Uncertainty Shocks in a Model of Effective Demand[*]

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Abstract

This paper examines the role of uncertainty shocks in a one-sector, representative-agent dynamic stochastic general-equilibrium model. When prices are flexible, uncertainty shocks are not capable of producing business-cycle comovements among key macro variables. With countercyclical markups through sticky prices, however, uncertainty shocks can generate fluctuations that are consistent with business cycles. Monetary policy usually plays a key role in offsetting the negative impact of uncertainty shocks. If the central bank is constrained by the zero lower bound, then monetary policy can no longer perform its usual stabilizing function and higher uncertainty has even more negative effects on the economy. Calibrating the size of uncertainty shocks using fluctuations in the VIX, we find that increased uncertainty about the future may indeed have played a significant role in worsening the Great Recession, which is consistent with statements by policymakers, economists, and the financial press.

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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 and subsequent slow recovery. 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, Foetotto, and Jaimovich (2010), Fernàndez-Villaverde, Guerròn-Quintana, Kuester, and Rubio-Ramìrez (2011), and Gilchrist, Sim, and Zakrajšek (2010) also suggests that uncertainty shocks can cause fluctuations in macroeconomic aggregates. However, most of these papers experience difficulty in generating business cycle comovements among output, consumption, investment, and hours worked from changes in uncertainty. If uncertainty is a contributing factor in the Great Recession and persistently slow recovery, then increased uncertainty should reduce output and its components.

In this paper, we show why competitive, one-sector, closed-economy models generally cannot generate business-cycle comovements in response to changes in uncertainty. Under reasonable assumptions, an increase in uncertainty induces precautionary saving and, all else equal, lower consumption.[1] If households supply labor inelastically, then total output remains constant since the level of technology and capital stock do not change 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 an 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.

We also show that non-competitive, one-sector models with countercyclical markups through sticky prices can easily overcome the comovement problem and generate simultaneous drops in output, consumption, investment, and hours worked in response to an uncertainty shock. An increase in uncertainty induces precautionary labor supply by the representative household, which reduces the marginal

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[1] An increase in uncertainty has both wealth and substitution effects. With convex marginal utility and an intertemporal elasticity of substitution (IES) smaller than one, the wealth effect dominates the substitution effect. Thus, an increase in uncertainty results in precautionary saving and lower consumption. With an IES greater than one, an increase in uncertainty results in an increase in consumption. While estimates of the IES for the representative household differ across studies, we view the IES less than one case as standard and more in line with the evidence. For example, Basu and Kimball (2002) estimate an IES approximately equal to 0.50.

costs of production. Falling marginal costs with slowly-adjusting prices imply an increase in firm markups over marginal cost. A higher markup reduces the demand for consumption, and especially, investment goods. Since output is demand-determined in these models, output and employment must fall when consumption and investment both decline. Thus, comovement is restored, and uncertainty shocks cause fluctuations that look qualitatively like a business cycle. Returning to 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 easily cause fluctuations in the demand for labor in non-competitive, sticky price models with endogenously-varying markups. Thus, the non-competitive model captures the intuition articulated by Diamond, and this fact is the key to understanding why the two models behave so differently in response to a change in uncertainty.

To analyze the quantitative impact of uncertainty shocks under flexible and sticky prices, we calibrate and solve a representative-agent, dynamic stochastic general equilibrium model with nominal price rigidity. We examine uncertainty shocks to both technology and household preferences, which we interpret as cost and demand uncertainty. We calibrate our uncertainty shock processes using the Chicago Board Options Exchange Volatility Index (VIX), which measures the expected volatility of the Standard and Poor's 500 stock index over the next thirty days. Using a third-order approximation to the policy functions of our calibrated model, we show that uncertainty shocks can produce contractions in output and all its components when prices are sticky. In particular, we find that increased uncertainty associated with future demand can produce significant declines in output, hours, consumption, and investment. Our model predicts that a one-standard deviation increase in the uncertainty about future demand produces a peak decline in output of approximately 0.3 percentage points.

Finally, we examine the role of monetary policy in determining the equilibrium effects of uncertainty shocks. Monetary policy usually offsets increases in uncertainty by lowering its nominal policy rate. We show that increases in uncertainty have larger negative impacts on the economy if the monetary authority is constrained by the zero lower bound on nominal interest rates. When the monetary authority is unable to adjust its nominal interest rate, our model predicts that an increase in uncertainty causes a much larger and more persistent decline in output and its components. The sharp increase in uncertainty during the financial crisis in late 2008 corresponds to a period when the Federal Reserve had a policy rate near zero. Thus, we believe that greater uncertainty may have plausibly contributed significantly to the large and persistent output decline starting at that time.

2 Intuition

This section formalizes the intuition from the introduction using a few key equations that characterize a large class of one-sector business cycle models. We show that the causal ordering of these equations plays an important role in understanding the impact of uncertainty shocks. These equations link total output Y_t, household consumption C_t, investment I_t, hours worked N_t, and the real wage W_t/P_t. The key equations consist of a "demand" equation:

$$Y_t = C_t + I_t, \tag{1}$$

an aggregate production function:

$$Y_t = F(K_t, Z_t N_t), \tag{2}$$

and a static first-order condition for a representative consumer to maximize utility:

$$\frac{W_t}{P_t} U_1(C_t, 1 - N_t) = U_2(C_t, 1 - N_t). \tag{3}$$

Equation (1) suggests that if an increase in uncertainty lowers consumption and investment, then it should also lower total output. Higher uncertainty induces precautionary saving by risk-averse households (assuming that the IES is less than one, which is empirically plausible). An increase in uncertainty also depresses investment, particularly in the presence of non-convex costs of adjustment. In a setting where output is demand-determined, economic intuition suggests that higher uncertainty should depress total output and its components.

However, the previous intuition is incorrect in a neoclassical model with a representative consumer and firm. In this neoclassical setting, labor demand (the partial derivative of (2) with respect to N_t) is determined by the current level of capital and technology, neither of which changes when uncertainty increases. The first-order conditions for firm labor demand derived from equation (2) and the labor supply condition in equation (3) can be combined to yield:

$$Z_t F_2(K_t, Z_t N_t) U_1(C_t, 1 - N_t) = U_2(C_t, 1 - N_t). \tag{4}$$

Equation (4) defines a positively-sloped "income expansion path" for consumption and leisure for given level of capital and technology. Thus, if higher uncertainty does indeed reduce consumption, it must increase labor supply. However, equation (2) implies that total output must rise, means that investment and consumption must move in opposite directions according to equation (1).

In a non-neoclassical setting, especially one with a time-varying markup of price over marginal cost, equations (1) and (3) continue to apply, but equation (4) must be modified such that:

$$\frac{1}{\mu_t} Z_t F_2(K_t, Z_t N_t) U_1(C_t, 1 - N_t) = U_2(C_t, 1 - N)_t \tag{5}$$

where μ_t is the markup of price over marginal cost.

In such a setting, equation (1) is causally prior to (2) and (3). From (1), output is determined by aggregate demand. Then, for given values of K and Z, (2) determines the necessary quantity of labor input. Finally, given C (determined by demand and other factors), the necessary supply of labor is made consistent with consumer optimization by having the markup taking on its required value. (Alternatively, the wage moves to the level necessary for firms to hire the required quantity of labor, and the variable markup ensures that the wage can move independently of the marginal product of labor.)

The previous intuition can also be represented graphically using simplified labor supply and labor demand curves in real wage and hours worked space. Figures 1 and 2 show the impact of an increase in uncertainty under flexible prices with constant markups and sticky prices with endogenously-varying markups. An increase in uncertainty induces wealth effects on the representative household through the forward-looking marginal utility of wealth denoted by λ_t. An increase in the marginal utility of wealth shifts the household labor supply curve outward. With flexible prices and constant markups, the labor demand curve remains fixed for a given level of the real wage. In the flexible-price equilibrium, the desire of households to supply more labor translates into higher equilibrium hours worked and a lower real wage. When prices adjust slowly to changing marginal costs, however, firm markups over marginal cost rise when the household increases their labor supply. For a given level of the real wage, an increase in markups decreases the demand for labor from firms. Figure 2 shows that equilibrium hours worked may fall as a result of the outward shift in the labor supply curve and the inward shift of the labor demand curve. The relative magnitudes of the changes in labor supply and labor demand depend on the specifics of the macroeconomic model and its parameter values. The following section shows that in reasonably calibrated New-Keynesian sticky price model, firm markups increase enough to produce a decrease in equilibrium hours worked in response to an increase in uncertainty.

