term nominal interest rate surprise. Figure 3 shows that a positive short-term monetary policy shock causes an increase in the short-term nominal interest rate, driving down the output gap through consumers' consumption-savings decision, and lowering inflation as intermediate firms face less pressure to raise prices. The backward-looking component in the consumption Euler equation ensures a hump-shaped output gap response as in Fuhrer (2000) and Boldrin, Christiano, and Fisher (2001). The last column in Figure 4 sheds light on the asset price response, and in particular illustrates our new model channel whereby the total stock return response is equally due to time-varying risk premia and risk-neutral stock returns. Intuitively, as consumption declines towards habit, household risk aversion increases, driving down stock prices more than dividends.

To understand the model relationship between high-frequency changes in 10-year breakeven and stock returns on FOMC dates, we turn to the long-term monetary policy shock. Figure 3 shows that a negative long-term monetary policy shock leads to costly disinflation, lowering inflation expectations ahead of nominal interest rates, and thereby raising the real rate. Facing higher real rates, households postpone consumption, leading to contractions in consumption and the output gap. The long-term monetary policy shock therefore has the potential to move the output gap and long-term inflation expectations in the same direction around monetary policy news. Turning to asset prices, we see that stock returns are positively correlated with breakeven in response to a long-term monetary policy shock. In response to a negative long-term monetary policy shock, stocks fall more than their risk-neutral value while long-term breakeven falls to reflect lower long-term inflation expectations. The fall in stocks is amplified by changing risk premia because households' consumption declines towards habit. In contrast to stocks, the risk premium response in breakeven to monetary policy is smaller because breakeven returns have a stock market beta that is much smaller than one in magnitude.[21]

In addition to shedding light on the asset price responses to monetary policy, 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

[20]The risk neutral response for all asset prices is computed as if assets were priced by a risk neutral agent, holding macroeconomic dynamic fixed. The risk premium component is the difference between the total and the risk neutral responses.

[21]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)).

a temporary increase in output, and a smaller temporary increase in inflation. 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 to substitute consumption from the future towards today, 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. As consumption in the current period increases relative to habit with a positive demand shock, households require lower risk premia for holding stocks. The demand shock therefore acts as a "flight-to-safety" shock driving nominal bond prices and stock prices in opposite directions. A positive Phillips curve shock, due to an increase in markups, leads to a decline in output and an increase in inflation.

5.4 Stock responses to monetary policy and the economic state

So far, we have documented that the model matches the average relationship between stock returns and monetary policy shock. In addition, the model model provides a new economic mechanism that predicts heterogeneity in the stock response to the same monetary policy shocks across economic states, which may appear as outliers in the overall empirical relationship between high-frequency stock returns and monetary policy shocks.[22] In Figure 5 we present the model high-frequency stock response to monetary policy news conditional on the surplus consumption ratio decile. The figure shows that the overall stock response (solid) to both long- and short-term monetary policy shocks increases in magnitude when surplus consumption is low. However, the macroeconomic consequences of the shocks reported in Figure 3 are invariant to the level of surplus consumption, as reflected in the risk-neutral stock responses (dashed) being flat. The variation in stock return responses to long- and short-term monetary policy shocks across economic states hence reflects different risk premium responses (dotted) rather than variation in the real effects of monetary policy.

In line with the model predictions, we find that stocks responded more strongly to both types of monetary policy surprises after the financial crisis of 2008, a period that was characterized by persistently negative output gaps and the lowest equity price-dividend ratio in our sample. In terms of magnitude, the post-crisis period yields a stock return coefficient onto Federal Funds rate surprises of around negative -7.5 and a stock return coefficient onto breakeven surprises of around positive 7.5, in line with the regression coefficients predicted by the model when the surplus consumption ratio is within its

[22] For example, Bernanke and Kuttner (2005) discuss in length the role of outliers, and in particular that stock returns responded especially strongly to monetary policy during the aftermath of the 2000 burst of the dotcom bubble.

bottom tercile.[23] The model prediction of greater stock return sensitivity to announcements during recessions is also consistent with the empirical evidence from macroeconomic announcements, which has found that stock prices and in particular the risk premium component of stock returns respond more strongly to non-farm payroll and other macroeconomic news when the state of the economy is bad (Boyd, Hu, and Jagannathan (2005), Law, Song, and Yaron (2019)).

6 Conclusion

We integrate a small-scale New Keynesian model of monetary policy with countercyclical risk premia 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 explains the large stock return decline in response to a positive Federal Funds rate surprise with time-varying risk premia, that are however a reflection of the real effects of monetary policy for output and consumption. A surprise increase in the short-term nominal interest rate has the standard effect of contracting consumption and output, which in turns lowers consumption relative to habits and reduces financial markets' risk bearing capacity. Our model attributes the large and positive empirical relationship between breakeven inflation innovations and stock returns around monetary policy announcements to news about long-term inflation, whose effect on stocks is again amplified by fundamental-driven risk premia.

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. Our model suggests that policy makers, economists, and market observers need to be careful to account for time-varying risk premia when interpreting the stock market response to monetary policy news, as stock markets may react significantly more to the same macroeconomic news when investors are risk averse and risk bearing capacity is low.

