Inflation in the Great Recession and New Keynesian Models

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Abstract

It has been argued that existing DSGE models cannot properly account for the evolution of key macroeconomic variables during and following the recent great recession, and that models in which inflation depends on economic slack cannot explain the recent muted behavior of inflation, given the sharp drop in output that occurred in 2008-09. In this paper, we use a standard DSGE model available prior to the recent crisis and estimated with data up to 2008:Q3 to explain the behavior of key macroeconomic variables since the crisis. We show that as soon as the financial stress jumped in the fourth quarter of 2008, the model successfully predicts a sharp contraction in economic activity along with a modest and more protracted decline in inflation. The model does so even though inflation remains very dependent on the evolution of economic activity and of monetary policy. We conclude that while the model considered does not capture all short-term fluctuations in key macroeconomic variables, it has proven to be surprisingly accurate during the recent crisis and the subsequent recovery.

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1 Introduction

As dramatic as the recent Great Recession has been, it constitutes a potential test for existing macroeconomic models. Prominent researchers have argued that existing DSGE models cannot properly account for the evolution of key macroeconomic variables during and following the crisis. For instance, Hall (2011), in his Presidential Address, has called for a fundamental reconsideration of models in which inflation depends on a measure of slack in economic activity. He suggests that all theories based on the concept of non-accelerating inflation rate of unemployment or NAIRU should have predicted more and more deflation as long as the unemployment rate has remained above a natural rate of, say, around 6 percent. Since inflation has declined somewhat in early 2009 and then remained contained for a few years, Hall (2011) concludes that such theories based on a concept of slack must be wrong. Most notably, he states that popular DSGE models based on the simple New Keynesian Phillips curve according to which prices are set on the basis of a markup over expected future marginal costs "cannot explain the stabilization of inflation at positive rates in the presence of long-lasting slack" as they rely on a NAIRU principle. Hall (2011) thus concludes that inflation behaves in a nearly exogenous fashion.

Similarly, Ball and Mazumder (2011) argue that Phillips curves estimated over the 1960-2007 period in the US cannot explain the behavior of inflation in the 2008-2010 period. Moreover, they conclude that the "Great Recession provides fresh evidence against the New Keynesian Philips curve with rational expectations." They stress the fact that the fit of that equation deteriorates once data for the years 2008-2010 are added to the sample. One of the reasons for this is that the labor share, a proxy for firms marginal costs, declines dramatically during the crisis, resulting in a change in the comovement with other measures of slack, such as the unemployment rate.

A further challenge to the New Keynesian Phillips curve is raised by King and Watson (2012) who find a large discrepancy between the inflation predicted by a popular DSGE model, the Smets and Wouters (2007) model, and actual inflation. They thus conclude that the model can successfully explain the behavior of inflation only when assuming the existence of large exogenous markup shocks. This is disturbing to the extent that such mark-up shocks are difficult to interpret and have small effects on variables other than inflation.

In this paper, we use such a standard DSGE model, which was available prior to the recent crisis and that is estimated with data up to 2008, to explain the behavior of key macroeconomic variables since the crisis. The model used is the Smets and Wouters (2007) model extended to include financial frictions as in Bernanke et al. (1999) and Christiano et al. (2003). We show that as soon as the financial stress jumped in the fall of 2008, the model successfully predicts a sharp contraction in economic activity along with a modest and more protracted decline in inflation. The model can explain the comovement of output and inflation in the aftermath of the Great Recession. The evidence that we provide is based on out-of-sample forecasts and makes sure that the model is not estimated to fit the post-2008 data. The forecast of output is quite weak (indeed somewhat weaker than actual), yet inflation is projected to remain in the neighborhood of 1%. The out-of-sample forecast of inflation does not perfectly capture the high frequency movements in inflation which were largely due to oil price fluctuations, but it does capture the overall contour of actual inflation data. These results contrast with the commonly held belief that such models are bound to fail to capture the broad contours of the Great Recession and the near stability of inflation. We will thus re-interpret the results of Hall (2011), Ball and Mazumder (2011), and King and Watson (2012), in the context of our model.

It is important to note that while inflation does not appear to have declined much even in the face of the sharp drop in real GDP in 2008 and 2009, it is in fact very dependent on the evolution of economic activity and of monetary policy, as we will show. The key to understand this is that inflation is more dependent on expected future marginal costs than on the current level of activity. Even though GDP growth contracted sharply, monetary policy has in fact been sufficiently stimulative to promise inflation in the future to remain near 2%. As a result, inflation expectations remained fairly stable. Well anchored inflation expectations imply that inflation did not need to decline much, even in the face of a big drop in economic activity.

While King and Watson (2012) have shown that price mark-up shocks are crucial to explain inflation fluctuations in the Smets and Wouters (2007) model, our variant of that model does not suffer from that problem. A key reason for the difference is that our estimated model involves a higher degree of price rigidities than is the case in Smets and Wouters (2007). This allows our model to successfully explain inflation with much smaller mark-up shocks. Yet, while the slope of the short-run Phillips curve is lower in our model than in Smets and Wouters (2007), monetary policy still has an important effect on inflation.

Our analysis leads us to conclude that while the model considered, which again was available before the recent crisis, does not capture all short-term fluctuations in key macroeconomic variables, it has proven to be surprisingly accurate during the recent crisis and the subsequent recovery. The remainder of this paper is organized as follows. Section 2 presents the model used for the empirical analysis. Section 3 discusses the post-2008 forecasts of key macroeconomic variables, and decomposes the inflation forecast to explain how predicted inflation remained so moderate despite the large drop in economic activity. It then proceeds with a discussion of the effects of monetary policy on inflation. Section 4 concludes. Information on the construction of the data set used for the empirical analysis as well as detailed estimation results and supplementary tables and figures are available in the Online Appendix.

2 The DSGE Model

The model considered is the one used in Smets and Wouters (2007), which is based on earlier work by Christiano et al. (2005) and Smets and Wouters (2003). It is a medium-scale DSGE model, which augments the standard neoclassical stochastic growth model with nominal price and wage rigidities as well as habit formation in consumption and investment adjustment costs. As discussed before, the model is augmented with financial frictions, as in Bernanke et al. (1999) and Christiano et al. (2003). All ingredients of the model were however publicly available prior to 2008. As such, the model does not include some of the features that may have been found to be relevant following the crisis.

2.1 The Smets-Wouters Model

We begin by briefly describing the log-linearized equilibrium conditions of the Smets and Wouters (2007) model. We follow Del Negro and Schorfheide (forthcoming) and detrend the non-stationary model variables by a stochastic rather than a deterministic trend.[1] Let $\tilde{z}_t$ be the linearly detrended log productivity process which follows the autoregressive law of motion

$$\tilde{z}_t = \rho_z \tilde{z}_{t-1} + \sigma_z \varepsilon_{z,t}. \tag{1}$$

We detrend all non stationary variables by $Z_t = e^{\gamma t + \frac{1}{1-\alpha}\tilde{z}_t}$, where γ is the steady state growth rate of the economy. The growth rate of Z_t in deviations from γ, denoted by z_t, follows the process:

$$z_t = \ln(Z_t/Z_{t-1}) - \gamma = \frac{1}{1-\alpha}(\rho_z - 1)\tilde{z}_{t-1} + \frac{1}{1-\alpha}\sigma_z \epsilon_{z,t}. \tag{2}$$

All variables in the following equations are expressed in log deviations from their non-stochastic steady state. Steady state values are denoted by $*$-subscripts and steady state formulas are provided in the technical appendix of Del Negro and Schorfheide (forthcoming).[2] The consumption Euler equation is given by:

$$\begin{aligned} c_t = &-\frac{(1-he^{-\gamma})}{\sigma_c(1+he^{-\gamma})}\left(R_t - \mathbb{E}_t[\pi_{t+1}] + b_t\right) + \frac{he^{-\gamma}}{(1+he^{-\gamma})}\left(c_{t-1} - z_t\right) \\ &+ \frac{1}{(1+he^{-\gamma})}\mathbb{E}_t\left[c_{t+1} + z_{t+1}\right] + \frac{(\sigma_c - 1)}{\sigma_c(1+he^{-\gamma})}\frac{w_* L_*}{c_*}\left(L_t - \mathbb{E}_t[L_{t+1}]\right), \end{aligned} \tag{3}$$

where c_t is consumption, L_t is labor supply, R_t is the nominal interest rate, and π_t is inflation. The exogenous process b_t drives a wedge between the intertemporal ratio of the marginal utility of consumption and the riskless real return $R_t - \mathbb{E}_t[\pi_{t+1}]$, and follows an AR(1) process with parameters ρ_b and σ_b. The parameters σ_c and h capture the degree of relative risk aversion and the degree of habit persistence in the utility function, respectively. The following condition expresses the relationship between the value of capital in terms of consumption q_t^k

[1] This approach makes it possible to express almost all equilibrium conditions in a way that encompasses both the trend-stationary total factor productivity process in Smets and Wouters (2007), as well as the case where technology follows a unit root process.

