A Finance-Integrated New Keynesian Model

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June 30, 2020

Abstract

We integrate a standard New Keynesian model with financial asset prices through consumption-based habits. Finance habit preferences generate volatile stock returns from macroeconomic fundamentals, and plausible hedging properties of long-term bonds. The model sheds light on three empirical facts around monetary policy announcements. First, the model matches the large stock return response to Federal Funds rate surprises, but only if stock responses are amplified by consumption-based habit risk premia. Second, the relationship between breakeven inflation changes and stock returns around monetary policy dates is consistent with the effect of long-term inflation news. Third, if growth expectations respond to an increase in the short term monetary rate, flight-to-safety mitigates the direct increase in long-term real bond yields.

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1 Introduction

This paper introduces a new simple and tractable structure to think about financial asset prices and monetary policy in an internally consistent way. Policy makers and economists follow financial asset prices closely, because they are forward-looking and fundamentally linked to the macroeconomy. The link is, however, complicated, as financial markets often appear to be driven by sentiment or investor risk aversion.

Our model integrates two standard building blocks: the work-horse New Keynesian model and Campbell and Cochrane (1999) consumption habits for financial asset prices. Macroeconomic dynamics are log-linear and depend only on standard state variables. By contrast, financial asset prices in the model depend on consumption innovations in a highly non-linear fashion, thereby explaining high and volatile stock returns in the data. The model is block-recursive in macroeconomic dynamics and financial asset prices, making it suitable for adding macroeconomic state variables, and opening up research avenues to understand the financial market implications of macroeconomic channels more broadly.

Macroeconomic dynamics in our model are described by a log-linear real rate Euler equation and a log-linearized Phillips curve. We obtain the log-linear real rate Euler equation exactly with no approximation, similarly to Campbell, Pflueger, and Viceira (2020), and advance this research by fully nesting a simple New Keynesian model of macroeconomic dynamics. The firm problem is standard, augmented with learning-by-doing (Lucas (1988)) to generate an endogenous stochastic output trend, and predictable productivity growth. As in Greenwood, Hercowitz, and Huffman (1988) we assume that leisure is valued for its value in home production, thereby separating wages from the intratemporal consumption-savings decision, and sidestepping the counterfactual labor implications of earlier research seeking to unite asset pricing habits with a production economy (Lettau and Uhlig (2000)). We derive the log-linearized Phillips curve from standard Calvo (1983) staggered price setting with backwards indexation. The model features habit shocks and markup shocks, which microfound demand and Phillips curve shocks for output and inflation. All fundamental shocks are assumed to be conditionally homoskedastic, so time varying risk premia arise solely from preferences.

We illustrate our model by applying it to three asset pricing findings around Federal Open Market Committee (FOMC) meetings. Figure 1, Panel A shows the well-known result of Bernanke and Kuttner (2005) that stock returns on FOMC dates decline surprisingly strongly with Federal Funds rate surprises, potentially due to risk premia. Panel B investigates variation in breakeven inflation, which is often used as a measure of long-term inflation expectations, and shows that FOMC dates with declines in breakeven inflation

also tend to have declines in the stock market. This speaks to the "nominal Fed information effect" (Romer and Romer (2000), Gürkaynak, Sack, and Swanson (2005)), according to which financial market participants learn from monetary policy communications about long-term inflation. The bond-stock comovement on FOMC dates documented in Panel B is consistent in sign but conceptually different from the unconditional stock market beta of nominal bond returns, because FOMC dates are plausibly more informative about monetary policy shocks, and because only the unconditional beta determines whether bonds are hedges and hence their risk premium properties. Panel C shows that long-term bond yields increase significantly with monetary policy surprises on FOMC dates (e.g. Cochrane and Piazzesi (2002), Gürkaynak, Sack, and Swanson (2005), Hanson and Stein (2015), Nakamura and Steinsson (2018))), which Nakamura and Steinsson (2018) attribute to investors revising their macroeconomic growth expectations in response to shocks to the short-term monetary policy rate.[1]

We close the model with a Taylor (1993)-type interest rate rule suited to study these applications. The rule has short-term monetary policy shocks, shocks to long-term inflation expectations, and assumes that the central bank sets short-term interest rates partly in response to expectations about macroeconomic growth. The short-term monetary policy shock is a traditional news shock about the Federal Funds rate this quarter and affects output and consumption through the Euler equation. The link to long-term inflation expectations is modeled via a long-term monetary policy shock, which lowers nominal interest rates and inflation permanently and acts as a costly disinflation similarly to Ball (1994) and Gürkaynak, Sack, and Swanson (2005). A more recent literature has interpreted permanent shocks to interest rates in terms of forward guidance (Cochrane (2018), Uribe (2018), and Schmitt-Grohé and Uribe (2018)). We model the link to growth expectations as in Nakamura and Steinsson (2018), assuming that monetary policy partly follows changes in the frictionless real rate. For simplicity, we model FOMC dates as occurring instantaneously and bearing no risk premium on average.

We estimate the model in two steps. We first calibrate the preference parameters, the parameters governing the firms' problem, and the monetary policy rule to standard values in the literature. In a second step, we use simulated method of moments (SMM) to estimate the volatilities of shocks. Our estimation matches reduced-form macroeconomic

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

impulse responses for output, inflation, and the Federal Funds rate, and the volatility of quarterly changes in long-term breakeven, defined as the difference between nominal and real long-term bond yields. The model not only matches these macroeconomic moments, but it also replicates the asset pricing successes of Campbell and Cochrane (1999). 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. We also match the empirical finding that the beta of nominal bond returns with respect to the stock market has been negative post-2000, and that of real bond returns close to zero. Nominal bonds hence act as hedges against fluctuations in the representative agent's stochastic discount factor. In our model, nominal bond prices hence benefit from flight-to-safety when investor risk aversion is high, as tends to be the case after adverse shocks to consumption, amplifying the negative comovement between long-term nominal bonds and stocks.

The model naturally explains the empirical evidence in Figure 1, Panel A, but only if the stock return response is amplified by consumption-based risk premia. In the model, a positive shock to the short term nominal rate leads leads to a hump-shaped decline in output and consumption because of habits as in Fuhrer (2000) and Boldrin, Christiano, and Fisher (2001). In addition, finance habits imply that this contractionary shock lowers consumption relative to habit, raising risk aversion and the return that consumers require to hold risky stocks. Stock prices hence fall more than expected dividends, and our model attributes about one-half of the decline in stock prices an increase in equity risk premia, in line with the empirical decomposition in Bernanke and Kuttner (2005).

The model ascribes the empirical evidence on breakeven inflation in Figure 1, Panel B, primarily to long-term monetary policy shocks, which lower expected inflation, output, and stock prices. Risk premia again amplify the decline in stock prices as consumption falls towards habit. Short-term monetary policy shocks also induce a positive comovement between inflation expectations and stock returns, but on their own generate too little variation in breakeven because the Phillips curve based on standard parameters is relatively flat.

Finally, risk premia imply that a given empirical relationship between long-term real bond yields and short-term monetary policy surprises, as shown in Figure 1, Panel C, may require stronger and more persistent changes in expected growth. In the model, the dynamics of bond risk premia depend on the perceived link between expected growth and the real risk-free rate. If investors expect low short-term interest rates to go along with low expected growth, this raises real bond returns in bad states of the world, making real bonds safer. Relative to a counterfactual with constant technology growth, investors are

hence willing to hold real bonds at lower risk premia, and especially so when consumption is close to habit. This effect mitigates the direct increase in long-term real bond yields from higher growth expectations following a surprise increase in the short-term monetary policy rate.

There is a growing literature jointly modeling financial asset prices with New Keynesian macroeconomic dynamics. One strand of this literature uses long-run risks and Epstein-Zin preferences to understand asset pricing implications of macroeconomic channels (e.g. Van Binsbergen, Fernández-Villaverde, Koijen, and Rubio-Ramírez (2012), Kung (2015), Bretscher, Hsu, and Tamoni (2020), Gourio and Ngo (2020)). A different strand of the literature, including Uhlig (2007), Dew-Becker (2014), Rudebusch and Swanson (2008), Lopez (2014), and Bretscher, Hsu, and Tamoni (2019), embeds simplified finance habit preferences into a New Keynesian model. By preserving the full non-linearity of Campbell and Cochrane (1999)'s consumption-based habit formation preferences we retain their favorable asset pricing properties for stocks and interest rates, and moreover obtain a convenient and exactly log-linear Euler equation. We thereby build directly on Campbell, Pflueger, and Viceira (2020) but, different from this prior research, we do not rely on reduced-form descriptions of macroeconomics dynamics. This paper is also related to theoretical work explaining the strong stock return response to Federal Funds rate surprises. Lagos and Zhang (2020) present an explanation based on liquidity, and Kekre and Lenel (2020) rationalize this finding in a model of shifting wealth shares between agents with differing risk aversion. The advantage of our framework is that it is simple and versatile, as illustrated by its ability to also provide structure for the nominal and real Fed information effects. Our central contribution is therefore to provide a new and versatile model that can be used to understand the asset pricing implications of macroeconomic shocks more broadly.

