Federal Reserve Bank of New York
Staff Reports

Inflation in the Great Recession and New Keynesian Models

Marco Del Negro
Marc P. Giannoni
Frank Schorfheide

Staff Report No. 618
May 2013
Revised April 2014

FRBNY Staff REPORTS

Inflation in the Great Recession and New Keynesian Models
Marco Del Negro, Marc P. Giannoni, and Frank Schorfheide
Federal Reserve Bank of New York Staff Reports, no. 618
May 2013; revised April 2014
JEL classification: C52, E31, E32, E37

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. We challenge this argument by showing that a standard DSGE model with financial frictions available prior to the recent crisis successfully predicts a sharp contraction in economic activity along with a modest and protracted decline in inflation following the rise in financial stress in the fourth quarter of 2008. The model does so even though inflation remains very dependent on the evolution of economic activity and of monetary policy.

Key words: Great recession, missing disinflation, fundamental inflation, DSGE models, Bayesian estimation

---

Del Negro, Giannoni: Federal Reserve Bank of New York (e-mail: marco.delnegro@ny.frb.org, marc.giannoni@ny.frb.org). Schorfheide: University of Pennsylvania (e-mail: schorf@ssc.upenn.edu). The authors thank Raiden Hasegawa for outstanding research assistance. Schorfheide gratefully acknowledges financial support from the National Science Foundation under Grant SES 1061725. The authors also thank Gauti Eggertsson, Jon Faust, Michael Kiley, and participants at several seminars and conferences for their helpful feedback.

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 predict deflation as long as the unemployment rate remains above a natural rate of, say, six percent. Since inflation has declined somewhat in early 2009 and then remained contained for a few years, Hall (2011) argues 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 Phillips 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 (henceforth, NKPC) 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 markup 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 output growth, inflation, and marginal costs since the crisis. The model used is the Smets and Wouters (2007) model, based on Christiano et al. (2005), extended to include financial frictions as in Bernanke et al. (1999), Christiano et al. (2003), and Christiano et al. (2014b). We show that as soon as the financial stress jumps 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. Price changes are projected to remain in the neighborhood of one percent. This result contrasts 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.

According to the NKPC, inflation is determined by the discounted sum of future expected marginal costs (fundamental inflation). The key to understanding our result is that inflation is more dependent on expected future marginal costs than on the current level of economic activity. Even though GDP and marginal costs contracted by the end of 2008, we will show that monetary policy has in fact been sufficiently stimulative to ensure that marginal costs are expected to eventually rise.[1] While – with hindsight – the DSGE model understates the observed drop in marginal costs, conditioning on the realized drop in marginal costs only leads to a modest downward revision of the inflation forecast, and not to a prediction of an extended period of deflation. This result stands in sharp contrast to an analysis based on backward-looking Phillips curve models, which indeed predict a strong deflation conditional on the observed slack in the economy.

Because the relationship between inflation and future marginal cost is the defining characteristic of the NKPC, we carefully document that, unlike in King and Watson (2012), the DSGE model with financial frictions generates a measure of fundamental inflation that has been accurately tracking the low- and medium-frequency movements of inflation since 1964, lending credibility to the NKPC relationship. A key reason for the difference is that our

[1] Instead of solving the NKPC forward, Coibion and Gorodnichenko (2013) replace the inflation-expectations term in the NKPC by household survey expectations, which rose sharply after 2009 and thereby capture most of the "missing" deflation.

estimated model involves a higher degree of price rigidities than is the case in Smets and Wouters (2007). This results in endogenous and more persistent marginal costs which in turn allow our model to successfully explain inflation with much smaller markup 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 important effects on inflation.

From an ex-post perspective, we decompose the forecast errors made by our DSGE models into errors due to markup shocks and non-markup shocks. While the non-markup shocks explain the observed drop in marginal costs, they contribute to a reduction in the inflation forecast by only about 0.8 percentage point, substantiating our argument that the absence of deflation after 2008 is perfectly consistent with a DSGE model that is built around an NKPC.[2] These results challenge the claims set forth by Hall (2011), Ball and Mazumder (2011), and King and Watson (2012). Markup shocks do not appear to constitute an important source of fluctuations of inflation over the medium term. They capture high frequency movements in inflation such as those attributable to temporary energy price changes.

The remainder of this paper is organized as follows. Section 2 presents the DSGE model used for the empirical analysis, defines the concept of fundamental inflation, and discusses how we solve the model post 2008 to account for the zero lower bound on interest rates and the forward guidance. Forecasts of output growth, inflation, marginal costs, and interest rates for the period from 2009 to 2012 are presented in Section 3. In Section 4 we examine various aspects of the relationship between inflation and marginal cost forecasts: the sensitivity of marginal cost forecasts to price rigidity and the central bank's reaction to inflation fluctuations; we show that the DSGE model-implied fundamental inflation is able to track

[2] Christiano et al. (2011) use the model in Altig et al. (2011), which is similar to the one used here but without financial financial fictions, to generate simulations of the Great Recession taking the zero lower bound on interest rates into account. They also find that inflation declines only modestly in their model, in part because, as is the case here, their estimated Phillips curve is relatively flat. In their model the flatness of the Phillips curve partly results from the assumption of firm-specific capital. In Christiano et al. (2014a), instead, inflation does not decline much because total factor productivity drops substantially during the Great Recession and its aftermath. In contrast, we find that there is considerable slack after 2008, with actual output being well below the corresponding level that would be obtained if prices and wages were flexible.

actual inflation; and we assess the DSGE model's marginal cost forecasts over time. Section 5 examines the ex-post forecast errors, demonstrating that non-markup shocks explain the drop of marginal costs but do not lead to a substantial downward revision of the inflation forecast. Finally, section 6 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 in this paper is an extension of the model developed in Smets and Wouters (2007) (SW model), which is in turn based on earlier work by Christiano et al. (2005). The SW model 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. We extend the SW model by allowing for a time-varying target inflation rate and incorporating financial frictions as in Bernanke et al. (1999), Christiano et al. (2003), and Christiano et al. (2014b). The ingredients of our DSGE model were publicly available prior to 2008. As such, the model does not include some of the mechanisms that have been developed more recently in response to the financial crisis. The specification of the model is presented in Section 2.1. An important concept for our empirical analysis is the so-called fundamental inflation, which is defined in Section 2.2. The data set as well as the prior distribution used for the estimation is discussed in Section 2.3. Finally, Section 2.4 discusses how the DSGE model is solved to generate forecasts as of 2008Q4 and how it is solved to examine the 2009-2012 data in view of the zero lower bound on nominal interest rates and the forward guidance policy pursued by the Federal Reserve.

2.1 DSGE Model Specification

Since the derivation of the SW model is discussed in detail in Christiano et al. (2005) we only present a summary of the log-linearized equilibrium conditions. We first reproduce the equilibrium conditions for the SW model and then discuss the two extensions that underly the DSGE model used for our empirical analysis. We refer to our model as SWFF, where FF highlights the presence of financial frictions.

2.1.1 The SW Model

Let $\tilde{z}_t$ be the linearly detrended log productivity process which follows the autoregressive law of motion

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

Following Del Negro and Schorfheide (2013) 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 (2013), which is available online. 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 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:

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

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 w_t is the real wage and 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:

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

if the log productivity is trend stationary. 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:

$$\pi_t = \kappa\; mc_t + \frac{\iota_p}{1+\iota_p\bar{\beta}}\pi_{t-1} + \frac{\bar{\beta}}{1+\iota_p\bar{\beta}}I\!E_t[\pi_{t+1}] + \lambda_{f,t}, \tag{13}$$

and

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

where $\kappa = \frac{(1-\zeta_p\bar{\beta})(1-\zeta_p)}{(1+\iota_p\bar{\beta})\zeta_p((\Phi_p - 1)\epsilon_p + 1)}$, the parameters ζ_p, ι_p, and ϵ_p are the Calvo parameter, the degree of indexation, and the curvature parameter 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 markups $\lambda_{f,t}$ 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}.

