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Abstract

Can increased uncertainty about the future cause a contraction in output and its components? An identified uncertainty shock in the data causes significant declines in output, consumption, investment, and hours worked. Standard general-equilibrium models with flexible prices cannot reproduce this comovement. However, uncertainty shocks can easily generate comovement with countercyclical markups through sticky prices. Monetary policy plays a key role in offsetting the negative impact of uncertainty shocks during normal times. Higher uncertainty has even more negative effects if monetary policy can no longer perform its usual stabilizing function because of the zero lower bound. We calibrate our uncertainty shock process using fluctuations in implied stock market volatility, and show that the model with nominal price rigidity is consistent with empirical evidence from a structural vector autoregression. We argue that increased uncertainty about the future likely played a role in worsening the Great Recession. The economic mechanism we identify applies to a large set of shocks that change expectations of the future without changing current fundamentals.

JEL Classification: E32, E52

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1 Introduction

Economists and the financial press often discuss uncertainty about the future as an important driver of economic fluctuations and a contributor in the Great Recession. For example, Diamond (2010) says, "What's critical right now is not the functioning of the labor market, but the limits on the demand for labor coming from the great caution on the side of both consumers and firms because of the great uncertainty of what's going to happen next." Recent research by Bloom (2009), Bloom et al. (2014), Bachmann and Bayer (2013), and Gilchrist, Sim and Zakrajšek (2013) also suggests that uncertainty shocks can cause fluctuations in macroeconomic aggregates. However, these papers experience difficulty in generating business-cycle comovements among output, consumption, investment, and hours worked from changes in uncertainty.

We argue that this macroeconomic comovement is a key empirical feature of the economy's response to an uncertainty shock. Using a structural vector autoregression (VAR), we identify an uncertainty shock in the data as an exogenous increase in the implied volatility of future stock returns, an identification strategy that is consistent with our theoretical model. Empirically, an uncertainty shock causes statistically significant declines in output, consumption, investment, and hours, with a peak response occurring after about one year. A one standard deviation increase in uncertainty produces a peak decline in output of about 0.2 percent. Based on this empirical evidence, we view this macroeconomic comovement as a key minimum condition that business-cycle models driven by uncertainty fluctuations should satisfy.

After presenting this stylized fact, we show why competitive, one-sector, closed-economy models generally cannot reproduce this comovement in response to changes in uncertainty. Under reasonable assumptions, an increase in uncertainty about the future induces precautionary saving and lowers consumption. If households supply labor inelastically, then total output remains constant since the level of technology and capital stock remain unchanged in response to the uncertainty shock. Unchanged total output and reduced consumption together imply that investment must rise. If households can adjust their labor supply and consumption and leisure are both normal goods, an increase in uncertainty also induces "precautionary labor supply," or a desire for the household to supply more labor for any given level of the real wage. As current technology and the capital stock remain unchanged, the competitive demand for labor remains unchanged as well. Thus, higher uncertainty reduces consumption but raises output, investment, and hours worked. This lack of comovement is a robust prediction of simple neoclassical models subject to uncertainty fluctuations.

Yet intuition suggests that the reduction in household expenditure resulting from increased uncertainty could lead to a general decline in output and its components. We show that this intuition is typically correct in models where output is demand-determined, at least over some time horizon. In such models, the reduction in consumption demand reduces output and labor input, which in turn reduces the demand for capital and hence investment. Aggregate demand-determined output is made consistent with household and firm optimization through endogenous movements in markups, which in our model is driven by the standard assumption of nominal price rigidity. Following Diamond's (2010) intuition, simple competitive business-cycle models do not exhibit movements in "the demand for labor" as a result of an uncertainty shock. However, uncertainty shocks do cause shifts in labor demand in non-competitive, sticky-price models with endogenously-varying markups, which capture the intuition articulated by Diamond. Understanding the dynamics of the demand for labor explains why the two models behave so differently in response to a change in uncertainty.

Importantly, the non-competitive model is able to match the estimated effects of uncertainty shocks in the data. To analyze the quantitative impact of uncertainty shocks, we calibrate and solve a representative-agent, dynamic, stochastic general equilibrium (DSGE) model with capital accumulation and nominal price rigidity. We examine the effects of second-moment shocks to household discount factors, which we interpret as demand uncertainty. We calibrate our uncertainty shock process using the Chicago Board Options Exchange Volatility Index (VXO), which measures the expected volatility of the Standard and Poor's 100 stock index over the next 30 days. When prices adjust slowly, uncertainty shocks can produce contractions in output and all its components. In particular, the declines in output, hours, consumption, and investment in the model are consistent with our empirical evidence. Using simulated data from our model, we show that our empirical identification strategy can recover the true macroeconomic effects of higher uncertainty.

Finally, we examine the role of monetary policy in determining the equilibrium effects of uncertainty shocks. Standard monetary policy rules imply that the central bank usually offsets increases in uncertainty by lowering its nominal policy rate. We show that increases in uncertainty have larger negative effects on the economy if the monetary authority is constrained by the zero lower bound on nominal interest rates. The sharp increase in uncertainty in late 2008 corresponds to a period when the Federal Reserve had a policy rate near zero. Our results suggest that greater uncertainty, in conjunction with the zero lower bound, can explain over one-fourth of the drop in output that occurred in late 2008.

2 Empirical Evidence

This section presents our key stylized fact: Higher uncertainty about the future causes declines in output, consumption, investment, and hours worked. To document this feature of the data, we estimate a VAR with the following variables: a measure of uncertainty, gross domestic product (GDP), consumption, investment, hours worked, the GDP deflator, the M2 money stock, and a measure of the stance of monetary policy. We measure uncertainty using the VXO, a well-known and readily-observable measure of aggregate uncertainty. Since the VXO data start in 1986, we estimate our baseline empirical model using quarterly data over the 1986-2014 sample period. With the exception of the monetary policy measure, all other variables enter the VAR in log levels. Appendix A.1 provides further details on the data construction and the VAR estimation.

We identify an uncertainty shock using a Cholesky decomposition with the VXO ordered first. This ordering assumes that uncertainty shocks can have an immediate impact on output and its components, but non-uncertainty shocks do not affect the implied stock market volatility on impact. In Section 5.3, we show that our theoretical model fully supports this identification strategy: First-moment or non-uncertainty shocks in the model have almost no effect on the expected volatility of future equity returns.

Figure 1 plots the estimated responses to an identified uncertainty shock along with the 95% confidence intervals. A one-standard deviation uncertainty shock increases the VXO by 15%.[1] On impact, higher uncertainty causes statistically significant declines in output, consumption, and investment.[2] Following the shock, output, consumption, investment, and hours all decline together, with their peak responses occurring after about one year. The peak decline in investment is roughly twice as large as the decline in total output, while consumption moves by slightly less than output. Prices fall for about two years following the shock. The declines in inflation and economic activity lead the monetary authority to reduce its nominal policy rate significantly. The impulse responses are statistically indistinguishable from zero after about three years. Figure A.1 in the Appendix shows the time-series of identified uncertainty shocks. The empirical model identifies large uncertainty shocks after the 1987 stock market crash, the

[1]In annualized percentage points, a one-standard deviation shock raises the level of the VXO to about 24.5%, from its unconditional average of about 21%.

[2]Our results are quantitatively similar to the findings of Alexopoulos and Cohen (2009) and Jurado, Ludvigson and Ng (2015). These papers find that higher uncertainty decreases several monthly indicators of economic activity. Our responses also share many features with the impulse responses in Figure 3 of Fernández-Villaverde et al. (2015) following a policy uncertainty shock.

failure of Lehman brothers, and the euro area sovereign debt crisis.

Macroeconomic comovment following an uncertainty shock is a robust feature of the data. Appendix A.2 shows that our key stylized fact survives if we include stock prices in the VAR, measure uncertainty with the VIX rather than the VXO, order uncertainty last in the VAR, use higher frequency estimation, or restrict our analysis to the pre-Great Recession sample period.