The paper is organized as follows. Section 2 presents the model. Section 3 solves the model and discusses how individual modeling assumptions affect the equilibrium properties. Section 4 estimates the model and assesses macroeconomic and financial asset pricing moments. Section 5 describes the empirical applications. Section 6 concludes.

2 Model

2.1 Summary

Preferences and production are specified to generate the smallest scale New Keynesian work-horse model, i.e. a log-linear consumption Euler equation and Phillips curve:

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

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

while exactly nesting the leading asset pricing model of Campbell and Cochrane (1999).

Here, r_t denotes the log real risk-free interest rate that can be earned from time t to time $t+1$, The output gap, x_t, equals log real output minus log potential output at the hypothetical equilibrium without price–setting frictions (Woodford (2003), p.245), and π_t is log quarterly inflation. The rate r_t^a is the frictionless real rate related to expected productivity growth. The demand and Phillips curve shocks $v_{x,t}$ and $v_{\pi,t}$, and the positive coefficients f^x, ρ^x, ψ, f^π, ρ^π, κ arise from consumer preferences and the firm's problem. The consumption Euler equation is exact, and the Phillips curve is derived from the usual log-linearization. Both equations are specified up to a constant. We use lower-case letters to denote logs variables throughout.

2.2 Preferences

2.2.1 Finance habit

As in Campbell and Cochrane (1999), we assume that there is a representative agent whose utility depends on the difference between consumption C_t and external habit H_t:

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

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

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

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

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

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

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

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

2.2.2 Surplus consumption dynamics

We model implicitly how habit adjusts to the history of consumption, by modeling the evolution of the surplus consumption ratio:

$$\begin{aligned} s_{t+1} &= (1 - \theta_0)\bar{s} + \theta_0 s_t + \theta_1 x_t + \theta_2 x_{t-1} + \varepsilon_{s,t} + \lambda(s_t)\varepsilon_{c,t+1}, & (7) \\ \varepsilon_{c,t+1} &= c_{t+1} - \mathrm{E}_t c_{t+1}. & (8) \end{aligned}$$

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

We use the sensitivity function $\lambda(s_t)$ from Campbell and Cochrane (1999):

$$\begin{aligned} \lambda(s_t) &= \begin{cases} \frac{1}{\bar{S}}\sqrt{1 - 2(s_t - \bar{s})} - 1 & s_t \leq s_{max} \\ 0 & s_t \geq s_{max} \end{cases}, & (9) \\ \bar{S} &= \sigma_c \sqrt{\frac{\gamma}{1 - \theta_0}}, & (10) \\ \bar{s} &= \log(\bar{S}), & (11) \\ s_{max} &= \bar{s} + 0.5(1 - \bar{S}^2). & (12) \end{aligned}$$

The downward-sloping relation between $\lambda(s_t)$ and s_t has the intuitive implication that marginal consumption utility is particularly sensitive to consumption innovations when investors are close to their habit consumption level, as would be the case after a sequence of bad shocks. Its particular non-linear form implies that s_t drops out of the asset pricing Euler equation for the real risk-free rate, because the associated intertemporal substitution and precautionary savings terms cancel exactly. The terms $\theta_1 x_t$ and $\theta_2 x_{t-1}$ make habit depend on the output gap, as in Campbell, Pflueger, and Viceira (2020). Our model has no real investment, so in this context it is more intuitive to interpret x_t as consumption relative to a frictionless level. If $\theta_1 > 0$ and $\theta_2 < 0$, as in our empirical

specification, the dependence of habit on the most recent consumption lag increases and its dependence on longer lags decreases relative to the Campbell and Cochrane (1999) benchmark. The habit shock $\varepsilon_{s,t}$ captures independent fluctuations in habit. A positive $\varepsilon_{s,t}$ lowers future expected habit and increases future expected surplus consumption, reducing risk aversion.[2]

2.2.3 Labor-leisure trade-off

Before describing the firm's problem we need to specify households' intratemporal labor-leisure trade-off, which is at the heart of wage determination. To achieve a standard functional form for the Phillips curve, we choose a labor disutility specification that ensures surplus consumption does not enter into the intratemporal labor-leisure trade-off. Following the classic model of Greenwood, Hercowitz, and Huffman (1988), we assume that the representative household's total consumption, C_t^{tot}, is the sum of market consumption, C_t, and home production C_t^{home}:

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

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

Here, $L_{i,t}$ denotes the differentiated labor used for production by firm i and $(1 - L_{i,t})$ is labor used for home production. Home production has decreasing returns to scale, as in Campbell and Ludvigson (2001), and the parameter χ determines the elasticity of market labor supply.

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

[2] 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. This shock is new relative to Campbell, Pflueger, and Viceira (2020), which corresponds to the case $\varepsilon_{s,t} = 0$.

2.3 Firm Problem

2.3.1 Demand

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

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

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

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

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

2.3.2 Production

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

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

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

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

Alternatively, the process (18) can be interpreted as a simple endogenous capital stock, similarly to Woodford (2003) (Chapter 5), if a fixed proportion of employment each period is used as an input to produce investment goods. If real investment comes out of labor, this interpretation would leave the relationship between consumption and output unchanged and only the constants in the home production function (14) would change.

The purpose of n_t is simply to detrend the output gap, so the specific interpretation is not central for us.

2.3.3 Price setting

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

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

2.4 Monetary Policy

While any conditionally homoskedastic interest rate rule could be used to close the model, we choose the simplest Taylor-type rule to fit our three specific applications (ignoring constants):

$$
\begin{aligned}
i_t^* &= \gamma^x x_t + \gamma^\pi \pi_t + (1-\gamma^\pi)\, v_t^*, && (19)\\
i_t &= \rho^i i_{t-1} + \left(1-\rho^i\right) i_t^* + v_{ST,t} && (20)\\
v_t^* &= v_{t-1}^* + v_{LT,t} && (21)
\end{aligned}
$$

Here, i_t^* denotes the central bank's interest rate target, to which it adjusts slowly with a smoothing coefficient ρ^i.

The three important elements for our applications are the short-term monetary policy shock, $v_{ST,t}$, the long-term monetary policy shock, $v_{LT,t}$, and the link between the real risk-free rate and expected technology growth. The short-term monetary policy shock represents a standard innovation to the short-term nominal interest rate. The long-term monetary policy shock shifts the random walk component of the interest rate target v_t^*, thereby moving the entire term structure of nominal interest rates and, through the Fisher equation, long-term inflation expectations.[3] The two monetary policy shocks are assumed to be serially uncorrelated, and conditionally homoskedastic. To reflect that changes in

[3]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, where the economy is expected to exit the ZLB at a constant rate.

short-term interest rates and breakeven have no significant correlation in our sample, we take the short-term and long-term monetary policy shocks to be independent. We link monetary policy and expected technology growth by allowing the real risk-free rate to be correlated with the frictionless real rate (Nakamura and Steinsson (2018)):

$$r_t^a = \rho^a r_t. \tag{22}$$

We define the frictionless real rate related to variation in expected productivity growth:[4]

$$r_t^a = \gamma \Delta a_{t+1}. \tag{23}$$

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

$$i_t = r_t + E_t \pi_{t+1}. \tag{24}$$

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

2.5 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 $(1-\delta)P_t^c$. Stocks in our model should therefore simply be interpreted as a financial asset with pro-cyclical dividends, rather than a financial claim tied specifically to firm cash flows.[5]

[4]Note that, however, r_t^a does not equal the natural real rate in our model, which would also absorb the demand shock $v_{x,t}$. Because we are interested in studying the possibility that investors update their growth expectations in response to monetary policy, we define r_t^a directly in terms of expected growth.

[5]Alternatively, one could models stocks as a claim on firm profits rather than consumption. However, this would require modeling infrequent wage setting to match the cyclical behavior of dividends (Favilukis and Lin (2016)). Since our goal is to combine the smallest-scale New Keynesian model with asset pricing preferences, we leave these additional investigations for future research.

