A Possible Explanation of the Missing Deflation Puzzle*

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Abstract

During the Great Recession, despite the large fall in output, the fall in inflation was modest. This is known as the missing deflation puzzle. In this paper, we develop and estimate a New Keynesian model to provide an explanation for the puzzle. The new model allows for time-varying volatility in cross-sectional idiosyncratic uncertainty and accounts for changes in intermediate goods prices. Our model can forecast the large fall in output and stable inflation during the Great Recession. We show that inflation did not fall much because intermediate goods prices were increasing during the Great Recession.

Keywords: Price Mark-up Shocks; Great Recession; Inflation; DSGE; Intermediate Inputs.

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1 Introduction

New Keynesian Dynamic Stochastic General Equilibrium (DSGE) models have become an important tool for monetary policy analysis and forecasting at central banks and other policy institutions around the world. However, the failure of these models to forecast the behaviour of inflation and other key macroeconomic variables during the Great Recession has been interpreted as evidence against this class of models. Two important papers in this regard are Ball and Mazumder (2011) and Hall (2011). Ball and Mazumder make their point by forecasting inflation during Great Recession using the New Keynesian Phillips Curve (NKPC), which determines inflation in the models. They find that the NKPC estimated from 1960 to 2007 cannot forecast inflation during the Great Recession. Hall criticises the NKPC on the basis that it fails to provide an explanation for the "missing deflation" puzzle. Missing deflation is characterised as higher levels of actual inflation during the Great Recession than the NKPC predicts. The NKPC relates inflation and economic activity. Given the depth and duration of the recession caused by the 2008 financial crisis, the NKPC would predict severe deflation. However, this did not happen and inflation remained positive.

This paper offers an explanation for the missing deflation puzzle. We argue that the reason for stable inflation is the increasing intermediate goods prices during the Great Recession. To show this, we reformulate the Smets and Wouters (2007) (henceforth SW) model to include the financial frictions mechanism in Bernanke et al. (1999) (henceforth BGG) and to account for the changes in intermediate materials prices. Further, we remove the price mark-up shocks in the model and following

Aoki (2001), De Walque et al. (2006) and Huang and Liu (2005), consider supply-side shocks that arise from changes in relative intermediate goods prices. Let us briefly explain these additions to the SW model.

To incorporate intermediate prices in the SW model, we divide production into two sectors. In one of the sectors intermediate materials are produced and in the other finished goods. We assume that intermediate materials are used as a factor input for the production of finished goods, while a small proportion of the intermediate materials is also needed to convert finished goods into consumption goods. Prices in both sectors are set according to Calvo (1983) pricing. Inflation in the finished goods sectors depends on future marginal costs. We further assume that prices in the intermediate materials sector are subject to a sector-specific shock. This shock is meant to capture exogenous factors affecting intermediate prices (e.g. Arab Spring). As a result, inflation in the intermediate goods sector depends on future marginal cost and the sector specific shock.

Turning to the second addition, as is well-known (see, e.g., Christiano et al. (2014), henceforth CMR), the BGG mechanism models the idiosyncratic uncertainty faced by entrepreneurs. The common assumption is that the volatility of cross-sectional idiosyncratic uncertainty fluctuates over time. This measure of volatility is referred to as risk. In line with CMR, we assume that the risk shock process has both unanticipated (or stochastic) and anticipated (or news) components. Several recent papers (e.g. CMR and Schmitt-Grohe and Uribe (2012)) show that accounting for the unanticipated component improves the empirical performance of the model significantly. The rest of the model is exactly the same as that in SW.

Next, we estimate the new model for US data using Bayesian techniques. Finally, we compare the out-of-sample forecasts of inflation, output, marginal cost and the interest rate from our model to those of a model variant without the intermediate sector and of the Survey of Professional Forecasters (SPF). Our results suggest that our model forecasts key macroeconomic variables better than the alternate specification and the SPF. Importantly, it achieves this in a way that is consistent with the micro evidence on prices.

The BGG mechanism plays a crucial role in our model in that it helps to capture the drop in output at the beginning of the crisis. We find that both components of the risk shock process are important to capture the fall in output. With the unanticipated component of the risk shock only, the fall in output is muted and is similar to that in the version of the model without the BGG mechanism. When we consider both components of the shock process, the fall in output is in line with the fall in output observed in the data. The intuitive explanation for this result is straightforward. Anticipating that future uncertainty will increase, banks increase the interest rate on loans more. An increased interest rate depresses investment further, leading to a larger fall in output.

Turning to the inflation forecast, we show that in the model with intermediate materials (henceforth SW-BGG-I) forecasts inflation better than the version of the model without (henceforth SW-BGG). The reason for this is simple. Since the SW-BGG-I model accounts for the changes in intermediate prices, it forecasts marginal cost better. In the SW-BGG-I, since intermediate materials are an input in production, marginal cost depends also on intermediate goods prices. During the Great

Recession, intermediate prices were increasing. As a result, during the Great Recession, the marginal cost in our model remains significantly high, relative to that suggested by the SW-BGG. To put it differently, the SW-BGG-I suggests that the increase in intermediate prices during the Great Recession offset most of the decrease in marginal cost due to decreased economic activity.

This paper is closely related to earlier papers by Coibion and Gorodnichenko (2013) and Del Negro et al. (2015) (henceforth NGS). Coibion and Gorodnichenko (2013) show that 'missing deflation' is a one-off event in response to rising oil prices. However, in our model, accounting for oil prices alone does not have a significant impact on inflation, as, at around 1%, the share of oil in production is very small. Nevertheless, we reach similar conclusions using intermediate materials prices. As we will discuss in the text, the volatility in the prices of intermediate materials closely tracks the volatility in energy prices. The correlation between the two data series is as high as 0.84, suggesting that the factors driving changes in energy prices may be the same as those underlying changes in intermediate goods prices. Our paper differs further from Coibion and Gorodnichenko in its modelling approach. While their analysis is based on the expectations−augumented Phillips curve proposed by Friedman (1968), ours is carried out in a New Keynesian general equilibrium framework in which the Phillips curve is micro-founded. However, this paper further strengthens their conclusion by showing that their finding of missing deflation being a one-off event has a wider applicability and holds also in a New Keynesian general equilibrium model.

NGS, on the other hand, argue, using a New Keynesian model with BGG-type financial frictions, that the near stability of inflation during the Great Recession was due to anchored expectations. Their results depend on having a large degree of price stickiness and therefore a very flat NKPC. At 7 quarters, average age of price contracts in NGS is twice that in micro evidence on prices (Klenow and Malin (2011)). NGS suggest that since inflation expectations of the households remained anchored, prices were not revised downwards substantially despite sharp contraction in output.

Another possible explanation for the stability of inflation during the Great Recession is noted by Christiano et al. (2015). At the start of the crisis, borrowing costs increased substantially. Therefore, financially constrained firms, which were previously financing their operating costs (e.g. wage bills) through borrowing, experienced an increase in their financing costs during the crisis. This increased firms' marginal costs and, therefore, kept inflation stable.

In line our results, Linde et al. (2015) also find the BGG mechanism to play a crucial role in matching output dynamics during the Great Recession. However, they question its usefulness in making accurate out-of-sample forecasts during normal times.

The rest of the paper is organised as follows. Section 2 describes the model. Section 3 explains the estimation strategy. Section 4 presents the estimation results. Section 5 analyses the forecasting performance across the models with and without an intermediate sector. Finally, section 6 concludes.

2 The Model

The framework in this paper builds on the model in SW to allow for input-output linkages between intermediate materials and finished goods. The framework also accounts for the idiosyncratic uncertainty faced by entrepreneurs. While the production of intermediate materials requires labour and capital as inputs, the production of finished goods requires labour, capital and intermediate materials as inputs. Finished goods and a fraction of intermediate materials are combined to produce the final consumption goods that are consumed by households. The two sectors also face the financial accelerator mechanism of BGG where financial market frictions arising through information asymmetry and agency costs affect the real side of the economy. In this we follow the work of NGS and CMR. Finally, the modelling of households and the monetary policy are standard New Keynesian.

In the rest of the section, we describe the behaviour of firms followed by the description for the behaviour of households and monetary policy. The model is detrended using a deterministic trend and nominal variables are replaced with their real counterparts. Finally, the model is linearised around the stationary steady state of the detrended variables.

2.1 Intermediate and Finished Goods

There is a continuum of firms $f \in [0, 1]$. We divide the unit interval into two subintervals representing each sector: a finished goods sector (s) and an intermediate sector (m). Firms in both sectors produce under an imperfectly competitive market and have monopoly power over a differentiated good. The share of intermediate sector in total production in the economy is given by (1-μ^u), while the share of the finished goods sector is μ^u. The total intermediate production is denoted by Y^m. A fraction (μ^c) of the intermediate goods is used as input in the production of the finished goods. So, the share of the intermediate goods in the production of the finished goods is $(1-\mu^u)\mu^c$. A small fraction of intermediate goods, which are not used in production, is combined with the finished goods to produce the final consumption good,[1] C_t. This fraction is equal to $(1-\mu^u)(1-\mu^c)$ and we denote it by $\bar{\alpha}$. C_t enters the utility function of the representative household. Each firm within the two sectors produces a single differentiated good, $Y^s(f)$ and $Y^m(f)$, which are combined to produce a final good in each sector, Y^s and Y^m, respectively. The aggregation is done according to a Dixit-Stiglitz aggregator. Total consumption is given by:

$$C_t = \left((1-\bar{\alpha})(Y_t^s)^{\frac{1}{1+\rho}} + \bar{\alpha}(Y_t^m)^{\frac{1}{1+\rho}}\right)^{1+\rho} \tag{1}$$

where $\frac{1+\rho}{\rho}$ is the elasticity of substitution between the finished goods and the intermediate goods such that Y_t^s and Y_t^m are given by

$$Y_t^s = \left[\int_0^{\mu^u} (Y_{ft})^{1/(1+\rho)} df\right]^{1+\rho} \tag{2}$$

$$Y_t^m = \left[\int_{\mu^u}^{1} (Y_{ft})^{1/(1+\rho)} df\right]^{1+\rho} \tag{3}$$