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

[23]The regressions for the post-crisis sample are reported in Appendix G.3. These empirical findings are in line with Paul (2020) who uses a time-varying coefficients model to show that stocks responded more strongly to monetary policy news after the financial crisis. He also finds that stocks responded less during the early 1990s, though this evidence is harder to interpret because the Federal Reserve only started to announce formal targets after FOMC meetings in 1994.

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)).

References

Abel, Andrew B, 1990, Asset Prices under Habit Formation and Catching up with the Joneses, *American Economic Review* pp. 38–42.

Aguiar, Mark, Erik Hurst, and Loukas Karabarbounis, 2013, Time use during the great recession, *American Economic Review* 103, 1664–96.

Andrade, Philippe, and Filippo Ferroni, 2020, Delphic and Odyssean monetary policy shocks: Evidence from the euro area, *Journal of Monetary Economics*.

Auclert, Adrien, Matthew Rognlie, and Ludwig Straub, 2020, Micro jumps, macro humps: Monetary policy and business cycles in an estimated hank model, National Bureau of Economic Research Working Paper wp26647.

Baele, Lieven, Geert Bekaert, and Koen Inghelbrecht, 2010, The determinants of stock and bond return comovements, *Review of Financial Studies* 23, 2374–2428.

Ball, Laurence, 1994, Credible disinflation with staggered price-setting, *American Economic Review* 84, 282–289.

Ball, Laurence, and David Romer, 1990, Real rigidities and the non-neutrality of money, *Review of Economic Studies* 57, 183–203.

Bekaert, Geert, Eric Engstrom, and Steven R Grenadier, 2010, Stock and bond returns with moody investors, *Journal of Empirical Finance* 17, 867–894.

Bekaert, Geert, Eric C Engstrom, and Nancy R Xu, 2019, The time variation in risk appetite and uncertainty, .

Bernanke, Ben S, and Kenneth N Kuttner, 2005, What explains the stock market's reaction to federal reserve policy? *Journal of Finance* 60, 1221–1257.

Bianchi, Francesco, Cosmin L Ilut, and Martin Schneider, 2018, Uncertainty shocks, asset supply and pricing over the business cycle, *Review of Economic Studies* 85, 810–854.

Bianchi, Francesco, Howard Kung, and Mikhail Tirskikh, 2018, The origins and effects of macroeconomic uncertainty, NBER Working Paper wp25386.

Bianchi, Francesco, Martin Lettau, and Sydney C Ludvigson, 2020, Monetary policy and asset valuation, Discussion paper, Working Paper, Duke University, NYU and Berkeley.

Blanchard, Olivier Jean, and Charles M Kahn, 1980, The solution of linear difference models under rational expectations, *Econometrica* pp. 1305–1311.

Boldrin, Michele, Lawrence J Christiano, and Jonas DM Fisher, 2001, Habit persistence, asset returns, and the business cycle, *American Economic Review* 91, 149–166.

Boyd, John H, Jian Hu, and Ravi Jagannathan, 2005, The stock market's reaction to unemployment news: Why bad news is usually good for stocks, *Journal of Finance* 60, 649–672.

Bretscher, Lorenzo, Alex Hsu, and Andrea Tamoni, 2019, The real response to uncertainty shocks: The risk premium channel, *Working Paper, London Business School, Rutgers, and Georgia Tech*.

Caballero, Ricardo J, and Alp Simsek, 2020, A risk-centric model of demand recessions and macroprudential policy, *Quarterly Journal of Economics* forthcoming.

Calvo, Guillermo A, 1978, On the Time Consistency of Optimal Policy in a Monetary Economy, *Econometrica: Journal of the Econometric Society* pp. 1411–1428.

Calvo, Guillermo A, 1983, Staggered Prices in a Utility-Maximizing Framework, *Journal of Monetary Economics* 12, 383–398.

Campbell, John Y, 2003, Consumption-Based Asset Pricing, *Handbook of the Economics*