3 Model Solution and Discussion

3.1 Steady-State and Output Gap

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

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

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

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

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

3.2 Euler Equation

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

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

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

Our modeling choices simplify the no-arbitrage condition for the one-period real risk-free bond, and ensure that it takes exactly the form of a New-Keynesian consumption Euler equation. The specific form of the sensitivity function $\lambda(s_t)$ has the unique advantage that the precautionary savings and intertemporal substitution terms from s_t cancel,

and s_t is not a state variable for macroeconomic dynamics. Surplus consumption dynamics are of course linked to the consumption Euler equation (27) through the output gap and habit shock terms.

The Euler equation (27) shows that $\theta_2 > 0$ generates a lagged output gap term. In our finance integrated New-Keynesian model the parameter θ_2 therefore acquires a new importance, because a lagged output gap term is known to be crucial for matching hump-shaped output gap responses in macro models (Boldrin, Christiano, and Fisher (2001) and Fuhrer (2000)). In our estimation, we choose the parameter θ_1 so that the forward- and backward-looking terms in the consumption Euler equation sum to one.

The habit shock microfounds risk-centric demand shocks in the Euler equation, driving bonds and stocks in the opposite direction as in Caballero and Simsek (2020) and Pflueger, Siriwardane, and Sunderam (2020). Demand shocks from other microfoundations, such as a gap between interest earned by consumers relative to the interest rate controlled by the central bank (Smets and Wouters (2007)), or a shock to the rate of time preference (e.g. Justiniano and Primiceri (2008), Albuquerque, Eichenbaum, Luo, and Rebelo (2016)), would lead to similar macroeconomic dynamics but different asset pricing implications. Microfounding demand shocks from habit allows us to use a single stochastic discount factor to price the real risk-free rate, as well as long-term bonds and stocks, and drives down the comovement between bonds and stocks similarly to the data.

3.3 Phillips Curve

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

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

Equation (28) makes clear that the log-linearized real wage takes a standard form independent of habit, thereby sidestepping the issue noted by Lettau and Uhlig (2000) that habit may affect labor supply decisions in a production economy. Comparing to standard New Keynesian models (e.g. Galí (2008)) our log real wage is even somewhat simpler because it does not depend on aggregate consumption.[6] Intuitively, when consumption is close to habit in our model the marginal utilities from market and home consumption are both high, leaving the wage unaffected. For example, after an adverse shock consumers

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

might shift from eating out to cooking at home, as documented in Aguiar, Hurst, and Karabarbounis (2013). The assumption that home production increases with aggregate productivity, $A_t N_t$, ensures that the labor-leisure trade-off does not become irrelevant over time (Kehoe, Lopez, Midrigan, and Pastorino (2019)), consistent with empirical evidence (Chodorow-Reich and Karabarbounis (2016)). The differentiated labor assumption follows Woodford (2003, Chapter 3) and generates real rigidities from labor immobility across sectors (Ball and Romer (1990)).

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

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

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

A complementary approach to separate wages from consumption habit would be to introduce a separate habit for leisure and labor market frictions, though matching asset pricing moments can be challenging in such a setup (Uhlig (2007), Rudebusch and Swanson (2008), Lopez (2014)). Our formulation is more parsimonious and requires only one parameter, closely related to the Frisch elasticity of labor supply, to describe preferences over leisure (χ). Because of this parsimony we consider our model a useful template to study the interaction between labor market frictions and habits in future research.

3.4 Macroeconomic Equilibrium Dynamics

The equilibrium is tractable because it is block recursive in macroeconomic dynamics and asset prices. The surplus consumption ratio does not appear directly in the Euler equation or the Phillips curve, so we first solve for log-linear macroeconomic dynamics using standard methods. Equilibrium macroeconomic dynamics are determined by the real rate Euler equation (27), the log-linearized Phillips curve (29), and the monetary policy rule (19) through (21). The macroeconomic state vector is:

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

and the vector of structural shocks is

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

The vector of shocks v_t is serially uncorrelated and multivariate normal with diagonal variance-covariance matrix. We denote the standard deviations σ_x, σ_π, σ_{ST}, and σ_{LT}. We solve for an equilibrium of the form:

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

where B and Σ are $[3 \times 3]$ and $[3 \times 4]$ matrices, respectively. We solve for the matrix B using Uhlig (1999)'s methodology, which is equivalent to Blanchard and Kahn (1980). While the Euler equation (27) and Phillips curve (29) might appear inconsistent with an equilibrium of the form (32), the Blanchard-Kahn solution resolves this apparent inconsistency by imposing that equilibrium shocks are a particular linear combination of fundamental shocks. In our empirical application, there exists a unique equilibrium of the form (32) such that all eigenvalues of B are less than one in absolute value and we select this equilibrium. However, New Keynesian models are subject to well-known equilibrium multiplicity issues and equilibria with additional state variables or sunspots may exist (Cochrane (2011)), though resolving these issues is beyond this paper.

3.5 Solving for Asset Prices

Next, we use numerical best practices to solve for highly non-linear asset prices, which do depend on surplus consumption (Wachter (2005)). We use the following recursion to solve for the price-consumption ratio of an n-period zero-coupon consumption claim:

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

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

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

The price of the levered equity claim equals $P_t^\delta = \delta P_t^c$. Leverage hence scales stock returns roughly proportionally, increasing stock return volatility but leaving the Sharpe ratio unchanged.

We initialize the recursions for real and nominal zero coupon bond prices:

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

The n-period zero coupon prices follow the recursions:

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

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

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

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

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

We solve for asset prices numerically on a four-dimensional grid consisting of the macroeconomic state vector $\hat{Y}_t$ and the surplus consumption ratio s_t. Iterating along a grid, as opposed to local approximation or global solution methods, is the best practice for this type of numerical problem because it imposes the least structure (Wachter (2005)). By contrast, approximation with polynomials would miss the particularly strong nonlinearity of the sensitivity function as the log surplus consumption ratio becomes small, distorting numerical asset prices even around the steady-state. The intuition is that the numerical algorithm needs to capture a small probability of entering a state where

marginal consumption utility is extremely high, not unlike the intuition in asset pricing models with rare disasters (e.g. Barro (2006), Gabaix (2008), Wachter (2013)). Grid iteration is facilitated in our framework because the model is block recursive and macroeconomic dynamics are simple and standard. For details of the numerical solution see the Appendix.

3.6 Announcement Effects

We model FOMC announcements as occurring instantaneously, so no dividends are paid and the aggregate price level is constant during the short FOMC interval. We assume that the quarterly fundamental shock vector v_t consists of independent pre-FOMC and FOMC shocks:

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

The vector of FOMC shocks is assumed to have a diagonal variance-covariance matrix with standard deviations σ_x^{FOMC}, σ_π^{FOMC}, σ_{ST}^{FOMC}, and σ_{LT}^{FOMC}. We solve for the variance-covariance matrix of v_t^{pre} such that the standard deviations of v_t are as described in section 3.4. We solve for pre-FOMC prices of stocks, real and nominal bonds by setting the FOMC shock to its mean (i.e. $v_t^{FOMC} = 0$), whereas the post-FOMC price is computed at random realizations of v_t^{FOMC}.

4 Estimated Model

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

4.1 Calibrated Parameters

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

(2005). The parameter θ_1 is set to ensure that the forward- and backward-looking parameters in the real rate Euler equation sum to one.

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

We choose conventional monetary policy parameters. The reaction coefficients for inflation and output fluctuations are from Taylor (1993) and equal $\gamma_x = 0.5$ and $\gamma_\pi = 1.5$, so the central bank raises nominal interest rates more than one-for-one with inflation. The monetary policy smoothing parameter is set to 0.9 to match the larger root in interest rates estimated by Nakamura and Steinsson (2018). We set ρ^a determining the relationship between the frictionless real rate and the actual real rate to 0.68 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

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

Following Christiano, Eichenbaum, and Evans (2005), the vector $\hat{\Psi}$ collects empirical macroeconomic impulse responses, and we weight each moment by the inverse of its bootstrapped variance. Our sample begins in 2001Q2, when the relationship between inflation and empirical output gap measures displays a structural change (Campbell, Pflueger, and Viceira, 2020), and ends in 2019Q2. The vector $\Psi(\sigma)$ collects the corresponding model moments, obtained by applying the same procedure to simulated data of the same length. Our moments are from a one lag VAR in the log output gap, the one-quarter change in inflation, and the difference between the nominal Federal Funds rate and inflation, thereby respecting the joint unit root in inflation and nominal interest rates in the model.[7] Impulse responses are orthogonalized so shocks to the Fed Funds

[7] 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

rate do not contemporaneously affect inflation or output, and inflation innovations do not enter into the same period output. This orthogonalization does not directly identify the structural shocks in our model, and merely defines a unique set of empirical macroeconomic moments that are comparable to the literature. We target the output gap, inflation, and Fed Funds rate responses in periods 0, 1, 2 , 4, 8, and 12 quarters after the initial shock giving us $3 \times 6 = 18$ moments. Since σ_{LT} is not well identified from the reduced-form macroeconomic impulse responses, we additionally target the standard deviation of quarterly changes in inflation swap rates for 10-year inflation starting 10 years from now, which we estimate to equal 0.26% over our sample.[8] For details of the SMM procedure see the Appendix.