The corresponding price index is:

$$P_t = \left((1-\bar{\alpha})^{\frac{1+\rho}{\rho}}(P_t^s)^{-\frac{1}{\rho}} + \bar{\alpha}^{\frac{1+\rho}{\rho}}(P_t^m)^{-\frac{1}{\rho}}\right)^{-\rho} \tag{4}$$

[1]Such use of intermediate materials can be thought as packaging and transportation of the finished goods before they could be sold as final consumption goods.

where P_t is the general price index, P_t^m is the price of intermediate materials and P_t^s is the price level in the finished goods sector. In what follows, we will first describe the finished goods sector and then the intermediate sector. The demand for the finished goods sector and the intermediate goods sector is given by

$$Y_t^s = \left(\mu^u \frac{P_t}{P_t^s}\right)^{\frac{1+\rho}{\rho}} Y_t \tag{5}$$

$$Y_t^m = \left((1-\mu^u)\frac{P_t}{P_t^m}\right)^{\frac{1+\rho}{\rho}} Y_t \tag{6}$$

In the finished goods sector, with a constant returns to scale (CRS) technology, firms have a production function of the form:

$$Y_t^s(f) = Y_t^m(f)^{\mu^c(1-\mu^u)} \left(A_t K_t^s(f)^{\alpha}\left[\gamma^t L_t^s(f)\right]^{1-\alpha}\right)^{1-\mu^c(1-\mu^u)} - \gamma^t\Phi + E_t \tag{7}$$

where $Y_t^m(f)$ denotes intermediate sector goods used as input by firm f in the finished goods sector, $L_t^s(f)$ is a composite of labour input, $K_t^s(f)$ is capital services and Φ is the fixed cost. γ^t represents the labour-augmenting deterministic growth rate in the economy and α is the share of capital in the production function. A_t is the productivity shock which follows an AR(1) process with parameters ρ_a and σ_a. E_t is a stochastic shock process that is meant to capture changes in production that arise from external factors, such as unusually cold winters and rare disasters. To ensure that E_t is distinct from A_t and affects the output directly without affecting the marginal cost, it is assumed that E_t enters the production function additively. A variance decomposition analysis for our estimated model suggests that this shock explains about 2% of the fluctuations in total output. We assume that the shock affects the finished goods sector only. But it has an indirect effect on the intermediate goods sector. An unusually cold winter would cause a disruption in the production of the finished goods which will consequently reduce the demand for intermediate goods as well.[2] The log-linearised version of the production function in equation (7) is:

$$y_t^s = \phi_p(\mu^u(1-\mu^c)y_t^m + (1-\mu^u(1-\mu^c))(\alpha k_t^s + (1-\alpha)L_t^s + a_t)) + e_t \tag{8}$$

where $e_t = \ln E_t$ and $a_t = \ln A_t$. Unlike the finished goods sector, firms in the intermediate sector have labor and capital as the only two factor inputs such that their production function is given by:

$$Y_t^m = A_t(K_t^m)^\alpha(\gamma^t L_t^m)^{1-\alpha} - \gamma^t\Phi \tag{9}$$

where $L_t^m(f)$ is a composite of labour input and $K_t^m(f)$ is capital services used in the intermediate sector. Log-linearising Equation (9) gives:

$$y_t^m = \phi_p(\alpha k_t^m + (1-\alpha)L_t^m + a_t) \tag{10}$$

Prices in both sectors are set according to Calvo pricing with no ad-hoc partial indexation. Log-linearisation of the aggregate price index in equation (4) is represented as:

$$0 = \bar{\alpha}\bar{p}_t^m + (1-\bar{\alpha})\bar{p}_t^s \tag{11}$$

where $\bar{p}_t^s = p_t^s - p_t$ is the relative price level in the finished goods sector and $\bar{p}_t^m = p_t^m - p_t$ is the relative price level in the intermediate goods sector. Profit maximisation by the price-setting firms in the finished goods sector gives the following sectoral NKPC:

$$\pi_t^s = \beta\gamma^{1-\sigma_c}\pi_{t+1}^s + \kappa(\bar{mc}_t^s - \bar{p}_t^s) \tag{12}$$

[2]In an alternative setting, we assume that the shock affects both the finished goods sector and the intermediate goods sector directly. Doing so does not change our main results significantly.

where κ is the slope coefficient of the form:

$$\kappa = \frac{(1 - \zeta_p \beta \gamma^{1-\sigma_c})(1 - \zeta_p)}{\zeta_p} \tag{13}$$

and $\bar{mc}_t^s$ is the real marginal cost in the finished goods sector:

$$\bar{mc}_t^s = (1 - \mu^c(1 - \mu^u))(\alpha r_t^k + (1 - \alpha)w_t - a_t) + (\mu^c(1 - \mu^u))\bar{p}_t^m \tag{14}$$

ζ_p in equation (13) is the Calvo parameter for price stickiness. β is the discount factor. σ_c represents the elasticity of intertemporal substitution such that when it is above unity consumption and labor hours are complements. In equation (14) w_t is the real wage and r_t^k is the real rental rate of capital.

The NKPC in the intermediate sector is given by:

$$\pi_t^m = \beta \gamma^{1-\sigma_c} \pi_{t+1}^m + \kappa^m (\bar{mc}_t^m - \bar{p}_t^m) + \epsilon_t^{a^f} \tag{15}$$

where κ^m is the slope coefficient of the form:

$$\kappa^m = \frac{(1 - \zeta_p^m \beta \gamma^{1-\sigma_c})(1 - \zeta_p^m)}{\zeta_p^m} \tag{16}$$

where ζ_p^m is the Calvo parameter for price stickiness specific to the intermediate sector. $\bar{mc}_t^m$ is the real marginal cost in the intermediate sector:

$$\bar{mc}_t^m = \alpha r_t^k + (1 - \alpha)w_t - a_t \tag{17}$$

$\epsilon_t^{a^f}$ in equation (15) is an exogenous shock to intermediate materials prices and follows an AR(2) process of the form in equation (18):

$$a_t^f = \rho_{a^f} a_{t-1}^f + \rho_{a^f}^2 a_{t-2}^f + \epsilon_t^{a^f} \tag{18}$$

The aggregate output, labour and capital in logs are given by

$$\begin{aligned} y_t &= \mu^u y_t^s + (1-\mu^u) y_t^m \\ l_t &= \mu^u l_t^s + (1-\mu^u) l_t^m \\ k_t &= \mu^u k_t^s + (1-\mu^u) k_t^m \end{aligned} \tag{19}$$

Equation (20) is the log-linearised aggregate marginal cost:

$$mc_t = (1-\bar{\alpha}) \bar{mc}_t^s + \bar{\alpha} \bar{mc}_t^m \tag{20}$$

In the next subsection, we will describe the financial accelerator mechanism which is identical to that in NGS.

2.2 The Financial Accelerator Mechanism and the Risk Shock

The introduction of financial frictions in the model alters the arbitrage equation. The arbitrage equation between the return on capital and the riskless rate in SW is replaced with an equation for capital returns and an equation for the spread between capital returns and the riskless rate. The equation determining the spread is:

$$E_t[\tilde{R}_{t+1}^k - R_t] = b_t + \zeta_{sp,b}(q_t^k + \bar{k}_t - n_t) + \tilde{\sigma}_{w,t} \tag{21}$$

Equation (21) has the SW arbitrage equation as a special case when the parameter, $\zeta_{sp,b}$, associated with the ratio of the value of installed capital to net worth, $\frac{Q_{t+i-1}^k \bar{K}_{t+i-1}}{N_{t+i-1}}$, is zero. q_t^k is the real value of the capital stock. $\tilde{\sigma}_{w,t}$ is the risk shock and $\tilde{R}_t^k$ denotes capital return to the entrepreneurs. $\tilde{R}_t^k$ can also be interpreted as required returns on capital, since entrepreneurs' borrowing cost within the model always equals $\tilde{R}_t^k$, given by:

$$\tilde{R}_t^k - \pi_t = \frac{r_*^k}{r_*^k + (1-\delta)} r_t^k + \frac{1-\delta}{r_*^k + (1-\delta)} q_t^k - q_{t-1}^k \tag{22}$$

n_t in equation (21) is the net worth of entrepreneurs expressed as:

$$n_t = \zeta_{n,\tilde{R}^k}(\tilde{R}_t^k - \pi_t) - \zeta_{n,R}(R_{t-1} - \pi_t) + \zeta_{n,q^k}(q_{t-1}^k + \bar{k}_{t-1}) + \zeta_{n,n} n_{t-1} \tag{23}$$

Following CMR and Fernandez-Villaverde et al. (2011), we assume the following process for the risk shock:

$$\tilde{\sigma}_{w,t} = \rho_{\tilde{\sigma}} \tilde{\sigma}_{w,t-1} + u_{\tilde{\sigma},t} \tag{24}$$

where

$$u_{\tilde{\sigma},t} = \rho_{\tilde{\sigma},n} u_{\tilde{\sigma},t-1} + \epsilon_{\tilde{\sigma},t} \tag{25}$$

After straightforward algebra, the last two equations can be rewritten as:

$$\tilde{\sigma}_{\omega,t+i} = \rho_{\tilde{\sigma}} \tilde{\sigma}_{\omega,t+i-1} + \rho_{\tilde{\sigma},n}^i \boldsymbol{\epsilon_{\tilde{\sigma},t}} + \rho_{\tilde{\sigma},n}^i \sum_{j=1}^{\infty} \rho_{\tilde{\sigma},n}^j \epsilon_{\tilde{\sigma},t-j} \tag{26}$$

where $0 < \rho_{\tilde{\sigma}}, \rho_{\tilde{\sigma},n} < 1$ and $\epsilon_{\tilde{\sigma},t}$ is i.i.d. (independent and identically distributed) and denotes the unanticipated component of risk, $\tilde{\sigma}_{\omega,t}$. Eq. (26) is an attempt to mimic the effect of the Lehman shock which increased both current and future risk in the economy. To see this more clearly, consider a financial shock, $\boldsymbol{\epsilon_{\tilde{\sigma},t}}$, in period '$t$'. $\boldsymbol{\epsilon_{\tilde{\sigma},t}}$ affects the economy in period 't' via two channels. First, $\boldsymbol{\epsilon_{\tilde{\sigma},t}}$ increases risk in period 't' ($\tilde{\sigma}_{\omega,t}$). Second, it also increases future risk ($\tilde{\sigma}_{\omega,t+i}$) and thus affects the current state of the economy through agents' intertemporal adjustment. $\boldsymbol{\epsilon_{\tilde{\sigma},t}}$ will receive less weight the further agents look into the future. $\rho_{\omega,n}^i$ is the weight on $\epsilon_{\tilde{\sigma},t}$ for risk in period '$t + i'$.