[2] Available at `http://economics.sas.upenn.edu/~schorf/research.htm`.

and the level of investment i_t measured in terms of consumption goods:

$$q_t^k = S'' e^{2\gamma}(1+\bar{\beta})\Big(i_t - \frac{1}{1+\bar{\beta}}\left(i_{t-1} - z_t\right) - \frac{\bar{\beta}}{1+\bar{\beta}}\mathbb{E}_t\left[i_{t+1} + z_{t+1}\right] - \mu_t\Big), \tag{4}$$

which is affected by both investment adjustment cost (S'' is the second derivative of the adjustment cost function) and by μ_t, an exogenous process called the "marginal efficiency of investment" that affects the rate of transformation between consumption and installed capital (see Greenwood et al. (1998)). The exogenous process μ_t follows an AR(1) process with parameters ρ_μ and σ_μ. The parameter $\bar{\beta} = \beta e^{(1-\sigma_c)\gamma}$ depends on the intertemporal discount rate in the utility function of the households β, the degree of relative risk aversion σ_c, and the steady-state growth rate γ.

The capital stock, $\bar{k}_t$, evolves as

$$\bar{k}_t = \left(1 - \frac{i_*}{\bar{k}_*}\right)\left(\bar{k}_{t-1} - z_t\right) + \frac{i_*}{\bar{k}_*} i_t + \frac{i_*}{\bar{k}_*} S'' e^{2\gamma}(1+\bar{\beta})\mu_t, \tag{5}$$

where $i_*/\bar{k}_*$ is the steady state ratio of investment to capital. The arbitrage condition between the return to capital and the riskless rate is:

$$\frac{r_*^k}{r_*^k + (1-\delta)}\mathbb{E}_t[r_{t+1}^k] + \frac{1-\delta}{r_*^k + (1-\delta)}\mathbb{E}_t[q_{t+1}^k] - q_t^k = R_t + b_t - \mathbb{E}_t[\pi_{t+1}], \tag{6}$$

where r_t^k is the rental rate of capital, r_*^k its steady state value, and δ the depreciation rate. Given that capital is subject to variable capacity utilization u_t, the relationship between $\bar{k}_t$ and the amount of capital effectively rented out to firms k_t is

$$k_t \;=\; u_t - z_t + \bar{k}_{t-1}. \tag{7}$$

The optimality condition determining the rate of utilization is given by

$$\frac{1-\psi}{\psi} r_t^k = u_t, \tag{8}$$

where ψ captures the utilization costs in terms of foregone consumption. Real marginal costs for firms are given by

$$mc_t \;=\; w_t + \alpha L_t - \alpha k_t, \tag{9}$$

where α is the income share of capital (after paying markups and fixed costs) in the production function. From the optimality conditions of goods producers it follows that all firms have the same capital-labor ratio:

$$k_t \;=\; w_t - r_t^k + L_t. \tag{10}$$

The production function is:

$$y_t \;=\; \Phi_p\left(\alpha k_t + (1-\alpha)L_t\right) + \mathcal{I}\{\rho_z < 1\}(\Phi_p - 1)\frac{1}{1-\alpha}\tilde{z}_t, \tag{11}$$

under trend stationarity. The last term $(\Phi_p - 1)\frac{1}{1-\alpha}\tilde{z}_t$ drops out if technology has a stochastic trend, because in this case one has to assume that the fixed costs are proportional to the trend. Similarly, the resource constraint is:

$$y_t = g_t + \frac{c_*}{y_*}c_t + \frac{i_*}{y_*}i_t + \frac{r_*^k k_*}{y_*}u_t - \mathcal{I}\{\rho_z < 1\}\frac{1}{1-\alpha}\tilde{z}_t, \tag{12}$$

where again the term $-\frac{1}{1-\alpha}\tilde{z}_t$ disappears if technology follows a unit root process. Government spending g_t is assumed to follow the exogenous process:

$$g_t = \rho_g g_{t-1} + \sigma_g \varepsilon_{g,t} + \eta_{gz}\sigma_z\varepsilon_{z,t}.$$

Finally, the price and wage Phillips curves are, respectively:

$$\pi_t = \frac{(1-\zeta_p\bar{\beta})(1-\zeta_p)}{(1+\iota_p\bar{\beta})\zeta_p((\Phi_p-1)\epsilon_p+1)}mc_t + \frac{\iota_p}{1+\iota_p\bar{\beta}}\pi_{t-1} + \frac{\bar{\beta}}{1+\iota_p\bar{\beta}}\mathbb{E}_t[\pi_{t+1}] + \lambda_{f,t}, \tag{13}$$

and

$$\begin{aligned} w_t = {} & \frac{(1-\zeta_w\bar{\beta})(1-\zeta_w)}{(1+\bar{\beta})\zeta_w((\lambda_w-1)\epsilon_w+1)}\left(w_t^h - w_t\right) - \frac{1+\iota_w\bar{\beta}}{1+\bar{\beta}}\pi_t + \frac{1}{1+\bar{\beta}}\left(w_{t-1} - z_t - \iota_w\pi_{t-1}\right) \\ & + \frac{\bar{\beta}}{1+\bar{\beta}}\mathbb{E}_t\left[w_{t+1} + z_{t+1} + \pi_{t+1}\right] + \lambda_{w,t}, \end{aligned} \tag{14}$$

where ζ_p, ι_p, and ϵ_p are the Calvo parameter, the degree of indexation, and the curvature parameters in the Kimball aggregator for prices, and ζ_w, ι_w, and ϵ_w are the corresponding parameters for wages. w_t^h measures the household's marginal rate of substitution between consumption and labor, and is given by:

$$w_t^h = \frac{1}{1-he^{-\gamma}}\left(c_t - he^{-\gamma}c_{t-1} + he^{-\gamma}z_t\right) + \nu_l L_t, \tag{15}$$

where ν_l characterizes the curvature of the disutility of labor (and would equal the inverse of the Frisch elasticity in absence of wage rigidities). The mark-ups $\lambda_{f,t}$ and $\lambda_{w,t}$ follow exogenous ARMA(1,1) processes

$$\lambda_{f,t} = \rho_{\lambda_f}\lambda_{f,t-1} + \sigma_{\lambda_f}\varepsilon_{\lambda_f,t} + \eta_{\lambda_f}\sigma_{\lambda_f}\varepsilon_{\lambda_f,t-1}, \text{ and}$$

$$\lambda_{w,t} = \rho_{\lambda_w}\lambda_{w,t-1} + \sigma_{\lambda_w}\varepsilon_{\lambda_w,t} + \eta_{\lambda_w}\sigma_{\lambda_w}\varepsilon_{\lambda_w,t-1},$$

respectively. Finally, the monetary authority follows a generalized feedback rule:

$$\begin{aligned} R_t \;=\; & \rho_R R_{t-1} + (1-\rho_R)\Big(\psi_1\pi_t + \psi_2(y_t - y_t^f)\Big) \\ & + \psi_3\Big((y_t - y_t^f) - (y_{t-1} - y_{t-1}^f)\Big) + r_t^m, \end{aligned} \tag{16}$$

where the flexible price/wage output y_t^f is obtained from solving the version of the model without nominal rigidities (that is, Equations (3) through (12) and (15)), and the residual r_t^m follows an AR(1) process with parameters ρ_{r^m} and σ_{r^m}.

2.2 Adding Observed Long Run Inflation Expectations

In order to capture the rise and fall of inflation and interest rates in the estimation sample, we replace the constant target inflation rate by a time-varying target inflation. While time-varying target rates have been frequently used for the specification of monetary policy rules in DSGE model (e.g., Erceg and Levin (2003) and Smets and Wouters (2003), among others), we follow the approach of Aruoba and Schorfheide (2008) and Del Negro and Eusepi (2011) and include data on long-run inflation expectations as an observable into the estimation of the DSGE model. At each point in time, the long-run inflation expectations essentially determine the level of the target inflation rate. To the extent that long-run inflation expectations at the forecast origin contain information about the central bank's objective function, e.g. the desire to stabilize inflation at 2%, this information is automatically included in the forecast. Clark (2011) constructs a Bayesian VAR in which variables are expressed in deviations from long-run trends. For inflation and interest rates these long-run trends are given by long-horizon Blue Chip forecasts and the VAR includes equations that capture the evolution of these forecasts. Our treatment of inflation in the DSGE model bears similarities to Clark (2011)'s VAR.