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

4.3 Model Fit

4.3.1 Macroeconomic Dynamics

Figure 2 shows that the model matches the empirical volatilities of the output gap, inflation, and Fed Funds rate, their persistence over time, and key cross-correlations. 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. We turn to structural impulse responses in section 4.4.1.

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

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.

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

4.3.2 Asset Prices

Table 2 shows that our finance-integrated New Keynesian model replicates the asset pricing successes of Campbell and Cochrane (1999), generating volatile stock returns with an empirically plausible equity Sharpe ratio of 0.50, an equity premium of 6.57%, and annualized equity return volatility of 13.02%. This high stock return volatility is achieved through time-varying risk premia of the form (39).[9] For our subsequent applications, it is important that the model fits the comovement between both the nominal and real components of bond returns with stocks, as the comovement between an asset's return with the stochastic discount factor determines whether risk premia increase or decrease following an adverse shock to consumption. Table 2 shows that the comovement between 10-year breakeven returns, defined as returns on nominal in excess of real bonds, and stocks is negative as in the data, indicating that long-term nominal bonds are hedges. It also shows that 10-year real bond excess returns are largely uncorrelated with stock returns, similarly to the small real bond-stock beta in the data. Breakeven excess returns are volatile at 5.01% similarly to the data, and real bond excess returns in the model have substantial volatility at 1.56%. The empirical volatility of 10-year TIPS excess returns exceeds the real bond return volatility in the model at 6.82%. However, we regard this empirical moment with caution 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 does well along many dimensions, it misses realized excess bond returns over our sample period. We face a choice between fitting betas or term premia and we prefer to fit second moments, which are measured more precisely 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 regime switches are beyond this current paper we believe that the convenient log-linear macroeconomic dynamics would make our model a natural building block to study such regime switches.

[9] To compute the empirical asset pricing moments, we use value-weighted combined NYSE/AMEX/-Nasdaq stock returns including dividends from CRSP, and 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.

4.4 Model Drivers

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

4.4.1 Structural Macroeconomic Responses

Figure 3 confirms that the macroeconomic side of our model behaves like a standard three-equation New Keynesian model. A positive demand shock – driven by an expected increase in surplus consumption in our asset pricing preferences – leads to a temporary increase in output, and a smaller temporary increase in inflation. A positive Phillips curve shock, due to an increase in markups, leads to a decline in output and an increase in inflation. A short-term increase in the short-term interest rate causes a decline in output through consumers' consumption-savings decision, and lower inflation through the Phillips curve. As this monetary policy shock reflects partly the frictionless growth rate, the output gap reverses and overshoots after 10 quarters. Finally, a negative long-term monetary policy shock leads to a costly disinflation, lowering inflation expectations ahead of nominal interest rates, and thereby raising the real rate and contracting output. The backward-looking component in the consumption Euler equation ensures a hump-shaped output gap responses as in Fuhrer (2000) and Boldrin, Christiano, and Fisher (2001).

4.4.2 Structural Asset Price Responses

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

Comparing the first rows across Figures 3 and 4 shows that stock prices move in the same direction as output gap responses, with the overall stock response quantitatively dominated by time-varying risk premia.[10] The second row of Figure 4 shows that long-term nominal bond yields respond in the same direction as the Federal Funds rate in Figure 3. The third row of Figure 4 shows that 10-year real bond yields respond in the same direction as the short-term real rate and are almost exclusively driven by the risk-neutral component.

[10]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.

To understand how macroeconomic dynamics drive time-varying risk premia, consider the example of a short-term monetary policy shock shown in the third column. A positive short-term monetary policy shock represents a contractionary shock to output and consumption, as seen in Figure 3. As surplus consumption falls investors become more risk averse and require higher compensation for holding risky stocks, driving down stock prices relative to dividends. Nominal bonds are hedges in our model, as their beta with respect to the stock market is negative. As risk aversion increases, nominal bonds therefore benefit from flight-to-safety, driving up nominal bond prices and driving down nominal bond yields. The risk premium effect in nominal bond yields is small following short-term monetary policy shocks, but quantitatively significant following habit shocks. Finally, real bonds in our model are neither risky nor hedges, as their betas with respect to the stock market are close to zero, so their risk premium responses to all shocks are small. However, this is an equilibrium outcome, as real bond risk premia in our model are endogenous to the macroeconomic regime.

The first column of Figure 4 illuminates the habit shock, and shows that it affects asset prices through both intertemporal substitution and risk aversion. The expected increase in surplus consumption generates an incentive for intertemporal substitution, driving down risk-neutral prices of both real bonds and stocks. Because bond yields move inversely with prices, risk-neutral long-term real bond yields increase. Higher expected surplus consumption also affects risk premia, because it leads to higher consumption today through the consumption Euler equation, raising surplus consumption and driving up stock prices. The risk premium effect dominates the stock price response, whereas the risk-neutral component dominates the real bond yield response. The demand shock therefore has the unique ability to generate a negative real bond-stock beta. By contrast, the other three structural shocks drive the prices of stocks and real bonds in the same direction (or stock prices and bond yields in the opposite direction) and generate a positive real bond-stock beta. The habit shock is therefore crucial to generating a low and empirically plausible correlation between real bond and stock returns.

5 Stocks and Bonds on FOMC Dates

Having seen that the model fits basic macroeconomic and financial asset pricing moments, we now turn to the bond and stock price changes around FOMC dates. In this section we show how the model replicates the three stylized empirical facts reported in Figure 1.

5.1 Application A: Fed Funds Effect

The model is designed to generate volatile equity risk premia from changes in fundamentals, and hence easily explains the well-known finding that stock prices fall sharply in response to surprise increases in the Federal Funds rate (Figure 1, Panel A). Table 3, Panel A shows regressions of the form

$$r_t^{\delta,FOMC} = b_0 + b_1 \Delta^{FOMC} i_t + \varepsilon_t, \tag{40}$$

where $\Delta^{FOMC} i_t$ is the change in the short term risk free rate in a one-hour window around FOMC announcements and $r_t^{\delta,FOMC}$ is the equity return in the same period.[11]

Column (1) reveals that a 25 bps surprise increase in the Federal Funds rate empirically leads to a one percentage point drop in the stock price on average. Column (2) shows that the model matches this moment and that roughly half of the model stock return response is due to risk premia, matching the empirical results in Bernanke and Kuttner (2005). Column (2) assumes empirically plausible short-term and long-term monetary policy shocks on FOMC dates, setting the standard deviations to $\sigma_{ST}^{FOMC} = 4.3$ bps and $\sigma_{LT}^{FOMC} = 3.3$ bps to match the empirical volatilities of one-hour Fed Funds surprises and daily 10-year breakeven changes on FOMC dates. We verify that modeling short-term and long-term monetary policy shocks on FOMC dates as uncorrelated is consistent with the data, as evidenced by the fact that the FOMC date regression of breakeven changes onto the change in the 6-month nominal bond yield is very similar in the model (-0.09 with R^2 below 1%) and in the data (-0.06 with $R^2 = 1\%$).