of Finance 1, 803–887.
Campbell, John Y, and John H Cochrane, 1999, By force of habit: A consumption-based explanation of aggregate stock market behavior, *Journal of Political Economy* 107, 205–251.
Campbell, John Y, and Sydney Ludvigson, 2001, Elasticities of substitution in real business cycle models with home production, *Journal of Money, Credit and Banking* 33, 847–875.
Campbell, John Y, Carolin Pflueger, and Luis M Viceira, 2020, Macroeconomic drivers of bond and equity risks, *Journal of Political Economy* 128, 3148–3185.
Campbell, John Y, Adi Sunderam, Luis M Viceira, et al., 2017, Inflation Bets or Deflation Hedges? The Changing Risks of Nominal Bonds, *Critical Finance Review* 6, 263–301.
Chodorow-Reich, Gabriel, and Loukas Karabarbounis, 2016, The cyclicality of the opportunity cost of employment, *Journal of Political Economy* 124, 1563–1618.
Christiano, Lawrence H., Martin Eichenbaum, and Charles L. Evans, 2005, Nominal rigidities and the dynamic effects of a shock to monetary policy, *Journal of Political Economy* 113, 1–45.
Christiano, Lawrence J, Roberto Motto, and Massimo Rostagno, 2014, Risk shocks, *American Economic Review* 104, 27–65.
Cieslak, Anna, Adair Morse, and Annette Vissing-Jorgensen, 2019, Stock returns over the FOMC cycle, *Journal of Finance* 74, 2201–2248.
Cieslak, Anna, and Hao Pang, 2019, Common shocks in stocks and bonds, *Duke University, Working Paper*.
Cochrane, John H, 2011, Determinacy and Identification with Taylor Rules, *Journal of Political Economy* 119, 565–615.
Cochrane, John H., 2017, Macro-Finance, *Review of Finance*.
Cochrane, John H, 2018, Michelson-Morley, Fisher, and Occam: The Radical Implications of Stable Quiet Inflation at the Zero Bound, *NBER Macroeconomics Annual* 32, 113–226.
Cogley, Timothy, and Argia M. Sbordone, 2008, The time-varying volatility of macroeconomic fluctuations, *American Economic Review* 98, 2101–2126.
Coibion, Olivier, Yuriy Gorodnichenko, and Michael Weber, 2020, Monetary policy communications and their effects on household inflation expectations, *NBER WP 26778*.
Dew-Becker, Ian, 2014, Bond pricing with a time-varying price of risk in an estimated medium-scale Bayesian DSGE model, *Journal of Money, Credit and Banking* 46, 837–888.
Drechsler, Itamar, Alexi Savov, and Philipp Schnabl, 2018, A model of monetary policy and risk premia, *Journal of Finance* 73, 317–373.
Favilukis, Jack, and Xiaoji Lin, 2016, Wage rigidity: A quantitative solution to several asset pricing puzzles, *Review of Financial Studies* 29, 148–192.
Fleckenstein, Matthias, Francis A Longstaff, and Hanno Lustig, 2014, The TIPS-Treasury bond puzzle, *the Journal of Finance* 69, 2151–2197.
Fuhrer, Jeffrey C, 2000, Habit formation in consumption and its implications for monetary-policy models, *American Economic Review* 90, 367–390.
Gabaix, Xavier, 2019, A behavioral New Keynesian model, *Harvard University Working Paper*.
Galí, Jordi, 2008, *Monetary Policy, Inflation, and the Business Cycle* (Princeton Univer-

sity Press).
Gali, Jordi, and Tommaso Monacelli, 2005, Monetary Policy and Exchange Rate Volatility in a Small Open Economy, *The Review of Economic Studies* 72, 707–734.
Goodfriend, Marvin, and Robert G King, 2005, The incredible volcker disinflation, *Journal of Monetary Economics* 52, 981–1015.
Gorodnichenko, Yuriy, and Michael Weber, 2016, Are sticky prices costly? evidence from the stock market, *American Economic Review* 106, 165–99.
Gourio, Francois, 2012, Disaster risk and business cycles, *American Economic Review* 102, 2734–66.
Gourio, François, and Phuong Ngo, 2020, Risk Premia at the ZLB: A Macroeconomic Interpretation, *Federal Reserve Bank of Chicago*.
Greenwood, Jeremy, Zvi Hercowitz, and Gregory W Huffman, 1988, Investment, capacity utilization, and the real business cycle, *American Economic Review* pp. 402–417.
Gürkaynak, Refet S, Brian Sack, and Eric Swanson, 2005, The sensitivity of long-term interest rates to economic news: Evidence and implications for macroeconomic models, *American Economic Review* 95, 425–436.
Gürkaynak, Refet S, Brian Sack, and Jonathan H Wright, 2007, The US treasury yield curve: 1961 to the present, *Journal of Monetary Economics* 54, 2291–2304.
Gürkaynak, Refet S, Brian Sack, and Jonathan H Wright, 2010, The TIPS yield curve and inflation compensation, *American Economic Journal: Macroeconomics* 2, 70–92.
Hanson, Samuel G, and Jeremy C Stein, 2015, Monetary policy and long-term real rates, *Journal of Financial Economics* 115, 429–448.
Jarociński, Marek, and Peter Karadi, 2020, Deconstructing monetary policy surprises—The role of information shocks, *American Economic Journal: Macroeconomics* 12, 1–43.
Jermann, Urban J., 1998, Asset pricing in production economies, *Journal of Moentary Economics* 41, 257–275.
Jurado, Kyle, Sydney C Ludvigson, and Serena Ng, 2015, Measuring uncertainty, *American Economic Review* 105, 1177–1216.
Kaplan, Greg, Benjamin Moll, and Giovanni L Violante, 2018, Monetary policy according to hank, *American Economic Review* 108, 697–743.
Kehoe, Patrick J, Pierlauro Lopez, Virgiliu Midrigan, and Elena Pastorino, 2019, Asset prices and unemployment fluctuations, Discussion paper, National Bureau of Economic Research.
Kekre, Rohan, and Moritz Lenel, 2020, Monetary policy, redistribution, and risk premia, *Working Paper, University of Chicago and Princeton University*.
Kilic, Mete, and Jessica A Wachter, 2018, Risk, unemployment, and the stock market: A rare-event-based explanation of labor market volatility, *Review of Financial Studies* 31, 4762–4814.
Kung, Howard, 2015, Macroeconomic linkages between monetary policy and the term structure of interest rates, *Journal of Financial Economics* 115, 42–57.
Laarits, Toomas, 2019, Pre-announcement risk, Working Paper, NYU Stern.
Lagos, Ricardo, and Shengxing Zhang, 2020, Turnover liquidity and the transmission of monetary policy, *American Economic Review, forthcoming*.
Law, Tzuo Hann, Dongho Song, and Amir Yaron, 2019, Fearing the Fed: How Wall Street reads Main Street, Working Paper, Boston College, Johns Hopkins University,

and Wharton.