More specifically, for the SW model the interest-rate feedback rule of the central bank (16) is modified as follows:[3]

$$\begin{aligned} R_t &= \rho_R R_{t-1} + (1-\rho_R)\Big(\psi_1(\pi_t - \pi_t^*) + \psi_2(y_t - y_t^f)\Big) \\ &\quad + \psi_3\Big((y_t - y_t^f) - (y_{t-1} - y_{t-1}^f)\Big) + r_t^m. \end{aligned} \tag{17}$$

The time-varying inflation target evolves according to:

$$\pi_t^* = \rho_{\pi^*}\pi_{t-1}^* + \sigma_{\pi^*}\epsilon_{\pi^*,t}, \tag{18}$$

where $0 < \rho_{\pi^*} < 1$ and $\epsilon_{\pi^*,t}$ is an iid shock. We follow Erceg and Levin (2003) and model π_t^* as following a stationary process, although our prior for ρ_{π^*} will force this process to be highly persistent (see Panel III of Table A-1). The assumption that the changes in the target inflation rate are exogenous is, to some extent, a short-cut. For instance, the learning models of Sargent (1999) or Primiceri (2006) would suggest that the rise in the target inflation rate in the 1970's and the subsequent drop is due to policy makers learning about the output-inflation trade-off and trying to set inflation optimally. We are abstracting from such a mechanism in our specification.

2.3 Adding Financial Frictions

We now add financial frictions to the SW model building on the work of Bernanke et al. (1999), Christiano et al. (2003), De Graeve (2008), and Christiano et al. (2009). This amounts to replacing (6) with the following conditions:

$$E_t\left[\tilde{R}_{t+1}^k - R_t\right] = b_t + \zeta_{sp,b}\left(q_t^k + \bar{k}_t - n_t\right) + \tilde{\sigma}_{\omega,t} \tag{19}$$

and

$$\tilde{R}_t^k - \pi_t = \frac{r_*^k}{r_*^k + (1-\delta)} r_t^k + \frac{(1-\delta)}{r_*^k + (1-\delta)} q_t^k - q_{t-1}^k, \tag{20}$$

[3] We follow the specification in Del Negro and Eusepi (2011), while Aruoba and Schorfheide (2008) assume that the inflation target also affects the intercept in the feedback rule.

where $\tilde{R}^k_t$ is the gross nominal return on capital for entrepreneurs, n_t is entrepreneurial equity, and $\tilde{\sigma}_{\omega,t}$ captures mean-preserving changes in the cross-sectional dispersion of ability across entrepreneurs (see Christiano et al. (2009)) and follows an AR(1) process with parameters ρ_{σ_ω} and σ_{σ_ω}. The second condition defines the return on capital, while the first one determines the spread between the expected return on capital and the riskless rate.[4] The following condition describes the evolution of entrepreneurial net worth:

$$\begin{aligned}\hat{n}_t \;=\;& \zeta_{n,\tilde{R}^k}\left(\tilde{R}^k_t - \pi_t\right) - \zeta_{n,R}\left(R_{t-1} - \pi_t\right) + \zeta_{n,qK}\left(q^k_{t-1} + \bar{k}_{t-1}\right) + \zeta_{n,n} n_{t-1} \\ & - \tfrac{\zeta_{n,\sigma_\omega}}{\zeta_{sp,\sigma_\omega}} \tilde{\sigma}_{\omega,t-1}.\end{aligned} \tag{21}$$

2.4 Fundamental Inflation

To understand the behavior of inflation, it will be useful to extract from the model-implied inflation series an estimate of "fundamental inflation" as in King and Watson (2012), and similarly to Galí and Gertler (1999) and Sbordone (2005). To obtain this measure, we rewrite the Phillips curve (13) as:

$$\hat{\pi}_t = \frac{\iota_p}{1+\iota_p\bar{\beta}}\hat{\pi}_{t-1} + \frac{\bar{\beta}}{1+\iota_p\bar{\beta}}\mathbb{E}_t[\hat{\pi}_{t+1}] + \kappa\widehat{mc}_t + \hat{\lambda}_{f,t}, \tag{22}$$

where $\kappa = \frac{(1-\zeta_p\bar{\beta})(1-\zeta_p)}{(1+\iota_p\bar{\beta})\zeta_p((\Phi_p-1)\epsilon_p+1)}$. Quasi-differencing inflation by defining $\Delta\pi_t = \hat{\pi}_t - \iota_p\hat{\pi}_{t-1}$, one can simplify the expression for the Phillips curve as follows:

$$\Delta\pi_t = \bar{\beta}\mathbb{E}_t[\Delta\pi_{t+1}] + (1+\iota_p\bar{\beta})\left(\kappa\widehat{mc}_t + \hat{\lambda}_{f,t}\right). \tag{23}$$

This difference equation can be solved forward to obtain

$$\Delta\pi_t = (1+\iota_p\bar{\beta})\kappa\sum_{j=0}^{\infty}\bar{\beta}^j\mathbb{E}_t[\widehat{mc}_{t+j}] + (1+\iota_p\bar{\beta})\sum_{j=0}^{\infty}\bar{\beta}^j\mathbb{E}_t[\lambda_{f,t+j}]. \tag{24}$$

The first component captures the effect of the sum of discounted future marginal costs on current inflation, whereas the second term captures the contribution of future mark-up shocks. Defining

$$S^\infty_t = \sum_{j=0}^{\infty}\bar{\beta}^j\mathbb{E}_t[mc_{t+j}], \tag{25}$$

[4] Note that if $\zeta_{sp,b} = 0$ and the financial friction shocks are zero, (6) coincides with (19) plus (20).

and noting that the mark-up shock evolves exogenously as AR(1) process with autoregressive parameter ρ_{λ_f} we can decompose inflation into

$$\begin{aligned}\hat{\pi}_t &= (1-\iota_p L)^{-1}\kappa(1+\iota_p\bar{\beta})S_t^\infty + (1-\iota_L)^{-1}\frac{1}{1-\bar{\beta}\rho_{\lambda_f}}\hat{\lambda}_{f,t} \\ &= \tilde{\pi}_t + (1-\iota_p L)^{-1}\frac{1}{1-\bar{\beta}\rho_{\lambda_f}}\hat{\lambda}_{f,t},\end{aligned}$$

where L denotes the lag operator and

$$\tilde{\pi}_t = \kappa(1+\iota_p\bar{\beta})(1-\iota_p L)^{-1}S_t^\infty. \tag{26}$$

We refer to the first term on the right-hand-side of (26), $\tilde{\pi}_t$, as *fundamental inflation*. Fundamental inflation corresponds to the discounted sum of expected marginal costs.[5] Thus, our decomposition removes the direct effect of mark-up shocks from the observed inflation. Note, however, that the summands in (26) are not orthogonal. Fundamental inflation still depends on $\lambda_{f,t}$ indirectly, through the effect of the markup shock on current and future expected marginal costs.

2.5 State-Space Representation and Estimation

We use the method in Sims (2002) to solve the log-linear approximation of the DSGE model. We collect all the DSGE model parameters in the vector θ, stack the structural shocks in the vector ϵ_t, and derive a state-space representation for our vector of observables y_t. The state-space representation is comprised of the transition equation:

$$s_t = \mathcal{T}(\theta)s_{t-1} + \mathcal{R}(\theta)\epsilon_t, \tag{27}$$

which summarizes the evolution of the states s_t, and the measurement equation:

$$y_t = \mathcal{Z}(\theta)s_t + \mathcal{D}(\theta), \tag{28}$$

which maps the states onto the vector of observables y_t, where $\mathcal{D}(\theta)$ represents the vector of steady state values for these observables. The measurement equations for real output,

[5] Our measure differs however slightly from the measure of Galí and Gertler (1999) and Sbordone (2005), who define fundamental inflation as $\tilde{\pi}_t = \iota_p\pi_t + \kappa(1+\iota_p\bar{\beta})S_t^\infty$.

consumption, investment, and real wage growth, hours, inflation, and interest rates are given by:

$$\begin{aligned}
\textit{Output growth} &= \gamma + 100\left(y_t - y_{t-1} + z_t\right) \\
\textit{Consumption growth} &= \gamma + 100\left(c_t - c_{t-1} + z_t\right) \\
\textit{Investment growth} &= \gamma + 100\left(i_t - i_{t-1} + z_t\right) \\
\textit{Real Wage growth} &= \gamma + 100\left(w_t - w_{t-1} + z_t\right)\ , \\
\textit{Hours} &= \bar{l} + 100 l_t \\
\textit{Inflation} &= \pi_* + 100\pi_t \\
\textit{FFR} &= R_* + 100 R_t
\end{aligned} \tag{29}$$

where all variables are measured in percent, where π_* and R_* measure the steady state level of net inflation and short term nominal interest rates, respectively and where $\bar{l}$ captures the mean of hours (this variable is measured as an index).