Our model is simple and transparent enough that we can understand the channels driving the large stock return response. Columns (3) and (4) show that the model Fed Funds effect is driven by the short-term monetary policy shock revealed on FOMC dates. In column (3), where FOMC dates are assumed to reveal only short-term monetary policy shocks, the coefficient is similar to column (2). By contrast, column (4) shows that the

[11] For the empirical analysis of FOMC announcements in Table 3, we report coefficients corresponding to the regression lines of Figure 1. Specifically, we collect the release date of FOMC statements from January 1st 2001 until Dec 31st 2020 from the Federal Reserve's website. Following the literature on FOMC announcements, we remove dates corresponding to unscheduled announcements. We also drop the announcement dates of December 16 2008 and March 18 2009, which were associated with significant Quantitative Easing announcements which are not well captured by the monetary shocks in our model. Table 3, Panel A uses one-hour changes in Federal Funds rate around FOMC announcements from the updated data of Gorodnichenko and Weber (2016) as well as S&P 500 returns in the same one-hour windows constructed from the Trade and Quote database, accessed through WRDS. Panel B regresses daily S&P 500 returns from the CRSP S&P 500 file, accessed through WRDS, onto daily changes in 10-year breakeven. Panels B and C use one-day changes in zero coupon nominal Treasury yields and TIPS yields are from Gürkaynak, Sack, and Swanson (2005) and Gürkaynak, Sack, and Wright (2010). Panels B and C use daily asset prices, due to data availability for long-term bond yields. The 6 month constant maturity treasury rate is from FRED (DGS6MO).

coefficient is very different if FOMC dates are assumed to reveal only long-term monetary policy shocks.

The intuition is clear from comparing the short-term monetary policy shock responses in Figures 3 and 4. A surprise increase in the short-term nominal interest rate leads to a hump-shaped decrease in output and consumption. As surplus consumption declines towards habit, investors require a higher risk premium on risky assets such as stocks. The fall in stocks due to lower expected consumption is therefore compounded by risk premia, and these risk premia are quantitatively important. Long-term monetary policy shocks have little immediate impact on the Fed Funds rate, so the combined slope coefficient in column (2) is similar to column (3), and the slope coefficient in column (4) is degenerate.

Table 4, Panel A shows that the strong relationship between equity returns and Fed Funds rate surprises on FOMC dates – and the significant role of risk premia in this relationship – are a robust feature of the model. When we switch off the link between monetary policy and the frictionless real rate by setting $\rho_a = 0$ contractionary short-term monetary policy shocks are not offset by higher expected growth, so stocks fall even more. The link between monetary policy and the frictionless real rate therefore ensures that the stock return response to monetary policy shocks is not too large compared to the data, as in Nakamura and Steinsson (2018). Switching off the habit shock in column (3) also leads to a stock return coefficient that is significantly larger than in the data. Intuitively, in the absence of independent habit shocks the consumption claim is conditionally perfectly correlated with surplus consumption, so stocks are even riskier for investors. Finally, reducing the equilibrium volatility of Phillips curve, short-term monetary policy, or long-term monetary policy shocks leaves the stock-Fed Funds rate relationship on FOMC dates unchanged. Note that in column (5) of Table 4 short-term monetary policy shocks on FOMC dates are still non-zero, but they are unanticipated and out-of-equilibrium because the equilibrium volatility of short-term monetary policy shocks is expected to be zero.

5.2 Application B: Nominal Fed Information Effect

We now examine the possibility that monetary policy announcements may reveal information about long-term inflation, the "nominal Fed information effect" of Romer and Romer (2000). We study changes in breakeven inflation on FOMC dates, defined as the difference between long-term nominal and real bond yields, because this asset price most closely reflects long-term inflation expectations in our model. In the data, we find that breakeven changes on FOMC dates are positively correlated with FOMC day stock returns. Table 3, Panel B estimate the regression

$$r_t^{\delta,FOMC} = b_0 + b_1 \Delta^{FOMC} b_{n,t} + \varepsilon_t \tag{41}$$

where $\Delta^{FOMC} b_{n,t}$ is the change of the 10-year breakeven rate on the FOMC day and $r_t^{\delta,FOMC}$ is the equity return in the same period. The breakeven rate is computed as the difference between the 10-year nominal and real bond yields. Column (1) shows the estimated slope coefficient in the data, and column (2) shows that the model matches this relationship. Similarly to the Fed Funds effect, the model attributes about half of the stock return response to risk premia.

Columns (3), (4), and (5) show that long-term monetary policy shocks are a crucial ingredient to obtain an empirically plausible stock-breakeven relationship on FOMC dates. Column (4) assumes that FOMC dates reveal only long-term monetary policy news. Because news about lower long-term inflation is costly for the economy in the model, the long-term monetary policy shock can match the positive empirical stock return-breakeven correlation on FOMC dates. Column (3) shows that short-term monetary policy shocks also contribute to a positive stock-breakeven relationship, but our Phillips curve based on standard parameters is too flat to generate sufficient variation in breakeven inflation, so short-term monetary policy shocks on their own generate a stock-breakeven slope coefficient that is too high compared to the data. While our results support the notion that FOMC dates reveal news about long-term inflation, caution is warranted regarding policy conclusions. Whether specific tools and communications move investors' long-term inflation expectations may very well be time-varying (Goodfriend and King (2005)), context-specific (Coibion, Gorodnichenko, and Weber (2020)), and depend on behavioral channels (Orphanides and Williams (2004), Gabaix (2019), Zhao (2020)).

Table 4, Panel B shows that the stock-breakeven relationship on FOMC dates is robust to switching off any model shock or the link between monetary policy and expected output growth. Column (1) shows that setting $\rho_a = 0$ amplifies both the risk neutral and risk premium stock responses. Switching off the demand shock in column (3) also leads to stock return responses that are larger than in the data. As in Panel A, both the link between monetary policy and the frictionless real rate and demand shocks are hence again important to obtain stock return responses that are not larger than in the data. Column (6) shows that we can match the empirical stock-breakeven slope coefficient on FOMC dates even if long-term inflation expectations are expected to have zero volatility in equilibrium, as long as FOMC dates reveal some news about long-term inflation.

5.3 Application C: Real Fed Information Effect

We now use our model to analyze the possibility that monetary policy announcements reveal news about expected output growth, or the "real Fed information effect". Table 3, Panel C documents the well-known relationship between long term real yields and short

term nominal yields on FOMC days:

$$\Delta^{FOMC} y_{n,t} \quad = \quad b_0 + b_1 \Delta^{FOMC} i_{6m,t} + \varepsilon_t, \tag{42}$$

where $\Delta^{FOMC} y_{n,t}$ is the change in either the 10-year or the 5-year real bond yield and $\Delta^{FOMC} i_{6m,t}$ is the change in the 6-month nominal yield around FOMC dates.[12] Column (1) shows that in our data a one percentage point increase in the six-month nominal rate on FOMC dates is associated with a 65 bps increase in the 5-year TIPS yield, and a 40 bps increase in the 10-year TIPS yield.

Column (2) shows that the model replicates the positive empirical relationship between long-term real bond yields and short-term nominal yields on FOMC dates. In the model, a one percentage point increase in the 6 month yield is associated with a 38 bps increase in the 5-year real bond yield, and a 19 bps increase in the 10-year real bond yield. Both of these coefficients are economically meaningful and within two standard deviations of the empirical estimates, though smaller than in the data. The overall relationship is driven by the short-term monetary policy shock, as the long-term monetary policy shock induces little variation in the right-hand-side variable of (42).

Our model highlights that risk premia matter in a perhaps unexpected way for the real Fed information effect. As expected, the response of the 5-year real bond yield is partly driven by the link between monetary policy and expected growth. Comparing columns (1) and (2) in Table 4, Panel C shows that switching off this link ($\rho^a = 0$), reduces the 5-year yield slope coefficient to 0.34 outside the empirical 95% confidence interval. Maybe more surprisingly, the difference between columns (1) and (2) is even larger for the corresponding risk-neutral coefficient.

The role for risk premia in our model arises because the extent to which real bond prices benefit from flight-to-safety is endogenous to the macroeconomic regime (including ρ^a). Table 4, Panel D illustrates this mechanism, showing that when investors do not learn about growth ($\rho^a = 0$) the real bond beta is positive, so real bonds are risky. Conversely, when investors learn about expected growth from interest rates ($\rho^a > 0$), the real bond beta declines and real bonds have greater hedging benefits for investors. Intuitively, when investors associate high interest rates with growth, negative real bond returns are associated with good macroeconomic news, driving down real bond betas. In turn, investors prefer to hold real bonds when investor risk aversion rises after a contractionary short-term monetary policy shock, dampening the increase in long-term real bond yields. Overall, this risk premium channel suggests that larger or more persistent changes in growth expectations may be required to explain the empirical behavior of real bond

[12] We use the 6 month rate to capture the somewhat longer duration of the monetary policy rate in Nakamura and Steinsson (2018) in a way that easily maps into our model.

yields on FOMC dates.