Based on this empirical evidence, we argue that this macroeconomic comovement is a key litmus test for models of uncertainty fluctuations. In the following sections, we show that a standard model with nominal price rigidity is consistent with this empirical evidence. We show that monetary policy plays a key role in determining the effects of higher uncertainty. At the end of 2008, the Federal Reserve became constrained by the zero lower bound on nominal interest rates. In the later sections, we discuss this issue in detail using our theoretical model. From an econometric standpoint, however, it is less clear how to empirically model the stance of monetary policy over our full 1986-2014 sample period. In our baseline VAR results, we use the Wu and Xia (2016) shadow rate as our indicator of monetary policy. In Appendix A.2, we also show that our key stylized fact remains unchanged if we use alternative measures for the stance of monetary policy in the VAR.

3 Intuition

We now examine the ability of standard macroeconomic models to generate comovement among aggregates following an uncertainty shock. We find that demand-determined output is the key mechanism for generating comovement in response to uncertainty fluctuations. As we show below, changes in aggregate demand are made consistent with household and firm optimization via endogenous changes in markups. The economics, however, is that higher uncertainty increases desired saving. Higher desired savings is expansionary if full employment of all factors is guaranteed, but may be contractionary if output is demand-determined. In such models, the increase in *desired* saving by households can easily lead to lower *actual* saving in general equilibrium.

We now illustrate these ideas using a few key equations that characterize a large class of one-sector business-cycle models. These equations link output Y_t, consumption C_t, investment I_t, hours worked N_t, and the real wage W_t/P_t through the national income accounts identity, an aggregate production function, and first-order conditions for household labor supply and firm labor demand:

$$Y_t = C_t + I_t, \tag{1}$$
$$Y_t = F(K_t, Z_t N_t), \tag{2}$$
$$\frac{W_t}{P_t} U_1(C_t, 1 - N_t) = U_2(C_t, 1 - N_t), \tag{3}$$
$$\frac{W_t}{P_t} = Z_t F_2(K_t, Z_t N_t). \tag{4}$$

Households want to consume less and save more when uncertainty increases in the economy. In a model where output is always at its flexible-price or "natural" level, this higher desired saving translates into higher actual saving. To save more, households would like to reduce consumption and increase hours worked. Figure 2 illustrates this intuition graphically. Higher uncertainty increases the marginal utility of wealth $\lambda_t = U_1(C_t, 1 - N_t)$, which shifts the household labor supply curve outward.[3] When prices are flexible, firm labor demand in Equation (4) only depends on the level of the capital stock K_t and technology Z_t, neither of which changes in response to higher uncertainty. Through the production function, higher labor supply with unchanged capital and technology means that output must rise. Higher output with lower consumption implies that investment must rise via the national income accounts identity. Thus, higher uncertainty under flexible prices lowers consumption but causes an expansion in output, investment, and hours worked.[4]

When prices adjust slowly, however, aggregate demand determines output in the short run which reverses the causal ordering of these equations. Higher uncertainty reduces the demand for consumption goods, which lowers output directly in Equation (1). Lower output reduces the benefit to owning capital, since the marginal revenue product of capital falls. The decline in the desired capital stock is reflected in a lower level of investment. Since consumption and investment both fall, output and hours worked both decline, since labor is the only input to production that can change in response to higher uncertainty.

To make this outcome consistent with household and firm optimization, firm markups must increase. When prices are sticky, the labor demand curve now becomes:

$$\frac{W_t}{P_t} = \frac{1}{\mu_t} Z_t F_2(K_t, Z_t N_t), \tag{5}$$

where μ_t is the markup of price over marginal cost. To make the increase in desired labor supply consistent with the reduced demand for output, the labor demand curve in Figure 2 shifts

[3]Domeij and Flodén (2006), Pijoan-Mas (2006), Low (2005), and Flodén (2006) show that households also display precautionary labor supply when they face uninsurable, idiosyncratic income risk.

[4]This argument follows Barro and King (1984).

inward. Mechanically, precautionary labor supply reduces firm marginal cost, which increases the markup when prices are sticky. Thus, equilibrium hours worked may fall as a result of the shifts in labor supply and labor demand. In the next section, we show that in a reasonably calibrated model with nominal price rigidity, firm markups increase enough to produce a decrease in equilibrium hours worked in response to a rise in uncertainty.

Our insights about macroeconomic comovement also apply to other sources of fluctuations, such as news shocks, shocks to the financial system, or expected changes in future tax rates. Like uncertainty shocks, these disturbances change expected future marginal products of capital without affecting the intratemporal optimality condition in a competitive model with time-separable preferences. Our mechanism will also restore comovement in standard models in response to such shocks, making the resulting predictions more intuitive.[5] For example, an adverse financial shock will cause a decline in consumption and hours worked on impact instead of leading to a temporary consumption boom. In general, we view our results as a test of the overidentifying predictions of the New Keynesian model. The model was developed to explain why real variables change in response to monetary shocks, and as Christiano, Eichenbaum and Evans (2005) show, it can do so quite well. However, the model was not developed to explain the effects of real shocks. To the extent that the model can also match the responses to other shocks, then we have more confidence that the model can serve as a parsimonious way of modeling economic fluctuations in general.

4 Model

This section outlines the baseline dynamic, stochastic general-equilibrium model that we use in our analysis of uncertainty shocks. The model features optimizing households and firms and a central bank that follows a Taylor rule to stabilize inflation and offset adverse shocks. We allow for sticky prices using the quadratic-adjustment cost specification of Rotemberg (1982). Our baseline model considers household discount rate and technology shocks. The discount rate shocks have a time-varying second moment, which we interpret as the degree of *ex ante* uncertainty about future demand. Appendix B contains a detailed derivation of our model.

[5]Thus, the mechanism we identify echoes findings from the prior news shocks literature of Wang (2012), Kobayashi and Nutahara (2010), and Christiano et al. (2010). These papers show that countercyclical markups via nominal rigidities can generate macroeconomic comovement following a news shock.

4.1 Households

The representative household maximizes lifetime utility given Epstein-Zin preferences over streams of consumption C_t and leisure $1 - N_t$. The key parameters governing household decisions are its risk aversion σ over the consumption-leisure basket and its intertemporal elasticity of substitution ψ. The parameter $\theta_V \triangleq (1-\sigma)(1-1/\psi)^{-1}$ controls the household's preference for the resolution of uncertainty.[6] The household receives labor income W_t for each unit of labor N_t supplied to the intermediate goods-producing firms. The representative household also owns the intermediate goods firm and holds equity shares S_t and one-period riskless bonds B_t issued by the representative intermediate goods firm. Equity shares have a price of P_t^E and pay dividends D_t^E for each share S_t owned. The riskless bonds return the gross one-period risk-free interest rate R_t^R. The household divides its income from labor and its financial assets between consumption C_t and holdings of financial assets S_{t+1} and B_{t+1} to carry into next period. The discount rate of the household β is subject to shocks via the stochastic process a_t.

The representative household maximizes lifetime utility by choosing C_{t+s}, N_{t+s}, B_{t+s+1}, and S_{t+s+1} for all $s = 0, 1, 2, \ldots$ by solving the following problem:

$$V_t = \max \left[a_t \left(C_t^{\eta} (1-N_t)^{1-\eta} \right)^{\frac{1-\sigma}{\theta_V}} + \beta \left(\mathbb{E}_t V_{t+1}^{1-\sigma} \right)^{\frac{1}{\theta_V}} \right]^{\frac{\theta_V}{1-\sigma}}$$

subject to its intertemporal household budget constraint each period,

$$C_t + \frac{P_t^E}{P_t} S_{t+1} + \frac{1}{R_t^R} B_{t+1} \leq \frac{W_t}{P_t} N_t + \left(\frac{D_t^E}{P_t} + \frac{P_t^E}{P_t} \right) S_t + B_t.$$