2.1.2 Time-Varying Target Inflation and 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.

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

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

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 model π_t^* as a stationary process, although our prior for ρ_{π^*} forces this process to be highly persistent. 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) imply 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.

2.1.3 Financial Frictions

Building on the work of Bernanke et al. (1999), Christiano et al. (2003), De Graeve (2008), and Christiano et al. (2014b) we also add financial frictions to our DSGE model. We assume that banks collect deposits from households and lend to entrepreneurs who use these funds as well as their own wealth to acquire physical capital, which is rented to intermediate goods producers. Entrepreneurs are subject to idiosyncratic disturbances that affect their ability to manage capital. Their revenue may thus be too low to pay back the bank loans. Banks protect themselves against default risk by pooling all loans and charging a spread over the deposit rate. This spread may vary as a function of the entrepreneurs' leverage and their riskiness. Adding these frictions to the SW model amounts to replacing equation (6) with the following conditions:

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

and

$$\tilde{R}^k_t - \pi_t = \frac{r^k_*}{r^k_* + (1-\delta)} r^k_t + \frac{(1-\delta)}{r^k_* + (1-\delta)} q^k_t - q^k_{t-1}, \tag{20}$$

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. (2014b)) 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. Note that if $\zeta_{sp,b} = 0$

and the financial friction shocks $\tilde{\sigma}_{\omega,t}$ are zero, (19) and (20) coincide with (6). The following condition describes the evolution of entrepreneurial net worth:

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

2.2 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 define $\Delta_{\iota_p}\pi_t = \pi_t - \iota_p \pi_{t-1}$, and rewrite the expression for the Phillips curve (13) as follows:

$$\Delta_{\iota_p}\pi_t = \bar{\beta}\mathbb{E}_t[\Delta_{\iota_p}\pi_{t+1}] + (1 + \iota_p\bar{\beta})\left(\kappa\; mc_t + \lambda_{f,t}\right). \tag{22}$$

This difference equation can be solved forward to obtain

$$\Delta_{\iota_p}\pi_t = (1 + \iota_p\bar{\beta})\kappa \sum_{j=0}^{\infty} \bar{\beta}^j \mathbb{E}_t[mc_{t+j}] + (1 + \iota_p\bar{\beta}) \sum_{j=0}^{\infty} \bar{\beta}^j \mathbb{E}_t[\lambda_{f,t+j}]. \tag{23}$$

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 markup shocks. Defining

$$S^\infty_t = \sum_{j=0}^{\infty} \bar{\beta}^j \mathbb{E}_t[mc_{t+j}], \tag{24}$$

we can decompose inflation into

$$\pi_t = \tilde{\pi}_t + \Lambda_{f,t}, \tag{25}$$

where

$$\tilde{\pi}_t = \kappa(1 + \iota_p\bar{\beta})(1 - \iota_p L)^{-1} S^\infty_t, \tag{26}$$

$$\Lambda_{f,t} = (1 + \iota_p\bar{\beta})(1 - \iota_p L)^{-1} \sum_{j=0}^{\infty} \bar{\beta}^j \mathbb{E}_t[\lambda_{f,t+j}], \tag{27}$$

and L denotes the lag operator. We refer to the first term on the right-hand-side of (25), $\tilde{\pi}_t$, as *fundamental inflation.* Fundamental inflation corresponds to the discounted sum of expected marginal costs (our measure differs slightly from that of Galí and Gertler (1999) and Sbordone (2005), who define fundamental inflation as $\tilde{\pi}_t = \iota_p \pi_t + \kappa(1 + \iota_p \bar{\beta}) S_t^{\infty})$. Thus, our decomposition removes the direct effect of markup shocks from the observed inflation. Note, however, that the summands in (25) 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.

2.3 Data and Priors

The estimation of the DSGE model is based on data on real output growth, consumption growth, investment growth, real wage growth, hours worked, inflation (as measured by the GDP deflator), interest rates, 10-year inflation expectations, and spreads. Measurement equations related the model variables that appeared in Section 2.1 to the observables:

$$\begin{array}{lcl}
\text{Output growth} & = & \gamma + 100\,(y_t - y_{t-1} + z_t) \\
\text{Consumption growth} & = & \gamma + 100\,(c_t - c_{t-1} + z_t) \\
\text{Investment growth} & = & \gamma + 100\,(i_t - i_{t-1} + z_t) \\
\text{Real Wage growth} & = & \gamma + 100\,(w_t - w_{t-1} + z_t) \\
\text{Hours worked} & = & \bar{l} + 100 l_t \\
\text{Inflation} & = & \pi_* + 100\pi_t \\
\text{FFR} & = & R_* + 100 R_t \\
\text{10y Infl Exp} & = & \pi_* + 100 \mathbb{E}_t \left[\frac{1}{40} \sum_{k=1}^{40} \pi_{t+k} \right] \\
\text{Spread} & = & SP_* + 100 \mathbb{E}_t \left[\tilde{R}^k_{t+1} - R_t \right]
\end{array} . \tag{28}$$

All variables are measured in percent. π_* and R_* measure the steady state level of net inflation and short-term nominal interest rates, respectively, and $\bar{l}$ captures the mean of hours (this variable is measured as an index). The first seven series are commonly used in the estimation of the SW model. The 10-year inflation expectations contain information about low-frequency inflation movements and are obtained from the Blue Chip Economic Indicators survey and the Survey of Professional Forecasters. As spread variable we use a Baa Corporate Bond Yield spread over the 10-Year Treasury Note Yield at constant maturity. Details on the construction of the data set are provided in Appendix A.

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 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 fix the parameters corresponding to the steady state default probability and the survival rate of entrepreneurs, respectively. In turn, these parameters imply values for the parameters of (21). A summary of the priors is provided in Table A-1 in Appendix B.

2.4 Forecasting and Ex-Post Analysis

Our empirical analysis essentially consists of two parts. In the first part, we are using the DSGE model to generate forecasts based on information that was available in 2008Q4, which is the quarter with the largest output growth drop during the Great Recession episode. These forecasts are generated from a version of the model that ignores the presence of the zero lower bound (ZLB) on nominal interest rates, which is partly justified on the ground that the posterior mean prediction of the short term interest rate does not violate the ZLB. The second part of the empirical analysis takes an ex-post perspective and examines the shocks that have contributed to the errors associated with the 2008Q4 forecasts. Ex post it turned out that the conduct of monetary policy changed after 2008. Policy was constrained by the ZLB and, in order to alleviate this constraint, the central bank made announcements that it would deliberately keep interest rate at zero for an extended period of time (forward guidance). In order to conduct the ex-post analysis we use a solution method that accounts for the ZLB and forward guidance. Based on this solution we study the contributions of various types of aggregate shocks to macroeconomic fluctuations. In the remainder of this subsection we describe the information set used to generate the forecasts for the ex-ante analysis as well as the solution method that is used for the ex-post analysis. All of our analysis is based on modal forecasts. This is partly because a full-fledged characterization of the forecast distribution has already been conducted in Del Negro and Schorfheide (2013), and partly because explicitly considering parameter uncertainty would not change the main message of the paper.

2.4.1 Generating Forecasts of the Great Recession

In order to generate forecasts using the information set of a DSGE-model forecaster in 2008Q4 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 a transition equation:

$$s_t = \mathcal{T}(\theta)s_{t-1} + \mathcal{R}(\theta)\epsilon_t, \tag{29}$$

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

$$y_t = \mathcal{Z}(\theta)s_t + \mathcal{D}(\theta), \tag{30}$$

which maps the states onto the vector of observables y_t. This measurement equation expresses (28) in a more compact notation.