Following CMR, we assume that 'j' can take values up to 8. We call $\epsilon_{\tilde{\sigma},t-j}$, where

$j = 1...8$, an anticipated component whose value was revealed in $t - j$. Thus, at time t the realisation of the risk $\tilde{\sigma}_{\omega,t}$ is influenced by the combined impact of both the unanticipated and the anticipated components. Furthermore, as Christiano et al. (2010) argue, such a generalised shock process helps to "tackle the deep-seated misspecification problems in DSGE models." The rest of the model equations are the same as in the SW model and are listed in the Appendix.

3 Estimation Strategy

This section starts with explaining the estimation methodology and macroeconomic data used for estimation purpose. We then explain the difference in the shock processes across the two models estimated in this paper. We also present a brief overview of the prior distributions assumed for key parameters. Finally, the calibration of intermediate materials sector and the financial sector parameters is discussed.

We estimate the model in this paper both with and without the intermediate sector. The two variants of the model with and without the intermediate sector are referred to as SW-BGG-I and SW-BGG, respectively. Importantly, in the SW-BGG, the value of Calvo parameter, ξ_p, is calibrated to equal the posterior estimate in the SW-BGG-I. This is done to ensure that the subsequent analysis for both the model variants is done under micro-consistent price rigidities.[3] Following Smets and Wouters (2003), estimation is done using Bayesian estimation techniques.[4]

[3]In an alternate setting we estimate ξ_p for the SW-BGG. The posterior estimate for ξ_p is 0.83, suggesting an average age of the price contract of 6 quarters. This specification reproduces the results in Del Negro et al. (2015).

[4]We ensure an acceptance rate of around 30% and allow for 250,000 replications for the

Data from 1981Q1 to 2008Q3 are used to estimate the models, while forecasting is done over 2008Q4-2009Q4. We use ten macroeconomic series at the quarterly frequency for the US economy. Seven of the data series are identical to SW: the log difference of real GDP, real consumption, real investment, real wage, log hours worked, log difference of the GDP deflator and the federal funds rate. Data for quarterly credit spread and 10-year inflation expectations are also included as in NGS. The credit spread is measured by the difference between the interest rate on BAA-rated corporate bonds and the 10 year US government bond rate. The Blue Chip Economic Indicators survey and the Survey of Professional Forecasters are used to obtain data for 10-year inflation expectations. Adding 10-year inflation expectations data is helpful since, as pointed out in Del Negro and Eusepi (2011) and Kiley (2008), inflation expectations contain information about people's beliefs regarding the Fed's inflation objectives. We further include data on the log difference of real intermediate materials prices. Seasonally adjusted intermediate price data are obtained from the St. Louis FED database[5] which are then deflated using the GDP

Metropolis-Hastings algorithm. Estimation is done in Dynare 4.3.3.

[5]Producer Price Index by Commodity Intermediate Materials: Supplies & Components (PPI-ITM).

deflator. The measurement equations relating the data to the model variables are:

$$\begin{aligned}
OutputGrowth &= \gamma + 100(y_t - y_{t-1}) \\
ConsumptionGrowth &= \gamma + 100(c_t - c_{t-1}) \\
InvestmentGrowth &= \gamma + 100(i_t - i_{t-1}) \\
RealWageGrowth &= \gamma + 100(w_t - w_{t-1}) \\
HoursWorked &= \bar{l} + 100 l_t \\
Inflation &= \pi_* + 100\pi_t \\
FederalFundsRate &= R_* + 100R_t \\
Spread &= SP_* + E_t[\tilde{R}^k_{t+1} - R_t] \\
10yrInflExp &= \pi_* + E_t[\frac{1}{40}\Sigma_{k=1}^{40}\pi_{t+k}] \\
IntermediateInflation &= \gamma + 100(\bar{p}^m_t - \bar{p}^m_{t-1})
\end{aligned} \tag{27}$$

where $\bar{l}$, $\pi_* = 100(\Pi_* - 1)$ and $R_* = 100(\beta^{-1}\gamma^{\sigma_c}\Pi_* - 1)$ are the steady state of the quarterly hours worked, inflation and nominal interest rates, respectively. All the variables are expressed in percent.

Table 4 and Table 5 summarise the assumptions regarding prior distributions. Priors for most of the model parameters are similar to SW. In the SW-BGG-I, Calvo parameters for intermediate and finished goods sectors are specified a Beta prior distribution with standard deviation of 0.10. Since prices in the intermediate sector are flexible relative to the finished goods sector, in line with microevidence on prices, we assume that Calvo parameter for the intermediate sector has a prior mean of 0.40. In contrast, Calvo parameter for the finished goods sector has a prior mean of 0.60.

The price mechanism in the SW-BGG-I does not include price indexation.

In the SW-BGG, all the shock processes follow an AR(1) process except for the risk shock, government spending shock and the two mark-up shocks. Both the price and wage mark-up shocks follow an ARMA(1,1) process, as in the SW model. The risk shock follows a process that allows for anticipated signals as explained in equation (24).

The shock processes in the SW-BGG-I are identical to the SW-BGG except that the price mark-up shock in the SW-BGG is replaced with the two supply side shocks. We interpret ϵ^{a^f} in equation (15) as shocks arising from changes in real intermediate prices. Arguably changes in intermediate prices are driven by the factors underlying changes in energy prices. Figure 1 plots the real energy and intermediate materials price data. It can be seen that the volatility in the prices of the intermediate materials closely tracks the volatility in energy prices. The correlation between the first difference in logs of the two data series is as high as 0.78. The persistence parameters of the two shocks follow a beta prior distribution with mean 0.50 and standard deviation 0.20. The standard deviation of the intermediate input shock, σ_{a^f}, has an Inverse Gamma prior distribution with mean 2.50 and standard deviation 2.0. σ_{ei} also follows an Inverse Gamma distribution with mean 0.10 and standard deviation 2.0.

Following the evidence provided by Strassner and Moyer (2002), the parameters of the intermediate sector, μ^u and μ^c, are calibrated such that the share of intermediate materials in finished goods production is 20%. Since the corresponding data on intermediate price inflation used in estimation does not include intermediate services, we also calibrate the model only for the share of intermediate manufacturing inputs in finished goods production. The share of intermediate materials in final consumption good is kept fixed at 2%. Note that in the SW-BGG, as in SW, we assume that the curvature of the Kimball aggregator in the goods market (ϵ_p) is 10. In the SW-BGG-I we assume that the aggregation is done using a Dixit and Stiglitz aggregator and therefore ϵ_p equals 1. Following Woodford (2003) and De Walque et al. (2006), the elasticity of substitution between the finished and the intermediate goods, $(1+\rho)/\rho$, is also assumed to equal 1. Table 1 reports the values for the parameters that are fixed in estimation.

Table 1: Exogenous parameter values

Parameter	Definition	Values
β	Discount factor	0.9995
γ	Trend growth rate	1.004
δ	Depreciation rate	0.025
ϵ_w	Curvature of the Kimball labor market aggregator	10
g_y	Government spending-output ratio	0.18
$\mu^c(1-\mu^u)$	Share of intermediate materials in firms' production	0.20
$(1-\mu^c)(1-\mu^u)$	Share of intermediate materials in consumption goods	0.02

Turning to the parameter values for the financial sector, following CMR, we calibrate the survival rate of entrepreneurs (τ) as 97.28% and the percentage of businesses going bankrupt ($F^*(\bar{\omega})$) as 1% annually. The rental rate of capital is assumed to be 0.045 to match the risk premiumi in the steady state. $Var(log\omega)$ is set at 0.24. Different from CMR, μ^e is endogenous in our model and has a steady-state value of 0.31, which is less than the value of 0.94 assumed in CMR. Parameters in the net worth equation are also endogenous and are derived in the model. All these numbers are summarised in Table 2.

Table 2: Exogenous parameter values

Entrepreneurs:		
$F^*(\bar{\omega})$	Percent of businesses that go into bankruptcy in a year	0.01
$Var(log\omega)$	Variance of the log-normally distributed i.i.d shock	0.24
τ	Fraction of entrepreneurs surviving to the next period	0.9728
μ^e	Monitoring costs	0.31
r^k	Rental rate of capital	0.045

We estimate the two financial sector parameters in equations (21) and (27), $\zeta_{sp,b}$ and SP_*, respectively. Priors for the financial sector parameters are set in line with NGS and are given in Table 5. SP_* follows a Gamma distribution with prior mean of 2 and standard deviation of 0.10. $\zeta_{sp,b}$ is assumed to follow a Beta distribution with mean of 0.05 and standard deviation of 0.005. The three parameters related to the risk shock are the persistence of the shock process ($\rho_{\bar{\sigma}}$), the standard deviation of the shock ($\sigma_{\bar{\sigma}}$) and the parameter on the anticipated components of the risk shock ($\rho_{\bar{\sigma},n}$). $\rho_{\bar{\sigma}}$ has a Beta prior distribution with mean 0.75 and standard deviation 0.15. $\sigma_{\bar{\sigma}}$ has mean 0.05 and standard deviation of 4 with an Inverse Gamma distribution. $\rho_{\bar{\sigma},n}$ also follows an Inverse Gamma prior distribution with mean 1 and standard deviation 2.

Prior distributions of the remaining parameters in the model are identical to those in SW.