Epstein-Zin utility implies a stochastic discount factor M between periods t and $t+1$:

$$M_{t+1} \triangleq \left(\frac{\partial V_t / \partial C_{t+1}}{\partial V_t / \partial C_t} \right) = \left(\beta \frac{a_{t+1}}{a_t} \right) \left(\frac{C_{t+1}^{\eta} \left(1 - N_{t+1}\right)^{1-\eta}}{C_t^{\eta} \left(1 - N_t\right)^{1-\eta}} \right)^{\frac{1-\sigma}{\theta_V}} \left(\frac{C_t}{C_{t+1}} \right) \left(\frac{V_{t+1}^{1-\sigma}}{\mathbb{E}_t \left[V_{t+1}^{1-\sigma} \right]} \right)^{1-\frac{1}{\theta_V}}$$

4.2 Intermediate Goods Producers

Each intermediate goods-producing firm i rents labor $N_t(i)$ from the representative household to produce intermediate good $Y_t(i)$. Intermediate goods are produced in a monopolistically competitive market where producers face a quadratic cost ϕ_P of changing their nominal price $P_t(i)$ each period. The intermediate-goods firms own their capital stocks $K_t(i)$, and face convex costs ϕ_K of changing the quantity of installed capital. Firms also choose the rate of utilization

[6] Our main qualitative results regarding macroeconomic comovement are robust to using standard expected utility preferences. Epstein-Zin preferences allow us to calibrate our model using stock market data. Appendix D.5 discusses the role of risk aversion in generating our quantitative results.

of their installed physical capital $U_t(i)$, which affects its depreciation rate. Each firm issues equity shares $S_t(i)$ and one-period risk-less bonds $B_t(i)$. Firm i chooses $N_t(i)$, $I_t(i)$, $U_t(i)$, and $P_t(i)$ to maximize firm cash flows $D_t(i)/P_t(i)$ given aggregate demand Y_t, the elasticity of substitution among intermediate goods θ_μ, and the price P_t of the finished goods sector. The intermediate goods firms all have the same constant-returns-to-scale Cobb-Douglas production function, subject to a fixed cost of production Φ and the level of productivity Z_t.

Each maximizes discounted cash flows using the household's stochastic discount factor:

$$\max \mathbb{E}_t \sum_{s=0}^{\infty} \left(\frac{\partial V_t / \partial C_{t+s}}{\partial V_t / \partial C_t} \right) \left[\frac{D_{t+s}(i)}{P_{t+s}} \right]$$

subject to the production function,

$$\left[\frac{P_t(i)}{P_t} \right]^{-\theta_\mu} Y_t \leq \left[K_t(i) U_t(i) \right]^{\alpha} \left[Z_t N_t(i) \right]^{1-\alpha} - \Phi,$$

and subject to the capital accumulation equation,

$$K_{t+1}(i) = \left(1 - \delta\Big(U_t(i)\Big) - \frac{\phi_K}{2} \left(\frac{I_t(i)}{K_t(i)} - \delta \right)^2 \right) K_t(i) + I_t(i),$$

where

$$\frac{D_t(i)}{P_t} = \left[\frac{P_t(i)}{P_t} \right]^{1-\theta_\mu} Y_t - \frac{W_t}{P_t} N_t(i) - I_t(i) - \frac{\phi_P}{2} \left[\frac{P_t(i)}{\Pi P_{t-1}(i)} - 1 \right]^2 Y_t.$$

Depreciation depends on utilization via the following functional form:

$$\delta\Big(U_t(i)\Big) = \delta + \delta_1 \Big(U_t(i) - U \Big) + \left(\frac{\delta_2}{2} \right) \Big(U_t(i) - U \Big)^2$$

Ξ_t denotes the marginal cost of producing one additional unit of intermediate good i.

Following Jermann (1998), each intermediate goods firm finances a percentage ν of its capital stock each period with one-period riskless bonds. The bonds pay the one-period real risk-free interest rate. Thus, the quantity of bonds $B_t(i) = \nu K_t(i)$. Total firm cash flows are divided between payments to bond holders and equity holders as follows:

$$\frac{D_t^E(i)}{P_t} = \frac{D_t(i)}{P_t} - \nu \left(K_t(i) - \frac{1}{R_t^R} K_{t+1}(i) \right). \tag{6}$$

Since the Modigliani and Miller (1958) theorem holds in our model, leverage does not affect firm value or optimal firm decisions. Leverage makes the price of equity more volatile and allows us to define a concept of equity returns.

4.3 Final Goods Producers

The representative final goods producer uses $Y_t(i)$ units of each intermediate good produced by the intermediate goods-producing firm $i \in [0,1]$. The market for final goods is perfectly competitive, and thus the final goods-producing firm earns zero profits in equilibrium. Appendix B.3 shows that the aggregate price index P_t can be written as follows:

$$P_t = \left[\int_0^1 P_t(i)^{1-\theta_\mu} di \right]^{\frac{1}{1-\theta_\mu}}$$

4.4 Equilibrium

In the symmetric equilibrium, all intermediate goods firms choose the same price $P_t(i) = P_t$, employ the same amount of labor $N_t(i) = N_t$, and choose the same level of capital and utilization rate $K_t(i) = K_t$ and $U_t(i) = U_t$. Thus, all firms have the same cash flows and are financed with the mix of bonds and equity. The markup of price over marginal cost is $\mu_t = 1/\Xi_t$, and gross inflation is $\Pi_t = P_t/P_{t-1}$.

4.5 Monetary Policy

We assume a cashless economy where the monetary authority sets the nominal interest rate r_t to stabilize inflation and output growth. Monetary policy adjusts the nominal interest rate in accordance with the following rule:

$$r_t = r + \rho_\pi (\pi_t - \pi) + \rho_y \Delta y_t, \tag{7}$$

where $r_t = \ln(R_t)$, $\pi_t = \ln(\Pi_t)$, and $\Delta y_t = \ln(Y_t/Y_{t-1})$. Changes in the gross nominal interest rate R_t affect expected inflation and the real interest rate. Thus, we include the following Euler equation for a zero-net supply-nominal bond as one of our equilibrium conditions:

$$1 = R_t \mathbb{E}_t \left\{ M_{t+1} \left(\frac{1}{\Pi_{t+1}} \right) \right\} \tag{8}$$

4.6 Shock Processes

The demand and technology shock processes are parameterized as follows:

$$a_t = (1 - \rho_a)\, a + \rho_a a_{t-1} + \sigma^a_{t-1} \varepsilon^a_t$$

$$\sigma^a_t = (1 - \rho_{\sigma^a})\, \sigma^a + \rho_{\sigma^a} \sigma^a_{t-1} + \sigma^{\sigma^a} \varepsilon^{\sigma^a}_t$$

$$Z_t = (1 - \rho_Z)\, Z + \rho_Z Z_{t-1} + \sigma^Z \varepsilon^Z_t$$

ε_t^a and ε_t^Z are first-moment shocks that capture innovations to the level of the stochastic process for technology and household discount factors. We refer to $\varepsilon_t^{\sigma^a}$ as second-moment or "uncertainty" shock since it captures innovations to the volatility of the exogenous process for household discount factors. An increase in the volatility of the shock process increases the uncertainty about the future time path of household demand. All three stochastic shocks are independent, standard normal random variables.[7]

4.7 Uncertainty Shock Calibration

The quantitative impact of uncertainty on the macroeconomy depends on the calibration of the size and persistence of the uncertainty shock process. Thus, we discipline our model to produce fluctuations in uncertainty that are consistent with the VXO, an observable indicator of *ex ante* stock market volatility.

To link our model with the data, we create a model counterpart to our observable measure of aggregate uncertainty. We compute a model-implied VXO index V_t^M as the expected conditional volatility of the return on firm equity:

$$R_{t+1}^E = \frac{D_{t+1}^E + P_{t+1}^E}{P_t^E}, \tag{9}$$

$$V_t^M = 100 * \sqrt{4 * \mathbb{VAR}_t \, R_{t+1}^E}, \tag{10}$$

where $\mathbb{VAR}_t \, R_{t+1}^E$ is the quarterly conditional variance of the return on equity R_{t+1}^E.[8] We annualize the quarterly conditional variance, and then transform the annual volatility units into percentage points. We calibrate our uncertainty shock parameters such that the impulse response for the model-implied log VXO closely matches the log VXO movements from our identified VAR.