We use data from 1964Q1 to 2008Q3 to obtain posterior mode estimates of the DSGE model parameters θ. These estimates are reported in Table A-2 in Appendix B. We refer to the estimation sample as $Y_{1:T} = \{y_1, \dots, y_T\}$ and let $\hat{\theta}$ be the mode of the posterior distribution $p(\theta|Y_{1:T})$. Our DSGE forecasts are made using information available to the econometrician in December 2008. Note that at this point the econometrician does not yet have access to NIPA data for 2008Q4. However, the forecaster already has information on the fourth quarter federal funds rate and the spread. We let $y_{1,t}$ be the federal funds rate and the spread in period t and compute multi-step posterior mean forecasts based on the predictive distribution $p(Y_{T+1:T_{full}}|Y_{1:T}, y_{1,T+1}, \hat{\theta})$, where T_{full} corresponds to 2012Q3.[3] For brevity, we will often refer to the information set

$$Y_{1:T_+} = \big(Y_{1:T}, y_{1,T+1}, \hat{\theta}\big).$$

2.4.2 Ex-Post Accounting for the ZLB and Forward Guidance

Starting in 2009Q1 nominal interest rates in the US hit the ZLB. Moreover, the central bank engaged in forward guidance regarding the time horizon of the lift-off from the ZLB. Given the size of our DSGE model, the use of a fully nonlinear solution method as in Judd et al. (2010), Fernández-Villaverde et al. (2012), Gust et al. (2012), Aruoba and Schorfheide (2013) is beyond the scope of this paper. Instead, we use an approximation method proposed by Cagliarini and Kulish (2013) and Chen et al. (2012) to capture the effect of the ZLB and forward guidance for post-2008Q4 data ($t = T + 1 : T_{full}$).

Suppose in period t the policy rate is expected to be at the ZLB for $\bar{H}$ periods, that is,

$$R_\tau = -R_*, \quad \text{for } \tau = t, .., t + \bar{H}, \tag{31}$$

and is determined by the feedback rule (17) afterwards (for $\tau > t + \bar{H}$). We can write the DSGE model's equilibrium conditions as (omitting the dependence on θ to simplify the notation)

$$\Gamma_{2,\tau}\mathbb{E}_\tau[s_{\tau+1}] + \Gamma_{0,\tau}s_\tau = \Gamma_{c,\tau} + \Gamma_{1,\tau}s_{\tau-1} + \Psi_\tau\varepsilon_\tau, \tag{32}$$

where s_τ includes all endogenous and exogenous variables and where the matrices $\Gamma_{2,\tau}$, $\Gamma_{0,\tau}$, $\Gamma_{c,\tau}$, $\Gamma_{1,\tau}$, and Ψ_τ differ depending on whether $\tau \leq t + \bar{H}$ or not (in fact, only the row corresponding to the policy rule differs across τs in this application). For $\tau > t + \bar{H}$ the solution of (32) is given by the transition equation (29). For $\tau = t, ..., t + \bar{H}$ the solution takes the time varying form:

$$s_\tau = \mathcal{C}_\tau^{(t,\bar{H})} + \mathcal{T}_\tau^{(t,\bar{H})}s_{\tau-1} + \mathcal{R}_\tau^{(t,\bar{H})}\varepsilon_\tau. \tag{33}$$

[3]We are taking two short-cuts. First, we do not re-estimate the model with the additional information contained in $y_{1,T+1}$. Given the size of our sample $Y_{1:T}$, the two additional observations have no noticeable effect on the posterior. Second, we condition on the posterior mode rather than integrating with respect to the posterior distribution of θ. Since we mostly focus on point estimates in this paper the conditioning has only small effects on the results but speeds up the computations considerably.

We used the superscript $(t, \bar{H})$ to indicate that the solution was obtained under the assumption that the announcement of zero interest rates for a duration of $\bar{H}$ periods was made in period t. The matrices $\mathcal{C}_\tau^{(t,\bar{H})}$, $\mathcal{T}_\tau^{(t,\bar{H})}$, and $\mathcal{R}_\tau^{(t,\bar{H})}$ can be computed using the recursion

$$\begin{aligned} \mathcal{C}_\tau^{(t,\bar{H})} &= \left(\Gamma_{2,\tau}\mathcal{T}_{\tau+1}^{(t,\bar{H})} + \Gamma_{0,\tau}\right)^{-1}\left(\Gamma_{c,\tau} - \Gamma_{2,\tau}\mathcal{C}_{\tau+1}^{(t,\bar{H})}\right), \\ \mathcal{T}_\tau^{(t,\bar{H})} &= \left(\Gamma_{2,\tau}\mathcal{T}_{\tau+1}^{(t,\bar{H})} + \Gamma_{0,\tau}\right)^{-1}\Gamma_{1,\tau}, \quad \mathcal{R}_\tau^{(t,\bar{H})} = \left(\Gamma_{2,\tau}\mathcal{T}_{\tau+1}^{(t,\bar{H})} + \Gamma_{0,\tau}\right)^{-1}\Psi_\tau, \end{aligned} \tag{34}$$

starting from $\mathcal{T}_{t+\bar{H}+1}^{(t,\bar{H})} = \mathcal{T}$, $\mathcal{C}_{t+\bar{H}+1}^{(t,\bar{H})} = 0$.

We use overnight index swap (OIS) rates available from the Board of Governors to measure the duration that the federal funds rate is expected to remain at the ZLB, denoted by $\bar{H}_t$. In order to construct a time-varying coefficient state-space model for the post-2008 period, in each period $t > T$ we use the matrices $\left(\mathcal{C}_t^{(t,\bar{H}_t)}, \mathcal{T}_t^{(t,\bar{H}_t)}, \mathcal{R}_t^{(t,\bar{H}_t)}\right)$. We assume that the agents are myopic in the sense that they do not attempt to forecast changes in the length of the central bank's zero-interest rate policy. This assumption is comparable to the anticipated utility approach in the learning literature, e.g., Sargent et al. (2006). Thus, the transition equation (29) is replaced by

$$s_t = \mathcal{C}_t^{(t,\bar{H}_t)} + \mathcal{T}_t^{(t,\bar{H}_t)} s_{t-1} + \mathcal{R}_t^{(t,\bar{H}_t)} \epsilon_t. \tag{35}$$

When applying the Kalman filter and smoother to extract the ex-post states and shocks we assume that the time t system matrices are known at the end of period $t-1$.

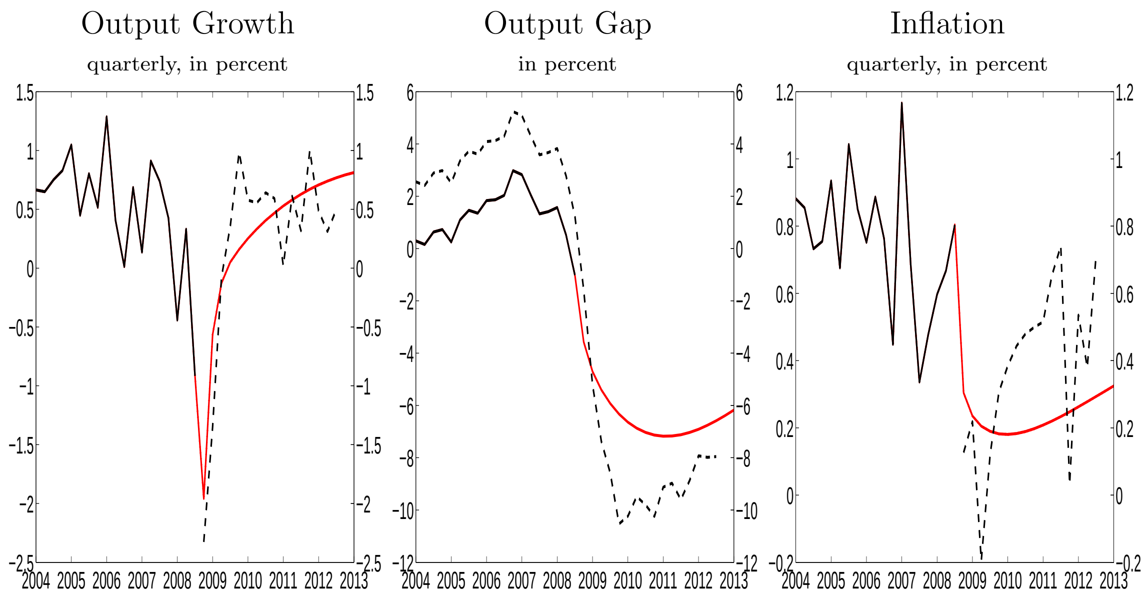
3 Forecasts During the Great Recession

We begin the empirical analysis by examining forecasts of inflation, output growth, and marginal costs during the 2007-2009 recession. We show that the New Keynesian DSGE model introduced in Section 2 predicts a deep recession and a subsequent weak recovery, just as observed in the data, and yet it does not predict deflation.