3 Model

This section outlines the baseline dynamic stochastic general equilibrium model that we use in our analysis of uncertainty shocks. Our model provides a specific quantitative example of the intuition of the previous section. The baseline model shares many features with the models of Ireland (2003), Ireland (2010), and Jermann (1998). The model features optimizing households and firms and a central bank that systematically adjusts the nominal interest rate to offset adverse shocks in the economy. We allow for sticky prices using the quadratic-adjustment costs specification of Rotemberg (1982). Our baseline model considers both technology shocks and household discount rate shocks. Both shocks are allowed to have time-varying second moments, which have the interpretation of cost uncertainty and demand uncertainty.

3.1 Households

In our model, the representative household maximizes expected lifetime utility from consumption C_t and leisure $1 - N_t$ subject to its intertemporal budget constraint. The household receives labor income W_t for each unit of labor N_t supplied in the representative intermediate goods-producing firm. The representative household also owns the intermediate goods firm and holds equity shares S_t and one-period risk-less bonds B_t issued by representative intermediate goods firm. Equity shares pay dividends D_t^E for each share S_t owned, and the risk-less 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 the amount 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, which we interpret as demand shocks for the economy.

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:

$$\max\, E_t \left[\sum_{s=0}^{\infty} \beta^s a_{t+s} \frac{C_{t+s}^{1-\sigma}(1 - N_{t+s})^{\eta(1-\sigma)}}{1-\sigma} \right]$$

subject to the intertemporal household budget constraint each period,

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

Household optimization implies the following first-order conditions:

$$a_t C_t^{-\sigma} (1 - N_t)^{\eta(1-\sigma)} = \lambda_t \tag{6}$$

$$\eta \frac{C_t}{(1 - N_t)} = \frac{W_t}{P_t} \tag{7}$$

$$\frac{P_t^E}{P_t} = E_t \left\{ \left(\frac{\beta \lambda_{t+1}}{\lambda_t} \right) \left(\frac{D_{t+1}}{P_{t+1}} + \frac{P_{t+1}^E}{P_{t+1}} \right) \right\} \tag{8}$$

$$1 = R_t^R E_t \left\{ \left(\frac{\beta \lambda_{t+1}}{\lambda_t} \right) \right\} \tag{9}$$

3.2 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 intermediate output is transformed into final output

Y_t using the following constant returns to scale technology:

$$\left[\int_0^1 Y_t(i)^{\frac{\theta-1}{\theta}} di\right]^{\frac{\theta}{\theta-1}} \geq Y_t$$

Each intermediate good $Y_t(i)$ sells at nominal price $P_t(i)$ and each final good sells at nominal price P_t. The finished goods producer chooses Y_t and $Y_t(i)$ for all $i \in [0,1]$ to maximize the following expression of firm profits:

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

subject to the constant returns to scale production function. Finished goods-producer optimization results in the following first-order condition:

$$Y_t(i) = \left[\frac{P_t(i)}{P_t}\right]^{-\theta} Y_t$$

The market for final goods is perfectly competitive, and thus the final goods-producing firm earns zero profits in equilibrium. Using the zero-profit condition, the first-order condition for profit maximization, and the firm objective function, the aggregate price index P_t can be written as follows:

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

3.3 Intermediate Goods Producers

Intermediate goods-producing firms rent labor $N_t(i)$ from the representative household in order to produce intermediate goods $Y_t(i)$. Intermediate goods are produced in a monopolistically competitive market where producers face a quadratic cost of changing their nominal price $P_t(i)$ each period. The intermediate-goods firms own the capital stock for the economy and face adjustment costs for adjusting its rate of investment. Each firm issues equity shares $S_t(i)$ and one-period risk-less bonds $B_t(i)$. Firm i chooses $N_t(i), I_t(i)$, and $P_t(i)$ to maximize firm cash flows $D_t(i)/P_t(i)$ given aggregate demand Y_t and price P_t of the finished goods sector. The intermediate goods firms all have access to the same constant returns-to-scale Cobb-Douglas production function, subject to a fixed cost of production Φ.

Each intermediate goods-producing firm solves the following problem:

$$\max E_t \sum_{s=0}^{\infty} \beta^s \left(\frac{\lambda_{t+s}}{\lambda_t}\right) \left[\frac{D_{t+s}(i)}{P_{t+s}}\right]$$

subject to the production function:

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

and subject to the capital accumulation equation:

$$K_{t+1}(i) = (1-\delta)K_t(i) + I_t(i)\left(1 - \frac{\phi_I}{2}\left(\frac{I_t(i)}{I_{t-1}(i)} - 1\right)^2\right)$$

where

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

The first-order conditions for the firm i are as follows:

$$\frac{W_t}{P_t}N_t(i) = (1-\alpha)\Xi_t K_t(i)^\alpha \left[Z_t N_t(i)\right]^{1-\alpha} \tag{10}$$

$$\frac{R_t^K}{P_t}K_t(i) = \alpha\Xi_t K_t(i)^\alpha \left[Z_t N_t(i)\right]^{1-\alpha} \tag{11}$$

$$\begin{aligned}\phi_P\left[\frac{P_t(i)}{\Pi P_{t-1}(i)} - 1\right]\left[\frac{P_t}{\Pi P_{t-1}(i)}\right] = (1-\theta)\left[\frac{P_t(i)}{P_t}\right]^{-\theta} + \theta\Xi_t\left[\frac{P_t(i)}{P_t}\right]^{-\theta-1} \\ +\beta\phi_P E_t\left\{\frac{\lambda_{t+1}}{\lambda_t}\frac{Y_{t+1}}{Y_t}\left[\frac{P_{t+1}(i)}{\Pi P_t(i)} - 1\right]\left[\frac{P_{t+1}(i)}{\Pi P_t(i)}\frac{P_t}{P_t(i)}\right]\right\}\end{aligned} \tag{12}$$

$$1 = E_t\left\{\left(\frac{\beta\lambda_{t+1}}{\lambda_t}\right)\left(\frac{R_{t+1}^K + q_{t+1}(1-\delta)}{q_t}\right)\right\} \tag{13}$$

$$\begin{aligned}\lambda_t =& \lambda_t q_t\left[1 - \frac{\phi_I}{2}\left(\frac{I_t(i)}{I_{t-1}(i)} - 1\right)^2 - \phi_I\left(\frac{I_t(i)}{I_{t-1}(i)} - 1\right)\left(\frac{I_t(i)}{I_{t-1}(i)}\right)\right] \\ &+ \beta E_t\left\{\lambda_{t+1}q_{t+1}\left[\phi_I\left(\frac{I_{t+1}(i)}{I_t(i)} - 1\right)\left(\frac{I_{t+1}(i)}{I_t(i)}\right)^2\right]\right\}\end{aligned} \tag{14}$$

where Ξ_t is the marginal cost of producing one additional unit of intermediate good i, and q_t is the price of capital.

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

$$\frac{D_t^E(i)}{P_t} = \frac{D_t(i)}{P_t} - \nu\left(K_t(i) - \frac{1}{R_t^R}K_{t+1}(i)\right). \tag{15}$$

The Modigliani & Miller (1963) theorem holds in our model and thus leverage does not affect firm value or optimal firm decisions. Leverage simply makes the payouts and price of equity more volatile. In equilibrium, our leverage ratio of debt to total firm value is approximately 50%.

3.4 Monetary Policy

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

$$\ln(R_t) = \rho_r \ln(R_{t-1}) + (1-\rho_r)(\ln(R) + \rho_\Pi \ln(\Pi_t/\Pi) + \rho_y \ln(Y_t/Y_{t-1})) \tag{16}$$

3.5 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 to hold the same amount of capital $K_t(i) = K_t$. Thus, all firms have the same cash flows and payout structure between bonds and equity. Thus, we can define inflation as $\Pi_t = P_t/P_{t-1}$, and define the markup over marginal cost as $\mu_t = 1/\Xi_t$. Thus, we can model our intermediate-goods firms with a single representative intermediate goods-producing firm.