4 Estimation Results

The estimated values for the structural parameters are reported in Table 4. Table 4 also includes the prior and posterior standard deviations for the corresponding parameters.

In the SW-BGG-I, the posterior mean of the price stickiness parameter, ξ_p, in the finished goods sector is estimated at 0.59. This suggests an average age of the price contract of 2.4 quarters and is closer to the evidence reported in Klenow and Malin (2011). Again consistent with the findings reported in Klenow and Malin, with the estimated value of ξ_p^m of 0.46, prices in the intermediate sector are more flexible than those in the finished goods sector. ξ_p is calibrated at 0.59 in the SW-BGG model.

A few other estimates are worth commenting on. The estimated degree of habit persistence (h) is larger in the SW-BGG-I (0.71) than in the SW-BGG (0.34). Contrary to the SW-BGG, the elasticity of intertemporal substitution (σ_c) is estimated at close to 1 for the SW-BGG-I, while it is 1.6 in the SW-BGG. The estimated degree of wage indexation (ι_w) in the SW-BGG-I (0.22) is lower than in the SW-BGG (0.31). Both the models suggest strong reaction to inflation by the Federal Reserve. The estimate of the parameter on inflation (r_π) in the Taylor rule is around 1.45 across the two models. In both models, the parameter on the *change in output gap* ($r_{\Delta y}$) receives a larger weight than the parameter on the *output gap* (r_y). The degree of interest rate smoothing (ρ_r) is also very high for both the models and is estimated to be more than 0.70. The estimates for the two financial sector parameters, SP_* and $\zeta_{sp,b}$, as well as the parameters of the risk shock, $\rho_{\bar{\sigma}}$, $\sigma_{\bar{\sigma}}$ and $\rho_{\bar{\sigma},n}$, are almost identical across the two models.

The supply-side shocks in the intermediate sector are relatively less persistent than the price markup shock in the SW-BGG. The e_t shock in the SW-BGG-I, which is intended to capture abrupt disruptions in production process due to factors such as natural disasters, has an estimated persistence of only 0.17 and 0.01 for its two persistence parameters, ρ_{ei} and ρ_{ei^1}, respectively. Persistence of the intermediate input shock, ρ_{a^f}, is estimated at 0.62. The persistence of the price markup shock, ρ_π, in the SW-BGG, on the other hand, is much larger at 0.92. The estimated standard deviation of the price mark-up shock in the SW-BGG is in line with that of SW. Reflecting the highly volatile nature of energy prices, the standard deviation of the intermediate input shock in the SW-BGG-I is large at around 1.5.

5 Forecasts Comparison During the Great Recession

This section compares the out-of-sample forecasting performance of the two models over the Great Recession period. As noted above, we estimate the model for the period from 1981Q1 to 2008Q3 and then use the estimated model to forecast for the period from 2008Q4 to 2009Q4. The data on the spread and interest rate were already available for the first forecast period but not for remaining variables. Therefore, in line with NGS, forecast is made with the information set, $Y_{1:T+}$, available as of December 31, 2008, including the two additional data points for the spread and interest rate in the first period of the forecast.

Figure 3 plots the forecast results for inflation and output from the two models, the SW-BGG and the SW-BGG-I, along with the actual data for inflation and output. We also include the forecast from the Survey of Professional Forecasters (SPF) and the SW model for comparison. Let us first consider the output forecasts. Both the models show a significant contraction in output growth followed by a relatively slower recovery vis-a-vis the actual data. However, the SW-BGG fails to capture to full scale of output contraction. On the contrary, the magnitude of output contraction in the SW-BGG-I is very close to the data.

The slower recovery in the models relative to the data can be attributed to unconventional monetary and fiscal policy measures taken during and after the Great Recession. The US economy experienced three rounds of large scale asset purchases and a large fiscal stimulus. Since the model in this paper is estimated for the pre-crisis period, the information on asset purchase program and fiscal stimulus is not included in the data. Both the SPF and the SW do poorly and do not forecast significant change in output.

Despite a sharp output contraction in the SW-BGG-I relative to the SW-BGG, the SW-BGG-I model predicts stable inflation over the forecast horizon. The SW-BGG model, on the other hand, predicts persistent deflation. This is consistent with the 'missing deflation' puzzle noted by Hall and others. Unlike the two variants of the New Keynesian DSGE model studied in this paper, the SPF and the SW do not predict any substantial change in inflation during the Great Recession. Inflation forecast from both of these is significantly higher relative to the actual. Table 3 provides the Root Mean Square Error (RMSE) for variable forecasts over the Great Recession.

Table 3: Root Mean Square Error (RMSE) over Forecast Period

Variable	SW-BGG-I	SW-BGG	SPF
Inflation	0.03	0.17	0.12
Output Growth	0.93	0.43	0.47
Marginal Cost	0.42	1.25	-
Interest Rate	0.00	0.06	0.02

We also plot forecasts for the interest rate from the two models and SPF. These are reported in Figure 5. The interest rate forecast from the SW-BGG-I closely follows the data. As the figure shows, in line with the behaviour of interest rates during the forecast period, the interest rate forecast is around zero throughout the Great Recession. The SPF, on the other hand, forecasts an immediate increase in interest rates. However, in the SW-BGG-I, allowing for increased uncertainty by including an anticipated component in the risk shock process is crucial for generating data consistent interest rate forecasts. When we replace our risk shock process with an AR(1) process, both the models forecast interest rates to start increasing immediately into the forecast period.

Taken together, the above findings suggest that the SW-BGG-I forecasts key macroeconomic variables better than the SW-BGG and SPF. Importantly, this is true even though the degree of price stickiness in the SW-BGG-I is consistent with the micro evidence on prices. Thus, the SW-BGG-I provides an explanation for the 'missing deflation' puzzle in a way that is consistent with micro evidence on prices. In what follows we will explain the findings from the SW-BGG and the SW-BGG-I in more detail. We will first focus on the output forecast and then on the inflation forecast.

5.1 Output Forecasts

In the two models, the SW-BGG and the SW-BGG-I, both anticipated and unanticipated components of the risk shock play an important role in capturing the full magnitude of the drop in output at the onset of crisis. When we remove the anticipated components of the shock process, as shown in Figure 4, the decline in output is much smaller across both models. Inflation in the two models also falls less in response to the muted output forecast compared to when the anticipated component is included. The intuition behind these results is as follows. Let us first focus on the unanticipated component of the shock process. When the shock hits the economy, uncertainty in the economy increases. This results in banks increasing the interest rate charged on loans to the entrepreneurs. With increased interest rates, entrepreneurs borrow less, leading to a decrease in investment. Consequently, output falls following a contraction in investment. Adding an anticipated element to the shock process amplifies the fall in output, since the anticipation that future uncertainty will increase leads banks to further increase the interest rate on loans. Increased interest rates depress investment further, leading to a larger fall in output.

5.2 Inflation Forecasts

To understand the reasons for improved inflation forecast in the SW-BGG-I under micro consistent price rigidities, we examine the behaviour of marginal costs in the two models. Doing so is helpful since in both models inflation is determined by future marginal costs. Figure 2 and Figure 6 plots the smoothed marginal costs (MC) for the two models over the full sample period, $Y_{1:T_{full}}$, and the out-of-sample forecast, respectively.

Two points must be made about the comparison between marginal costs in the SW-BGG-I and those in the SW-BGG. First, marginal costs in both models behave very differently. The SW-BGG predicts much lower marginal cost during the Great Recession than the SW-BGG-I. The relatively stable marginal cost in the SW-BGG-I results in stable inflation forecast without requiring large price stickiness - flatter NKPC. Since inflation depends on marginal costs and that the fall in marginal cost in the SW-BGG-I is muted, the SW-BGG-I matches the near stability of inflation data without requiring large degree of price stickiness. On the other hand, under micro-consistent Calvo parameter, sharp drop in marginal cost in the SW-BGG results in persistent deflation. Second, the difference between marginal costs forecast and the smoothed marginal costs is larger in the SW-BGG than in the SW-BGG-I, indicating larger forecast errors in the SW-BGG (see Table 3). Smaller ex-post forecast errors in the case of the SW-BGG-I provide support for the mechanism at work in the model.

The first observation brings up a natural question: why is the behaviour of marginal cost in the models with and without an intermediate sector so different?

The answer to this question is straightforward. As Figure 1 shows, real intermediate prices increased substantially before and during the Great Recession. Since intermediate prices directly affect the marginal cost in the SW-BGG-I (see equation 14), increasing intermediate prices almost completely offset the fall in the marginal costs following the sharp contraction in economic activity.

It is important to note that the price mark-up shocks are meant to capture the changes in energy prices (see, e.g. NGS). However, these shocks can have very different implications for the marginal costs than intermediate input shocks. When price mark-ups increase, marginal cost must fall. This is because of the fact that prices are sticky. A positive mark-up shock must, therefore, be compensated by reduced marginal cost. Firms achieve this by lowering their output. Since decrease in output leads to a fall in the prices of factor inputs, firms' marginal cost declines.

On the contrary, intermediate input shocks lead to an increase in marginal cost, since intermediate materials are an additional cost component of firms' marginal cost. Figure 7 highlights how these two shocks have different implications for the economy even when inflation dynamics in response to the two shocks are almost identical. In the SW-BGG-I, output contracts twice as much as in the SW-BGG which causes labour and capital to also fall more than in the SW-BGG. Thus the responses to exogenous changes in the intermediate prices are amplified when an intermediate materials producing sector is incorporated in the SW-BGG framework. The amplified response to the intermediate input shock is, however, sensitive to the shock process assumed for it in equation (18).

6 Conclusions

In this paper, we have reformulated the standard New Keynesian model to include a Bernanke-Gertler-Gilchrist financial accelerator mechanism and to account for changes in intermediate materials prices. In the new model, intermediate materials are used as an additional factor input in the production of finished goods. A fraction of intermediate goods are also combined with finished goods to produce the final consumption good. We have estimated the model for the period from 1981Q1 to 2008Q3 using quarterly US data. The estimated model is then used to forecast over the period from 2008Q4 to 2009Q4 to see if the reformulated model can account for the evolution of the key macroeconomic variables during the Great Recession.