3.1 Inflation and Output Growth

The output growth forecasts (quarter-on-quarter percentages) made with information $Y_{1:T_+}$ available to the econometrician as of December 31, 2008, are depicted in the left panel of

Figure 1: Forecasts of Output Growth, Output Gap, and Inflation



Notes: Output growth and inflation: actual data until 2008Q3 (solid black); forecast paths (solid red); actual data starting 2008Q4 (dashed black). Output gap: ex-ante smoothed $\mathbb{E}[gap_t|Y_{1:T_+}]$ until 2008Q3 (solid black); forecast path (solid red); ex-post smoothed $\mathbb{E}[gap_t|Y_{1:T_{full}}, \hat{\theta}]$ (dashed black).

Figure 1. Similar forecasts as well as a detailed description on how to compute them were reported in Del Negro and Schorfheide (2013).[4] When made aware – via the spread data – of the financial consequences of the Lehman default, the DSGE model with financial frictions predicts a sharp drop in GDP growth and a very sluggish recovery.[5] Indeed, the model's forecast for the log *level* of output in 2012Q3 (shown in the Appendix) is remarkably close to the actual value. This implies that based on the $Y_{1:T_+}$ information available right after the Lehman collapse, the DSGE model predicts output to remain well below trend four years after the financial crisis.

The center panel of Figure 1 depicts the DSGE model-implied output gap, that is the gap between actual output and counterfactual output in an economy without nominal rigidities,

[4]The forecasts in Del Negro and Schorfheide (2013) were based on real-time data, whereas the forecasts in this paper are based on the 2012Q3 vintage of data. Although revised and unrevised data are somewhat different as of 2008Q3, the forecasts turn out to be very similar.

[5]This is consistent with the findings of Gilchrist and Zakrajsek (2012) who use a reduced form approach (and a different measure of spreads).

markup shocks, and financial frictions. The figure illustrates that the low level of output after 2008Q4 is not an efficient outcome for the economy. Because the counterfactual output is unobserved, actual values of the output gap have to be replaced by smoothed values. The solid black line is based on $Y_{1:T_+}$ information and corresponds to $\mathbb{E}[gap_t|Y_{1:T_+}]$. The solid red line depicts forecasts conditional on $Y_{1:T_+}$ information and the dashed black line marks ex-post smoothed values $\mathbb{E}[gap_t|Y_{1:T_{full}}, \hat{\theta}]$. In order to obtain the ex-post smoothed values we use the time-varying coefficient state-space representation described in Section 2.4, accounting for the ZLB and the forward guidance after 2008. In 2008Q4 the model forecasts large and persistent gaps, up to -7%, which are only slightly smaller by the end of the sample (about -6%). The ex-post output gap is somewhat larger in absolute terms than the forecasted one: it falls below -10% by the end of 2009, and recovers only gradually.

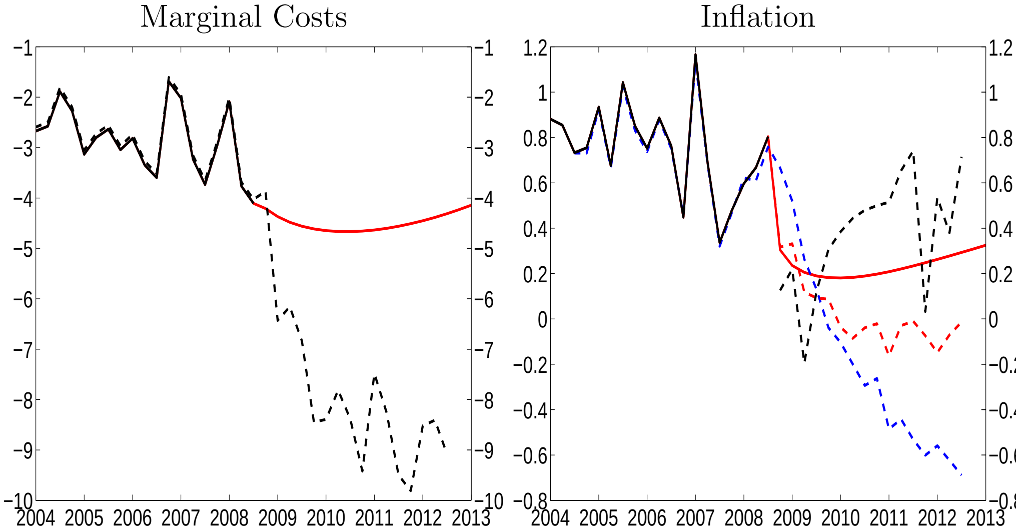
The right panel of Figure 1 shows the inflation forecasts (quarter-on-quarter percentages). The DSGE model prediction misses the deflation in 2009Q1 partly caused by the collapse in commodity prices and the subsequent reversal in inflation in 2010 and at beginning of 2011, which coincides with the Arab Spring and the associated surge in commodity prices. But aside from these high frequency movements, the model arguably produces reasonable inflation forecasts. In terms of the cumulative price change between 2008Q4 and 2012Q3 the model underpredicts the price *level* at the end of the sample by about 2%.

To summarize, using information available at the end of 2008 the DSGE model predicts a drop in output growth of roughly the same magnitude as the actual one as well as the subsequent sluggish recovery, and large and persistent output gaps. However, unlike Hall (2011)'s and Ball and Mazumder (2011)'s conjecture, the model-implied Phillips curve does not generate negative inflation forecasts.

3.2 Forecasts of Marginal Costs

According to the NKPC, inflation is determined by expectations of future marginal costs. We therefore inspect the marginal costs forecasts for the Great Recession period. In the absence of fixed costs in the DSGE model, marginal costs mc_t are proportional to the labor share. Moreover, changes in the labor share are spanned by the set of observables used

Figure 2: Marginal Cost and Conditional Inflation Forecasts



Notes: Left panel: ex-ante smoothed $\mathbb{E}[mc_t|Y_{1:T_+}]$ until 2008Q3 (solid black); forecast path (solid red); ex-post smoothed $\mathbb{E}[mc_t|Y_{1:T_{full}}, \hat{\theta}]$ starting 2008Q4 (dashed black). Right panel: actual inflation until 2008Q3 (solid black); actual inflation starting 2008Q4 (dashed black); forecasts (solid red); forecasts conditional on ex-post marginal costs $\mathbb{E}[mc_t|Y_{1:T_{full}}, \hat{\theta}]$ (dashed red); forecasts from a reduced-form Phillips curve conditional on realized unemployment (dashed blue).

in the estimation because our data set includes the growth rates of output and real wages as well as the level of hours worked. The presence of fixed costs in our model breaks the direct proportionality between marginal costs and the labor share and we have to treat marginal costs as a latent variable. The left panel of Figure 2 shows three objects: the smoothed marginal costs $\mathbb{E}[mc_t|Y_{1:T_+}]$ using data up to the forecast origin (black solid line), forecasts conditional on $Y_{1:T_+}$ information (solid red line), and ex-post smoothed values $\mathbb{E}_{[}mc_t|Y_{1:T_{full}}, \hat{\theta}]$ (dashed black line).