3.6 Shock Processes

In our baseline model, we are interested in capturing the effects of independent changes in the level and volatility of both the technology process and the preference shock process. The technology and preference shock processes are parameterized as follows, which allows us to examine both first and second moment shocks separately:

$$\ln(Z_t) = \rho_z \ln(Z_t) + \sigma_t^z \varepsilon_t^z, \quad \varepsilon_t^z \sim N(0,1)$$

$$\ln(\sigma_t^z) = (1-\rho_{\sigma^z})\ln(\sigma^z) + \rho_{\sigma^z}\ln(\sigma_{t-1}^z) + \sigma^{\sigma^z}\varepsilon_t^{\sigma^z} \quad \varepsilon_t^{\sigma^z} \sim N(0,1).$$

$$\ln(a_t) = \rho_a \ln(a_t) + \sigma_t^a \varepsilon_t^a, \quad \varepsilon_t^a \sim N(0,1)$$

$$\ln(\sigma_t^a) = (1-\rho_{\sigma^a})\ln(\sigma^a) + \rho_{\sigma^a}\ln(\sigma_{t-1}^a) + \sigma^{\sigma^a}\varepsilon_t^{\sigma^a} \quad \varepsilon_t^{\sigma^a} \sim N(0,1).$$

3.7 Solution Method

Our primary focus of this paper is to examine the effects of increases in the second moments of the shock processes. Using a standard first-order or log-linear approximation to all the equilibrium conditions of our model would not allow us to examine second moment shocks since the approximated policy functions are invariant of the volatility of the shock process. Alternatively, second moment shocks would only enter as cross-products with the other state variables in a 2nd-order approximation to the policy functions. In a 3rd-order approximation, however, second moment shocks enter independently in the approximated policy functions. Thus, a 3rd-order approximation allows us to compute an impulse response to an increase in the volatility of technology or discount rate shocks, while holding constant the levels of those variables.

To solve the baseline model, we use the Perturbation AIM algorithm and software developed by Swanson, Anderson, and Levin (2006), which is available on Eric Swanson's webpage. Perturbation AIM uses Mathematica to compute the rational expectations solution to the model using nth-order Taylor series approximation around the nonstochastic steady state of the model. Similarly to the findings of Fernàndez-Villaverde, Guerròn-Quintana, Rubio-Ramìrez, and Uribe (2010), we find that a 3rd-order approximation to the policy functions is sufficient to capture the dynamics of the model, and we find little gain to using an approximation higher than 3rd-order.

4 Calibration and Baseline Results

4.1 Calibration

Table 1 lists the calibrated parameters of the model. We calibrate the model at quarterly frequency using standard parameters for one-sector models of fluctuations. Since our model shares many features with the estimated models of Ireland (2003) and Ireland (2010), we calibrate our model to match the estimated parameters of reported by those papers. We calibrate our investment adjustment costs parameter to match the value of Christiano, Eichenbaum, and Evans (2005). We calibrate the steady-state volatilities for the technology and preference shocks, σ^a and σ^z, in line with the findings of Ireland (2003) and Ireland (2010). We discuss our calibration of the uncertainty shocks in depth in Section 6. In the following analysis, we compare the results from our baseline sticky-price calibration ($\phi_P = 160$) with a flexible-price calibration ($\phi_P = 0$), leaving all other parameters unchanged.

4.2 Uncertainty Shocks & Business Cycle Comovements

Holding the calibrated parameters fixed, we analyze the effects of an exogenous increase in uncertainty associated with both technology and household demand. Figure 3 plots impulse responses of the model to a technology uncertainty shock and Figure 4 plots the responses to a demand uncertainty shock. The results are consistent with the intuition of Section 2 and the labor market diagrams in Figures 1 and 2. Uncertainty from either technology or household demand both enter equation (4) or equation (5) through the marginal utility of wealth. An uncertainty shock associated with either stochastic process induces wealth effects on the household which triggers precautionary labor supply. Thus, the responses and time paths for the endogenous variables look qualitatively similar for both types of uncertainty shocks.

Households want to consume less and save more when uncertainty increases in the economy. In order to save more, households optimally wish to both reduce consumption and increase hours worked. Under flexible prices and constant markups, equilibrium labor supply and consumption follow the path that households desire when they face higher uncertainty. On impact of the uncertainty shock, the level of capital is predetermined, the level of the shock process is held constant, and thus labor demand is unchanged for a given real wage. Consequently, under flexible prices, the outward shift in labor supply combined with unchanged labor demand increases hours worked and output. After the impact period, households continue to save, accumulate more capital, consume less, and work more hours. Throughout the life of the uncertainty shock, consumption and investment move in opposite directions, which is inconsistent with basic business cycle comovements.

Under sticky prices, households also want to consume less and save more when the economy is hit by an uncertainty shock associated with technology or household demand. On impact, households increase their labor supply and reduce consumption to accumulate more assets. With sticky prices, however, increased labor supply decreases the marginal costs of production of the intermediate goods firms. A reduction in marginal cost with slowly-adjusting prices increases firm markups. An increase in markups lowers the demand for household labor and lowers the real wage earned by the representative household. The decrease in labor demand also lowers investment in the capital stock by firms. In equilibrium, these effects combine to produce significant and hump-shaped falls in output, consumption, investment, hours worked, and the real wage, which are consistent with business cycle facts. Thus, the desire by households to work more can actually lead to lower labor input and output in equilibrium.

For completeness, we also plot the responses to the first-moment technology and household preference shocks in Figures 4 and 5. As a check on our calibration strategy, we compare the impulse responses of the model to a first-moment technology shock to the empirical impulse responses to the same shock estimated by Basu, Fernald, and Kimball (2006). We find that the calibration of our baseline model produces impulse responses to first-moment technology shocks that are consistent with the estimates of Basu, Fernald, and Kimball (2006), which provides some evidence that our calibration is reasonable.

5 Discussion and Connections

5.1 Specific Example of General Principle

The differential response of our economy under flexible and sticky prices to uncertainty fluctuations is a specific instance of the general proposition established by Basu and Kimball (2005). They show that "good" shocks that cause output to rise in a flexible-price model generally tend to have contractionary effects in a model with nominal price rigidity. Basu and Kimball (2005) also show that the response of monetary policy is critical for determining the equilibrium response of output and other variables. If monetary policy follows a sensible rule, for example the celebrated Taylor (1993) rule, then the monetary authority typically lowers the nominal interest rate to offset the negative short-run effects of the shock. If the monetary policy rule allows the economy to mimic the flexible-price response to the shock, which is the optimal monetary policy if nominal price rigidity is the only friction in the model, then the equilibrium response to the shock would be expansionary and exactly mimic the response of the corresponding flexible-price model with a fixed markup. However, if the monetary authority is unable to lower the nominal interest rate due to the zero lower bound, then the short-run contractionary effect of the "good" shock dominates, and the equilibrium response of output becomes robustly negative.[2]

5.2 Extension to Sticky Nominal Wages

It might appear from our exposition so far that the mechanism we have identified works only in the special case where nominal prices are sticky but wages are flexible. Indeed, our intuition for the channel through which an increase in uncertainty raises the markup has emphasized these two elements. We argued that higher uncertainty induces households to work at lower wages, the reduction in the wage reduces firms marginal costs, but since their output prices are fixed, lower marginal costs translate to higher markups, which are contractionary. However, various types of evidence suggests that nominal wages are sticky, not flexible, especially at high frequencies. At the macro level, Christiano, Eichenbaum, and Evans (2005) find that nominal wage stickiness is actually more important than nominal price stickiness for explaining the observed impact of monetary policy shocks. At the micro level, Barattieri, Basu, and Gottschalk (2010) find that the wages of individual workers are often unchanged for long periods of time (with wages changed, on average, less than once a year).

In this subsection, we show that our results extend readily to the case where either or both nominal prices and wages are sticky. Rather than writing down an extended model with two nominal frictions, we make our point heuristically, using the graphical labor supply-labor demand apparatus of Section 2. As we argued above, if households act competitively in the labor market, we have

$$U_2(C_t, 1 - N_t) = \lambda_t W_t, \tag{17}$$

where W is the nominal wage and λ is the shadow value of nominal wealth (the utility value of the

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[2] This intuition helps understand the results of Eggertsson (2010). Eggertsson provides examples of "good" real shocks that cause output to contract at the zero lower bound in a sticky-price model, and argues that this result does not hold if the nominal policy rate is well above the zero lower bound. To understand the intuition behind Eggertsson's results, it helps to note that at an unchanged interest rate, good real shocks often lower short-run output in sticky-price models. However, typically the monetary authority follows a rule that has it lower the interest rate, thus avoiding the drop in output in equilibrium. It is this last part of the story that ceases to be relevant at the zero lower bound, but the basic economics are the same at any level of the interest rate.

marginal dollar). Assuming firms have market power,

$$W_t = \frac{P_t}{\mu_t^P} Z_t F_2(K_t, Z_t N_t) \tag{18}$$

$$\frac{U_2(C_t, 1 - N_t)}{\lambda_t} = \frac{P_t}{\mu_t^P} Z_t F_2(K_t, Z_t N_t) \tag{19}$$

Now assume a new model, where households also have market power, and set wages with a markup over their marginal disutility of work:

$$W_t = \mu_t^W \frac{U_2(C_t, 1 - N_t)}{\lambda_t} \tag{20}$$

Then,

$$\frac{U_2(C_t, 1 - N_t)}{\lambda_t P_t} = \frac{1}{\mu_t^W} \frac{1}{\mu_t^P} Z_t F_2(K_t, Z_t N_t) \tag{21}$$

That is, in our labor market diagrams, suppose we replace the labor supply curve with $U_2(C_t, 1 - N_t)/\lambda_t P_t$. This has the interpretation of being the disutility faced by the household of supplying one more unit of labor, expressed in units of real goods (the real marginal cost of supplying labor). On the vertical axis, put the equilibrium quantity of the real marginal disutility of work. Note that this 'supply curve' is shifted in exactly the same way by uncertainty as the standard labor supply curve of Figures 1 and 2 – higher uncertainty raises λ, which shifts the supply curve out. But now the 'demand curve' is shifted by both price and wage markups – only the product of the two matters. Take the polar opposite of the case we have analyzed so far: Assume perfect competition in product markets, but Rotemberg wage setting by monopolistically competitive households in the labor market. Then the price markup is always fixed at 1, but the wage markup would jump up in response to an increase in uncertainty (since the marginal cost of supplying labor falls but the wage is sticky), making the qualitative outcome exactly the same as in our current case with only sticky prices and flexible wages. Thus, while introducing nominal wage stickiness would certainly affect quantitative magnitudes, it would not change our qualitative results.