6 Conclusion

We present a new model that integrates a small-scale New Keynesian macroceconomic model with the leading asset pricing model of Campbell and Cochrane (1999). Our framework is tractable and portable towards broader macroeconomic models because we focus on non-linearities where they are most salient - namely in asset prices - while keeping macroeconomic dynamics log-linear. As such, our model naturally has its limitations. For example, episodes of non-linear macroeconomic dynamics, such as crises, would not fit into this basic model, though it would be interesting to incorporate them in the future through regime switches.

Three applications highlight the usefulness of our model to interpret empirical asset price movements around monetary policy announcements. The model easily matches the large stock return response to traditional monetary policy shocks, but only if stock responses are amplified by consumption-based habit risk premia. Our model also helps interpret evidence that FOMC dates reveal news about inflation and macroeconomic growth, and in particular suggests that the interpretation of growth news needs to be strengthened in the light of countervailing effects from flight-to-safety towards safe bonds.

We anticipate that our framework will be useful to interpret the macroeconomic drivers of asset price fluctuations more generally beyond the channels considered in this basic macroeconomic model, such as wage rigidities or heterogeneity in price-setting frictions (Weber (2015)). We also believe that the model framework will be useful to understand further empirical puzzles, such as the empirical finding that equity returns are typically high prior to FOMC dates and on regular dates during the FOMC cycle (Lucca and Moench (2015), Cieslak, Morse, and Vissing-Jorgensen (2019)), which has been attributed to a combination of negative monetary policy surprises and risk premia (Cieslak and Pang (2019)).

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Table 1: Model Parameters

Panel A: Calibrated Parameters		
Consumption Growth Rate	g	1.89
Utility Curvature	γ	2.00
Steady-State Riskfree Rate	$\bar{r}$	0.94
Persistence Surplus Consumption Ratio	θ_0	0.87
Dependence Output Gap	θ_1	-0.67
Dependence Lagged Output Gap	θ_2	0.60
Capital Share of Production	τ	0.33
Learning-by-Doing	ϕ	0.93
Frisch Elasticity	$\chi\frac{\bar{L}}{1-\bar{L}}$	1.00
Price Stickiness	α	0.67
Cross-Goods Substitutability	θ	6.00
Leverage	δ	0.40
MP Coefficient Output	γ^x	0.50
MP Coefficient Inflation	γ^π	1.50
MP Persistence	ρ^i	0.90
MP - Frictionless Real Rate	ρ^a	0.68
Panel B: Estimated Parameters		
Std. Demand Shock (%)	σ_x	0.37
Std. PC Shock (%)	σ_π	0.49
Std. Short-Term MP (%)	σ_{ST}	0.37
Std. Long-Term MP (%)	σ_{LT}	0.22
Panel C: Implied Parameters		
Discount Rate	β	0.90
Steady-State Surplus Consumption Ratio	$\bar{S}$	0.04
Maximum Surplus Consumption Ratio	S^{max}	0.07
Euler Equation Lag Coefficient	ρ^x	0.37
Euler Equation Forward Coefficient	f^x	0.63
Euler Equation Real Rate Slope	ψ	0.08
Phillips Curve Lag Coefficient	ρ^π	0.51
Phillips Curve Forward Coefficient	f^π	0.49
Phillips Curve Slope	κ	0.06

Note: Panel A shows the parameters we calibrate following previous literature, as detailed in Section 4.1. Panel B displays the parameters we estimate by matching the empirical impulse response functions and the volatility of long-term breakeven as described in Section 4.2. Panel C reports moments implied by the other parameters listed above. Consumption growth and the steady-state risk-free rate are in annualized percent. The discount rate and the persistence of surplus consumption are annualized. The monetary policy coefficients and the Phillips curve slope are reported in units corresponding to our empirical variables, i.e. the de-trended log output is in percent, and inflation, the Fed Funds rate are in annualized percent. So for instance, the implied Euler equation real rate slope is $\frac{1}{4(\phi-\theta_1)}$. We report quarterly standard deviations of shocks to percent output gap, annualized percent inflation, the annualized percent Fed Funds rate, and the annualized percent long-term monetary policy target.

Table 2: Asset Prices

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

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

Table 3: Financial Market Responses to Monetary Policy News

Panel A: Fed Funds Effect	(1) Data	(2) Combined	(3) Short Term	(4) Long Term
Slope(Equity Returns, Fed Funds)	-4.32	-6.03	-6.24	596.05
	(1.65)			
Risk Neutral		-3.14	-3.10	309.01
Panel B: Nominal Fed Information Effect				
Slope(Equity Returns, 10Y Breakeven)	7.77	6.81	49.37	6.03
	(4.25)			
Risk Neutral		3.68	28.39	3.18
Panel C: Real Fed Information Effect				
Slope(5Y Real Yield, 6M Nominal Yield)	0.65	0.38	0.40	-0.71
	(0.14)			
Risk Neutral		0.38	0.40	-0.70
Slope(10Y Real Yield, 6M Nominal Yield)	0.49	0.19	0.20	-0.33
	(0.11)			
Risk Neutral		0.18	0.19	-0.33

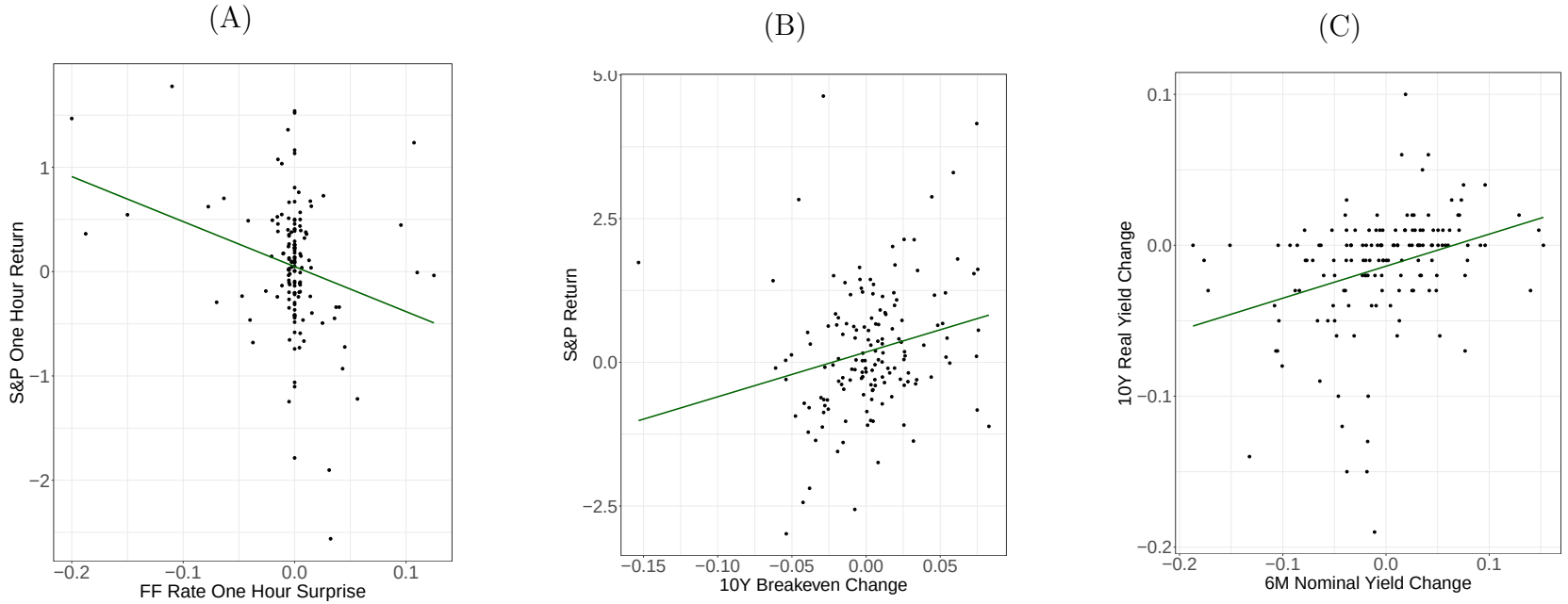
Note: This table compares the asset price reactions around monetary policy news in the model and in the data. The first column reports the empirical moment. The second column shows model asset prices assuming that FOMC dates are subject to uncorrelated long-term and short-term monetary policy shocks. The standard deviations of the ST and LT monetary policy shocks are set to 4.3 bps and 3.3 bps to match the volatilities of one-hour Fed Funds surprises and breakeven changes on FOMC dates in the data. The third column reports model asset prices assuming that only short-term monetary policy news is released on FOMC dates. The fourth column reports model asset prices assuming that only long-term monetary policy news is released on FOMC dates. For details of model FOMC asset prices see Section 3.6. Panel A reports regressions of the form $r_t^{\delta,FOMC} = b_0 + b_1 \Delta^{FOMC} i_t + \varepsilon_t$. In the data, we regress S&P 500 returns onto the surprise move in the Federal Funds rate in the one hour around FOMC announcements. The data on Federal Fund rate surprises is from Gorodnichenko and Weber (2016), and we construct the high frequency S&P 500 returns from TAQ data. Panel B reports regressions of the form $r_t^{\delta,FOMC} = b_0 + b_1 \Delta^{FOMC} b_{n,t} + \varepsilon_t$, where $\Delta^{FOMC} b_{n,t}$ is the change in the 10-year breakeven rate, defined as difference between 10-year nominal and 10-year real bond yields. The corresponding data moments are obtained from regressions of daily returns of the S&P 500 over daily changes 10 year breakeven inflation on FOMC days. Panel C shows regressions of the form $\Delta^{FOMC} y_{n,t} = b_0 + b_1 \Delta^{FOMC} i_t + \varepsilon_t$, where $\Delta^{FOMC} y_{n,t}$ is either the change in the 10-year or 5-year real bond yield. We use zero-coupon 10-year TIPS yields from Gürkaynak, Sack, and Wright (2010) and the 6 month constant maturity treasury rate from FRED (DGS6MO). The sample of FOMC days for the empirical regression in panel A is from the start of 2001 up to the end of 2019, excluding the QE episodes of 16th of December 2008 and the 18th of March 2009. For panels B and C we use the same sample but starting from 2003 since TIPS data is only available starting from that year. Heteroskedasticity adjusted standard errors are reported in parentheses below the empirical estimates. Risk neutral rows show the slope coefficients with both the right-hand side and left-hand side computed from the perspective of a risk neutral investor taking macroeconomic dynamics as given.