The left panel of Figure 2 makes clear that the DSGE model grossly over-predicts marginal costs. At first sight, Figure 2 presents damning evidence against this New Keynesian model: Even if the model captured the decline in output growth, it did not forecast the decline in marginal costs. One might think that if it had, the forecasts of inflation would have been substantially lower. This is essentially the point made by Ball and Mazumder (2011). The right panel of Figure 2 reproduces the model's baseline forecast of inflation (solid red line) from Figure 1 and depicts an alternative inflation forecast that is obtained by conditioning on the ex-post path of marginal costs (dashed red line).[6] This conditioning ensures that the agents' marginal cost expectations in the model match actual marginal costs over the period 2008Q4 to 2012Q3. The resulting forecast for inflation is of course lower than the baseline forecast, but not dramatically so. The key to understanding this, is that inflation still depends on expected future marginal costs, and that price setters know that marginal costs will eventually return to their steady state after the large decline between 2009 and 2012. Indeed, in this general equilibrium model, monetary policy provides enough accommodation for marginal costs to return to their steady state, so that inflation returns to the central bank's target.

For comparison, we also show inflation forecasts from a backward-looking Phillips curve obtained by feeding in actual realizations of unemployment (dashed blue line).[7] The backward-looking Phillips curve does forecast deflation (about -2% annualized), which may not be surprising given the amount of slack suggested by the level of unemployment. Marginal costs are also well below steady state, yet the NKPC's forecasts are not nearly as much at odds with ex-post outcomes as those from the backward looking Phillips curve. Ironically, it is precisely the forward-looking nature of the NKPC that keeps its forecasts afloat, as we will discuss in the next sections.

3.3 Why Doesn't Inflation Collapse?

In the remainder of this paper we examine the question why the DSGE model does not forecast deflation. Here, we briefly sketch the argument and provide the reader with a road

[6] The ex-post marginal costs are obtained using a Kalman smoother based on the time-varying state-space model described in Section 2.4.2. The conditional forecasts are generated based on the fixed-coefficient state-space model described in Section 2.4.1 using a generalized version of Algorithm 3 in Del Negro and Schorfheide (2013).

[7] Our version of the backward-looking Phillips curve is taken from Stock and Watson (2008) (equation (9), with four lags for both inflation and unemployment and no other regressor), estimated with quarterly data on the GDP deflator and unemployment up to 2008Q3. We also tried a version of the Phillips curve in differences (Equation (10) in Stock and Watson (2008), again with four lags), and obtained very similar results.

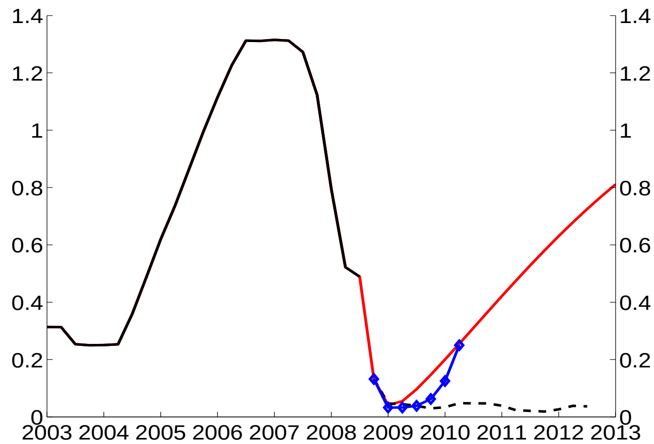
map. The answer lies in the forward-looking nature of the NKPC: Actual inflation is largely determined by fundamental inflation which depends on the expected present discounted value of future marginal costs (see Section 2.2). Thus, even if *current* marginal costs are low and the current output gap is well below steady state (as in Figures 1 and 2), as long as the marginal costs are expected to revert back to steady state in the future, the present value of marginal costs, and therefore inflation, may not fall dramatically.

This raises the question of what determines the expected reversion of marginal costs. First, exogenous shocks in the model are mean reverting, though many of the shocks have autocorrelations that are close to one and generate long-lasting effects on the economy. Second, monetary policy controls the persistence of marginal costs through the interest rate feedback rule. If inflation is below steady state or output below potential, the policy rule promises to lower the real rate for an extended period of time (due to interest rate smoothing). This promise stimulates consumption and investment demand by reducing the discounted sum of expected future real rates, and in turn raises marginal costs. Because inflation is determined by the sum of expected discounted value of future marginal costs, a fall of inflation is prevented.

The ZLB imposes a constraint on this mechanism because it limits the central bank's ability to lower interest rates. However, Figure 3 indicates that from an ex-ante perspective this constraint was not important. Indeed, as of the end of 2008, the model's forecasts of the federal funds rate (FFR) (red solid line) do not fall below zero. The predicted interest rate path is not just a feature of our DSGE model. It is very much in line with the January 10, 2009 Blue Chip FFR forecasts – the blue diamonds in Figure 3 – at least for the first six quarters (the horizon for which Blue Chip forecasts are available). Ex-post it turned out that interest rates stayed at the ZLB, as revealed by the dashed line, and the Taylor rule mechanism of reducing current interest rate in responses to below-target inflation and output was substituted by a policy of forward guidance (captured in the solution method described in Section 2.4.2) and quantitative easing (not directly modeled here).

Quantitatively, the arguments we just made rely on the fairly high price rigidities estimated for the model with financial frictions (a Calvo price-rigidity parameter of 0.87). This

Figure 3: Forecasts of the Federal Funds Rate



Notes: Actual FFR data until 2008Q3 (solid black); FFR forecast path (solid red); actual FFR data starting in 2008Q4 (dashed black); Blue Chip forecasts (solid blue with diamonds).

estimated degree of price rigidities is higher than the one estimated in the same model without financial frictions (that is, the SW model), and we will discuss in Section 4.4 how the introduction of credit spreads as an observable affects these estimates.[8] One contribution of this paper is to show that the higher degree of price rigidities is key not only because it yields a flatter Phillips curve, but also because it implies that the behavior of marginal costs in this model is largely endogenous. That is, marginal costs are for the most part explained by shocks other than markup shocks. This endogeneity is important as it makes it possible for policy to play a role in the determination of inflation.

[8] Our estimate of price rigidities implies that prices are re-optimized on average every $1/(1-0.87) = 7.7$ quarters in the SWFF model. This may appear large when compared to microeconomic evidence about the frequency of price changes reported, e.g., in Bils and Klenow (2004) or Nakamura and Steinsson (2008). However, recall that prices change in every quarter in this model, as prices that are not re-optimized are indexed to past inflation. Furthermore, as argued by Boivin et al. (2009), while individual or sectoral prices may vary frequently in response to sector-specific disturbances, they appear much more sluggish in response to aggregate shocks, which are arguably more relevant for our purposes. Finally, as shown in Woodford (2003) and Altig et al. (2011), a relatively flat slope of the NKPC can alternatively be obtained without large price rigidities by assuming that firms use firm-specific capital, or by assuming a larger curvature parameter in the Kimball aggregator for prices, ϵ_p.