4.8 Solution Method

Our primary focus is examining the effect of an increase in the second moment of the preference shock process. As discussed in Fernández-Villaverde et al. (2011), examining the impulse response to a second-moment shock requires at least a third-order approximation of the policy functions of the model. We use the Dynare software package developed by Adjemian et al.

[7] We specify the stochastic processes in levels rather than logs to prevent the volatility σ_t^a from impacting the average value of a_t through a Jensen's inequality effect.

[8] Technically, the VXO is the expected volatility of equity returns under the risk-neutral measure. In preliminary work, we found the results were quantitatively unchanged if we compute the model-implied VXO using the risk-neutral expectation.

(2011) to solve our baseline model. Dynare computes the rational expectations solution to the model using third-order Taylor series approximation around the deterministic steady state of the model. Appendix B contains all the equilibrium conditions for the baseline model and provides additional details on the construction of the model impulse responses.

4.9 Calibration Using Impulse Response & Moment Matching

Table 1 lists the calibrated and estimated parameters of our model. Following Christiano, Eichenbaum and Evans (2005), we partition the model parameters into two groups. We calibrate parameters in the first group using steady-state relationships or results from previous studies. To match our empirical evidence, we calibrate the model to quarterly frequency. We choose steady-state hours worked N and the model-implied value for η such that our model has a Frisch labor supply elasticity of two. We calibrate the intertemporal elasticity of substitution ψ to be less than one, which is consistent with the findings of Hall (1988) and a large succeeding literature. The fixed cost of production for the intermediate-goods firm Φ is calibrated to eliminate pure profits in the deterministic steady state of the model. We calibrate risk aversion over the consumption-leisure basket $\sigma = 80$, which is in line with the previous estimates of van Binsbergen et al. (2012) and Swanson and Rudebusch (2012). We set $\delta_1 = \beta^1 - 1 + \delta$ based on steady-state relationships and calibrate δ_2 such that the elasticity of capital utilization with respect to the rental rate of capital matches the value from Christiano, Eichenbaum and Evans (2005). We choose standard values for the monetary policy reaction to inflation and output growth and assume a two percent annualized inflation target. We calibrate our price adjustment cost parameter $\phi_P = 100$, which implies prices are reset about once every four quarters in a linearized Calvo setting. In the following analysis, we compare the results from our baseline sticky-price calibration with a flexible-price calibration ($\phi_P = 0$).

We estimate the second set of model parameters which include the investment adjustment costs ϕ_K, the size σ^{σ^a} and persistence ρ_{σ^a} of the uncertainty shock process, and the remaining first-moment exogenous shock parameters. We want to choose our uncertainty shock parameters to minimize the distance between the model-implied impulse responses and the empirical responses in Figure 1. However, our uncertainty shock calibration also affects other predictions of the model, such as the unconditional volatility of output and its components. Therefore, we estimate the model parameters using a combination of impulse response and moment matching.

Formally, we write our estimator as the solution of following problem,

$$J = \min \left[\hat{\Psi} - \Psi(\gamma)\right]' V^{-1} \left[\hat{\Psi} - \Psi(\gamma)\right] + \zeta \left[\hat{\xi} - \xi(\gamma)\right]' W^{-1} \left[\hat{\xi} - \xi(\gamma)\right] \quad (11)$$

where $\hat{\Psi}$ denotes the empirical impulse responses in Figure 1, $\gamma \triangleq (\phi_K, \sigma^{\sigma^a}, \rho_{\sigma^a}, \rho_a, \sigma^a, \rho_Z, \sigma^Z)$ is the vector of estimated parameters, and $\Psi(\gamma)$ is the model-implied impulse responses to an uncertainty shock. V is a diagonal matrix with the variances of the empirical impulse responses along the main diagonal. $\hat{\xi}$ is a vector that comprises the unconditional standard deviations of output, consumption, investment and hours worked in the data, and $\xi(\gamma)$ denotes its model counterpart.[9] W is a diagonal matrix with the empirical unconditional variances of output and its components along its main diagonal. We set the scalar ζ to roughly equalize the weight on matching the impulse responses and unconditional moments. While remaining consistent with the unconditional volatility in key macroeconomic aggregates, the estimation procedure chooses the uncertainty shock process such that the model generates the same movement in implied stock market volatility as in the data.

We denote the estimated parameters in bold in Table 1. We find that the data prefer a small amount of investment adjustment costs in the model. The estimated uncertainty shock process roughly doubles the uncertainty about future household demand at impact and the uncertainty remains elevated for some time. The remaining first-moment shock processes are broadly in line with the previous estimates from Ireland (2003) who estimates a similar model with capital and nominal price rigidity.

5 Macroeconomic Effects of Uncertainty Shocks

5.1 Uncertainty Shocks & Macroeconomic Comovement

Figure 3 plots the impulse responses of the model to a demand uncertainty shock under both flexible and sticky prices. Households want to consume less and save more when uncertainty increases in the economy. To save more, households would like to reduce consumption and increase hours worked. In a model where output is always at its flexible-price or "natural" level, this higher desired saving translates into higher actual saving and investment rises. Higher labor supply with unchanged capital and technology means that output must rise. Through the national income accounting identity, higher output with lower consumption implies that investment must rise. Thus, higher uncertainty under flexible prices lowers consumption but causes an expansion in output, investment, and hours worked.

[9] Appendix A.1 provides additional details on the construction of the empirical unconditional moments. Appendix D.3 contains further discussion and standard errors for the model-implied unconditional moments, including the model's implications for asset prices.

With sticky prices, however, aggregate demand determines output in the short run. Higher uncertainty reduces the demand for consumption goods, which lowers output directly. Lower output reduces the benefit to owning capital, since the marginal revenue product of capital falls. The decline in the desired capital stock is reflected in a lower level of investment. Since consumption and investment both fall, output and hours worked both decline, since labor is the only input to production that can change when the shock is realized. Finally, Figure 3 shows that consumption falls further when prices are sticky. The slow adjustment of prices creates a prolonged period of lower inflation, which raises the real interest rate relative to the flexible-price benchmark and further depresses consumption.

As we discuss in Section 3, demand-determined output is made consistent with household and firm optimization via endogenous changes in markups. The economics, however, is that higher uncertainty increases desired saving. Higher desired savings is expansionary if full employment of all factors is guaranteed, but may be contractionary if output is demand-determined. Since saving equals investment in a closed economy, the increase in *desired* saving by households can easily lead to lower *actual* saving in general equilibrium.

5.2 Quantitative Results

Our model also matches the quantitative implications of an identified uncertainty shock in the data. Figure 1 plots the impulse responses of the model versus the estimated responses from the vector autoregression. As in the data, an innovation to our uncertainty shock process raises implied stock market volatility in the model by roughly 15 percent. In both the data and model, the peak decline in output in the model is around 0.2 percent and the model generates a decline in investment that is significantly larger than the response of consumption. The model also captures the gradual decline in the price level following an uncertainty shock. In line with the empirical evidence, the monetary authority in our model lowers its nominal policy rate to help offset the declines in output and inflation. Our model replicates both the qualitative comovement among the four key macroeconomics aggregates and matches the quantitative implications of an identified uncertainty shock in the data. These results suggest that nominal price rigidity likely plays a key role in understanding the transmission of uncertainty to the macroeconomy.

In addition to matching the conditional correlations following an uncertainty shock, our model is also broadly consistent with the unconditional volatility in key macroeconomic aggregates. Table 2 contains the empirical and model-implied unconditional volatilities of output and its components. Our model closely matches the volatility of output, consumption, and investment we observe in the data. As with many other standard macroeconomic models, however, the model does struggle to generate sufficient fluctuations in hours worked relative to output.[10] With the exception of hours worked, the model is generally successful at reproducing the macroeconomic responses following an uncertainty shock while remaining consistent with the unconditional volatility of output and its components.