5.3 Connections with Existing Literature

Our framework can be used to understand the economic mechanisms at work in some recent papers in the literature. Recent work by Bloom, Foetotto, and Jaimovich (2010), Chugh (2010), and Gilchrist, Sim, and Zakrajšek (2010) wish to use flexible-price models to show that shocks to uncertainty can lead to fluctuations that resemble business cycles. Their modeling approach is to drop equation (2) and use multi-sector models of production. They follow the insight of Bloom (2009) that when firms differ in productivity levels, the normal industry equilibrium features resource reallocation from low- to high-productivity firms. Higher uncertainty impedes the reallocation process by reducing the necessary investment/disinvestment needed to move capital and labor to higher-productivity uses. Thus, the basic approach of these models is to use multi-sector production and costly factor adjustment to transform an expected future change in the dispersion of total factor productivity (TFP) into a change in the current mean of the TFP distribution. In this way, the model may allow equilibrium real wages, consumption and labor supply to move in the same direction. However, all three papers experience difficulties in getting the desired comovements, at least for calibrations that are consistent with steady-state growth. These approaches are complementary to ours, in the sense that both mechanisms (cyclical markups and cyclical reallocation) could be at work simultaneously. However, non-linear multi-sector models are computationally difficult to analyze, so we view our approach as a realistic and tractable alternative. Our model of time-varying markups allows us to analyze uncertainty in the same representative-agent DSGE framework used to study other real and monetary shocks.

Another recent paper by Gourio (2010) follows Rietz (1988) and Barro (2005) and introduces a time-varying "disaster risk" into an otherwise-standard real business cycle. 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. Thus, a higher disaster risk is a combination of a negative news shock and a shock that increases uncertainty about the future; both shocks reduce the risk-adjusted expected rate of return on capital. In calibrating his model, Gourio uses Epstein-Zin recursive utility with an intertemporal elasticity of substitution (IES) greater than one. An increase in the probability of disaster makes investment in the capital stock more risky. With an IES greater than one, the substitution effect dominates the wealth effect when the probability of disaster increases. The lower risk-adjusted rate of return on investment induces the household to decrease investment. In addition, households supply less labor since the return on investment is low, which lowers total output. Since leisure and consumption are normal goods, an increase in risk results in lower equilibrium output, investment, and hours, but higher equilibrium consumption. Thus, like the multi-sector papers discussed above, his competitive one-sector model is unable to match basic business cycle comovements, for the reasons we discuss in Section 2.[3]

In independent and simultaneous work, a recent paper by Fernàndez-Villaverde, Guerròn-Quintana, Kuester, and Rubio-Ramìrez (2011) examines the role of fiscal uncertainty shocks in a model with nominal wage and price rigidities. In their paper, uncertainty regarding future fiscal policy is transmitted to the macroeconomy primarily through uncertainty about future taxes on income from capital. As we discuss in the introduction, an increase in uncertainty with nominal rigidities changes markups and creates macroeconomic comovement. We view this work as highly complementary to our paper. Our work emphasizes the basic mechanism in a stripped-down model and shows *why* fluctuations in uncertainty

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[3] Gourio (2010) conjectures (in a suggestion he attributes to Emmanuel Farhi) that the comovement problem might be solved by introducing countercyclical markups into his model.

can create business cycle comovement in a model with time-varying markups. Fernàndez-Villaverde, Guerròn-Quintana, Kuester, and Rubio-Ramìrez (2011) show that the mechanism we identify can have important economic effects in the benchmark medium-scale model of Smets and Wouters (2007). Otherwise, the papers are fairly different. We focus on technology and, especially, demand uncertainty, rather than policy uncertainty, and follow a very different calibration strategy, discussed in the next section. The object of our paper is to understand the role of increased uncertainty in generating the Great Recession and the subsequent slow recovery. We also analyze the interaction between the zero lower bound on nominal interest rates and uncertainty shocks, which we view as important for understanding the economics of this period.

6 Quantitative Results and Application to the Great Recession

6.1 Uncertainty Shock Calibration

The intuition laid out in Sections 1 and 2, and the previous qualitative results suggest that uncertainty shocks can produce declines in output and its components when prices adjust slowly. This section uses the previous sticky price model to determine if uncertainty shocks are quantitatively important for business cycle fluctuations. A related issue is determining the proper calibration of our shock processes for the uncertainty shocks associated with technology and household demand. The transmission of uncertainty to the macroeconomy in our model crucially depends on the calibration of the size and persistence of the uncertainty shock processes. However, aggregate uncertainty shocks are an *ex ante* concept, which may be difficult to measure using *ex post* economic data. To ensure our calibration of an unobservable process is reasonable, we want our model and uncertainty shock processes to be consistent with a well-known and observable measure of aggregate uncertainty.

We choose the Chicago Board Options Exchange Volatility Index (VIX) as our observable measure of aggregate uncertainty due to its significant use in financial markets, ease of observability, and the ability to generate a model counterpart. The VIX is a forward-looking indicator of the expected volatility of the Standard and Poor's 500 stock index. To match the frequency our of model, we aggregate an end-of-month VIX series to quarterly frequency by averaging over the three months in each quarter. The top panel of Figure 7 plots our quarterly VIX series. Using our VIX data series, denoted V_t^D, we estimate the following simple reduced-form autoregressive time series model:

$$\ln(V_t^D) = (1-\rho_V)\ln(V^D) + \rho_V \ln(V_{t-1}^D) + \sigma^{V^D}\varepsilon_t^{V^D}, \quad \varepsilon_t^{V^D} \sim N(0,1). \tag{22}$$

The ordinary least squares regression results are $V^D = 20.4\%$, $\rho_V = 0.83$, and $\sigma^{V^D} = 0.19$ with an $R^2 = 0.68$. Using our reduced-form model, we can also compute a series of VIX-implied uncertainty shocks as the regression residuals divided by their sample standard deviations. A typical one-standard-deviation VIX-implied uncertainty shock increases the VIX by 19 percentage points. Compared to its sample average of 20.4%, a one-standard deviation VIX-implied uncertainty shock raises the level of the VIX to 24.27%. The bottom plot of Figure 7 shows the time series of the VIX-implied uncertainty shocks. We use this reduced-form time-series model for the quarterly VIX series to ensure that our calibration for our technology and demand uncertainty shocks is reasonable.

Using a third-order approximation, we compute a model-implied VIX index as the expected conditional volatility of the return on the equity of the representative intermediate-goods producing firm. Formally, we define our model-implied VIX V_t^M as follows:

$$V_t^M = 100 * \sqrt{4 * Var_t\left(R_{t+1}^E\right)}, \tag{23}$$

where $Var_t(R_{t+1}^E)$ is the quarterly conditional variance of the equity return. We annualize the quarterly conditional variance, and then transform the annual volatility units into percentage points. Using hat-notation to denote percentage deviations from the steady-state, we can write the model-implied VIX as follows using our third-order approximation:

$$\hat{V}_t^M = \ldots + \eta^{\sigma^a}\hat{\sigma}_{t-1}^a + \eta^{\varepsilon^a}\varepsilon_t^{\sigma^a} + \eta^{\sigma^Z}\hat{\sigma}_{t-1}^Z + \eta^{\varepsilon^Z}\varepsilon_t^{\sigma^Z}, \tag{24}$$

where we use the ellipsis as a place holder for the other state variables (a_{t-1}, I_{t-1}, K_{t-1}, R_{t-1}, Y_{t-1}, Z_{t-1}, ε_t^a, ε_t^Z) and their respective coefficients. Thus, conditional on the values of the state variables, our model-implied VIX has an AR(1) representation in each of the two types of uncertainty shocks. We choose our calibrated parameters such that a one-standard deviation uncertainty shock to either technology or household demand generates a conditional AR(1) representation that matches our reduced-form model for the VIX in the data. For example, a one-standard deviation uncertainty shock to technology or household demand produces a 19 percentage point increase in the model-implied VIX and has a first-order autoregressive term of 0.83.