4 Marginal Cost Forecasts and Inflation

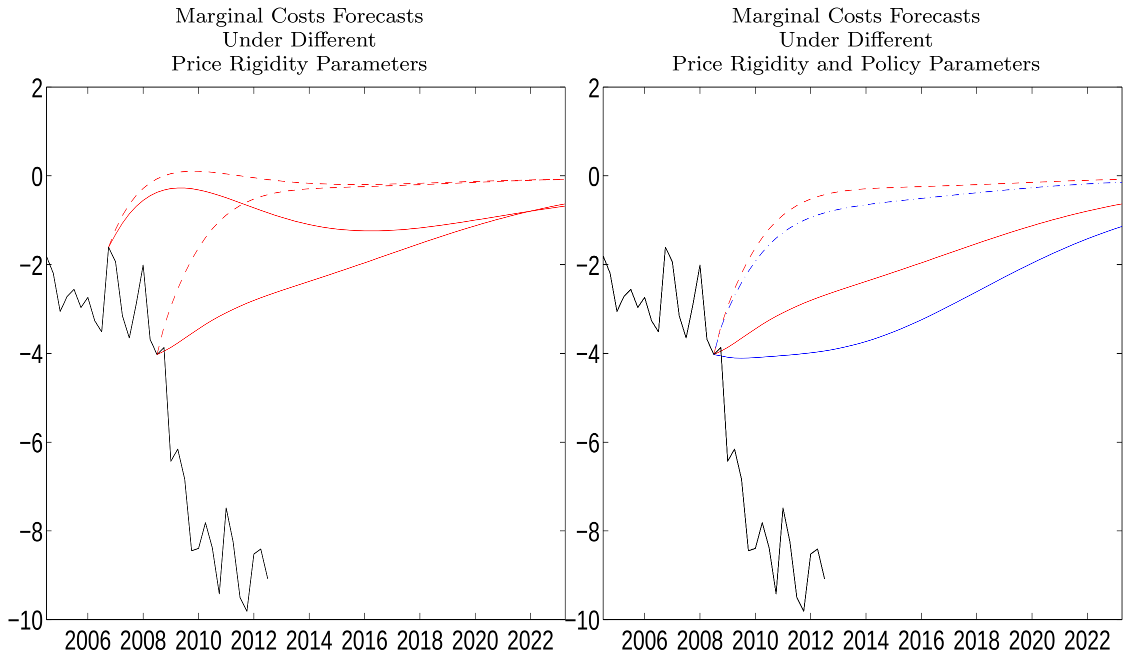
The NKPC implies that expectations about future marginal costs are a key determinant of inflation. We closely examine this relationship. In Section 4.1 we show that when price rigidities are relatively high, as they are in the estimated SWFF model, marginal costs have three important features: they are persistent, they are largely endogenous, meaning that they fluctuate in response to shocks other than markup shocks, and their dynamics are strongly influenced by the degree to which the central bank is committed to stabilize inflation. This supports our argument that inflation did not fall dramatically during the Great Recession because monetary policy managed to maintain expectations about future marginal costs and hence inflation expectations anchored. In Section 4.2 we extend our analysis of the NKPC relationship to the rest of the sample, prior to 2009. We document that the present value of marginal costs has historically been able to track low- and medium-frequency movements in inflation very well. In Section 4.3 we examine the historical accuracy of the SWFF-model-based marginal cost forecasts. Finally, we explain in Section 4.4 why our DSGE model with financial frictions delivers relatively high estimates of price stickiness.

4.1 Price Rigidities and Marginal Cost Dynamics

In this section we illustrate the dependence of marginal costs dynamics on the degree of price stickiness as well as the conduct of monetary policy. First, we compare marginal cost forecasts based on our posterior mode estimate of $\hat{\zeta}_p = 0.87$ to forecasts obtained based on Smets and Wouters (2007)'s estimate of $\hat{\zeta}_p^{SW} = 0.65$. Second, we illustrate the effect of lowering the central bank's response to inflation from the estimated value of $\hat{\psi}_1 = 1.37$ to the counterfactual value of 1.1. The results are summarized in Figure 4.

The left panel of Figure 4 illustrates the effect of changing the degree of nominal rigidity. The solid black line corresponds to smoothed estimates of marginal costs in deviations from steady state $\mathbb{E}[mc_t|Y_{1:T_{full}}, \hat{\theta}]$ for the post-2005 period. The red lines departing at two points in time from the black line are the projected path of future marginal costs. Formally, we are

Figure 4: Price Rigidities and Forecasts of Marginal Costs



Notes: Left panel: ex-post smoothed $\mathbb{E}[mc_t|Y_{1:T_{full}}, \hat{\theta}]$ (solid black); forecasts based on $\hat{\zeta}_p = 0.87$ (solid red); forecasts based on $\hat{\zeta}_p^{SW} = 0.65$ (dashed red). Right panel: ex-post smoothed $\mathbb{E}[mc_t|Y_{1:T_{full}}, \hat{\theta}]$ (solid black); forecasts based on ($\hat{\zeta}_p = 0.87,\ \hat{\psi}_1 = 1.3$) (solid red); forecasts based on ($\hat{\zeta}_p^{SW} = 0.65,\ \hat{\psi}_1 = 1.3$) (dashed red); forecasts based on ($\hat{\zeta}_p = 0.87,\ \psi_1 = 1.1$) (solid blue); forecasts based on ($\hat{\zeta}_p^{SW} = 0.65,\ \psi_1 = 1.1$) (dashed blue).

depicting

$$\mathbb{E}[mc_{t+h}|\hat{s}_{t|T_{full}}, \hat{\theta}], \quad \text{where} \quad \hat{s}_{t|T_{full}} = \mathbb{E}[s_t|Y_{1:T_{full}}, \hat{\theta}].$$

Thus, the marginal cost forecasts are conditional on the smoothed value of the state s_t. The solid red lines are forecasts using our estimated value of $\hat{\zeta}_p = 0.87$ whereas the dashed lines are based on the SW value $\hat{\zeta}_p^{SW} = 0.65$.

Figure 4 shows that marginal costs revert quickly to their state value if prices are relatively flexible. To understand this result, suppose that the prices are essentially fully flexible. In this case, firms would set their prices at a markup over the nominal marginal costs. As a consequence, real marginal costs would only move in response to exogenous markup shocks and would have no endogenous persistence.[9] Similarly, in Figure 4 when prices

[9]This can be seen by taking the limit as prices become fully flexible in the linearized NKPC (13). Noting that $\lambda_{f,t}$ is a renormalized version of the markup shock (i.e., $\lambda_{f,t} = \kappa\tilde{\lambda}_{f,t}$, following SW), this equation

are relatively flexible real marginal costs revert quickly to steady state (to the extent that exogenous markup shocks are not very persistent) so that the present discounted value of future marginal costs

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

defined in (24) essentially coincides with *current* real marginal costs mc_t (see figure A-3 in Appendix C). This is essentially what happens for the red dashed lines. In contrast, if prices are rigid, a persistent decline in the demand for goods is met by firms with a decline in the supply of goods, which results in a persistent fall in marginal costs. It follows that the present discounted value of future marginal costs, S_t^∞, may differ substantially from current real marginal costs mc_t.

To substantiate the claim that monetary policy also affects future marginal costs, we depict in the right panel of Figure 4 marginal costs forecasts under the estimated policy rule coefficient $\hat{\psi}_1 = 1.3$ and the counterfactual value $\psi_1 = 1.1$. The graph shows that a lower policy response to inflation makes little difference to the expected path of marginal costs for $\hat{\zeta}_p^{SW} = 0.65$ as marginal costs are essentially exogenous, and quickly revert back to steady state regardless of the conduct of monetary policy. However, under $\hat{\zeta}_p = 0.87$, the marginal cost forecasts are very sensitive to the central bank's reaction to inflation movements. Thus, if nominal rigidities are strong, marginal costs have a strong endogenous component which can be dampened by a monetary policy that reacts strongly to inflation. In turn, monetary policy is able to anchor current and future inflation.

The point that policy can exert control on inflation even with a flat Phillips curve (i.e., high nominal rigidities) is relevant for the current policy debate. Box 3.1 of the 2013 World Economic Outlook (International Monetary Fund (2013)) asks "Does Inflation Targeting Still Make Sense with a Flatter Phillips Curve?" The premise of this question is that with anchored inflation expectations and a flat Phillips curve it has become harder for central banks to affect inflation. Seen from the perspective of our model, the anchoring of inflation expectations is part and parcel of policy's influence on expected future marginal costs. In fact, to the extent that the dynamics of marginal costs are more affected by policy when

implies that $0 = mc_t + \tilde{\lambda}_{f,t}$, as $\zeta_p \to 0$.

the Phillips curve is relatively flat than when it is steep, policy may have more control of inflation under the former than the latter.