Lettau, Martin, and Harald Uhlig, 2000, Can habit formation be reconciled with business cycle facts? *Review of Economic Dynamics* 3, 79–99.

Lopez, Pierlauro, J. David, 2014, Macro- finance separation by force of habit, *unpublished paper, Federal Reserve Board and Banque de France.*

Lucas, Robert E. Jr., 1988, On the mechanics of economic development, *Journal of Monetary Economics* 22, 3–42.

Lucca, David O, and Emanuel Moench, 2015, The pre-FOMC announcement drift, *Journal of Finance* 70, 329–371.

McKay, Alisdair, Emi Nakamura, and Jón Steinsson, 2016, The power of forward guidance revisited, *American Economic Review* 106, 3133–58.

Nakamura, Emi, and Jón Steinsson, 2018, High-frequency identification of monetary non-neutrality: the information effect, *Quarterly Journal of Economics* 133, 1283–1330.

Neuhierl, Andreas, and Michael Weber, 2030, Monetary momentum, Working paper, Washington University in St. Louis and University of Chicago.

Orphanides, Athanasios, and John Williams, 2004, Imperfect Knowledge, Inflation Expectations, and Monetary Policy, in Ben S. Bernanke, and Michael Woodford, eds.: *The Inflation-Targeting Debate* . pp. 201–246 (University of Chicago Press).

Paul, Pascal, 2020, The time-varying effect of monetary policy on asset prices, *Review of Economics and Statistics* 102, 690–704.

Pflueger, Carolin, Emil Siriwardane, and Adi Sunderam, 2020, Financial market risk perceptions and the macroeconomy, *Quarterly Journal of Economics* 135, 1443–1491.

Pflueger, Carolin E, and Luis M Viceira, 2016, Return Predictability in the Treasury Market: Real Rates, Inflation, and Liquidity, in Pietro Veronesi, ed.: *Handbook in Fixed-Income Securities* (Wiley, New Jersey).

Ramey, Valerie A, 2016, Macroeconomic shocks and their propagation, *Handbook of Macroeconomics* 2, 71–162.

Romer, Christina D, and David H Romer, 2004, A new measure of monetary shocks: Derivation and implications, *American Economic Review* 94, 1055–1084.

Romer, David H., 2006, *Advanced Macroeconomics* (McGraw-Hill).

Rudebusch, Glenn D, and Eric T Swanson, 2008, Examining the bond premium puzzle with a dsge model, *Journal of Monetary Economics* 55, S111–S126.

Rudebusch, Glenn D, and Eric T Swanson, 2012, The bond premium in a dsge model with long-run real and nominal risks, *American Economic Journal: Macroeconomics* 4, 105–43.

Schmitt-Grohé, Stephanie, and Martín Uribe, 2018, Exchange rates and uncovered interest differentials: The role of permanent monetary shocks, Discussion paper, National Bureau of Economic Research.

Schularick, Moritz, and Alan M Taylor, 2012, Credit booms gone bust: Monetary policy, leverage cycles, and financial crises, 1870-2008, *American Economic Review* 102, 1029–61.

Shiller, Robert J, 1981, Do stock prices move too much to be justified by subsequent changes in dividends? *American Economic Review* 71, 421–436.

Smets, Frank, and Rafael Wouters, 2007, Shocks and frictions in us business cycles: A Bayesian DSGE approach, *American Economic Review* pp. 586–606.

Song, Dongho, 2017, Bond Market Exposures to Macroeconomic and Monetary Policy

Risks, *Review of Financial Studies* 30, 2761–2817.

Stavrakeva, Vania, and Jenny Tang, 2019, The dollar during the great recession: US monetary policy signaling and the flight to safety, Working Paper, London Business School and Boston Federal Reserve.

Taylor, John B, 1993, Discretion versus policy rules in practice, in *Carnegie-Rochester conference series on public policy* vol. 39 pp. 195–214. Elsevier.

Uhlig, Harald, 1999, A Toolkit for Analysing Nonlinear Dynamic Stochastic Models Easily, in Ramon Marimon, and Andrew Scott, eds.: *Computational Methods for the Study of Dynamic Economics* . pp. 30–61 (Oxford University Press).

Uhlig, Harald, 2007, Explaining asset prices with external habits and wage rigidities in a DSGE model, *American Economic Review* 97, 239–243.

Uribe, Martín, 2018, The neo-Fisher effect: Econometric evidence from empirical and optimizing models, Discussion paper, National Bureau of Economic Research.

Wachter, Jessica A., 2005, Solving models with external habit, *Finance Research Letters* 2, 210–226.

Wachter, Jessica A, and Yicheng Zhu, 2020, A model of two days: Discrete news and asset prices, *Working Paper, Wharton.*

Walsh, Carl E, 2017, *Monetary theory and policy* (MIT press).

Weber, Michael, 2015, Nominal rigidities and asset pricing, *Working Paper, University of Chicago.*

Woodford, Michael, 2003, *Interest and Prices* (Princeton University Press).