6.2 Quantitative Impact of Uncertainty Shocks

Figures 3 and 4 show the impact of our calibrated uncertainty shock process on the endogenous variables of the sticky price model. Section 4.2 shows that the responses are qualitatively similar for both technology and household demand uncertainty shocks. In this section, we analyze the quantitative differences between technology and household demand uncertainty shocks. The middle plot in the bottom row of both Figures 3 and 4 show that both uncertainty shocks under sticky prices produce a similar law of motion in the model-implied VIX, which approximately matches the reduced-form VIX model. The bottom right plot of each figure shows that the percentage increase in the volatility of the exogenous shocks to generate the same movement in the model-implied VIX differs between technology and household demand shocks. Household preference shocks require an 88 percent increase in volatility to produce the same movement in the model-implied VIX as a 42 percent increase in the volatility of technology.

In addition, the quantitative transmission of uncertainty to the macroeconomy differs greatly between the technology and household demand uncertainty shocks. A one-standard deviation technology uncertainty shock generates a peak drop in output of 0.02 percentage points. The size of this peak drop is output is very small in comparison to the movement generated by a first-moment technology shock in Figure 5. However, a one-standard deviation household demand uncertainty shock produces a 0.3 percentage point peak drop in output. Household demand uncertainty shocks can cause quantitatively significant fluctuations in output and its components.

6.3 The Role of Uncertainty Shocks in the Great Recession

The previous section shows that uncertainty shocks associated with household demand have quantitatively significant effects on output and its components. Many economists and the financial press believe the large increase in uncertainty in the Fall of 2008 may have played a role in the Great Recession and subsequent slow recovery.[4] The plot of the VIX in Figure 7 shows a large increase in expected stock market volatility around the collapse of Lehman Brothers in September of 2008. In particular, the bottom plot shows a three standard deviation VIX-implied uncertainty shock during the end of 2008. In calibrating our model, one-standard deviation uncertainty shocks to either household demand or technology generate one-standard deviation movements in the model-implied VIX. Thus, we cannot easily identify or partition the contribution of demand or technology uncertainty shocks in our model in generating the three-standard deviation VIX-implied uncertainty shock in the data. However, the utilization-adjusted total factor productivity series of Fernald (2011) shows very little evidence of stochastic volatility either during the Great Recession or over the entire data series. Thus, if we assume demand uncertainty shocks explain the bulk of the movement in the VIX during the Fall of 2008, our baseline model predicts that up to 0.9 percentage point drop in output may have been due to the increase in uncertainty alone in the Fall of 2008.[5]

One potential criticism of using our model to determine the role of uncertainty shocks in the Great Recession is that our model lacks a realistic financial sector and abstracts from financial frictions. A financial market disruption, such as the failure of Lehman Brothers in the Fall of 2008, is a single event which can have multiple effects. Recent work by Iacoviello (2011), Gertler and Karadi (2011), and

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[4] For example, Kocherlakota (2010) states, "I've been emphasizing uncertainties in the labor market. More generally, I believe that overall uncertainty is a large drag on the economic recovery."

[5] Given the AR(1) law of motion for volatility shocks in our third-order approximation to the policy functions, the impulse responses for the model scale approximately linearly in the size of the uncertainty shock.

many others focuses on the first-moment effects of the financial market disruption, such as a higher cost of capital and tighter borrowing constraints for households and firms. In this paper, we analyze the likely effects of the concurrent rise in uncertainty and its effect on the economy during the Great Recession. Indeed, we believe that the increased uncertainty in late 2008 might also be due to a large financial market disruption. To analyze the independent mechanism and effects of the increase in uncertainty, we choose to model uncertainty in a simple but reasonable macroeconomic model which abstracts from financial frictions. Our paper complements other work on the Great Recession, since one could easily combine changes in the expected mean and expected volatility of financial frictions to obtain a complete picture of the effects of the financial crisis. Adding a detailed financial sector to our model might obscure the transmission mechanism of uncertainty to the macroeconomy, and we eschew this course of action for the sake of clarity.

6.4 Uncertainty Shocks and the Zero Lower Bound

Finally, we examine the role of monetary policy in determining the equilibrium effects of uncertainty shocks. In our model, the monetary authority follows a standard interest rate rule that responds to inflation and output growth. The impulse responses in Figure 4 show that the monetary authority aggressively lowers the nominal interest rate in response to a demand uncertainty shock when prices are sticky. However, the calibrated interest rate rule does not decrease the policy rate enough to offset the negative impact on output and the other model variables. If the interest rate rule allowed the monetary authority conduct policy optimally and replicate the flexible price equilibrium allocations, then monetary policy could completely undo the negative effects of the uncertainty shock.[6] However, if the monetary authority is constrained by the zero lower bound on nominal interest rates, then monetary policy cannot replicate the flexible price outcome. The sharp increase in uncertainty during the financial crisis in late 2008 corresponds to a period when the Federal Reserve had a policy rate near zero. Thus, we believe that the zero lower bound may have plausibly contributed significantly to the large and persistent output decline starting at that time.

To formally analyze the impact of the zero lower bound, we append an unexpected monetary policy shock to our calibrated interest rate rule in Equation (16). To proxy for the zero lower bound, we posit a positive unexpected monetary policy shock in each period of the demand uncertainty impulse response such that the level of the nominal interest rate is unchanged from its steady state value. This experiment allows us examine the effect of the uncertainty shock when the monetary authority does not change its policy rate, which captures some effects of the zero lower bound.[7] Figures 8

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[6] Since our model has only one nominal rigidity, the optimal monetary policy prescription is to mimic the flexible price allocation.

[7] Rigorously accounting for the zero lower bound on nominal interest rates is a difficult modeling task due to two

and 9 plot the impulse responses of a demand uncertainty shock under "unconstrained" monetary policy, where the monetary authority follows its calibrated rule, and "constrained" monetary policy, where the unexpected monetary policy shocks prevent the nominal interest rate from changing from its steady state value. The impulse responses suggest that adverse effects of uncertainty shocks are both amplified and propagated at the zero lower bound. The peak drop in output in response to the uncertainty shock is about 50% larger when the monetary authority is constrained. In addition, the peak drop in the model variables occurs much later, almost two years after initial impact of the shock. Finally, output and all of the other model variables remain far below their steady state values even five years after the shock. The results suggest that the zero lower bound significantly amplifies and propagates negative shocks in the economy. In addition, under our previous assumptions in Section 6.3, our model suggests that uncertainty and the zero lower bound may have accounted for up to a one and a half percentage point drop in output during the Great Recession. Finally, our results suggest that the zero lower bound may be a significant factor in explaining the slow recovery following the Great Recession.

7 Conclusion

This paper examines the transmission mechanism of uncertainty to the macroeconomy in a standard representative-agent general equilibrium model. Under reasonable assumptions and countercyclical markups via sticky prices, fluctuations in uncertainty can generate business-cycle like comovements in output, consumption, investment, and hours worked. We calibrate our model to be consistent with a well-known and observable index of aggregate 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 and persistent decline in output starting at that time.

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primary factors. First, the zero lower bound represents an occasionally binding constraint, which needs to be handled using global solution methods. Second, Benhabib, Schmitt-Grohè, and Uribe (2001) shows that the zero lower bound introduces an "unintended" second steady state for inflation if the monetary authority follows a standard interest rate rule that satisfies the Taylor principle. To circumvent these two issues, we proxy for the effect of the zero lower bound by using a sequence of unexpected monetary policy shocks such that the nominal interest rate is unchanged in response to an uncertainty shock. While our results appear qualitatively reasonable, they should be interpreted as very preliminary.