As an additional check on our calibration, we also compare the model-implied stochastic volatility in key macroeconomic aggregates with the data. Since our model features stochastic volatility in the exogenous shocks, the endogenous variables also display time-varying volatility. Table 2 shows that the stochastic volatility generated by the model is generally in line with its empirical counterpart.[11] Similarly to our findings about the unconditional volatilities, the model also generates too little stochastic volatility in hours worked. However, these additional results suggest that we would likely draw similar conclusions about the effects of uncertainty shocks if we instead chose to calibrate our model using the stochastic volatility in key macro variables directly (as opposed to our impulse response-matching procedure based on implied stock market volatility).

5.3 Model-Based Support for Empirical Identification

In our empirical evidence, we identified an uncertainty shock using a Cholesky decomposition with the VXO ordered first. This ordering assumes that uncertainty shocks can have an immediate impact on output and its components, but non-uncertainty shocks do not affect the implied stock market volatility at impact. This identification strategy is supported by our theoretical model. Figure 4 plots the impulse responses for all three shocks in our model.[12] Consistent with the identifying assumptions in our VAR, a first-moment technology or demand shock has little effect on the expected volatility of future equity returns. Despite causing a decline in investment and equity prices, first-moment shocks primarily affect the expected mean equity return, not its expected future volatility.

[10] This gap can be attributed, at least in part, to the difference between model and data concepts. Solon, Barksy and Parker (1994) show that a disproportionate fraction of cyclical changes in total hours come from the hours of lower-wage workers. If relative wages measure relative productivity, then productivity-adjusted work hours fluctuate less than measured total hours in the data. Workers in the model, however, are homogeneous so the model-implied hours predictions are for workers with a common productivity level. If we had a quarterly time series on compositionally-adjusted hours worked, the fluctuations in hours in the data would be smaller and would align better with our model's concept of hours.

[11] We measure stochastic volatility using the standard deviation of the time-series estimate for the 5-year rolling standard deviation. See Appendix A for additional details.

[12] We plot a one standard deviation innovation for all three shocks. For comparison, we plot a negative technology shock to generate the appropriate sign on the investment and equity price responses.

Simulation evidence suggests that our identification strategy can recover the true macroeconomic effects of higher uncertainty. Using simulated data from our theoretical model, we replicate our empirical exercise from Section 2. We estimate 10,000 structural vector autoregressions, each estimated using only 30 years of simulated data from our model. Figure 5 plots the median estimated impulse responses, along with its 95% probability interval, versus the true impulse response from our model.[13] Our empirical methodology is generally successful at recovering the true impulse responses from the model. Even in a small sample, the estimated VAR responses suggest that an econometrician would likely be able to identify macroeconomic comovement following an uncertainty shock. We also find an average small-sample correlation of 0.77 between the series of identified uncertainty shocks from each SVAR with the true uncertainty shocks $\varepsilon_t^{\sigma^a}$ from the model. These findings suggest that our identification procedure is relatively successful at recovering both the model-implied impulse responses and the true series of structural uncertainty shocks.

5.4 Additional Results

In Appendix D, we further examine the ingredients and predictions of our theoretical model. We discuss the contributions of risk aversion, leverage, variable capital utilization, features of the labor supply curve, investment adjustment costs, and the persistence of the uncertainty shock process in generating our main results. While these features are not strictly necessary to generate qualitative comovement following an uncertainty shock, they help the model match quantitative features of the data. Epstein-Zin preferences allow us match the VAR evidence with smaller movements in the expected volatility of the exogenous shocks. Leverage increases the volatility of equity prices, which helps the model generate a non-trivial amount of implied stock market volatility. Similarly, fixed costs in production remove the steady-state pure profits induced by monopolistic competition in the market for intermediate goods.[14] If we fail to remove these profits, the model-implied equity premium falls dramatically, since equity holders receive significantly higher payouts in all states of the world.

Many of our model features help the model reproduce a key stylized fact in the data: In response to an uncertainty shock, investment declines significantly more than consumption. Investment is more intertemporally substitutable than consumption. Thus, an increase in uncertainty creates a situation like a preannounced sale on durables. Firms know that the price of investment goods will fall but due to sticky prices they have not fallen yet, so firms delay their

[13] Appendix C provides additional details about our estimation exercise using simulated data from the model.

[14] Fixed costs thus make the model consistent with the evidence of roughly zero average pure profits surveyed in Rotemberg and Woodford (1995).

purchases. This effect exists for consumption too but it is much stronger for investment, hence investment falls more. Investment adjustment costs also make it more difficult for households to convert their desired savings into physical capital, which also helps to generate a larger decline in investment. Finally, capacity utilization extends the half-life of price stickiness, and hence the period of time over which our results diverge substantially from those of a competitive model. Under nominal rigidities, firms set prices according to the expected present value of marginal cost. Variable capacity utilization creates an elastic supply of capital services and reduces the responsiveness of marginal cost to output, just as elastic labor supply does.

In Appendix D, we also explore uncertainty shocks about future technology. While technology uncertainty shocks can easily generate macroeconomic comovement, they struggle to match quantitative aspects of the empirical evidence. We also show that countercyclical markups, even without nominal rigidities, can generate macroeconomic comovement following an uncertainty shock. Our results also extend to the case where nominal wages, rather than prices, adjust slowly to changing economic conditions.

6 Discussion and Connections

6.1 Connections with Existing Literature

Recent work by Fernández-Villaverde et al. (2011) studies the effects of uncertainty in a small open economy setting, where they directly shock the exogenous process for the real interest rate. Since a small open economy is essentially a partial-equilibrium framework, they experience no difficulties in generating macroeconomic comovement from an uncertainty shock. As we show, the difficulties come when the real interest rate is endogenous in a general equilibrium framework.

In a general-equilibrium setting, Bloom et al. (2014) and Gilchrist, Sim and Zakrajšek (2013) use multi-sector, flexible-price models to show that shocks to uncertainty can lead to fluctuations that resemble business cycles. Through misallocation, these models can transform a change in the expected future dispersion of total factor productivity (TFP) into a change in the current mean of the TFP distribution. This approach may allow equilibrium real wages, consumption and labor supply to move in the same direction. However, both papers experience difficulties in getting the desired comovements. Gourio (2012) introduces a time-varying "disaster risk" into a real business cycle model. This shock can be viewed as bad news about the future first-moment of technology combined with an increase in the future dispersion of technology. An increased chance of a disaster results in lower equilibrium output, investment, and hours, but *higher* equilibrium consumption.

In simultaneous and independent work, Fernández-Villaverde et al. (2015) and Born and Pfeifer (2014) examine the role of fiscal uncertainty shocks. These two papers show that our mechanism can have important economic effects in medium-scale macroeconomic models with wage and price rigidities. Our work emphasizes the basic mechanism in a stripped-down model and shows why many types of uncertainty shocks can generate macroeconomic comovement. Other than sharing a mechanism for generating comovement, these papers differ greatly from our work. We focus on demand uncertainty, rather than policy uncertainty. We follow a very different calibration strategy, which allows us to closely link the model with the data using an observable *ex ante* measure of stock market volatility. Unlike the model of Fernández-Villaverde et al. (2015), our model can also reproduce the declines in prices and policy rates following an uncertainty shock that we observe in the data. Finally, we aim to understand the role of increased uncertainty in generating the Great Recession.

6.2 Evidence on Countercyclical Markups

Our mechanism for generating comovement relies on countercyclical markups following an uncertainty shock. However, Nekarda and Ramey (2013) argue that markups actually move procyclically after an identified government spending or monetary policy shock.[15] Thus, a natural test would be to include a measure of markups in our empirical VAR. However, simulation evidence from our model suggests that the empirical VAR would likely struggle to identify the true movements in markups. We now re-estimate our structural VARs using simulated model data but include actual firm markups. Despite perfectly observing firm markups, Figure 6 shows that the structural VAR underestimates the actual movements in markups. Our results suggest that identifying movements in markups remains difficult, even in a setting where we can likely identify the true movements in macroeconomic aggregates.

[15]This conclusion is disputed in the recent literature. Bils, Klenow and Malin (2014) find that measures of the markup that do not rely on wage data show clear evidence of countercyclical markup movements. Basu and House (2016) find markups rise significantly in response to identified contractionary monetary policy shocks if one uses a dynamic measure of labor cost instead of the spot wage.