To incorporate information about low-frequency movements of inflation the set of measurement equations (29) is augmented by

$$\begin{aligned}
\pi_t^{O,40} &= \pi_* + 100 I\!E_t\left[\frac{1}{40}\sum_{k=1}^{40}\pi_{t+k}\right] \\
&= \pi_* + \frac{100}{40}\Psi_2(\theta)_{(\pi,.)}(I - \Phi_1(\theta))^{-1}\left(I - [\Phi_1(\theta)]^{40}\right)\Phi_1(\theta)s_t,
\end{aligned} \tag{30}$$

where $\pi_t^{O,40}$ represents observed long run inflation expectations obtained from surveys (in percent per quarter), and the right-hand-side of (30) corresponds to expectations obtained from the DSGE model (in deviation from the mean π_*). The second line shows how to compute these expectations using the transition equation (27) and the measurement equation for inflation. $\Psi_2(\theta)_{(\pi,.)}$ is the row of $\Psi_2(\theta)$ in (28) that corresponds to inflation. Finally, we add a measurement equation for the spread:

$$\text{Spread} = SP_* + 100 I\!E_t\left[\tilde{R}^k_{t+1} - R_t\right], \tag{31}$$

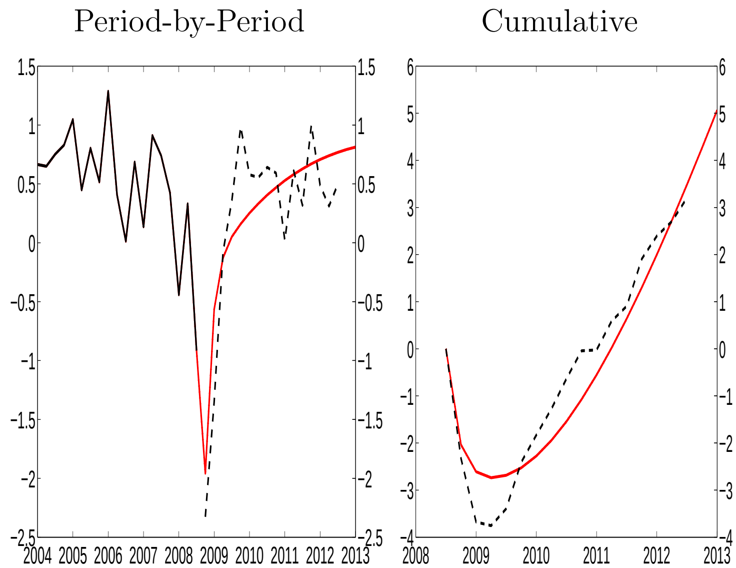
where the parameter SP_* measures the steady state spread.

We use Bayesian techniques in the subsequent empirical analysis, which require the specification of a prior distribution for the model parameters. For most of the parameters we use the same marginal prior distributions as Smets and Wouters (2007). There are two important exceptions. First, the original prior for the quarterly steady state inflation rate π_* used by Smets and Wouters (2007) is tightly centered around 0.62% (which is about 2.5% annualized) with a standard deviation of 0.1%. We favor a looser prior, one that has less influence on the model's forecasting performance, that is centered at 0.75% and is has a standard deviation of 0.4%. Second, for the financial frictions mechanism we specify priors for the parameters SP_*, $\zeta_{sp,b}$, ρ_{σ_ω}, and σ_{σ_ω}. We and fix the parameters $\bar{F}_*$ and γ_* (steady state default probability and survival rate of entrepreneurs, respectively). In turn, these parameters imply values for the parameters of (21). A summary of the prior is provided in Table A-1 in Appendix B.

3 Empirical Analysis

The empirical analysis consists of three parts. First, we examine the forecast performance of the DSGE model introduced in Section 2 during the 2007-2009 recession. We will show that the model, in which inflation is determined by a New Keynesian Phillips curve is able to predict inflation quite well (Section 3.1). Second, we compute fundamental inflation $\tilde{\pi}_t$ defined in (26). Unlike King and Watson (2012), we find that the model-generated $\tilde{\pi}_t$ tracks the low frequency component of actual inflation quite well (Section 3.2). We show that the ability to track inflation relies on a larger estimate of nominal price rigidity than the one reported in Smets and Wouters (2007). Third, we examine whether a flatter short-run Phillips curve implies that monetary policy looses some of its ability to stabilize inflation (Section 3.3). The construction of the data set is summarized in Appendix A. Most of our results are based on the version of the DSGE model that includes the time-varying target inflation rate (see Section 2.2) and financial frictions (see Section 2.3). We refer to this model as SWπFF. In some instances we provide comparisons to the basic Smets-Wouters model (see Section 2.1), denoted by SW, and the Smets-Wouters model with time-varying inflation target, SWπ.

Figure 1: Forecasts of Output Growth



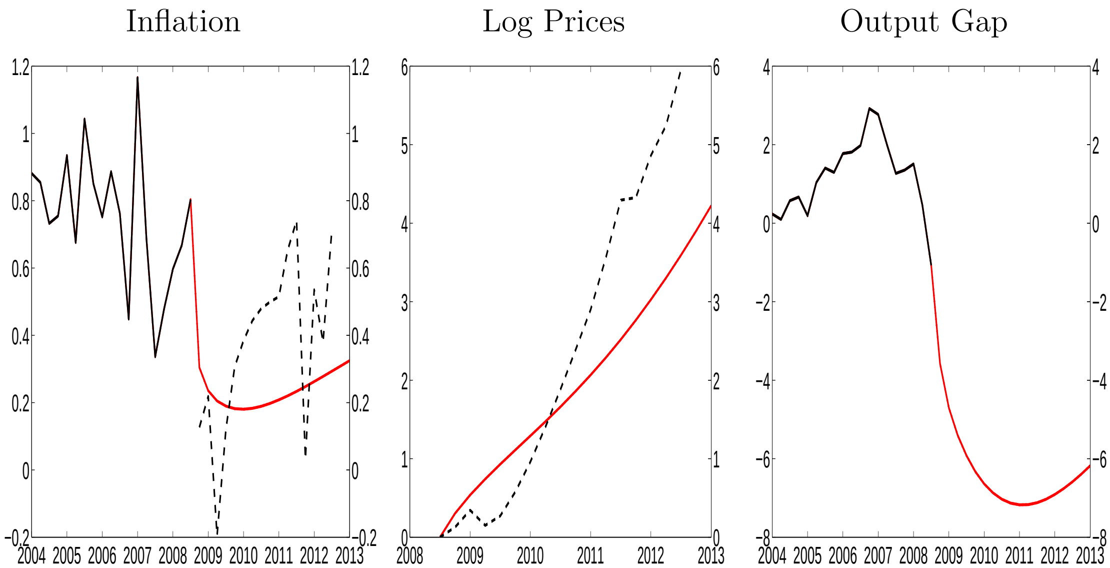
Notes: The solid black lines depict actuals up to the forecast origin; the solid red lines indicate the forecast paths; the dashed black lines correspond to the actual paths.

3.1 DSGE Forecasts of the Great Recession

We begin by estimating the DSGE model described in Section 2 based on macroeconomic data from 1964:Q1 to 2008:Q3. Suppose we denote this data set by $Y_{1:T} = \{y_1, \ldots, y_T\}$. A forecaster in the fourth quarter of 2008 would have observed the Lehman collapse and have had access to current-quarter information on the federal funds rate and the spread. We denote this information as $y_{1,T+1}$. Conditional on $(Y_{1:T}, y_{1,T+1})$ we generate multi-step forecasts. The output growth forecasts (quarter-on-quarter percentages and cumulative growth rates starting from the forecast origin) are depicted in Figure 1. Similar forecasts as well as a detailed description on how to compute them were reported in Del Negro and Schorfheide (forthcoming).[6] Conditional on the fourth-quarter federal funds rate and spread, the DSGE model with financial frictions is able to predict a sharp yet short-lived drop in GDP growth and the forecasts for the subsequent output growth rates are remarkably accurate in terms

[6] The forecasts in Del Negro and Schorfheide (forthcoming) were based on real-time data, whereas the forecasts in this paper are based on the 2012:Q3 vintage of data. Although revised and unrevised data are quite different as of 2008:Q3, the forecasts turn out to be very similar.