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Table 1: Baseline Calibration

Parameter	Description	Calibrated Value
α	Capital's Share in Production	0.333
β	Household Discount Factor	0.9987
δ	Depreciation Rate	0.025
η	Household Labor Supply	2.90
ϕ_I	Adjustment Cost to Changing Investment	2.5
ϕ_P	Adjustment Cost to Changing Prices	160.0
Π	Steady State Inflation Rate	1.0062
ρ_r	Central Bank Interest Rate Smoothing Coefficient	0.50
ρ_Π	Central Bank Reaction Coefficient on Inflation	1.50
ρ_y	Central Bank Reaction Coefficient on Output Growth	0.50
σ	Parameter Affecting Household Risk Aversion	2.0
θ	Elasticity of Substitution Intermediate Goods	6.0
ρ_a	First Moment Preference Shock Persistence	0.90
ρ_{σ^a}	Second Moment Preference Shock Persistence	0.83
σ_a	Steady-State Volatility of Preference Shock	0.03
σ_{σ^a}	Volatility of Second Moment Preference Shocks	0.88
ρ_z	First Moment Technology Shock Persistence	0.99
ρ_{σ^z}	Second Moment Technology Shock Persistence	0.83
σ_z	Steady-State Volatility of Technology	0.01
σ_{σ^z}	Volatility of Second Moment Technology Shocks	0.42

Figure 1: Flexible Price Model Intuition

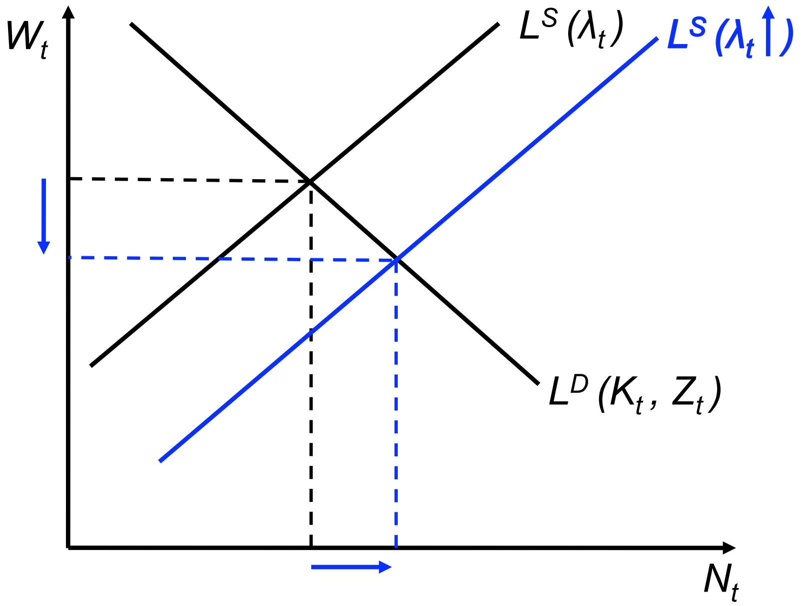


Figure 2: Sticky Price Model Intuition

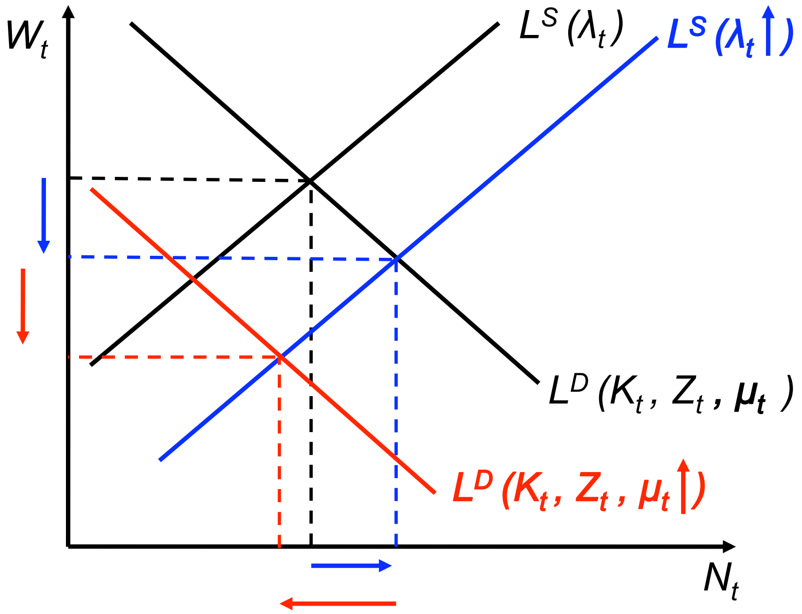
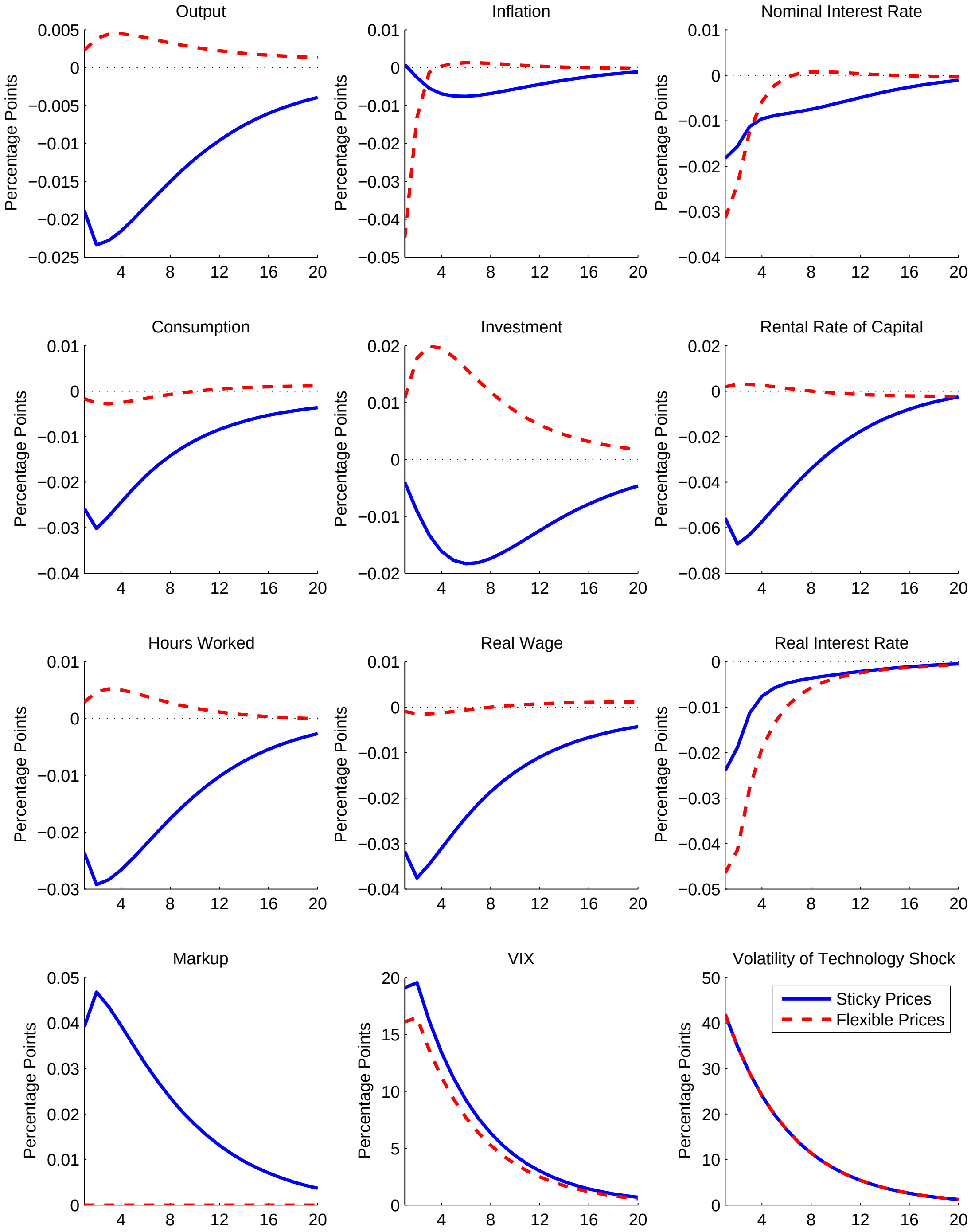
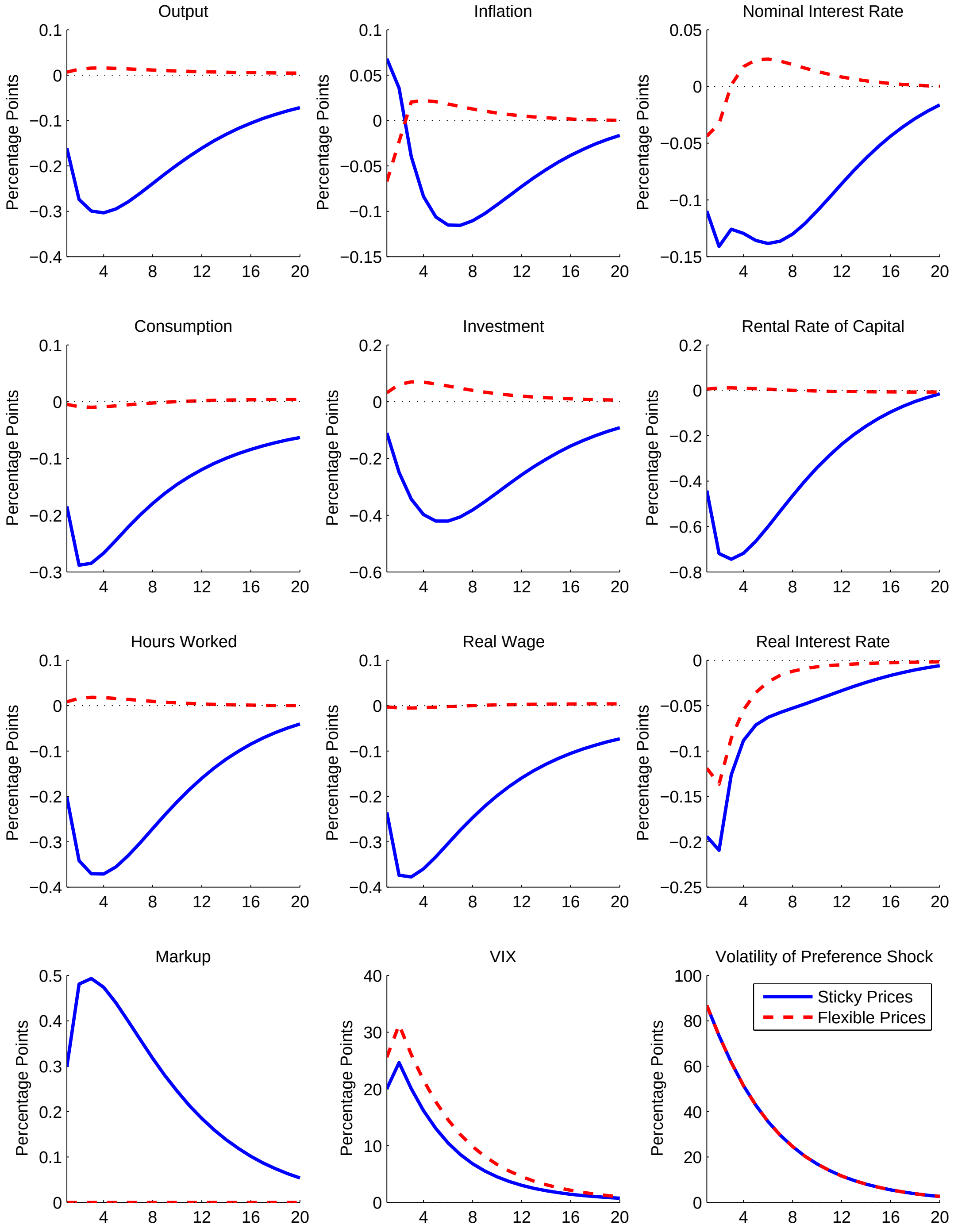