Table 4: Model Decomposition

	(1) Baseline	(2) $\rho^a = 0$	(3) $\sigma_x = 0$	(4) $\sigma_\pi = 0$	(5) $\sigma_{ST} = 0$	(6) $\sigma_{LT} = 0$
Panel A: Fed Funds Effect						
Slope(Equity Returns, Fed Funds)	-6.03	-13.19	-21.65	-5.89	-5.65	-5.90
Risk Neutral	-3.14	-4.30	-3.14	-3.06	-3.15	-3.12
Panel B: Nominal Fed Information Effect						
Slope(Equity Returns, 10Y Breakeven)	6.81	13.44	22.2	6.64	6.39	6.67
Risk Neutral	3.68	4.64	3.67	3.58	3.67	3.64
Panel C: Real Fed Information Effect						
Slope(5Y Real Yield, 6m Nom Yield)	0.38	0.34	0.57	0.37	0.38	0.38
Risk Neutral	0.38	0.31	0.38	0.37	0.38	0.38
Slope(10Y Real Yield, 6m Nom Yield)	0.19	0.20	0.4	0.18	0.18	0.18
Risk Neutral	0.18	0.16	0.19	0.18	0.19	0.18
Panel D: Bond Betas						
Real Bond-Stock Beta	0.03	0.07	0.17	0.02	-0.02	0.01
Breakeven-Stock Beta	-0.13	-0.16	-0.22	-0.13	-0.11	-0.04

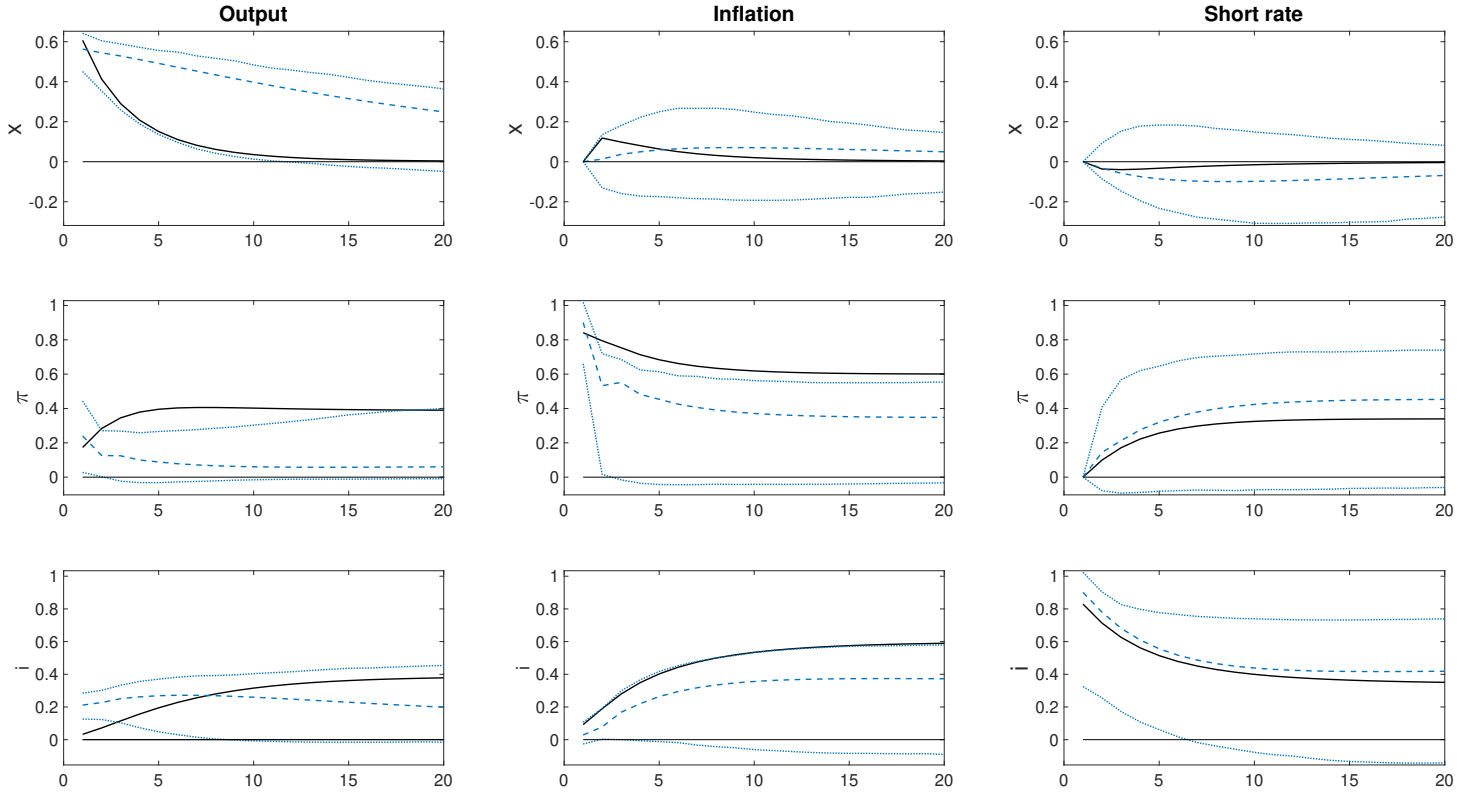
Note: This table compares asset pricing moments while switching off individual model components. The real and breakeven stock betas are computed as in Table 2, and the asset price reactions around monetary policy dates are as in Table 3. Risk neutral rows show the slope coefficients with both the right-hand side and left-hand side computed from the perspective of a risk neutral investor taking macroeconomic dynamics as given. Column (1) repeats the model asset pricing moments for the baseline model from Tables 2 and 3. Column (2) switches off predictable technology growth. Column (3) sets the demand shock to zero. Column (4) sets the Phillips curve shock to zero. Column (5) sets the short-term monetary policy shock to zero. Column (6) sets the long-term monetary policy shock to zero. All other parameters are held constant at the values listed in Table 1.