Figure 2: Inflation and the Output Gap

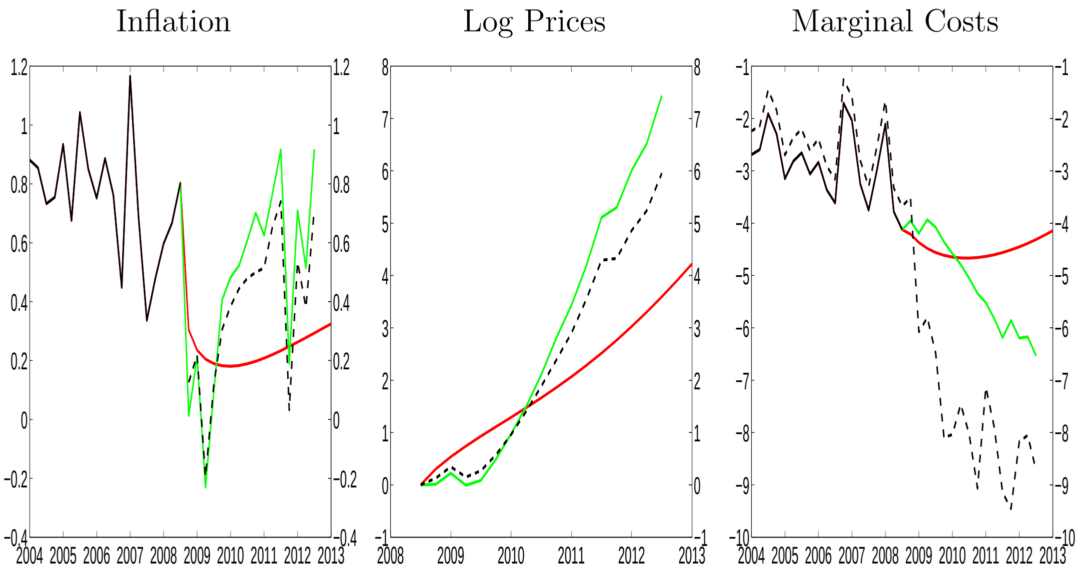


Notes: For inflation and log prices the solid black lines depict actuals up to the forecast origin; the solid red lines indicate the forecast paths; the dashed black lines correspond to the actual paths. The output gap is a latent variable. Thus, the black solid line corresponds to the smoothed path and the red solid is the forecast.

of the recovery. The right panel of Figure 1 shows the forecast of cumulative growth rates. As of mid 2012 the model's prediction for the level of output are almost perfectly in line with the data.

We now turn to the inflation forecasts, depicted in Figure 2. Inflation rates are also reported in terms of quarter-on-quarter percentages. The DSGE model forecast misses the deflation in 2009:Q1 and slightly under-predicts the average inflation rate between 2009:Q2 and 2012:Q3. The second panel of Figure 2 shows the cumulative inflation rates, that is, the change in the log price level relative to the forecast origin. This plot highlights that the model initially overpredicts and subsequently underpredicts inflation. The third panel of Figure 2 shows the DSGE model-implied output gap, that is the gap between actual output and counterfactual output in an economy without nominal rigidities and markup shocks. Since the counterfactual output is unobserved, the output gap is a latent variable and we plot the path of the smoothed gap prior to 2008:Q4. The model foresees large and persistent gaps, up to -7%. To summarize, using information available in the Fall of 2008, the DSGE model is able predict the drop in output growth as well as the subsequent recovery, it predicts that

Figure 3: Effect of Markup Shocks



Notes: See Figure 1. The solid green lines correspond to forecast that condition on future values of the markup shock.

the output gap falls well below -6% until 2013. However, unlike Hall (2011)'s and Ball and Mazumder (2011)'s conjecture, the model-implied Phillips curve does not generate negative inflation forecasts.

In (26) we highlighted that inflation can be decomposed into the sum of expected discounted marginal costs and the current level of the markup shock process $\lambda_{f,t}$. We now take a closer look at the role of markup shocks for the inflation forecasts. Since the markup shocks are not directly observed, we have to rely on smoothed values. Recall that we used T to denote the period 2008:Q3. Our forecasts were based on $Y_{1:T_+} = \{Y_{1:T}, y_{1,T+1}\}$, where $y_{1,T+1}$ corresponds to the federal funds rate and the interest rate spread in 2008:Q4. Let T_{full} denote the last period in our sample, which is 2012:Q3. The smoothed value of the markup shock in period t can therefore be expresses as $\mathbb{E}_{T_{full}}[\hat{\lambda}_{f,t}]$. The ex-post errors of forecasting the markup shock conditional on T_+ information can now be expressed as

$$\mathbb{E}_{T_{full}}[\hat{\lambda}_{f,t}] - E_{T_+}[\hat{\lambda}_{f,t}] \text{ for } t = T+1, \ldots, T_{full}.$$

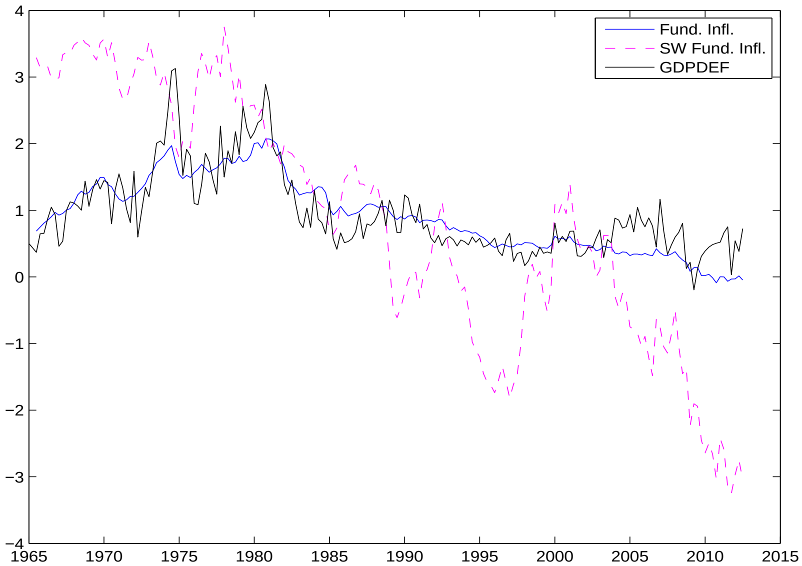
Since the markup shock is exogenous we can now easily back out estimates of the innovations, $\mathbb{E}_{T_{full}}[\epsilon_{\lambda_f,t}]$, for $t = T+1, \ldots, T_{full}$.

We now compute a new set of forecasts that condition on $\mathbb{E}_{T_{full}}[\epsilon_{\lambda_f,t}]$ and therefore illustrate the effect of the markup shocks on forecast errors. The results are plotted in Figure 3. The solid green lines depict the forecasts that are conditioned on the future realizations of the markup shocks. The left and center panels of the figure show that most of the inflation forecast errors in the aftermath of the Great Recession are due to unforeseen markup shocks. Actually, the center panel indicates that with price markup shocks only inflation would have been slightly higher than the ex-post realizations.

The right panel of Figure 3 shows the marginal costs $\widehat{mc}_t$. As in the case of the output gap, marginal costs are a latent variable and not directly observed. Thus, we are replacing actual values by smoothed values. More precisely, the solid black line corresponds to $\mathbb{E}_{T_+}[\widehat{mc}_t]$ for $t = 1, \ldots, T$, the solid red line depicts forecasts conditional on T_+ information, and the dashed black line marks ex-post smoothed values $\mathbb{E}_{T_{full}}[\widehat{mc}_t]$. The solid green lines are counterfactuals with price mark-up shocks only, as before. The DSGE model grossly overpredicts marginal costs. Only about half of the forecast errors can be explained by to markup shocks.

At first sight, Figure 3 presents damning evidence against this New Keynesian model. First, markup shocks seem to explain much of the fluctuations in inflation in the aftermath of the Great Recession. "Here we go again," would be the likely reaction of the skeptics, as this evidence apparently confirms their view that much of inflation is explained by the residual of the New Keynesian Phillips Curve (NKPC). Second, even if the model captured the decline in activity, it did not forecast the decline in marginal costs. If it had, its forecasts of inflation surely would have been substantially lower. This is essentially the point made by Ball and Mazumder (2011): Feeding into the NKPC post-recession measures of the "gap" (either unemployment, or the labor share) would surely result in deflation. In the next subsection we will show that, first, price mark-up shocks explain much of the high frequency fluctuations in inflation, but that medium and low frequency fluctuations are well captured by the NKPC. Second, the inflation forecasts would have been lower had the model correctly forecasted the decline in marginal costs, but not so much as to forecast a dramatic deflation.

Figure 4: Inflation and Fundamental Inflation



Notes: The solid black line corresponds to actual GDP deflator inflation; the dashed purple line is fundamental inflation computed from the SW/KW model; the solid blue line is $\tilde{\pi}_t$ associated with the SWπFF model.

3.2 Inflation and Fundamental Inflation

We begin with a detour from the analysis of post Great Recession data and study how this New Keynesian model explains the dynamics of inflation in the whole sample. Galí and Gertler (1999) and Sbordone (2005) introduce the concept of fundamental inflation, which measures the present discounted value of future marginal costs. We referred to this variable as $\tilde{\pi}_t$ and provided a formal definition in (26). The forward-looking NKPC is considered successful if fundamental inflation broadly captures the dynamics of inflation. Recently, King and Watson (2012), henceforth KW, reported a measure of fundamental inflation based on the posterior mode estimates of Smets and Wouters (2007). KW strongly criticized the New Keynesian Phillips curve for its inability to generate a plausible measure of fundamental inflation. We first reproduce the KW estimates and then present the fundamental inflation associated with our DSGE model.