Figure 3: Impulse Responses to Second Moment Technology Shock



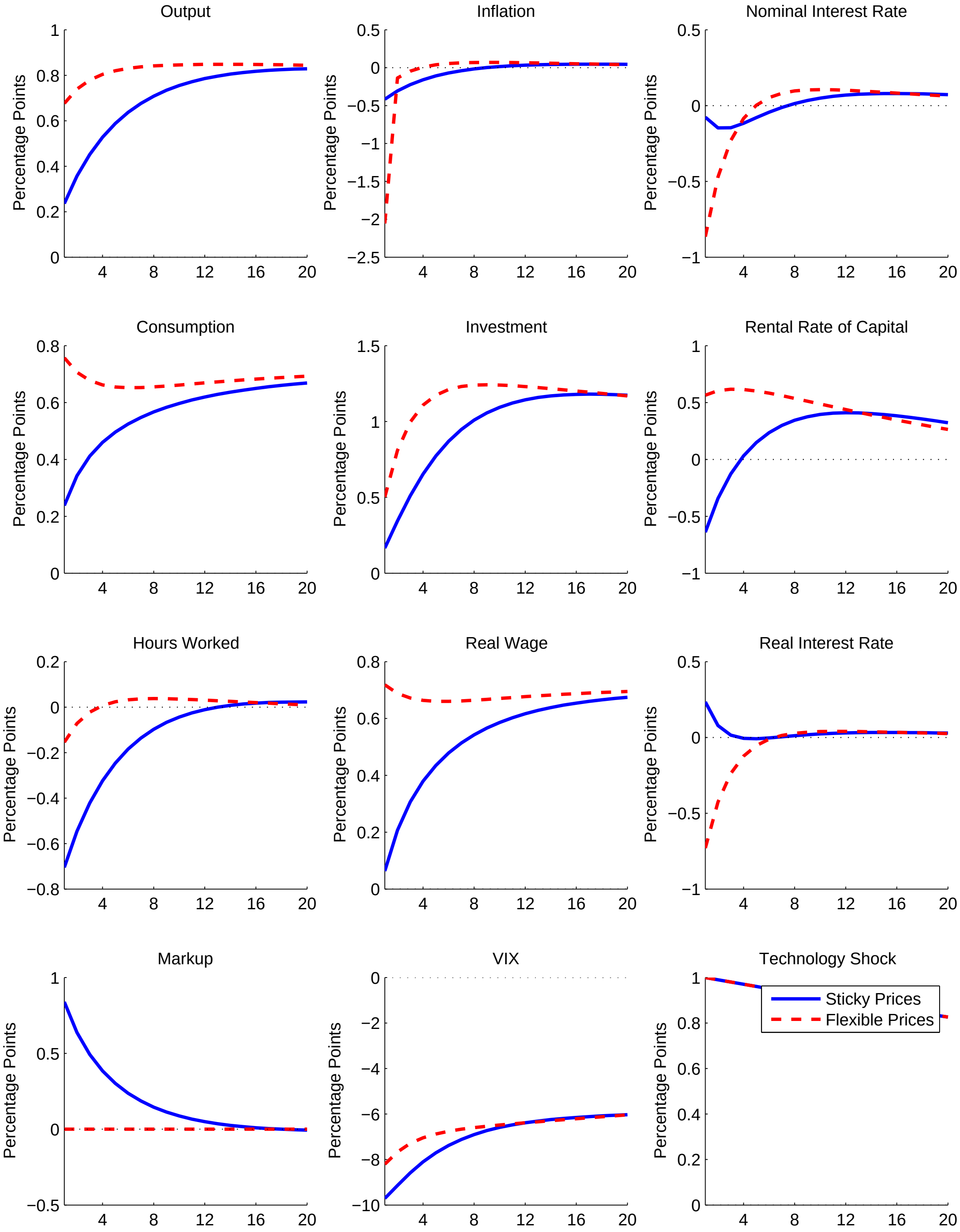
Note: Impulse responses are plotted as percentage deviations from their ergodic mean.