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 log output gap 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	4.76	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
	Excess Returns	0.07	3.76
	Sharpe Ratio	0.05	0.55

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). We report average excess real bond and breakeven log returns plus one-half times the log excess return variance. Excess returns 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 High-Frequency Stock Returns on FOMC Dates

	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: Columns (1) to (3) show regressions of the form: $r_t^{FOMC} = b_0 + b_1\Delta^{FOMC}i_t + b_2\Delta^{FOMC}b_{10,t} + \varepsilon_t$. $\Delta^{FOMC}i_{n,t}$ 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 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

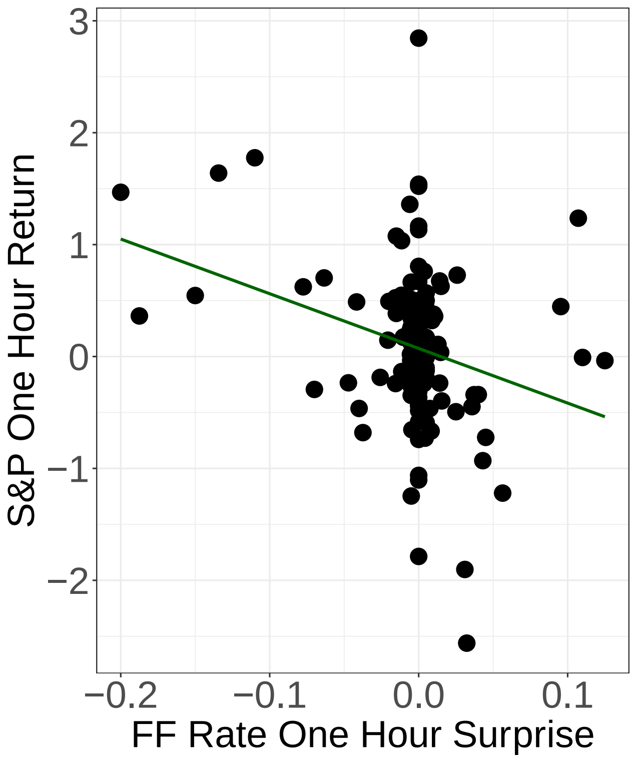
Table 4: Model High-Frequency Stock Returns around Monetary Policy News

	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 Expected Inflation			5.96		2.73

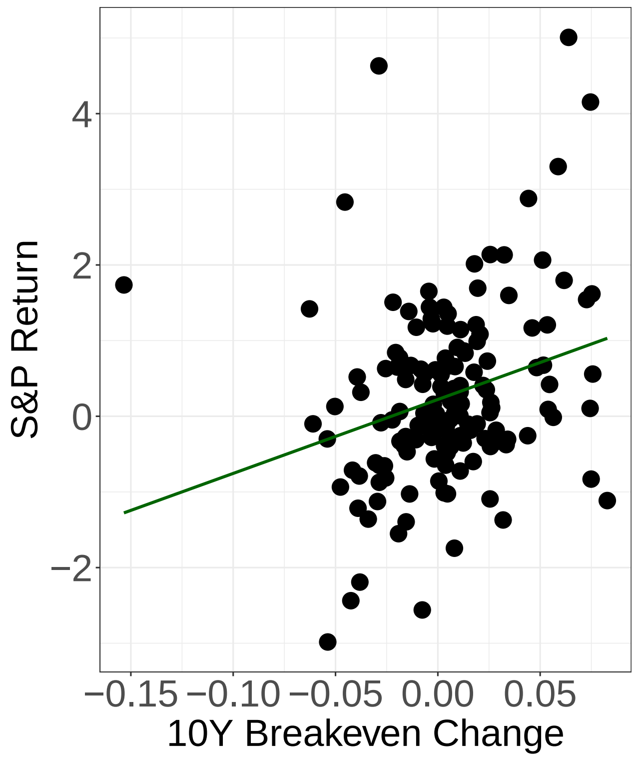
Note: This table compares the asset price reactions around monetary policy news in the model and in the data. Column (1) repeats the empirical estimates from Table 3, column (3). Column (2) estimates the analogous regression on model simulated data, assuming that FOMC dates are subject to uncorrelated long-term and short-term monetary policy shocks. The standard deviations of the ST and LT monetary policy shocks on FOMC dates are set to $\sigma_{ST}^{FOMC} = 4.3bps$ and $\sigma_{LT}^{FOMC} = 3.3bps$ to match the volatilities of one-hour Fed Funds surprises and daily 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, which is also equal to rational 10-year inflation expectations. 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