Figure 4 depicts actual GDP-deflator inflation (solid black line) and fundamental inflation. The dashed purple line depicts the $\tilde{\pi}_t$ estimate obtained from the SW model, and essentially reproduces the estimate reported by KW.[7] The discrepancy with actual inflation is staggering. In the first part of the sample, the SW measure grossly overestimates actual inflation, whereas in the second part of the sample it underestimates GDP-deflator inflation, in particular since 2007. Were inflation to coincide with the Smets and Wouters (2007)/KW fundamental inflation, it would be of the order of -12% annualized.

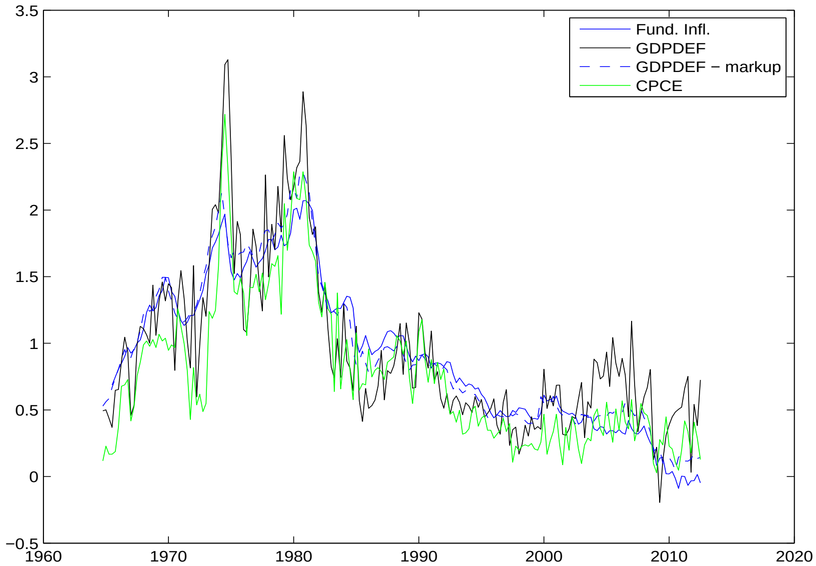
We now turn to the measure of fundamental inflation that corresponds to our SWπFF model, described in Section 2. Its path is given by the solid blue line. The solid blue line in Figure 4 indicates that $\tilde{\pi}_t$ from the SWπFF model is able to track actual inflation very well and essentially captures its low and mid-frequency variation. The difference between our estimate of fundamental inflation and the KW estimate is mainly driven by the degree of price rigidity ζ_p. If we replace our modal estimate of ζ_p with KW/Smets and Wouters (2007)'s (both are reported in the Appendix in Table A-2), we obtain very similar results as KW. The effect of all other coefficients is much more muted. The higher ζ_p in our model makes the slope of the Phillips curve κ smaller, which implies that inflation moves less with changes in economic activity, and specifically in the present discounted value of marginal costs.

While our measure of fundamental inflation defined in (26) removes the direct effect of markup shocks from inflation, it retains the indirect effect that arises from the impact of markup shocks on the evolution of marginal costs. Thus, we construct a second counterfactual measure of inflation, denoted by $\pi_t^{no\ mkup}$ which eliminates both the direct and indirect effect of markup shocks. This measure is plotted in Figure 5 with a dashed blue line and closely resembles $\tilde{\pi}_t$. Thus, stripping inflation of what causes its high-frequency variation, that is, mark-up shocks, delivers a measure that is very close to fundamental inflation $\tilde{\pi}_t$. Figure 5 also shows the core PCE inflation.[8] Both measures, $\tilde{\pi}_t$ and $\pi_t^{no\ mkup}$, track core inflation even better than GDP deflator inflation. More importantly, the comparison between core and actual inflation is revealing: differences between core and headline inflation usually reflect abrupt changes in commodity prices, as in the latest period or in the mid-2000, and these changes are captured by mark-up shocks in the model. But mark-up shocks also have

[7] We use a different vintage of data, so the smoothed series are not identical, but this makes little difference.

[8] A core measure for the GDP Deflator is not available.

Figure 5: Inflation, Fundamental Inflation, Counterfactual Inflation without Mark-up Shocks, and Core Inflation



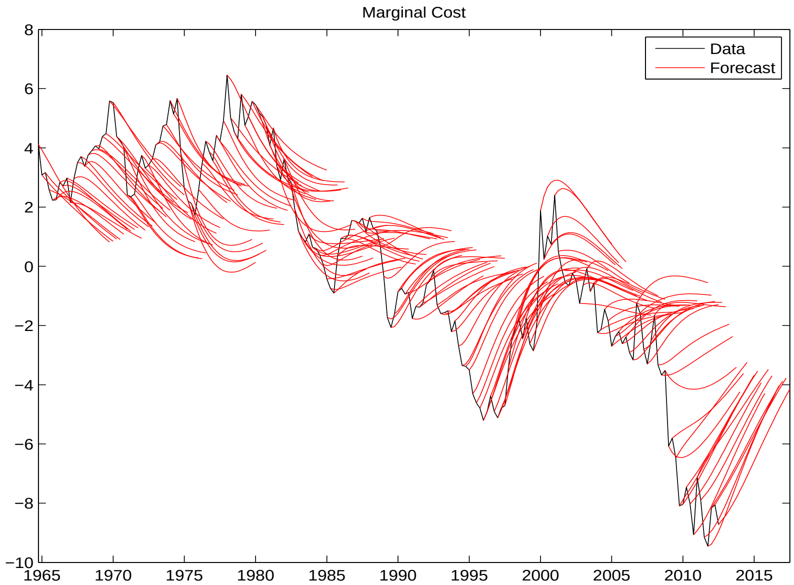
Notes: The solid black line corresponds to actual GDP deflator inflation; the solid green line is core PCE inflation; the solid blue line is $\tilde{\pi}_t$ associated with the SWπFF model; the dashed blue line is counterfactual inflation without markup shocks, $\pi_t^{no\ mkup}$.

an effect on marginal costs: positive mark-up shocks depress economic activity and make fundamental inflation lower, opening a gap between $\tilde{\pi}_t$ and $\pi_t^{no\ mkup}$.

Fundamental inflation is the sum of discounted future marginal costs. To gain further insights in the evolution of fundamental inflation we will examine the paths for expected future marginal costs. Figure 6 plots the smoothed historical marginal costs in deviations from steady state $\mathbb{E}_{T_{full}}[\widehat{mc}_t]$ (solid black lines), as well as the projected path of future marginal costs (that is, $\mathbb{E}[\widehat{mc}_{t+h}|s_{t|T_{full}}]$, where $s_{t|T_{full}} = \mathbb{E}_{T_{full}}[s_t]$ is the smoothed state of the economy for period t. The projected future paths are depicted by the red "hairs" that depart at each point in time from current marginal costs. Fundamental inflation in period t is the present discounted value of the "hair plots."

The "hair plots" present an interesting, but not too surprising, pattern: the more marginal costs differ from steady state, the faster the projections generally revert to steady state (Figure 9 in Section 3.3 below is a zoomed in version of Figure 6, and shows this pattern more clearly). Recall that this model uses long-run (ten year average) inflation expectations

Figure 6: Marginal Costs and Forecasts of Future Marginal Costs

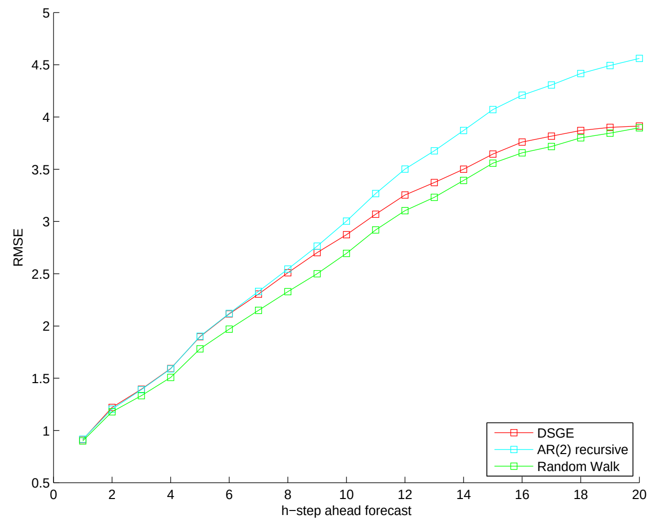


Notes: The black line corresponds to smoothed marginal costs; the red "hairs" depict forecasted paths of future marginal costs which determine fundamental inflation.

as an observable. Since expected inflation is also the present discounted value of the future marginal costs, if the former is not too far from, say, 2%, it better be that from some point onward expected marginal costs are such that their present discounted value delivers 2% (of course, expected inflation changed over time, which is why the hair plots do not converge to the same point).