7 The Role of Monetary Policy & the Zero Lower Bound

7.1 Optimal Policy Rule

In response to an uncertainty shock, the monetary authority in our model lowers its nominal policy rate. However, the response is not sufficient to offset the contractionary effects of higher uncertainty. If policy instead implements the following rule, which mimics optimal policy, then Figure 7 shows that the monetary authority can replicate the flexible price allocation even when prices adjust slowly:

$$r_t = r_t^n + \pi + \rho_\pi \left(\pi_t - \pi\right) + \rho_x x_t, \tag{12}$$

where r_t^n is the "natural" real rate of interest from the equivalent flexible-price economy and x_t is the gap between equilibrium and flexible-price output.[16]

7.2 Zero Lower Bound

However, monetary policy cannot replicate the flexible-price allocations when it is constrained by the zero lower bound. We now show that higher uncertainty has larger effects when monetary policy cannot lower its policy rate. We now assume that central bank implements policy through the following rule:

$$r_t^d = r + \rho_\pi \left(\pi_t - \pi\right) + \rho_y \Delta y_t, \tag{13}$$

$$r_t = \max\left(0, r_t^d\right), \tag{14}$$

where r_t^d is the desired policy rate of the central bank and r_t is the actual policy rate subject to the zero lower bound. To rigorously model the occasionally-binding zero lower bound constraint, we solve a fully nonlinear, but simplified, version of our baseline model using policy function iteration. Appendix E contains details on the simplified model, the policy function iteration algorithm, and the construction of the impulse responses.

Figure 7 plots the impulse responses of an uncertainty shock for our simplified model both at and away from the zero lower bound. We choose the size of the uncertainty shock such that, at the stochastic steady state, the simplified model generates roughly the same movements in output as our baseline model from Section 4. Away from the zero lower bound, an increase in uncertainty causes a 0.2 percent decline in output. When the central bank is unable to change its current nominal policy rate, the uncertainty shock produces a 0.6 percent drop in output on impact, and causes much larger declines in consumption, investment, and hours worked.[17] Thus, the zero lower bound more than doubles the negative effects of the uncertainty

[16] For this example, we calibrate $\rho_\pi = 1.5$ and $\rho_x = 0.2$.

[17] The zero lower bound lasts for six quarters in this simulation.

shock at impact. In a companion paper, Basu and Bundick (2015), we show this amplification emerges from the endogenous volatility generated by the zero lower bound. Since policy can no longer play its usual stabilizing role, households understand that the economy faces higher expected volatility at the zero lower bound. The exogenous uncertainty shock, amplified by the endogenous volatility generated by the zero lower bound, translates into a larger drop in output.

At the zero lower bound, increases in uncertainty can produce an additional source of fluctuations beyond the precautionary working and saving channel. This additional amplification mechanism, the contractionary bias in the nominal interest rate distribution, emerges from the interaction between uncertainty and the zero lower bound when monetary policy follows a standard Taylor-type policy rule. In Basu and Bundick (2015), we show that the form of the monetary policy rule is crucial for eliminating the contractionary bias. In the current paper, our primary interest in modeling an uncertainty shock at the zero lower bound is to quantify the likely impact of uncertainty shocks during the Great Recession. Following the previous literature, we assume that monetary policy continues to follow a standard Taylor-type policy rule at the zero lower bound. Thus, our zero lower bound responses contain the effects of both the precautionary working mechanism and the contractionary bias. Thus, we note that our exact quantitative conclusions regarding the amplification of uncertainty shocks at the zero lower bound depends on our assumptions about monetary policy.

7.3 Uncertainty in the Great Recession

Many economists argue higher uncertainty in the Fall of 2008 played a role in generating the Great Recession. Our structural VAR identifies a 2.75 standard deviation uncertainty shock in 2008:Q4. Feeding this shock into our baseline model from Section 4 implies a decline in output of about 0.6 percent. However, our zero lower bound exercise suggests that the zero lower bound more than doubles the negative effects of an uncertainty shock, which implies a larger 1.5 percent drop in output. The CBO estimates that the output gap was -5.0 percent in 2008Q4.[18] Thus, our results suggest that over one-fourth of the decline in output during the Great Recession can be explained by higher uncertainty about the future.

[18] Since flexible-price output increases only slightly after an uncertainty shock, the output gap is very close to output in our baseline model.

8 Conclusion

We argue that macroeconomic comovement between output, consumption, investment, and hours worked is a key empirical feature of the economy's response to an identified uncertainty shock. A standard model can replicate this stylized fact if prices adjust slowly to changing economic conditions. We calibrate our model to be consistent with a well-known and observable index of *ex ante* stock market volatility. We find that the dramatic increase in uncertainty during the Fall of 2008, combined with the zero lower bound on nominal interest rates, may be an important factor in explaining the large decline in output starting at that time. Finally, we show the economic mechanism we identify applies to a large set of shocks that change expectations of the future without changing current fundamentals.

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Figure 1: Empirical & Model-Implied Impulse Responses to Uncertainty Shock