We have shown that accounting for the changes in intermediate prices provides an explanation for the 'missing deflation' puzzle noted during the Great Recession. Importantly, our model achieves this with an empirically relevant degree of price stickiness. The key difference across the models with and without the intermediate sector is that in the model with an intermediate sector, marginal cost does not decline during the Great Recession unlike in the model without an intermediate sector. This is because during the Great Recession intermediate prices were increasing. Since intermediate materials in our model are required to produce finished goods, during the Great Recession, the marginal cost in our model does not fall as much as it does in the model without intermediate materials. As a consequence, despite the substantial drop in output, just as in the data, inflation does not fall much, providing an explanation for the "missing deflation" puzzle.

References

An, S. and Schorfheide, F. 2007. "Bayesian Analysis of DSGE Models," *Econometric Reviews,* 26(2-4): 113-172.

Aoki, K. 2001. "Optimal Monetary Policy Responses to Relative-Price changes," *Journal of Monetary Econoics,* 48: 55-80.

Ball, L. M. and Mazumder, S. 2011. "Inflation Dynamics and the Great Recession," *NBER Working Paper No. 17044.*

Bernanke, B., Gertler, M. and Gilchrist, S. 1999. "The Financial Accelerator in a Quantitative Business Cycle Framework," *Handbook of Macroeconomics, ed. by J. B. Taylor and M. Woodford,* North Holland, Amsterdam, vol. 1C.

Bils, M., Klenow, P. J. and Malin, B. A. 2012. "Testing for Keynesian Labor Demand," *NBER Chapters, in: NBER Macroeconomics Annual 2012,* 27: 311-349.

Calvo, Guillermo. 1983. "Staggered prices in a utility-maximizing framework," *Journal of Monetary Economics,* 12 (3): 383-398.

Chari, V. V., Kehoe, P. J. and McGrattan, E. R. 2009. "New Keynesian Models: Not Yet Useful for Policy Analysis," *American Economic Journal: Macroeconomics,* 1:1, 242-266.

Christiano, L., Motto, R. and Rostagno, M. 2010. "Financial Factors in Economic Fluctuations," *ECB Working Paper No. 1192.*

Christiano, L., Motto, R. and Rostagno, M. 2014. "Risk Shocks," *American Economic Review,* 104(1): 27-65.

Christiano, L. J., Eichenbaum, M. S. and Trabandt, M. 2015. "Understanding the Great Recession" *American Economic Journal: Macroeconomics,* 7(1): 110-167.

Coibion, O. and Gorodnichenko, Y. 2013. "Is the Phillips Curve Alive and Well After All? Inflation Expectations and the Missing Disinflation," *NBER Working Paper No. 19598.*

De Walque, G., Smets, F. R. and Wouters, R. 2006. "Price Shocks in General Equilibrium: Alternative Specifications," *CESifo Economic Studies,* 52: 153-176.

Del Negro, M. and Eusepi, S. 2011. "Fitting Observed Inflation Expectations," *Journal of Economic Dynamics and Control,* 35(12): 2105-2131.

Del Negro, M., Giannoni, M. P. and Schorfheide, F. 2015. "Inflation in the Great Recession and New Keynesian Models," *American Economic Journal: Macroeconomics,* 7(1): 168-196.

Fernandez-Villaverde, J., Guerron-Quintana, P., Rubio-Ramirez, J. F. and Uribe, M. 2011. "Risk Matters: The Real Effects of Volatility Shocks," *American Economic Review,* 101(6): 2530-2561.

Friedman, M. 1968. "The Role of Monetary Policy," *American Economic Review,* 58: 1-17.

Hall, R. E. 2011. "The Long Slump." *American Economic Review,* 101: 431469.

Huang, K. X. D. and Liu, Z. 2005. "Inflation Targeting: What Inflation Rate to Target?," *Journal of Monetary Economics,* 52(8): 1435-1462.

Kara, E. and Pirzada, A. J. 2015. "Fundamental Inflation and Intermediate Input Prices," *Working Paper, University of Bristol.*

Kiley, M. T. 2008. "Monetary Policy Actions and Long-Run Inflation Expectations," *FEDS Working Paper No. 2008-03.*

King, R. G. and Watson, M. W. 2012. "Inflation and Unit Labor Cost," *Journal of Money, Credit and Banking,* Blackwell Publishing, 44: 111-149.

Klenow, P. J. and Malin, B. A. 2011. "Microeconomic Evidence on Price-Setting," *Handbook of Monetary Economics,* 3A, B. Friedman and M. Woodford ed.: Elsevier, 231-284.

Linde, J., Smets, F. and Wouters, R. (forthcoming). "Macro Models Used at Central Banks and New Challenges," *Handbook of Macroeconomics,* J. B. Taylor and H. Uhlig.

Schmitt-Grohe, S. and Uribe, M. 2012. "What's News in Business Cycles," *Econometrica* 80: 2733-2764.

Smets, F. and Wouters, R. 2003. "An Estimated Dynamic Stochastic General Equilibrium Model of the Euro Area," *Journal of the European Economic Association,* 1: 1123-1175.

Smets, F. and Wouters, R. 2007. "Shocks and Frictions in US Business Cycles: A Bayesian DSGE Approach," *American Economic Review,* 97(3): 586-606.

Strassner, E. H. and Moyer, B. C. 2002. "An Analysis of the Composition of Intermediate Inputs by Industry," *BEA Working Paper No. 2002-05.*

Woodford, M. 2003. *Interest and Prices,* Princeton, New Jersey: Princeton University Press.

7 Appendix

The rest of the model is the same as that in the SW model. The Consumption Euler equation is given by:

$$c_t = -\frac{1-\frac{h}{\gamma}}{\sigma_c(1+\frac{h}{\gamma})}(R_t - E_t\pi_{t+1} + b_t) + \frac{\frac{h}{\gamma}}{1+\frac{h}{\gamma}}c_{t-1} + \frac{1}{1+\frac{h}{\gamma}}E_t c_{t+1} + \frac{\sigma_c - 1}{\sigma_c(1+\frac{h}{\gamma})}\frac{w_*^h L_*}{c_*}(L_t - E_t L_{t+1}) \tag{28}$$

where c_t is consumption, L_t is labour supply, R_t is nominal riskless interest rate, and π_t is inflation. b_t is an exogenous shock such that a positive shock increases the required return on assets and increases the cost of capital and reduces the value of capital and investment. b_t follows an AR(1) process with parameters ρ_b and σ_b. h is the habit persistence parameter which makes consumption more persistent for higher values of h and vice versa. Finally, σ_c is the relative risk aversion parameter. The consumption process is derived from non-separable utility in labour and consumption. Variables with $*$ are the respective steady states.

The resource constraint is given by (29) with g_t as the exogenous government spending:

$$y_t = \frac{c_*}{y_*}c_t + \frac{i_*}{y_*}i_t + \frac{r_*^k k_*}{y_*}u_t + g_t \tag{29}$$

Exogenous government spending is also affected by the productivity shock such that:

$$g_t = \rho_g g_{t-1} + \epsilon_t^g + \rho_{ga}\epsilon_t^a \tag{30}$$

Investment Euler equation is derived from the capital producers' optimization decision:

$$i_t = \frac{1}{1+\beta\gamma^{1-\sigma_c}}i_{t-1} + \frac{\beta\gamma^{1-\sigma_c}}{1+\beta\gamma^{1-\sigma_c}}E_t i_{t+1} + \frac{1}{(1+\beta\gamma^{1-\sigma_c})S''\gamma^2}q_t^k + \mu_t \tag{31}$$

where μ_t is the investment specific technology shock with parameters ρ_μ and σ_μ and is also called marginal efficiency of investment shock. β is the discount factor for the households. $S^{''}$ is the steady state elasticity of the capital adjustment cost function such that a higher value for it reduces the sensitivity of i_t to the real value of existing capital stock, q_t^k.

Existing capital stock itself evolves according to:

$$\bar{k}_t = (1 - \frac{i_*}{\bar{k}_*})\bar{k}_{t-1} + \frac{i_*}{\bar{k}_*} i_t + (1 + \beta\gamma^{1-\sigma_c})S^{''}\gamma^2 \frac{i_*}{\bar{k}_*}\mu_t \tag{32}$$

where $\bar{k}_t$ is the installed capital stock and $\frac{i_*}{\bar{k}_*}$ is the steady state ratio of investment to installed capital. Since there is a lag in the capital installation, capital services are a function of previously installed capital and the capital utilization decision taken by the entrepreneurs after observing the risk shock:

$$k_t = \bar{k}_{t-1} + u_t \tag{33}$$

where capital utilization, u_t, is a function of the rental rate of capital:

$$u_t = \frac{1-\varphi}{\varphi} r_t^k$$

such that a higher value for φ ($\in$ 0,1) reflects high adjustment costs in terms of consumption goods. Rental rate of capital , r_t^k, is assumed to be identical across the two sectors:

$$r_t^k = -(k_t^i - L_t^i) + w_t \tag{34}$$

where $i = s, m$ represent the finished goods and intermediate sector, respectively.