4.2 Price Rigidities and Fundamental Inflation

The analysis in Section 4.1 focused on the effect of price rigidities and monetary policy on the persistence of marginal costs. While policy affects inflation dynamics through the NKPC, a change in nominal rigidities not only affects the persistence of marginal costs, hence S_t^∞, but also the slope κ of the Phillips curve. Recall that in Section 2.2 we decomposed inflation into fundamental inflation defined as

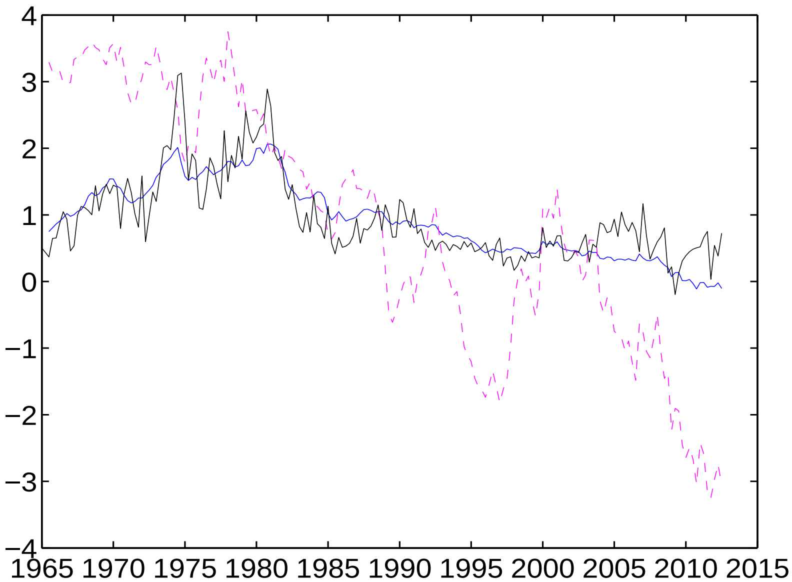
$$\tilde{\pi}_t = \kappa(1 + \iota_p\bar{\beta})(1 - \iota_p L)^{-1} S_t^\infty$$

and $\Lambda_{f,t}$ which is the exogenous present discounted value of markup shocks. It is well understood that a larger value of ζ_p implies a flatter Phillips curve, i.e., a smaller slope coefficient κ, as more rigid prices are less responsive to given changes in marginal costs. Our estimate of $\hat{\zeta}_p = 0.87$ and the Smets and Wouters (2007) estimate of $\hat{\zeta}_p^{SW} = 0.65$ offer two competing explanations for the historical U.S. inflation dynamics: $\hat{\zeta}_p = 0.87$ implies a relatively flat Phillips curve in conjunction with large movements in S_t^∞. The SW value, on the other hand, implies a steep Phillips curve but little movement in S_t^∞. Which one is the most plausible? In order to address this question we will examine the behavior of fundamental inflation.

Figure 5 compares fundamental inflation $\tilde{\pi}_t$ (solid blue line) to actual GDP deflator inflation (solid black line). For the NKPC to be a compelling model of inflation, fundamental inflation should explain a substantial portion of the variation in actual inflation. We can see that this is indeed the case for $\mathbb{E}[\tilde{\pi}_t | Y_{1:T_{full}}, \hat{\theta}]$ computed from our SWFF model.[10] Fundamental inflation from the SWFF model captures the low frequency variation of GDP deflator inflation. We also compared fundamental inflation to core PCE inflation and it turns out that the time paths of these two series are very similar (see Appendix C for details). The

[10] In computing these smoothed estimates, we are using the time-varying coefficient solution described in Section 2.4.2 that accounts for the ZLB and forward guidance.

Figure 5: Inflation and Fundamental Inflation



Notes: GDP deflator inflation (solid black); fundamental inflation $\mathbb{E}[\tilde{\pi}_t|Y_{1:T_{full}}, \hat{\theta}]$ from SWFF model (solid blue); fundamental inflation from SW model (dashed purple).

difference between core PCE and GDP deflator inflation typically reflects abrupt changes in commodity prices, which are attributed to markup shocks in our estimation results. We deduce that the NKPC of the SWFF model is successful in capturing the low- and medium-frequency movements of inflation, not just during the Great Recession and its aftermath but also over the historical period from 1964 to 2008.

To put the SWFF fundamental inflation into perspective, we also compute it for the SW model (dashed purple line in Figure 5). Our SW-model-based estimate of fundamental inflation essentially reproduces the estimate reported by King and Watson (2012), henceforth KW.[11] The discrepancy with actual inflation is staggering. In the first part of the sample, the SW/KW 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 SW/KW fundamental inflation, it would be of the order of -12% annualized in the aftermath of the Great Recession. The difference between our estimate of fundamental

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

inflation and the KW estimate is mainly driven by the degree of price rigidity ζ_p. If we replace our modal estimate of $\hat{\zeta}_p = 0.87$ with $\hat{\zeta}_p^{SW} = 0.65$ we obtain results that are very similar to the ones depicted by the dashed purple line in Figure 5.

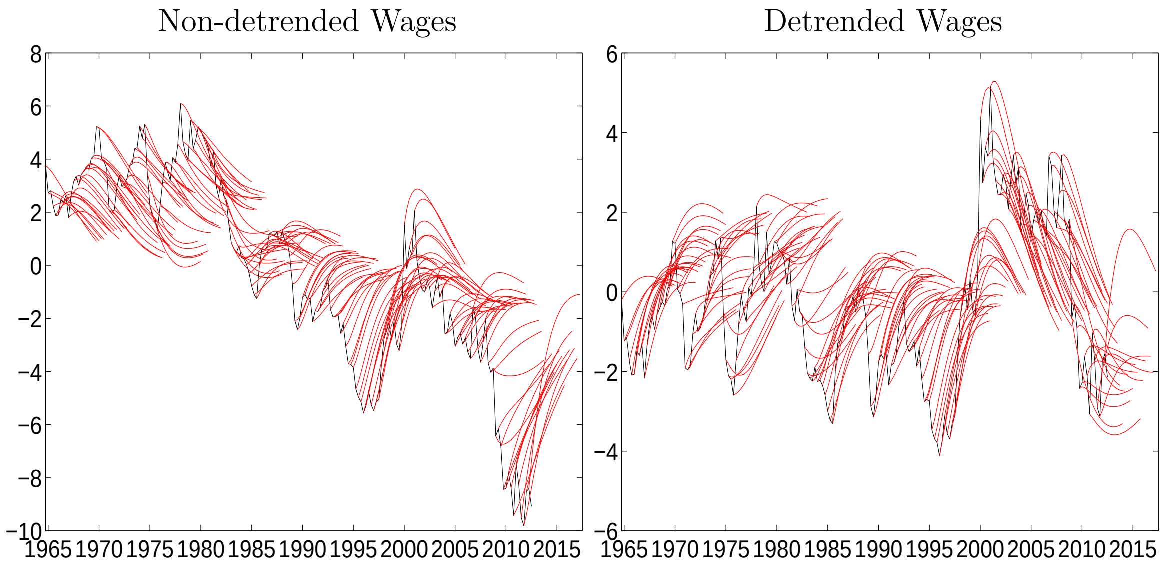
Recall from the analysis in Section 4.1 that for $\hat{\zeta}_p^{SW} = 0.65$ marginal costs are strongly mean reverting and mostly driven by exogenous markup shocks. This implies that fundamental inflation under the SW estimate of ζ_p mainly tracks *current* marginal costs. Markup shocks now play two roles: first, they are the main driver of marginal costs and fundamental inflation; second, the present discounted valued of markup shocks has to explain the discrepancy between actual inflation and fundamental inflation. Figure A-4 in Appendix C illustrate these points. Conversely, under the high estimate of $\hat{\zeta}_p = 0.87$ associated with the SWFF model, markup shocks are only important in matching high frequency movements in inflation, and play only a small role in driving fluctuations in marginal costs and fundamental inflation. Fluctuations in marginal costs and in S^{∞} are mostly explained endogenously by changes in economic activity.