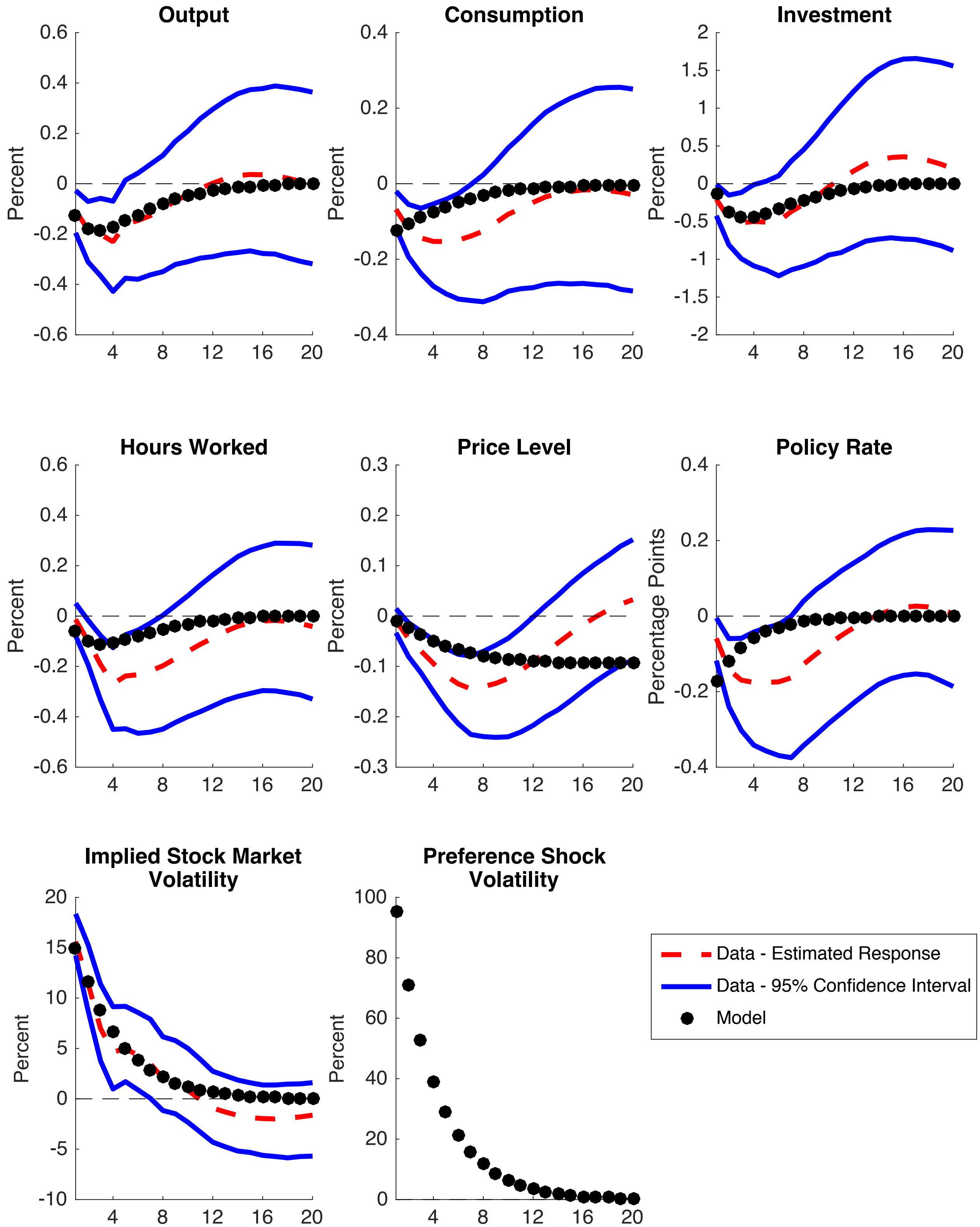

Figure 2: Model Intuition

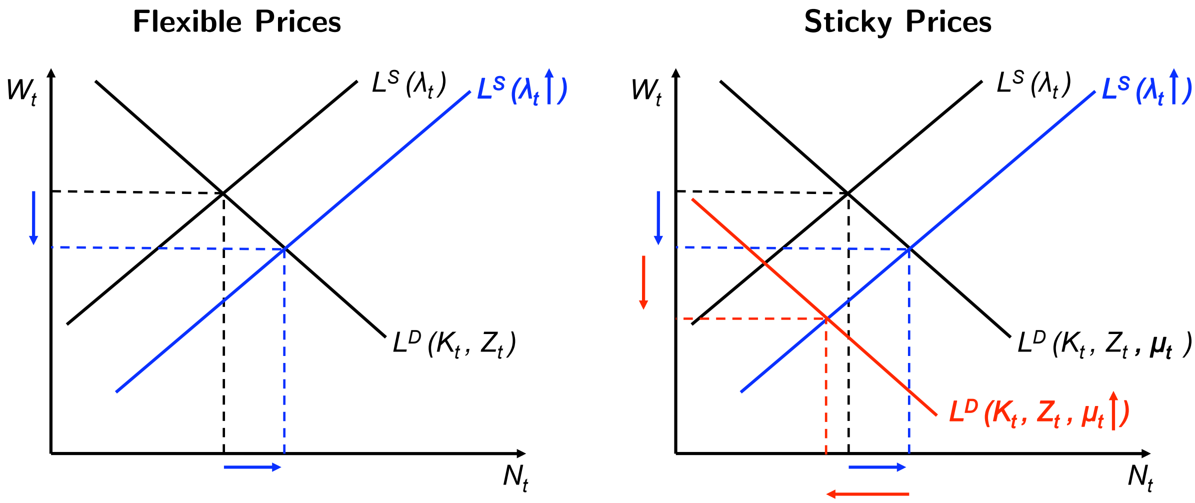

Table 1: Model Parameters

Household		Firm				Policy		Shocks			
β	0.994	α	0.333	$\boldsymbol{\phi_K}$	**2.09**	Π	1.005	$\boldsymbol{\rho_a}$	**0.94**	$\boldsymbol{\rho_Z}$	**0.99**
σ	80.0	δ	0.025	ϕ_P	100	ρ_π	1.5	$\boldsymbol{\sigma^a}$	**0.003**	$\boldsymbol{\sigma^Z}$	**0.001**
ψ	0.95	δ_1	0.03	θ_μ	6.0	ρ_y	0.2	$\boldsymbol{\rho_{\sigma^a}}$	**0.74**		
η	0.35	δ_2	0.0003	ν	0.9			$\boldsymbol{\sigma^{\sigma^a}}$	**0.003**		

Note: Parameters listed in bold are estimated via impulse response and moment matching.

Table 2: Empirical & Model-Implied Volatility in Macroeconomic Aggregates

	Percent		Relative to Output	
Moment	Data	Model	Data	Model
Unconditional Volatility				
Output	1.1	1.0	1	1
Consumption	0.7	0.8	0.6	0.7
Investment	3.8	4.7	3.4	4.5
Hours Worked	1.4	0.8	1.3	0.8
Stochastic Volatility				
Output	0.4	0.2	1	1
Consumption	0.2	0.2	0.5	0.7
Investment	1.6	1.2	3.6	5.0
Hours Worked	0.5	0.2	1.0	0.9

Note: Unconditional volatility is measured with the sample standard deviation. We measure stochastic volatility using the standard deviation of the time-series estimate for the 5-year rolling standard deviation. The empirical sample period is 1986 - 2014. See Appendix A for additional details.