Wages, w_t, are determined by the wage Phillips curves:

$$w_t = \frac{(1-\zeta_w\beta\gamma^{1-\sigma_c})(1-\zeta_w)}{(1+\beta\gamma^{1-\sigma_c})\zeta_w((\lambda_w-1)\epsilon_w+1)}(w_t^h - w_t) - \frac{1+\iota_w\beta\gamma^{1-\sigma_c}}{1+\beta\gamma^{1-\sigma_c}}\pi_t + \frac{1}{1+\beta\gamma^{1-\sigma_c}}(w_{t-1}-\iota_w\pi_{t-1}) + \frac{\beta\gamma^{1-\sigma_c}}{1+\beta\gamma^{1-\sigma_c}}\mathbb{E}_t[w_{t+1}+\pi_{t+1}] + \lambda_{w,t} \tag{35}$$

where ζ_w, ι_w and ϵ_w are the Calvo parameter for wage stickiness, degree of indexation and the curvature parameter in the Kimball aggregator for wages, respectively. $\lambda_{w,t}$ is the wage markup shock following an ARMA(1,1) process similar to SW with parameters ρ_w, σ_w and μ_w. w_t^h is the household's marginal rate of substitution between consumption and labor:

$$w_t^h = \frac{1}{1-\frac{h}{\gamma}}(c_t - \frac{h}{\gamma}c_{t-1}) + \sigma_l L_t \tag{36}$$

The model is closed with the central bank following a feedback rule of the type in equation (37). The central bank adjusts the nominal short-term interest rate in response to its lagged value, inflation and change in the inflation gap, in addition to output gap and change in the output gap:

$$R_t = \rho_R R_{t-1} + (1-\rho_R)[r_\pi(\pi_t - \pi_t^*) + r_y(y_t - y_t^*)] + r_{\triangle y}[(y_t - y_t^*) - (y_{t-1} - y_{t-1}^*)] + m_t^r \tag{37}$$

where y_t^* is the flexible level of output. π_t^* is the target level of inflation which evolves according to an AR(1) proces with parameters ρ_{π^*} and σ_{π^*}. The monetary policy shock, m_t^r, also follows an AR(1) process with parameters ρ_r and σ_r.

Table 4: Prior and Posterior Estimates of Structural Parameters

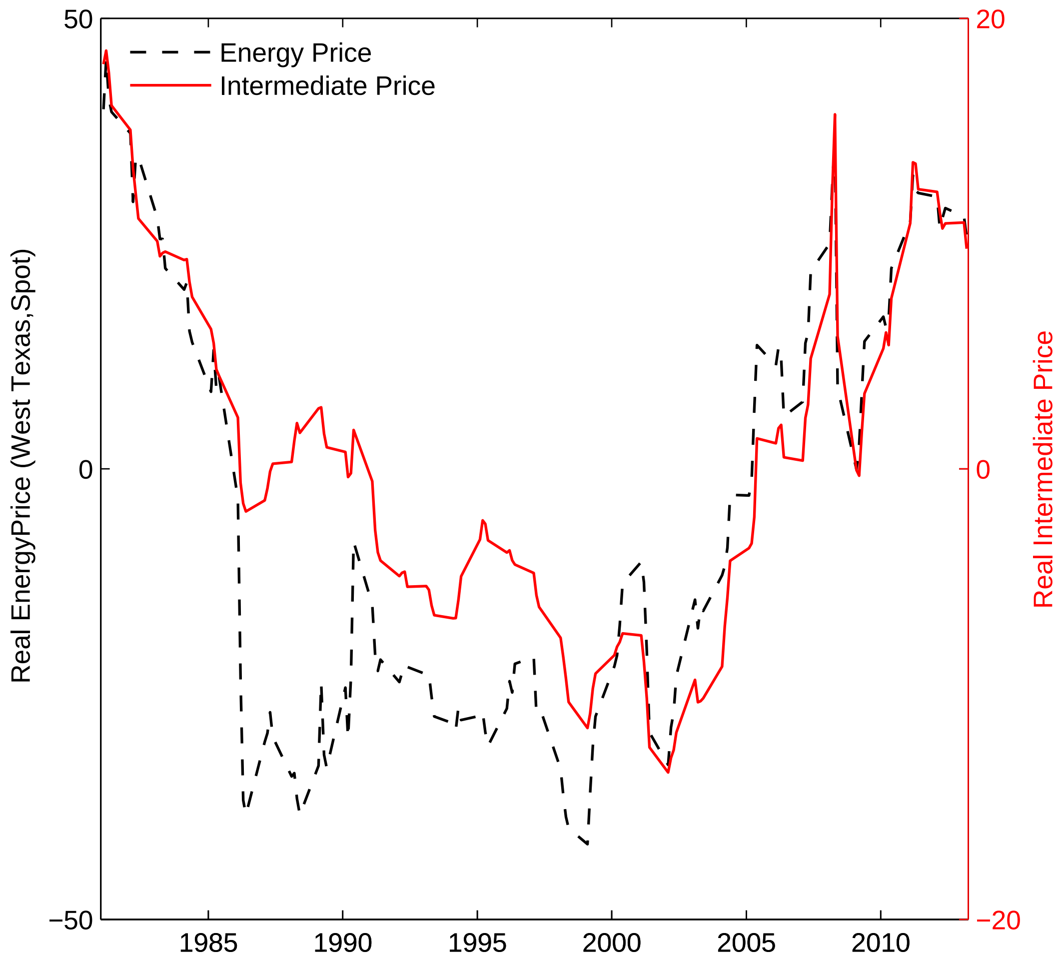
	Prior Distribution			Posterior Distribution			
				SW-BGG		SW-BGG-I	
	type	Mean	st. dev.	Mean	st. dev.	Mean	st. dev
structural parameters:							
φ	Normal	4.000	1.500	3.440	0.615	5.256	0.046
σ_c	Normal	1.500	0.375	1.580	0.158	0.912	0.012
h	Beta	0.700	0.100	0.340	0.055	0.707	0.003
ξ_w	Beta	0.500	0.100	0.750	0.102	0.946	0.001
σ_l	Normal	2.000	0.750	1.850	0.307	1.527	0.016
ξ_p^{**}	Beta	0.750	0.100	-	-	0.587	0.002
ξ_p^m	Beta	0.400	0.100	-	-	0.460	0.006
ι_w	Beta	0.500	0.150	0.310	0.159	0.220	0.005
ι_p	Beta	0.500	0.150	0.200	0.063	-	-
ψ	Beta	0.500	0.150	0.610	0.080	0.227	0.003
ϕ_p	Normal	1.250	0.120	1.670	0.071	1.355	0.004
r_π	Normal	1.500	0.250	1.450	0.065	1.423	0.009
ρ_r	Beta	0.750	0.100	0.710	0.043	0.766	0.003
r_y	Normal	0.130	0.050	0.030	0.008	0.006	0.002
$r_{\triangle y}$	Normal	0.125	0.050	0.170	0.028	0.112	0.001
π_*	Gamma	0.625	0.100	0.700	0.065	0.656	0.004
$\bar{l}$	Normal	0.000	2.000	-0.270	1.574	1.153	0.131
γ	Normal	0.400	0.100	0.500	0.023	0.404	0.003
α	Normal	0.300	0.050	0.230	0.030	0.286	0.003
SP_*	Beta	2.000	0.100	1.810	0.099	1.959	0.007
$\zeta_{sp,b}$	Beta	0.050	0.005	0.049	0.005	0.051	0.000

**ξ_p *in SW-BGG is calibrated to equal the posterior mean of* ξ_p *in SW-BGG-I.*

Table 5: Prior and Posterior Estimates of Shock Processes

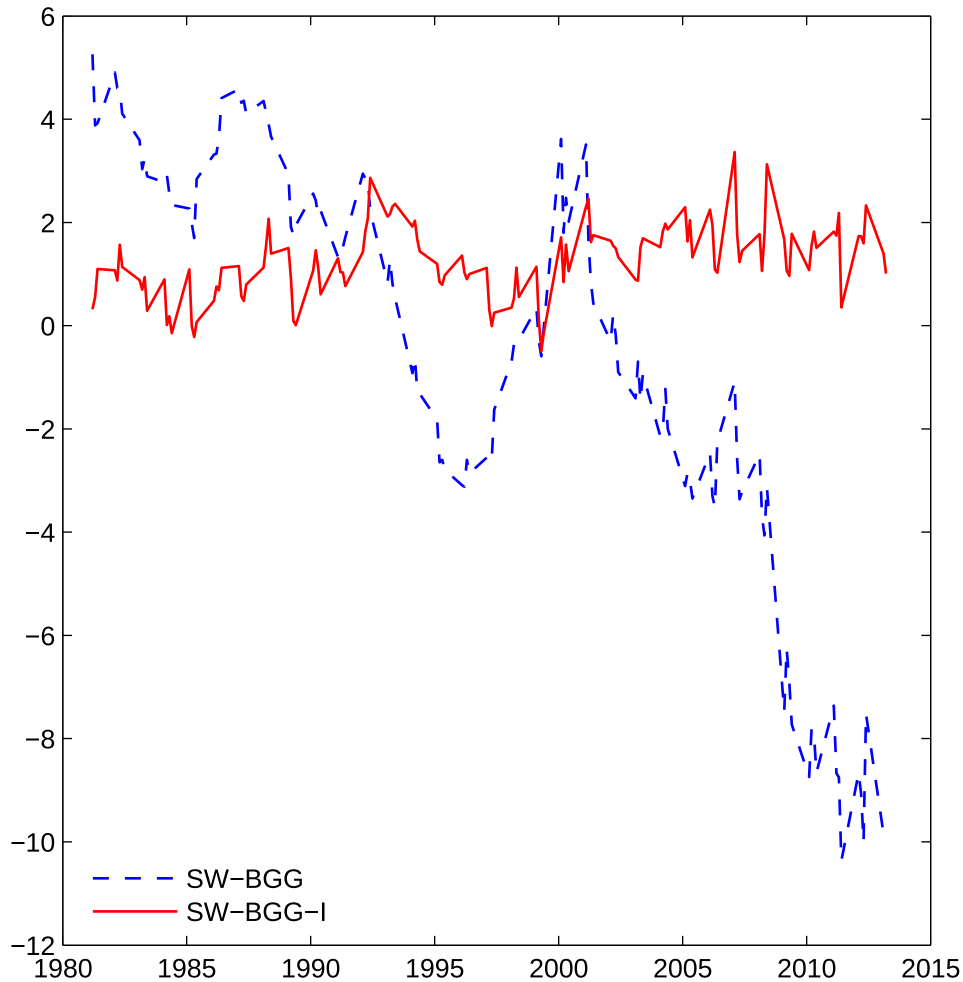
	Prior Distribution			Posterior Distribution			
				SW-BGG		SW-BGG-I	
	type	Mean	st. dev.	Mean	st. dev.	Mean	st. dev
persistence of exogenous shocks:							
ρ_a	Beta	0.500	0.200	0.886	0.025	0.995	0.002
ρ_{a^f}	Beta	0.500	0.200	-	-	0.616	0.002
ρ_{ei}	Beta	0.500	0.200	-	-	0.165	0.007
ρ_{ei^1}	Beta	0.500	0.200	-	-	0.012	0.001
$\rho_{\bar{\sigma}}$	Beta	0.750	0.150	0.972	0.007	0.987	0.002
ρ_b	Beta	0.500	0.200	0.994	0.004	0.996	0.001
ρ_g	Beta	0.500	0.200	0.982	0.009	0.986	0.004
ρ_μ	Beta	0.500	0.200	0.994	0.003	0.998	0.002
ρ_r	Beta	0.500	0.200	0.103	0.053	0.206	0.012
ρ_π	Beta	0.500	0.200	0.927	0.020	-	-
ρ_{π^*}	Beta	0.500	0.200	0.859	0.024	0.899	0.008
ρ_w	Beta	0.500	0.200	0.886	0.017	0.499	0.007
μ_p	Beta	0.500	0.200	0.748	0.083	-	-
μ_w	Beta	0.500	0.200	0.796	0.167	0.771	0.005
ρ_{ga}	Normal	0.500	0.250	0.480	0.114	0.398	0.006
$\rho_{\bar{\sigma},n}$	Inv.Gamma	1.000	2.000	0.741	0.042	0.664	0.039
σ_a	Inv.Gamma	0.100	2.000	0.364	0.025	0.570	0.038
σ_{a^f}	Inv.Gamma	1.000	2.000	-	-	1.473	0.064
σ_{ei}	Inv.Gamma	0.100	2.000	-	-	0.969	0.059
$\sigma_{\bar{\sigma}}$	Inv.Gamma	0.050	4.000	0.054	0.005	0.054	0.005
σ_b	Inv.Gamma	0.100	2.000	0.029	0.004	0.027	0.002
σ_g	Inv.Gamma	0.010	2.000	0.456	0.030	0.543	0.041
σ_μ	Inv.Gamma	0.100	2.000	0.350	0.058	0.249	0.020
σ_r	Inv.Gamma	0.100	2.000	0.196	0.018	0.222	0.015
σ_π	Inv.Gamma	0.100	2.000	0.106	0.012	-	-
σ_{π^*}	Inv.Gamma	0.100	2.000	0.161	0.027	0.163	0.022
σ_w	Inv.Gamma	0.100	2.000	0.361	0.058	0.476	0.030