Panel A: Stocks and the Federal Funds Rate

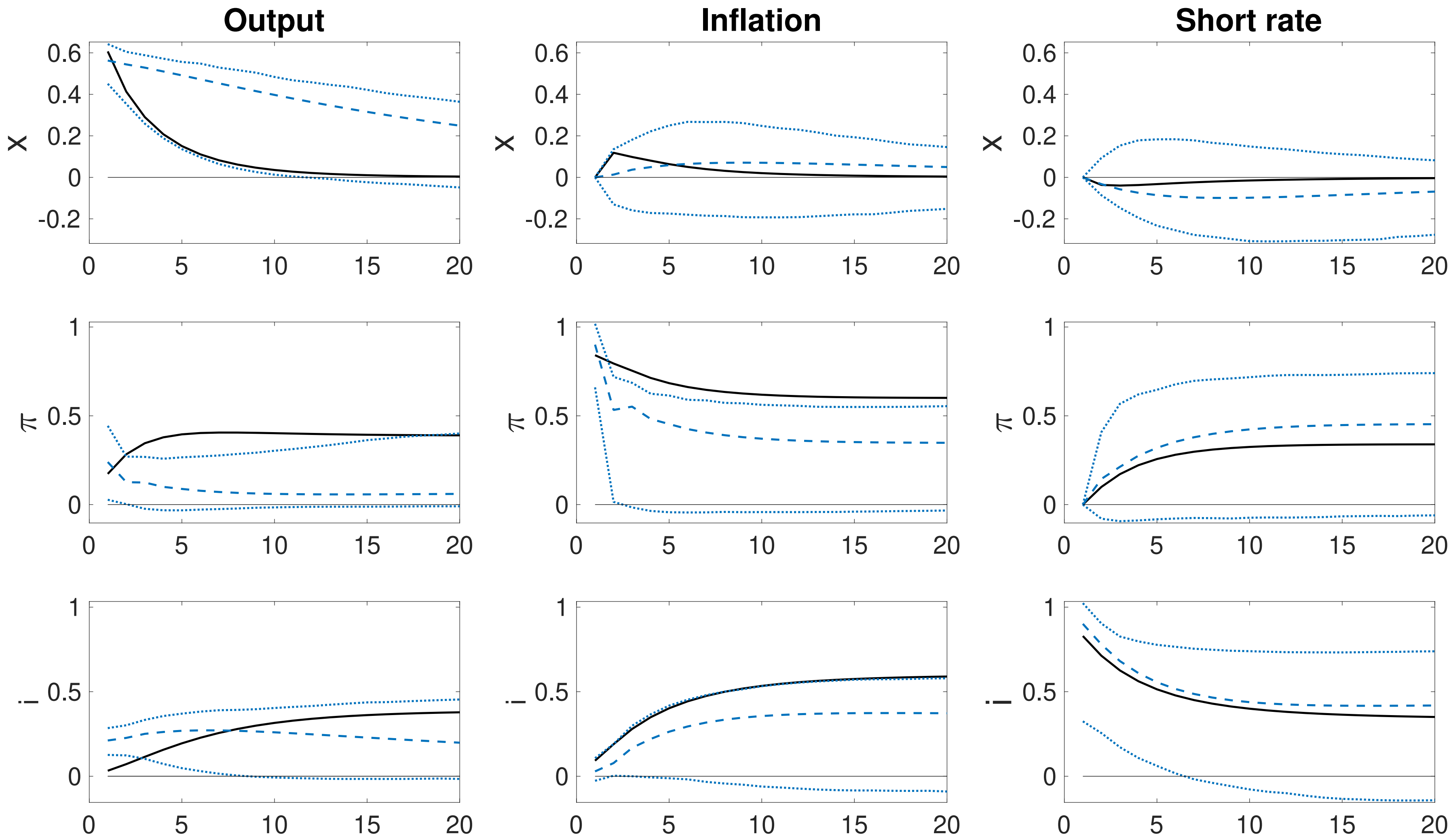


Panel B: Stocks and Breakeven Inflation



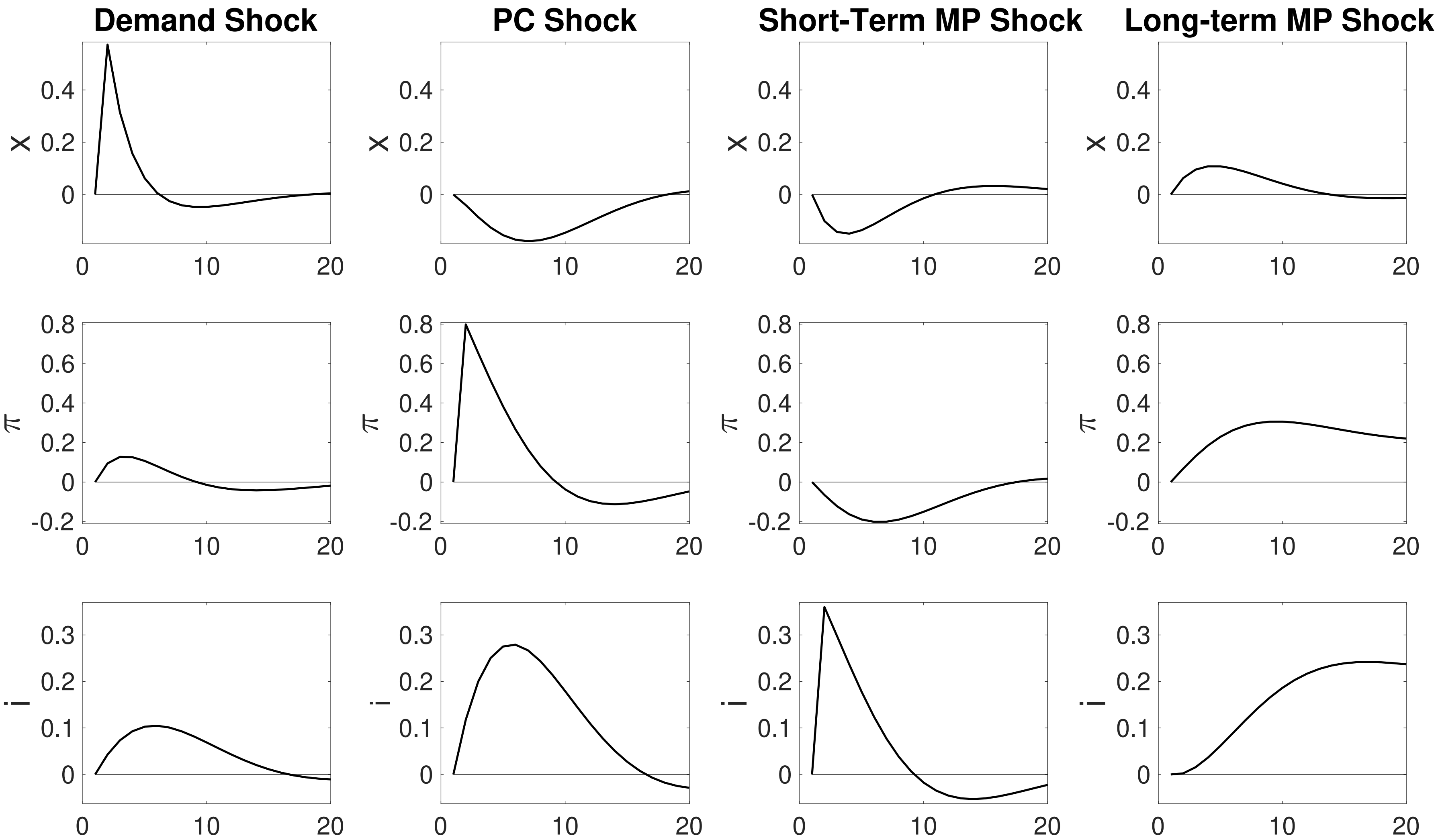
Note: Panel A shows the relationship of Federal Funds rates surprises in an hourly window around FOMC announcements from Gorodnichenko and Weber (2016) and S&P 500 returns in the same window constructed from TAQ data, where each data point corresponds to a FOMC meeting. Panel B shows the relationship 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. 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 scheduled FOMC days is from the start of 2001 until March 2019. For Panel B, the data begins from the start of 2003 since this is when the TIPS data start.