Figure 3: Model-Implied Impulse Responses Under Flexible & Sticky Prices

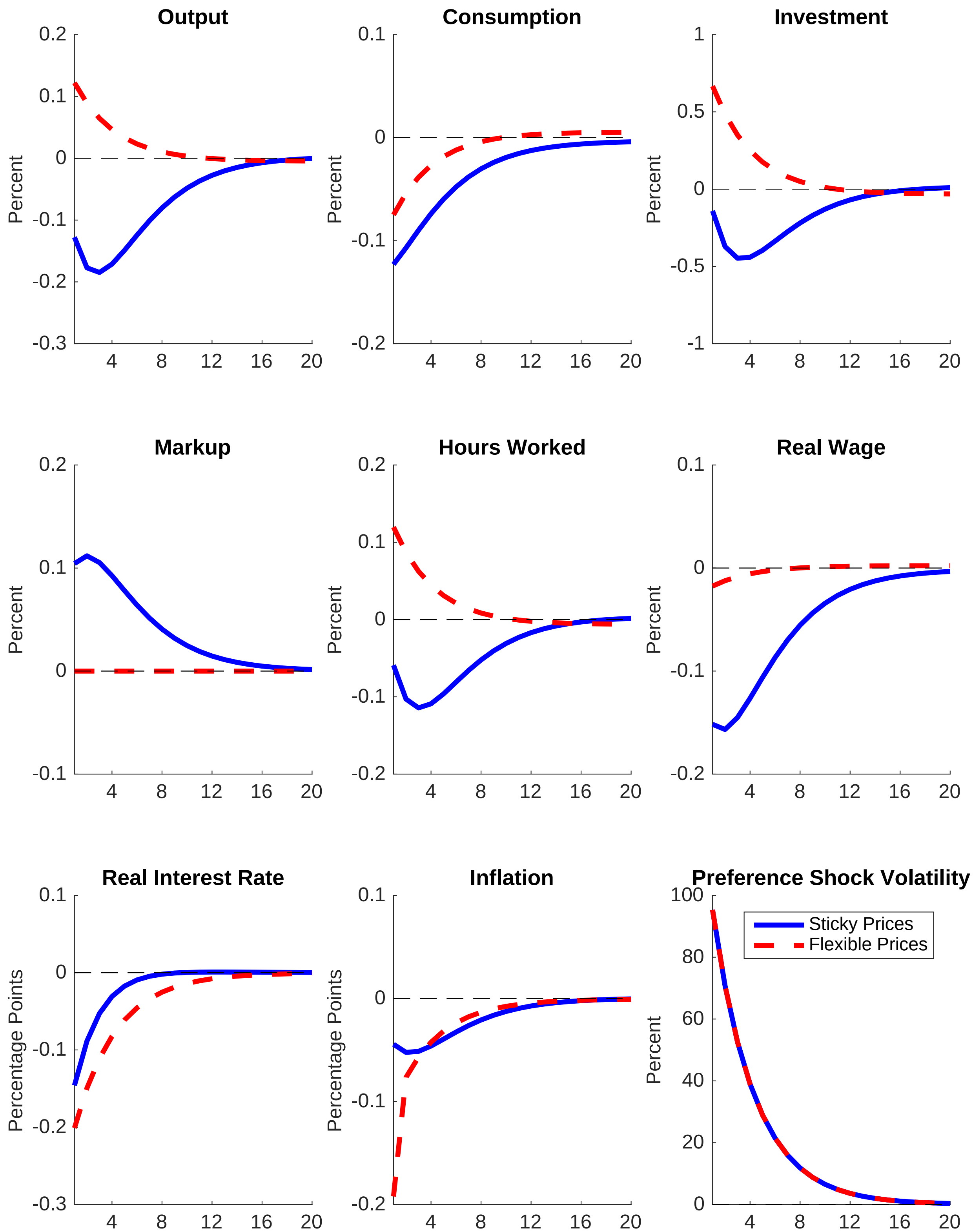

Figure 4: Model-Based Support for Empirical Identification Scheme

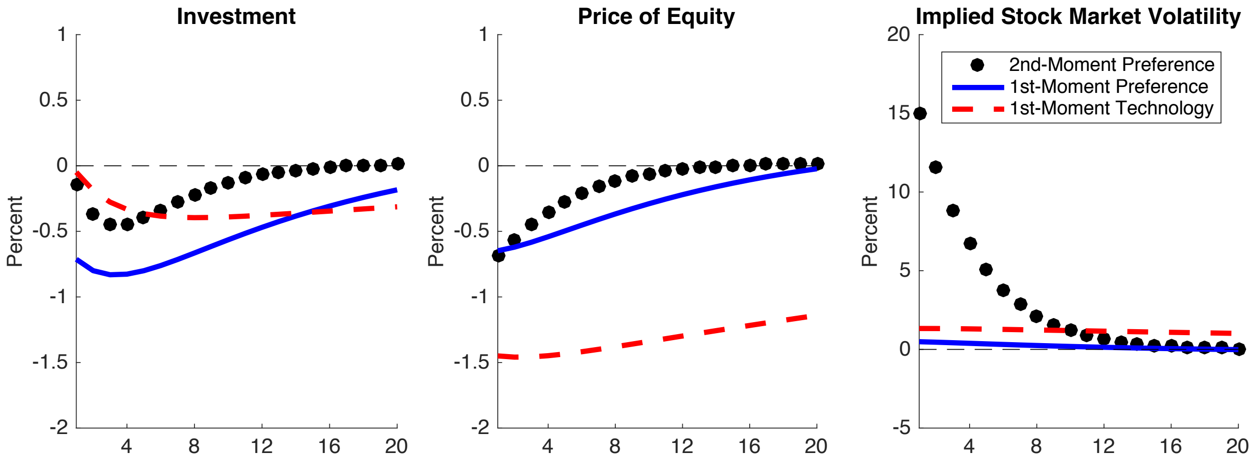

Figure 5: Estimating Structural Vector Autoregressions on Simulated Data from the Model

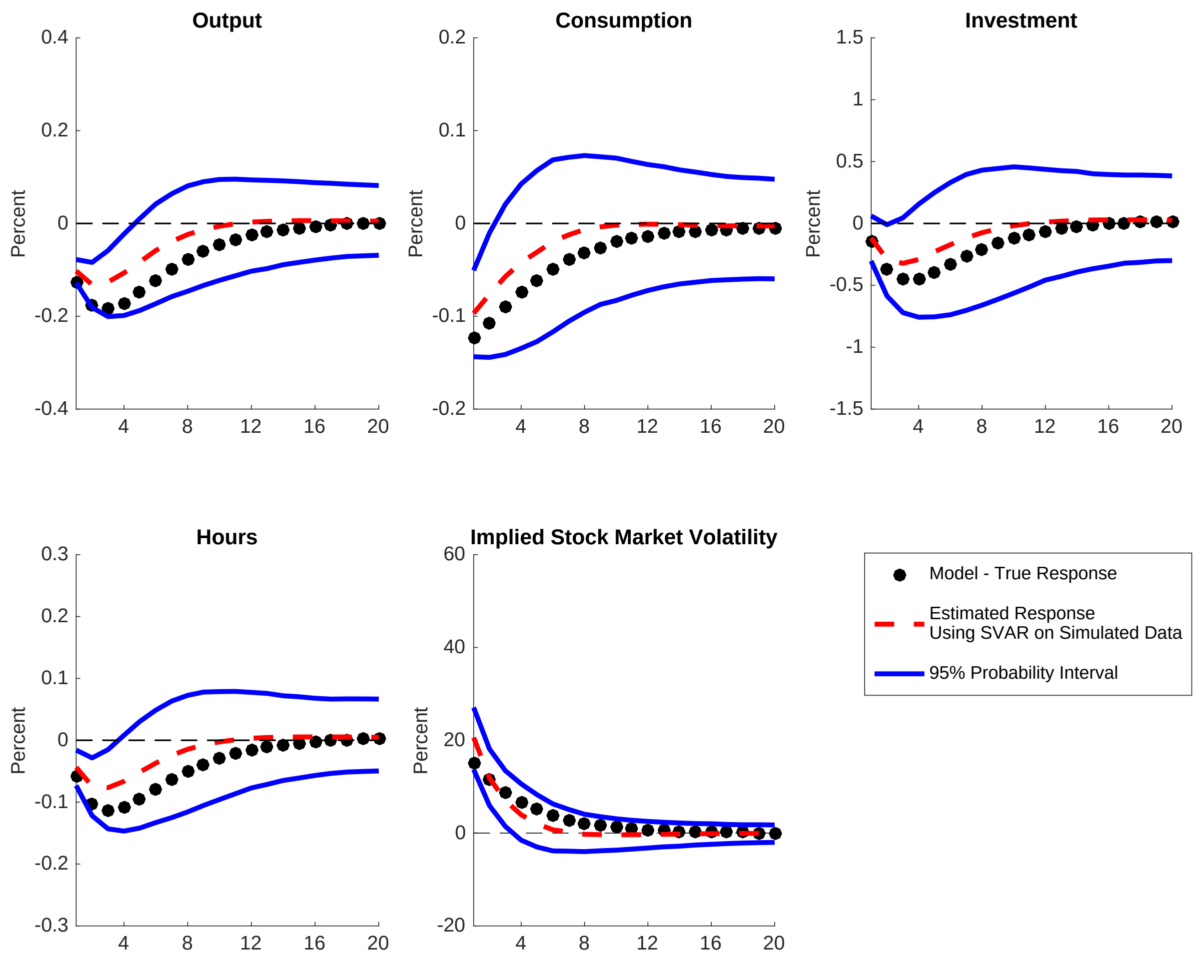

Figure 6: Estimating Conditional Movements in Markups

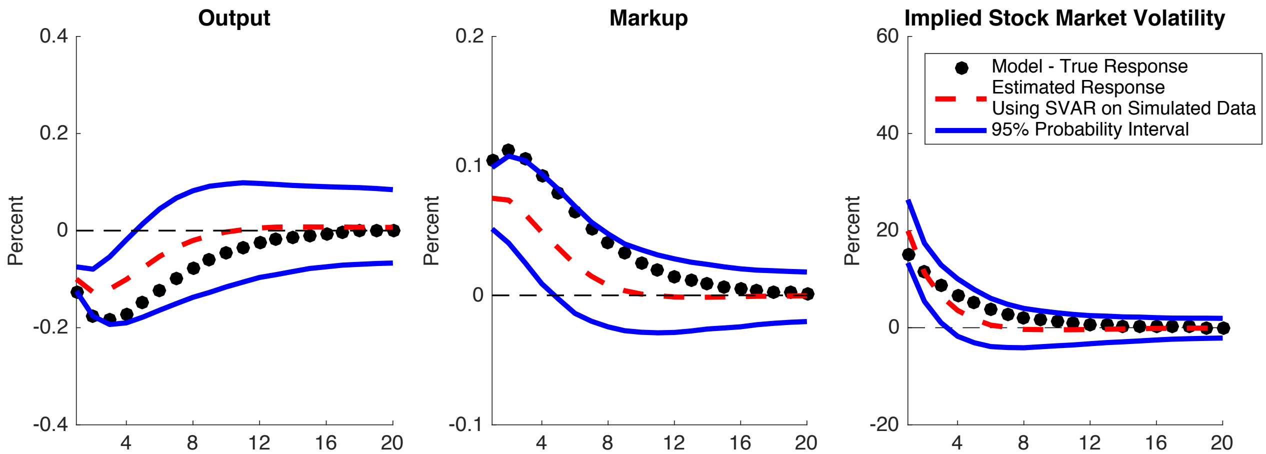

Figure 7: Role of Monetary Policy