Figure 1: Bonds and Stocks on FOMC Dates



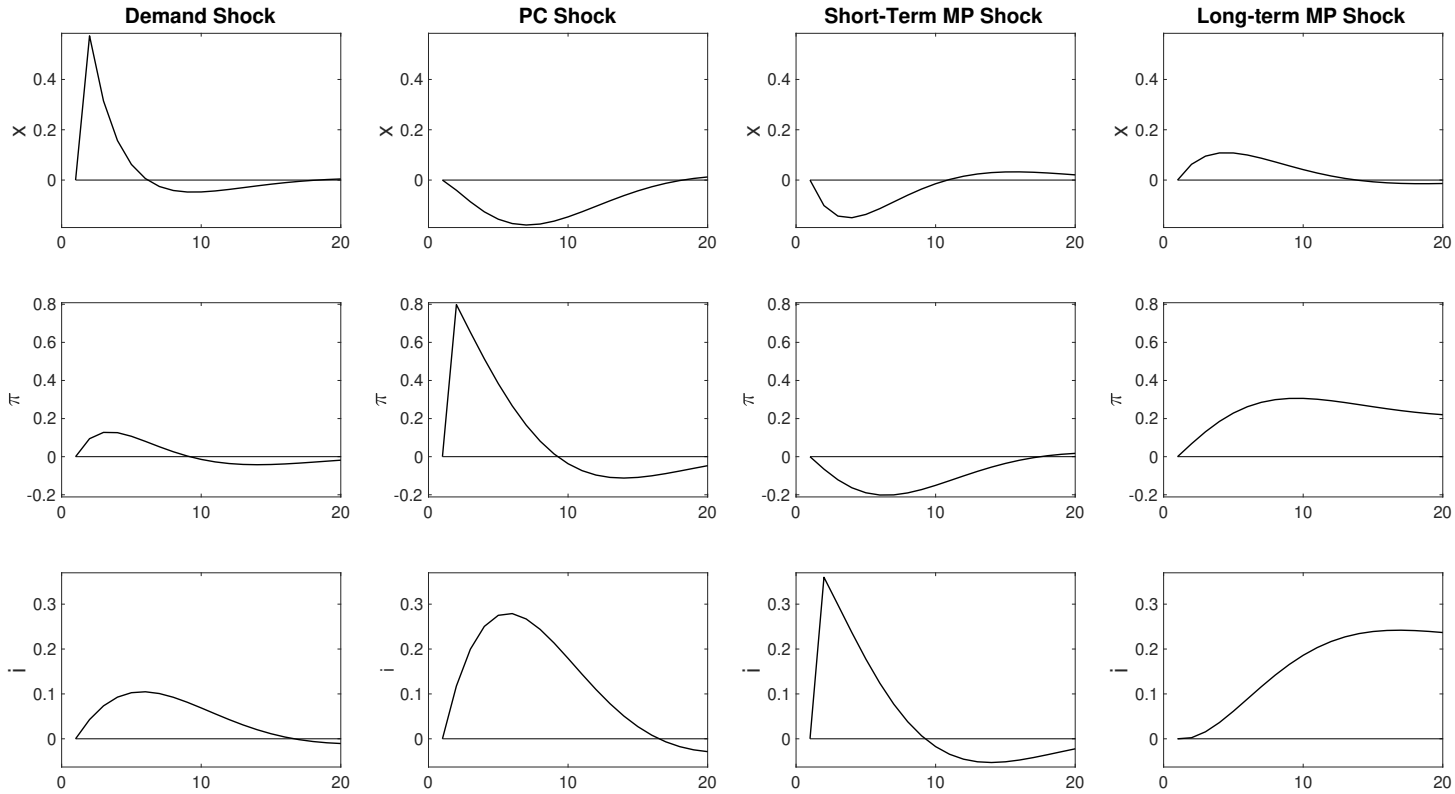
Note: Panel A shows the relationship of Federal Fund rates surprises in an hourly window around FOMC announcements from Gorodnichenko and Weber (2016) and S&P 500 returns in the same window constructed from TAQ data, where each data point corresponds to a FOMC meeting day. Panel B shows the relationship of the daily change in 10 year breakeven inflation rates and daily S&P 500 returns where again each data point corresponds to a FOMC meeting day. The breakeven rate is the difference between the 10-year nominal Treasury yield and 10-year TIPS yield from Gürkaynak, Sack, and Wright (2007, 2010). The right panel shows the relationship of daily changes in 6-month nominal treasury yields from FRED and 10 year real yield from Gürkaynak, Sack, and Wright (2010). The green lines are linear regression best fit lines. The sample of FOMC days is from the start of 2001 until end of 2019, excluding the QE episodes of 16th of December 2008 and the 18th of March 2009. For Panels B and C, the data begins from the start of 2003 since this is when the TIPS data start.

Figure 2: Reduced Form Macro Impulse Responses



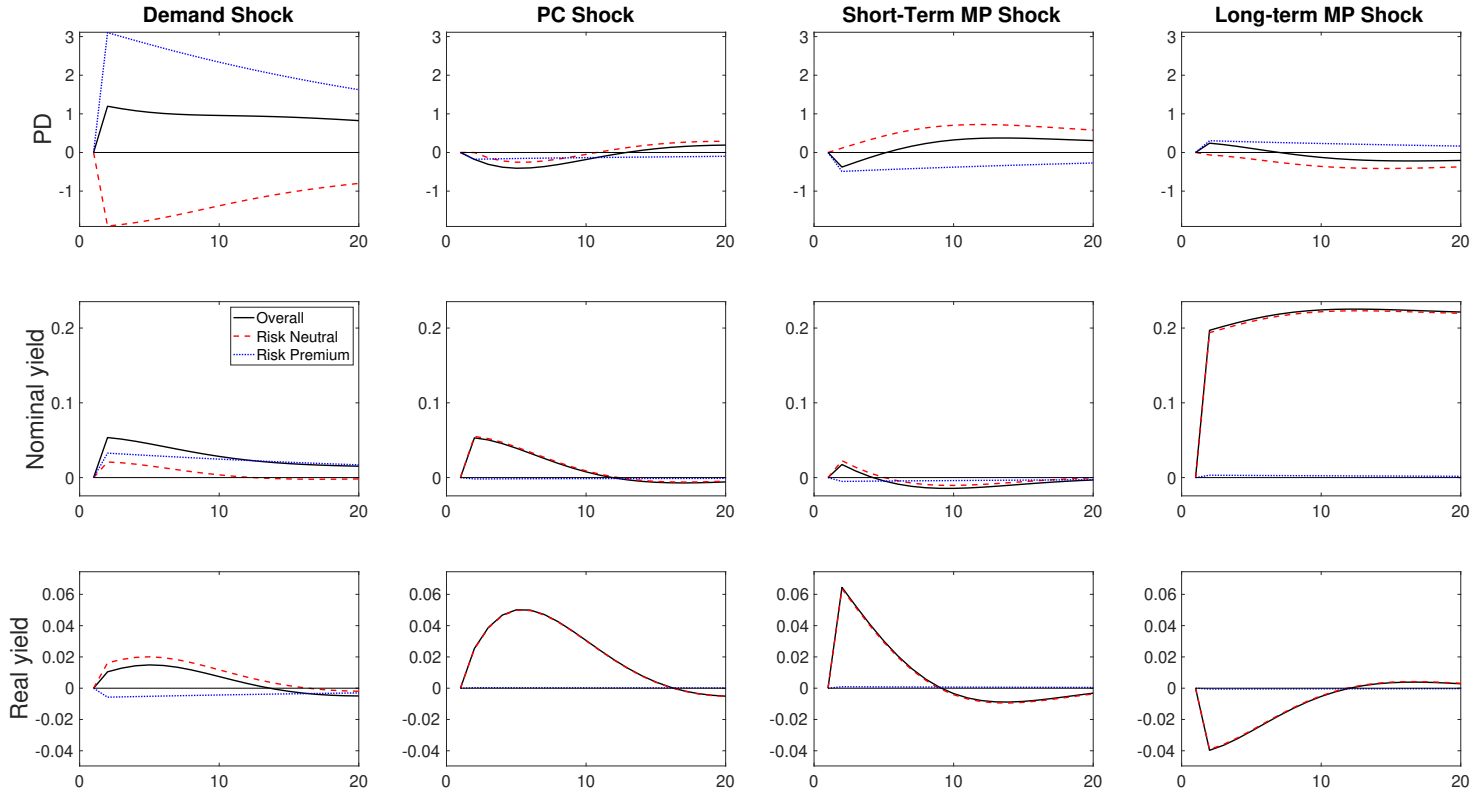
Note: This figure shows macroeconomic impulse responses to reduced-form output gap, inflation, and Federal Funds rate innovations in the model and in the data. The estimation of impulse responses is identical on actual and simulated data and is described in detail in Section 4.2. All impulses are one-standard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

Figure 3: Structural Macro Impulse Responses



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

Figure 4: Structural Financial Asset Price Impulse Responses



Note: Each column of this figure shows the impulse responses of asset prices to one of the structural shocks, namely the demand shock, the Phillips Curve (PC) shock, the short-term monetary policy shock, and the long-term monetary policy shock. All impulses are one-standard deviation shocks. The first row shows the response of the price dividend ratio of equities in its units, 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.