Figure 2: Reduced Form Macro Impulse Responses



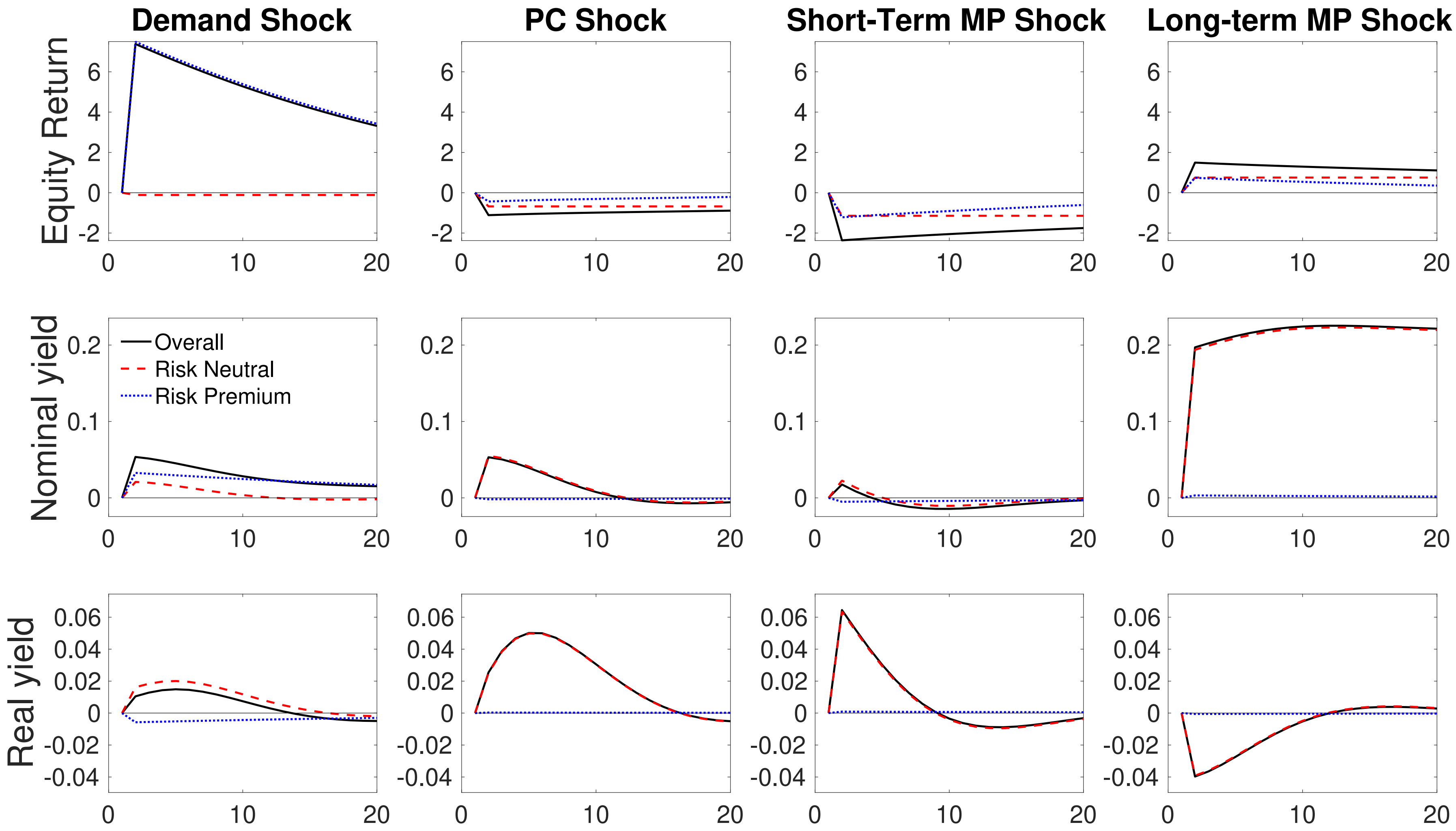
Note: Solid=model, dashed=data, dotted=95% confidence interval. This figure shows macroeconomic impulse responses to reduced-form output gap, inflation, and Federal Funds rate innovations in the model and in the data. The estimation of impulse responses is identical on actual and simulated data and is described in detail in Section 4.2. All impulses are one-standard deviation shocks and are orthogonalized so innovations 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 annualized percent. The third row shows the response of the Federal Funds rate in annualized percent. The horizontal axis of each panel shows the number of quarters after the shock.