As an important counterargument to Ball and Mazumder (2011)'s critique of the NKPC, it is not the current slack in the economy, i.e., the current value of $\widehat{mc}_t$, that matters for inflation. Instead, the entire hair plot matters, that is, the projected path for slack. According to the SWπFF model, one reason why inflation is not as low as the contemporanous measure of slack would suggest is that marginal costs are projected to increase over time, and the lower the current level of costs is, the faster the increase. This counterargument may not completely convince a skeptic. First, it relies on the promise of better times in the far distant future to make things better in the present. Second, the forecasts in Figure 6 are often at odds with ex post data. For instance, in the current recession the model predicted marginal costs to increase rapidly, and we have not yet seen any such increase. Yet, the figure also makes clear that historically marginal costs have reverted to steady state (e.g., in

Figure 7: RMSE of Forecasts of Marginal costs in Three Models

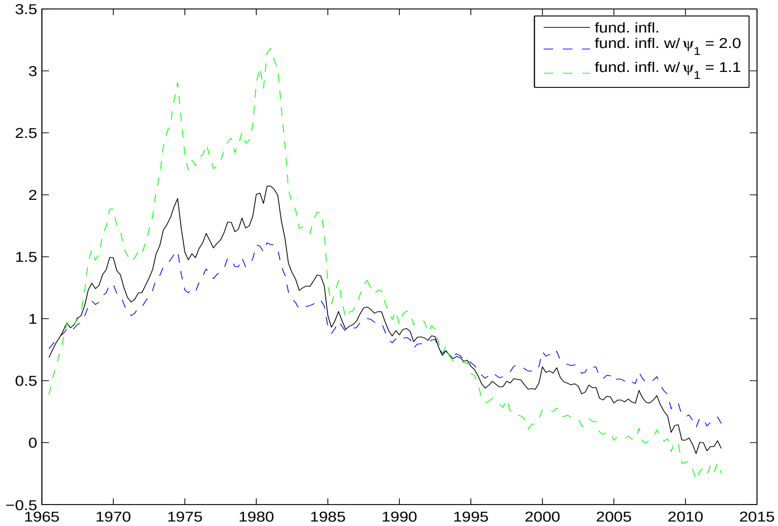


Notes: The figure shows the RMSE of forecasts of marginal costs in the SWπFF model (DSGE), an AR(2) model estimated recursively on past marginal cost data, and a random walk model, for the period 1989Q4-2012Q3.

the early 1980s, or the late 1990s).

While the path marginal costs that has realized following the Great Recession appears to have deviated widely from the model-based forecasts, the forecast errors are not particularly large when compared to those obtained with alternative models. A natural benchmark model for forecasting marginal cost is the random walk model, given the historical evolution of that series. Such a model would yield horizontal red "hair lines" instead of the ones reported in Figure 6. As yet another alternative, an econometrician may estimate each period an AR(2) model on the historical marginal costs to predict their future path. The "hair plots" generated by such a model are not too dissimilar from those obtained with the random walk model. Figure 7 compares the performance of these three models in forecasting marginal costs at various horizons, for the period 1989Q4 to 2012Q3. The forecasting performance is measured in terms of the root mean square error (RMSE) of the forecasts. While the random walk model marginally dominates the DSGE model, the latter predicts future marginal costs better than the recursive AR(2) model. As a result, the apparent failure of the DSGE model to predict the large drop in marginal costs since the Great Recession does not provide evidence for a rejection of that model.

Figure 8: Fundamental Inflation ($\tilde{\pi}_t$) and Counterfactuals for $\tilde{\pi}_t$ with Different Policy Coefficients (ψ_1)



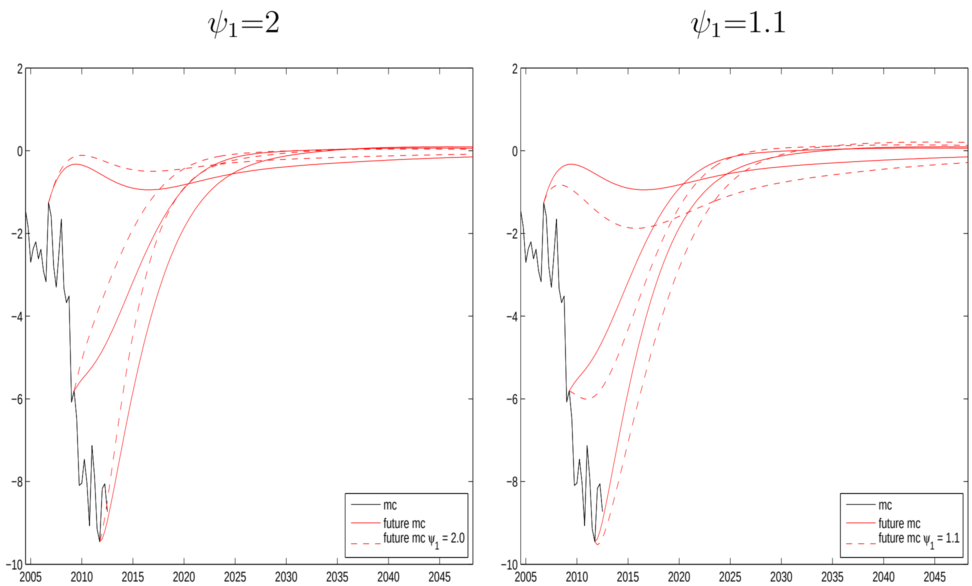
Notes: Fundamental Inflation using different values of ψ_1 in calculating S_t^{∞}.

3.3 Is Policy Irrelevant?

As discussed in the previous subsection, our model's ability to explain U.S. inflation relies on a higher degree of price rigidities than Smets and Wouters (2007). This yields a flatter short-run Phillips curve and thus involves smaller inflation fluctuations for any given fluctuations in economic activity and marginal costs. But this raises natural questions: doesn't a flatter Phillips curve imply that monetary policy looses some of its ability to stabilize inflation? Doesn't this lead credence to Hall (2011)'s assumption of a nearly exogenous inflation rate? As we now show, part of inflation's remarkable stability in the last several years can be attributed to a monetary policy focused on stabilizing inflation around its target level.

To illustrate this point, Figure 8 plots again the fundamental inflation $\tilde{\pi}_t$ (in black) estimated in our baseline model. The other two lines show $\tilde{\pi}_t$ using the same slope of the Phillips curve, κ, and the same estimated exogenous disturbances, but assume a different monetary policy response to inflation deviations from the inflation target. Specifically, while the policy coefficient ψ_1 is 1.37 in our baseline case, the green dashed line plots $\tilde{\pi}_t$ in the case that we set ψ_1 to 1.1, and the blue dashed line plots the case that ψ_1 is set to 2.0,

Figure 9: Marginal Costs (mc_t) Evolution and Counterfactuals with Different Policy Coefficients



Notes: The black line corresponds to smoothed marginal costs; the red "hairs" depict forecasted paths of future marginal costs which determine fundamental inflation. The solid red "hairs" are generated under the estimated policy rule whereas the dashed red "hairs" are obtained based on policy rules with alternative ψ_1 coefficients.

roughly the value estimated by Smets and Wouters (2007). As made clear by the picture, even though the Phillips curve is estimated to be relatively flat, a stronger policy response to inflation fluctuations results to substantially lower smaller fluctuations in fundamental inflation. Compared to a monetary policy little focused on inflation stabilization (low ψ_1), a policy with a high ψ_1 would have caused a much lower inflation from the late 1960s to the early 1980s, but conversely it would have yielded an even smaller disinflation following the recent great recession.

One way to understand this is to look at the projections of marginal costs in each of these cases. Figure 9 reports again the estimated path of marginal costs (black line), and the red solid lines plot, for three different dates, the expected future marginal costs according to our baseline model. In the left panel, the red dashed lines show the expected future marginal costs that would have obtained if the monetary policy rule had a higher coefficient ψ_1 equal to 2. The figure shows that in that case, marginal costs are expected to return to steady state faster than with the baseline policy. This implies that the discounted sum of future marginal costs, S_t^∞ remains closer tends to deviate less from its steady state level with higher ψ_1. Conversely, the right panel of Figure 9 shows with dashed lines the projected marginal costs in the case of a policy coefficient ψ_1 equal to 1.1. In this case, future marginal costs tend to wander off much farther away from their long-run steady state. In brief, a stronger policy response to inflation fluctuations tends to better anchor inflation expectations and hence actual inflation than is the case with a policy that responds little to inflation fluctuations, even if the slope of the Phillips curve is small.