Figure 1: **Evolution of Actual Energy and Intermediate Prices**



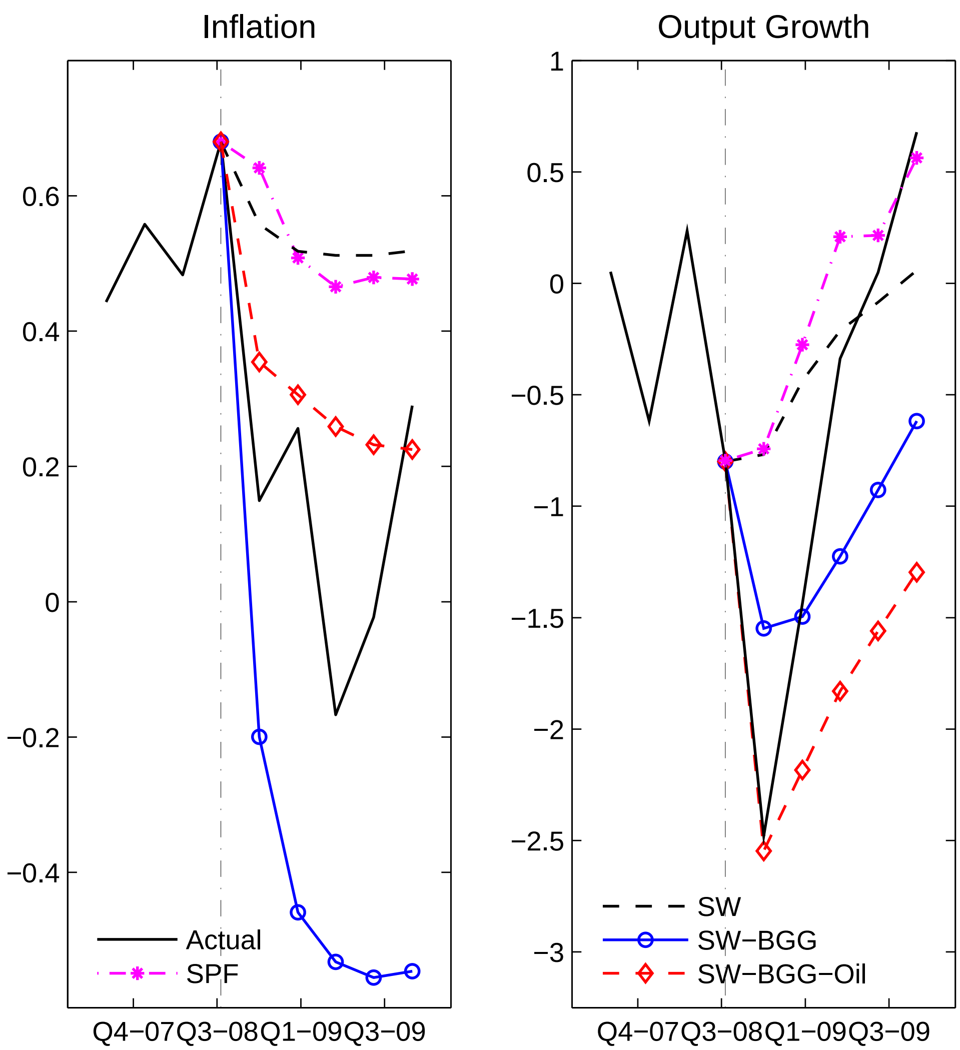
Note: The dashed black line is the log of deflated Energy Prices. The solid red line is the log of deflated intermediate prices. Both the data series are seasonally adjusted and are obtained from the St. Louis FED database. We deflate the two series using the GDP deflator. The intermediate price series is the Producer Price Index by Commodity Intermediate Materials: Supplies & Components (PPIITM). The energy price series is the Producer Price Index: Finished Energy Goods (PPIFEG).

Figure 2: **Marginal Cost with and without Intermediate Sector**



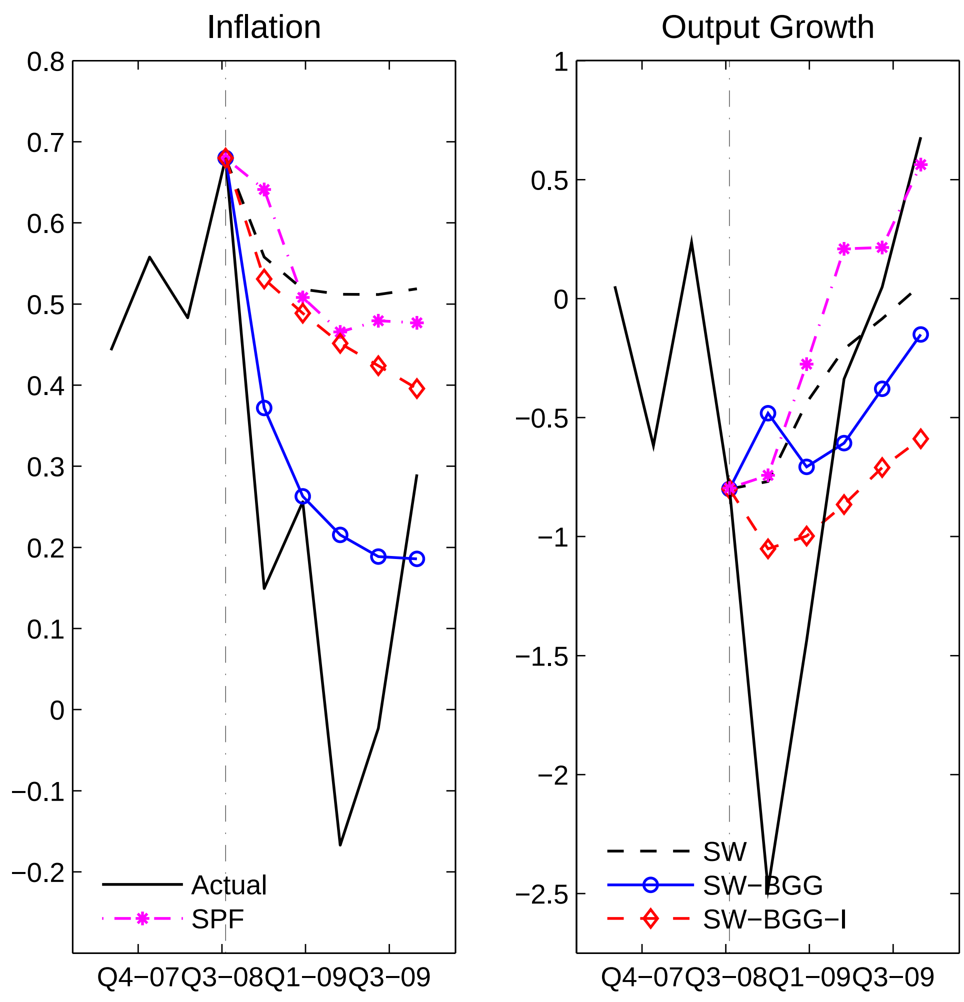
Note: The dashed blue line is the smoothed marginal cost, $E[mc_t|Y_{1:T_{full}}]$, from the SW-BGG. The solid red line is the smoothed marginal cost from the SW-BGG-I.