Figure 3: Structural Macro Impulse Responses



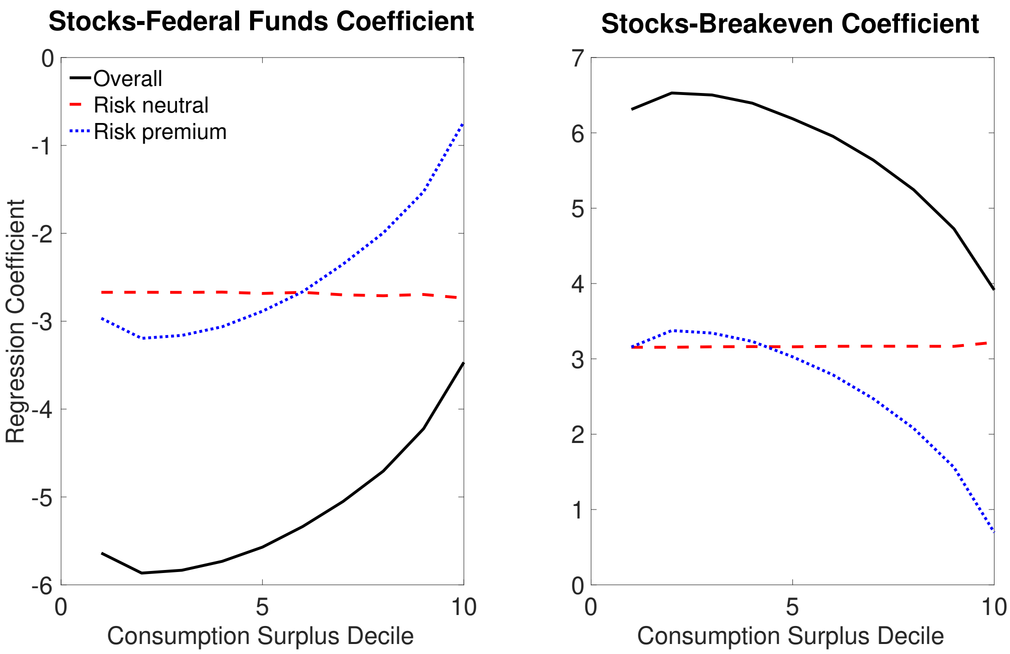
Note: Each column of this figure shows the macroeconomic impulse responses to one of the structural shocks, namely the demand shock ($v_{x,t}$), the Phillips Curve (PC) shock ($v_{\pi,t}$), the short-term monetary policy shock ($v_{ST,t}$), and the long-term monetary policy shock ($v_{LT,t}$). All impulses 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 annualized percent. The third row shows the response of the Federal Funds rate in annualized 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 ($v_{x,t}$), the Phillips Curve (PC) shock ($v_{\pi,t}$), the short-term monetary policy shock ($v_{ST,t}$), and the long-term monetary policy shock ($v_{LT,t}$). 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: State-Dependence of Model High-Frequency Stock Returns



Note: This figure shows model regressions of the same form as in Tables 3 and 4 conditional on the model surplus consumption ratio: $r_t^{FOMC} = b_0 + b_1 \Delta^{FOMC} i_t + b_2 \Delta^{FOMC} b_{10,t} + \varepsilon_t$. The left panel plots the coefficient b_1 on the y-axis against surplus consumption deciles on the x-axis. The right panel plots the coefficient b_2 against surplus consumption deciles on the x-axis. 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^{FOMC} is the equity return. The simulated data is split into ten sub samples according to the deciles of the log surplus consumption ration s_t 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. 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.