Figure 4: Impulse Responses to Second Moment Preference Shock



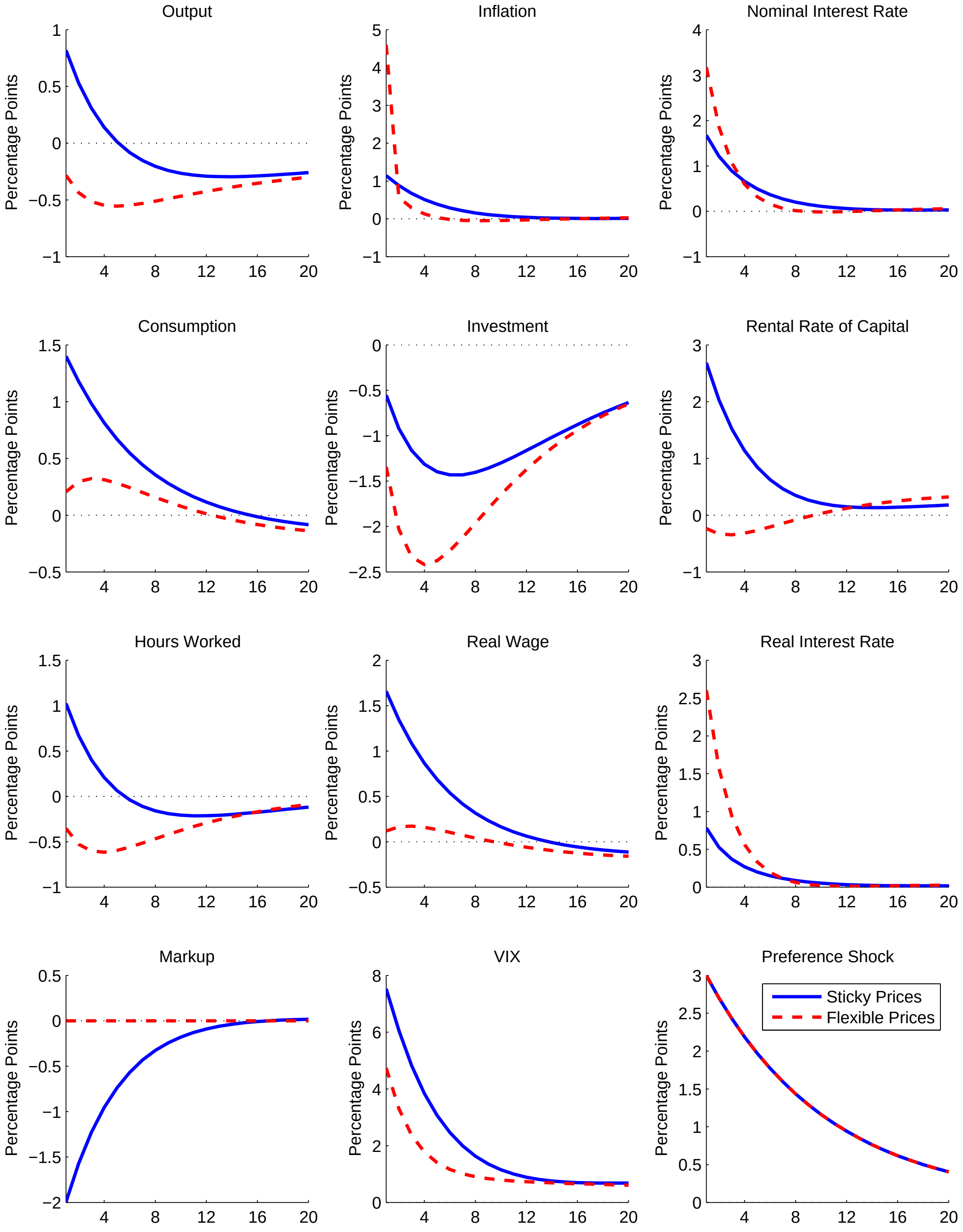
Note: Impulse responses are plotted as percentage deviations from their ergodic mean.

Figure 5: Impulse Responses to First Moment Technology Shock



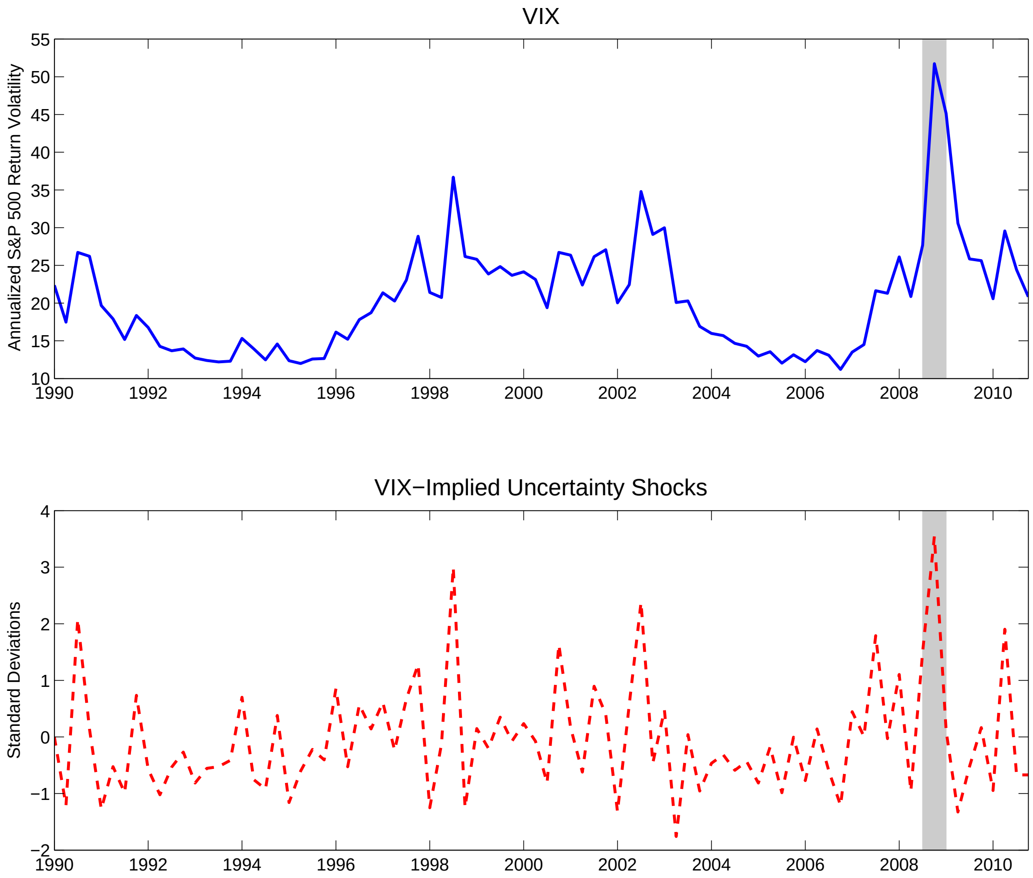
Note: Impulse responses are plotted as percentage deviations from their ergodic mean.

Figure 6: Impulse Responses to First Moment Preference Shock



Note: Impulse responses are plotted as percentage deviations from their ergodic mean.

Figure 7: VIX and VIX-Implied Uncertainty Shocks


VIX

VIX−Implied Uncertainty Shocks

Figure 8: Impulse Responses to Second Moment Preference Shock at ZLB (I)

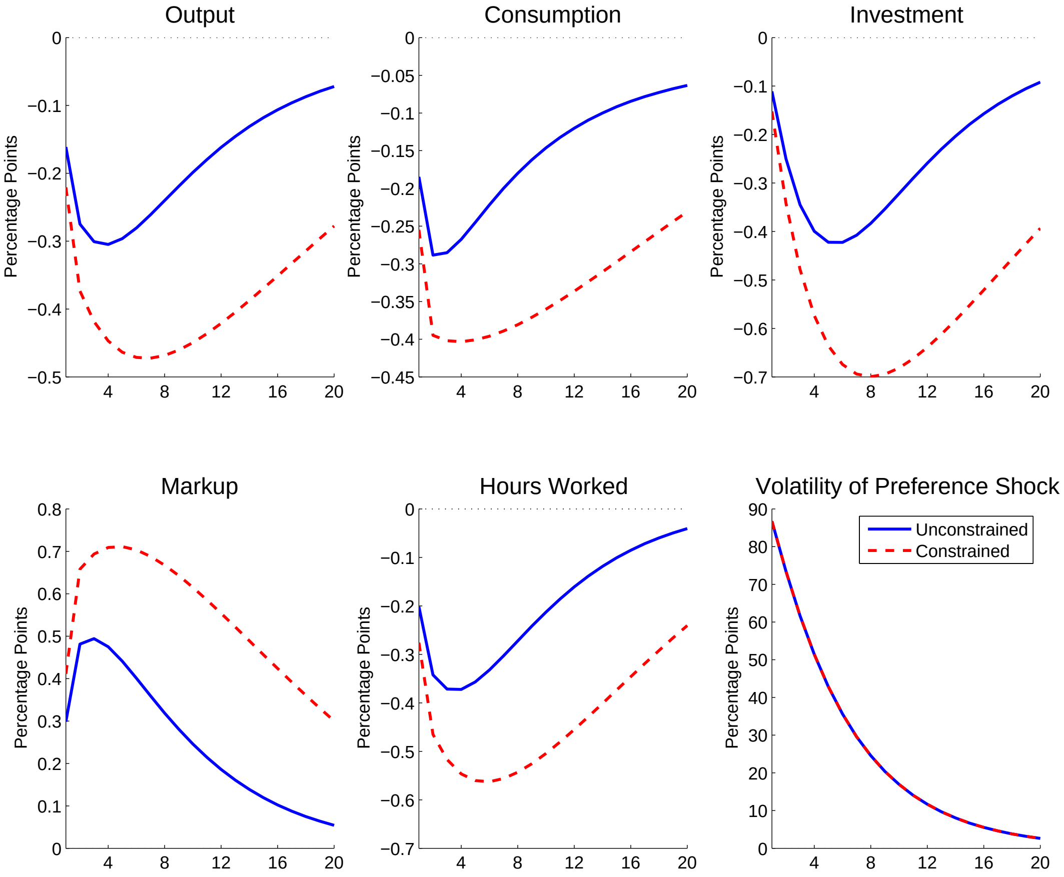


Figure 9: Impulse Responses to Second Moment Preference Shock at ZLB (II)