Figure 3: **Forecasts of Inflation and Output Growth**



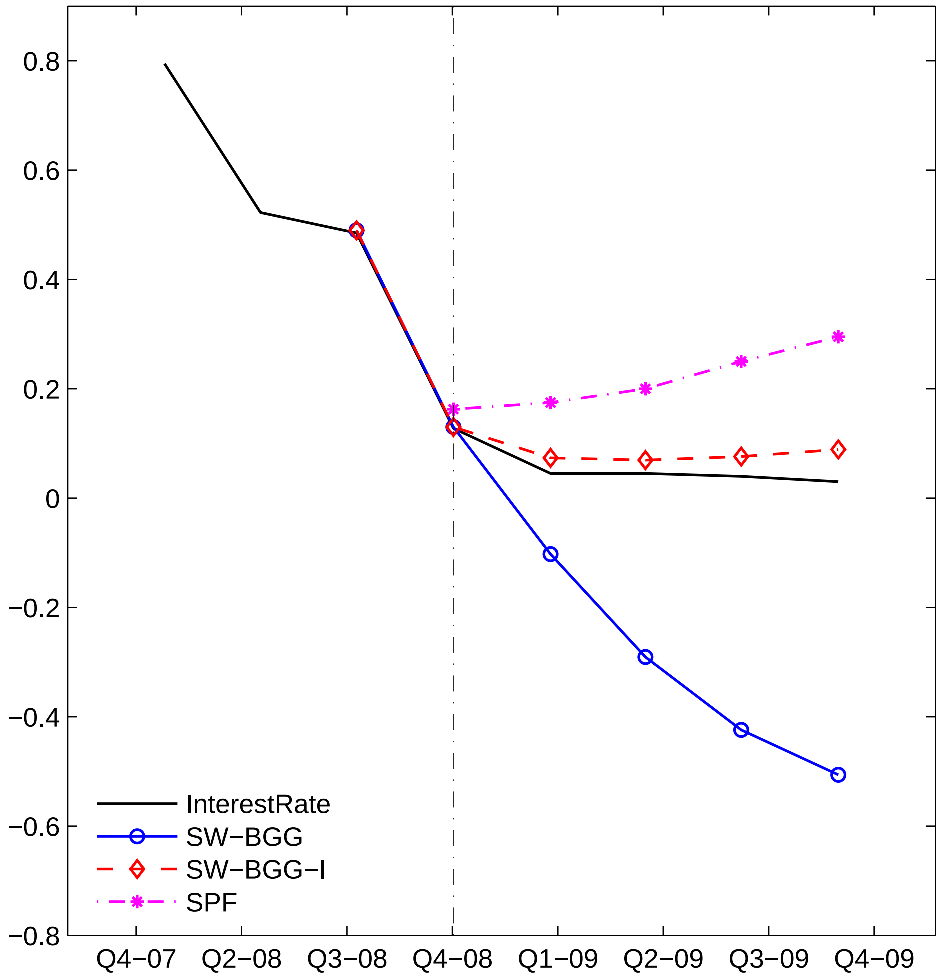
Note: The solid black line in the two panels is the data for inflation and output growth, respectively. Dashed red line with diamonds is the forecast from the SW-BGG-I whereas the solid blue line with circiles is the forecast from the SW-BGG. Dashed black line plots the SW forecast. Forecast from SPF is shown with the star-dotted-dashed magenta line.

Figure 4: **Forecasts of Inflation and Output Growth without the Anticipated Component of the Risk shock**



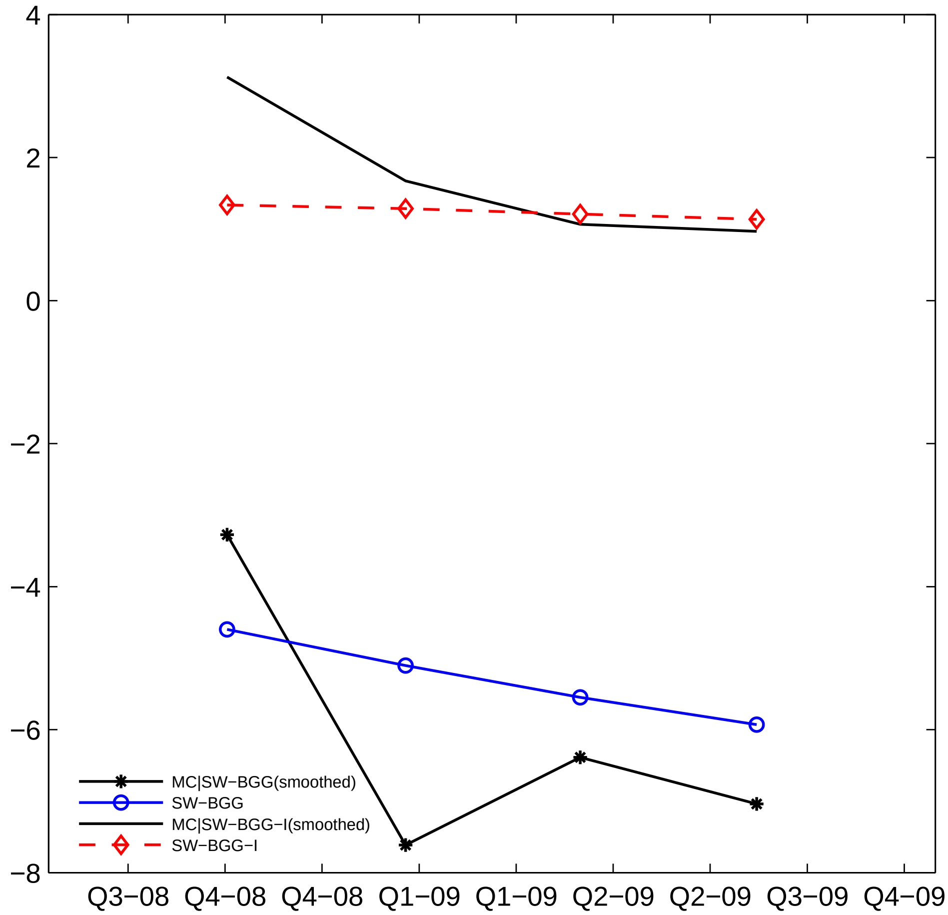
Note: The solid black line in the two panels is the data for inflation and output growth, respectively. Dashed red line with diamonds is the forecast from the SW-BGG-I whereas the solid blue line with circiles is the forecast from the SW-BGG. Dashed black line plots the SW forecast. Forecast from SPF is shown with the star-dotted-dashed magenta line.

Figure 5: **Forecasts of the Federal Funds Rate**



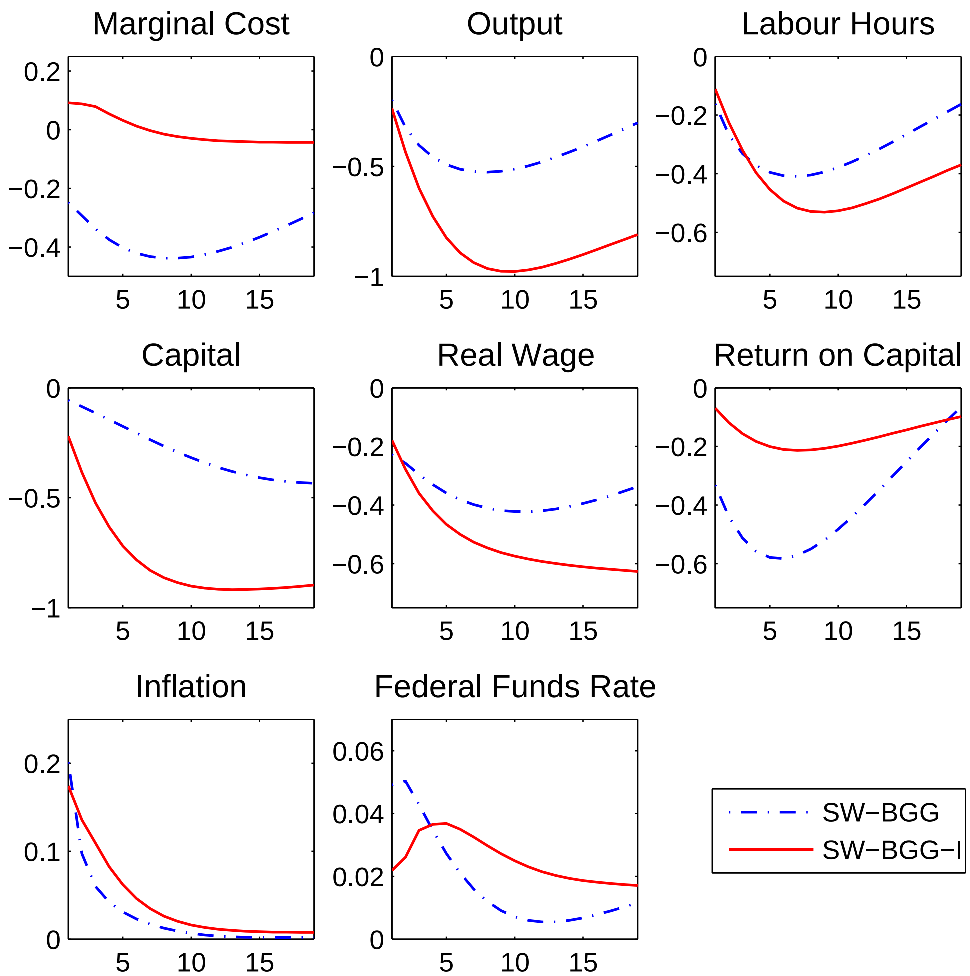
Note: Since model forecasts are conditional on Quarter 4, 2008 interest rate and spread data, the first forecast period for interest rate is Quarter1, 2009. The solid black line is the data for Federal Funds Rate. Dashed red line with diamonds is the forecast from the SW-BGG-I whereas dashed blue line is the forecast from the SW-BGG. The star-dotted-dashed line of magenta color is the SPF forecast.

Figure 6: **Marginal Cost and its Forecast**



Note: The solid black line is the smoothed marginal cost, $E[mc_t|Y_{1:T_{full}}]$, from the SW-BGG-I. The solid-star black line is the smoothed marginal cost from the SW-BGG. The colored lines show the forecasts where dashed red line with diamonds is the forecast from the SW-BGG-I and the solid blue line with circles is the forecast from the SW-BGG.

Figure 7: **Impulse Responses to Intermediate Input and Price Markup shocks**



Note: The dashed black blue line is the IRF to the price markup shock in the SW-BGG. The solid red line is the IRF to the intermediate input shock in the SW-BGG-I.