4 Conclusions

In this paper we examined the behavior of inflation forecasts generated from a Smets-Wouters style DSGE model, augmented by a time-varying target inflation rate and a financial friction mechanism. The model embodies a New Keynesian Phillips curve which relates current inflation to future expected real marginal costs. Several authors recently argued that the Phillips curve relationship seemed to have broken down during the Great Recession. The basis for this argument is the observation that real activity dropped sharply without generating a corresponding drop of inflation. We debunk this argument by showing that this observation can be reconciled with a standard DSGE model in which inflation is determined by expectations of future marginal costs. As of 2008:Q3 our DSGE model is able to predict a sharp decline in output without forecasting a large drop in inflation. The model predicts marginal costs to revert back to steady state after the crisis, which, through the forward-looking Phillips curve, prevents a prolonged deflationary episode. While the underlying optimistic marginal cost forecasts turned out to be inaccurate ex post, we show that forecasts from a recursively estimated AR(2) model are less accurate than model-implied marginal costs forecasts over the past two decades. We also document that our DSGE model generates a plausible measure of fundamental inflation for the post-1964 era which captures the low- to medium-frequency fluctuations of inflation and tracks core PCE inflation. The markup shocks, which are often interpreted as a wedge or misspecification of the Phillips-curve relationships, are only needed to explain high-frequency fluctuations of inflation.

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Online Appendix for *Inflation in the Great Recession and New Keynesian Models*

Marco Del Negro, Marc Giannoni, and Frank Schorfheide

A Data

Real GDP (GDPC), the GDP price deflator (GDPDEF), nominal personal consumption expenditures (PCEC), and nominal fixed private investment (FPI) are constructed at a quarterly frequency by the Bureau of Economic Analysis (BEA), and are included in the National Income and Product Accounts (NIPA). Average weekly hours of production and nonsupervisory employees for total private industries (PRS85006023), civilian employment (CE16OV), and civilian noninstitutional population (LNSINDEX) are produced by the Bureau of Labor Statistics (BLS) at the monthly frequency. The first of these series is obtained from the Establishment Survey, and the remaining from the Household Survey. Both surveys are released in the BLS Employment Situation Summary (ESS). Since our models are estimated on quarterly data, we take averages of the monthly data. Compensation per hour for the nonfarm business sector (PRS85006103) is obtained from the Labor Productvity and Costs (LPC) release, and produced by the BLS at the quarterly frequency. All data are transformed following Smets and Wouters (2007). Let Δ denote the temporal difference operator. Then:

$$
\begin{aligned}
\textit{Output growth} &= 100 * \Delta LN((GDPC)/LNSINDEX) \\
\textit{Consumption growth} &= 100 * \Delta LN((PCEC/GDPDEF)/LNSINDEX) \\
\textit{Investment growth} &= 100 * \Delta LN((FPI/GDPDEF)/LNSINDEX) \\
\textit{Real Wage growth} &= 100 * \Delta LN(PRS85006103/GDPDEF) \\
\textit{Hours} &= 100 * LN((PRS85006023 * CE16OV/100)/LNSINDEX) \\
\textit{Inflation} &= 100 * \Delta LN(GDPDEF).
\end{aligned}
$$

The federal funds rate is obtained from the Federal Reserve Board's H.15 release at the business day frequency. We take quarterly averages of the annualized daily data and divide by four. In the estimation of the DSGE model with financial frictions we measure *Spread* as the annualized Moody's Seasoned Baa Corporate Bond Yield spread over the 10-Year Treasury Note Yield at Constant Maturity. Both series are available from the Federal Reserve Board's H.15 release. Like the federal funds rate, the spread data is also averaged over each quarter and measured at the quarterly frequency. This leads to:

$$\begin{aligned} FFR &= (1/4) * FEDERAL\ FUNDS\ RATE \\ Spread &= (1/4) * (BaaCorporate\ -\ 10yearTreasury) \end{aligned}$$

The long-run inflation forecasts used in the measurement equation (30) are obtained from the Blue Chip Economic Indicators survey and the Survey of Professional Forecasters (SPF) available from the FRB Philadelphia's Real-Time Data Research Center. Long-run inflation expectations (average CPI inflation over the next 10 years) are available from 1991:Q4 onwards. Prior to 1991:Q4, we use the 10-year expectations data from the Blue Chip survey to construct a long time series that begins in 1979:Q4. Since the Blue Chip survey reports long-run inflation expectations only twice a year, we treat these expectations in the remaining quarters as missing observations and adjust the measurement equation of the Kalman filter accordingly. Long-run inflation expectations $\pi_t^{O,40}$ are therefore measured as

$$\pi_t^{O,40} = (\text{10-YEAR AVERAGE CPI INFLATION FORECAST} - 0.50)/4.$$

where .50 is the average difference between CPI and GDP annualized inflation from the beginning of the sample to 1992. We divide by 4 since the data are expressed in quarterly terms.

B Additional Tables

Table A-1 summarizes the prior distribution.

Table A-2 summarizes the posterior mode for selected model parameters.

Table A-1: Priors

	Density	Mean	St. Dev.		Density	Mean	St. Dev.
Panel I: Smets-Wouters Model (SW)							
Policy Parameters							
ψ_1	Normal	1.50	0.25	ρ_R	Beta	0.75	0.10
ψ_2	Normal	0.12	0.05	ρ_{r^m}	Beta	0.50	0.20
ψ_3	Normal	0.12	0.05	σ_{r^m}	InvG	0.10	2.00
Nominal Rigidities Parameters							
ζ_p	Beta	0.50	0.10	ζ_w	Beta	0.50	0.10
Other "Endogenous Propagation and Steady State" Parameters							
α	Normal	0.30	0.05	π^*	Gamma	0.75	0.40
Φ	Normal	1.25	0.12	γ	Normal	0.40	0.10
h	Beta	0.70	0.10	S''	Normal	4.00	1.50
ν_l	Normal	2.00	0.75	σ_c	Normal	1.50	0.37
ι_p	Beta	0.50	0.15	ι_w	Beta	0.50	0.15
r_*	Gamma	0.25	0.10	ψ	Beta	0.50	0.15
(Note $\beta = (1/(1 + r_*/100))$							
ρs, σs, and ηs							
ρ_z	Beta	0.50	0.20	σ_z	InvG	0.10	2.00
ρ_b	Beta	0.50	0.20	σ_b	InvG	0.10	2.00
ρ_{λ_f}	Beta	0.50	0.20	σ_{λ_f}	InvG	0.10	2.00
ρ_{λ_w}	Beta	0.50	0.20	σ_{λ_w}	InvG	0.10	2.00
ρ_μ	Beta	0.50	0.20	σ_μ	InvG	0.10	2.00
ρ_g	Beta	0.50	0.20	σ_g	InvG	0.10	2.00
η_{λ_f}	Beta	0.50	0.20	η_{λ_w}	Beta	0.50	0.20
η_{gz}	Beta	0.50	0.20				
Panel II: Model with Long Run Inflation Expectations (SWπ)							
ρ_{π^*}	Beta	0.50	0.20	σ_{π^*}	InvG	0.03	6.00
Panel III: Financial Frictions (SWπFF)							
SP_*	Gamma	2.00	0.10	$\zeta_{sp,b}$	Beta	0.05	0.005
ρ_{σ_w}	Beta	0.75	0.15	σ_{σ_w}	InvG	0.05	4.00

Notes: Smets and Wouters (2007) original prior is a $Gamma(.62, .10)$. The following parameters are fixed in Smets and Wouters (2007): $\delta = 0.025$, $g_* = 0.18$, $\lambda_w = 1.50$, $\varepsilon_w = 10.0$, and $\varepsilon_p = 10$. In addition, for the model with financial frictions we fix $\bar{F}_* = .03$ and $\gamma_* = .99$. The columns "Mean" and "St. Dev." list the means and the standard deviations for Beta, Gamma, and Normal distributions, and the values s and ν for the Inverse Gamma (InvG) distribution, where $p_{\mathcal{IG}}(\sigma|\nu, s) \propto \sigma^{-\nu-1} e^{-\nu s^2/2\sigma^2}$. The effective prior is truncated at the boundary of the determinacy region. The prior for $\bar{l}$ is $\mathcal{N}(-45, 5^2)$.

Table A-2: Posterior Mode for Selected Parameters

Parameter	Posterior Mode			
	SWπFF	SWπ	SW	SW[07]
	Nominal rigidities			
ζ_p	0.868025	0.654090	0.707666	0.65
ζ_w	0.887520	0.787482	0.803776	0.73
ι_p	0.225859	0.209080	0.290669	0.22
ι_w	0.418745	0.557742	0.570556	0.59
	Policy			
ψ_1	1.373653	1.969308	2.047710	2.03
ψ_2	0.018043	-0.005324	0.087254	0.08
ψ_3	0.239788	0.217532	0.235958	0.22
π^*	0.766193	0.687330	0.693283	0.81