4.3 How Accurate Were Agents' Marginal Cost Forecasts?

To assess the accuracy of agents' (and econometricians') marginal cost forecasts in the SWFF model, we depict in Figure 6 for the full sample what we previously showed in Figure 4 for only two periods toward the end of the sample: smoothed historical marginal costs in deviations from steady state ($\mathbb{E}[mc_t|Y_{1:T_{full}}, \hat{\theta}]$, solid black) and for each period t the projected path of future marginal costs ($\mathbb{E}[mc_{t+h}|\hat{s}_{t|T_{full}}, \hat{\theta}]$, red "hairs"). The forecasts are strongly mean-reverting, more so than the ex-post realized path of marginal costs. While there were some historical episodes in which the forecasts seem to systematically miss the prolonged fall in marginal costs, e.g., 1987 to 1995, there are other periods, e.g., 1995 to 2005, in which the forecasts captured the future movements of marginal costs quite well. To put the model's marginal cost forecasts into perspective, we compare them with forecasts from two reduced-form alternatives: a random walk model and an AR(2) model.[12] While the marginal cost forecast differ across specifications, the root mean squared errors (RMSEs) of the three

[12]The AR(2) model is estimated recursively using data on $\mathbb{E}[mc_{1:t}|Y_{1:T_{full}}, \hat{\theta}]$.

Figure 6: Marginal Costs and Forecasts of Future Marginal Costs



Notes: Smoothed marginal costs $\mathbb{E}[mc_t|Y_{1:T_{full}}, \hat{\theta}]$ (solid black); forecasts of future marginal costs (red "hairs"). The left panel is based on the raw wage growth series used for the estimation. The right panel is based on an adjusted wage series (see text for details).

types of forecasts are quite similar, with the AR(2) model performing slightly worse than the SWFF and the random walk model (details are reported in Appendix C). In sum, even if the marginal cost forecasts for the most recent years have been consistently over-optimistic, the historical forecast record of the model (and the agents in the model) is comparable with alternative reduced-form specifications.

The SWFF model assumes that marginal costs eventually return to their original steady-state level. The left panel of Figure 6 may, however, cast some doubts on that assumption as the historical path of marginal costs suggests the presence of a possible long-run downward trend in addition to the business cycle fluctuations. This trend captures a downward trend in the labor share since the early 1980s.[13] The decline in the labor share reflects two separate phenomena: a long-term decline in the labor share attributable to a slower growth of per capita labor compensation relative to per capita output from 1985 to 2000 and a sharp drop in employment during the Great Recession.

[13] While ex-post smoothed marginal costs in the SWFF model are not exactly equal to the labor share, the time paths of the two series are very similar.

To make sure that our results are not sensitive to the assumption of stationary marginal costs, we consider a robustness exercise in which we reproduce our calculations with the same model parameters, but we use an alternative wage series that is corrected to offset the drop in the wage-output ratio that occurred in the mid 1980s. We refer to this alternative wage series as "detrended." This detrending is achieved by changing the long-run growth rate of labor compensation so that it is equal to that of output from 1980 on.[14] The right panel of Figure 6 depicts marginal costs and their forecasts obtained by replacing actual real wage growth with the growth rate of detrended real wages when computing the smoothed estimate $\mathbb{E}[mc_t|Y_{1:T_{full}}, \hat{\theta}]$. We find that the output growth and inflation forecasts for the Great Recession generated based on the detrended wage series are almost identical to those reported for the raw wage series in Figure 1 (see Appendix C for further details), except that now the model's marginal costs forecasts for the Great Recession period appear much more in line with ex-post outcomes. The fact that the inflation forecast remains broadly unchanged reflect two offsetting forces: as evident from the right panel of Figure 6, smoothed marginal costs are higher than in the baseline case, which tends to push inflation up, but the marginal costs are not expected to revert back to steady state as quickly, which contributes to keeping inflation at level that was predicted with the non-detrended data.

4.4 Financial Frictions and Estimates of Price Rigidities

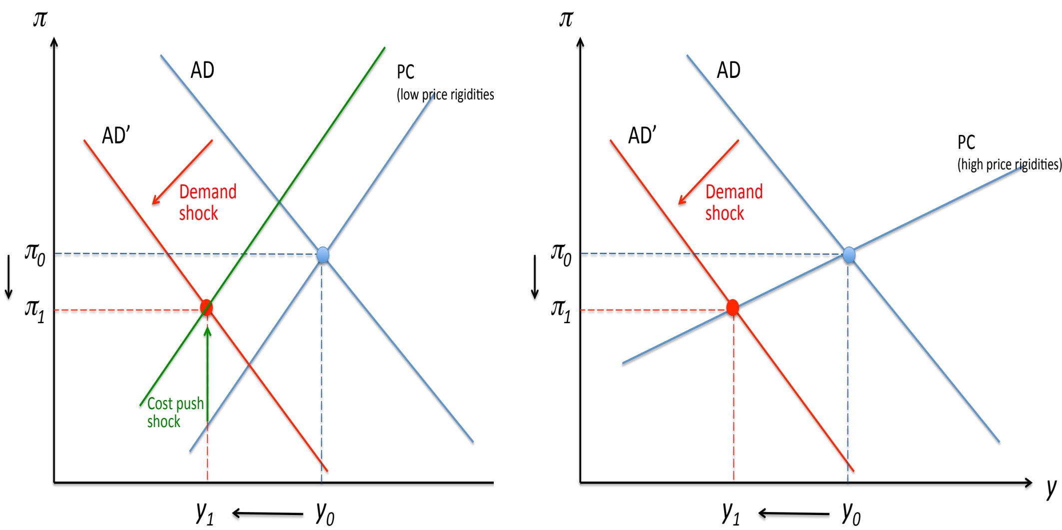
Our results are sensitive to the estimate of the price rigidity parameter ζ_p and are based on a value that is larger than the one reported in Smets and Wouters (2007). Why does the model with financial frictions and spreads as an observable yields a higher estimate of ζ_p?

The argument can be explained using Figure 7. Imagine that we knew for sure that we just observed a negative demand shock (a leftward shift in the AD curve), and that as a

[14] Altering the compensation data in this way addresses also in part the measurement issues identified by Elsby et al. (2013) regarding the compensation data. Indeed, they argue that around one third of the decline in the published labor share is an artifact of a progressive understatement of the labor income of the self-employed. However, they point out that offshoring of the labor-intensive component of the U.S. supply chain may also have contributed to the decline in the U.S. labor share over the past 25 years.

Figure 7: Demand Shocks and the slope of the Phillips Curve (AS)

Low rigidities High rigidities



result of this shock output dropped a lot but inflation fell only a little. A model with a steep Phillips curve (AS curve) would have to rationalize this chain of events with a joint shift of the AD and the AS curve (left panel), the latter caused by a positive markup shock — given that an AD shift only would cause a large fall in inflation. Conversely, a model with a flat Phillips curve would have no problem explaining this with a simple shift in the AD curve only (right panel). The first explanation would involve a negative correlation of demand and markup shocks — one that is at odds with the model's assumptions. The second explanation would be more natural, in that the outcomes can be explained as the result of one shock only.

If we knew that a good portion of business cycle fluctuations is explained by such demand shocks, we would arguably be more comfortable with the second, simpler, explanation (flat AS curve) than with the first one (steep AS curve and correlated markup shocks). It turns out that by including spreads as observables, the shocks that are predominantly responsible for explaining the variation in spreads, namely the "discount rate" (b) and the "spread" (σ_w) shocks, play a more important role for aggregate fluctuations, overall. These shocks by and large operate like the demand shocks described above. We substantiate this claim as follows. First, we re-estimate the SW model using spreads as an additional observable.

This raises the estimate of ζ_p from 0.65 to 0.81.[15] Second, we computed the correlation between demand and markup shocks in the SWFF and SW models. As suggested by the left panel of Figure 7, this correlation is negative for the SW model (-0.37), implying that adverse demand shocks are associated with positive markup shocks, and slightly positive for the SWFF model (0.18).

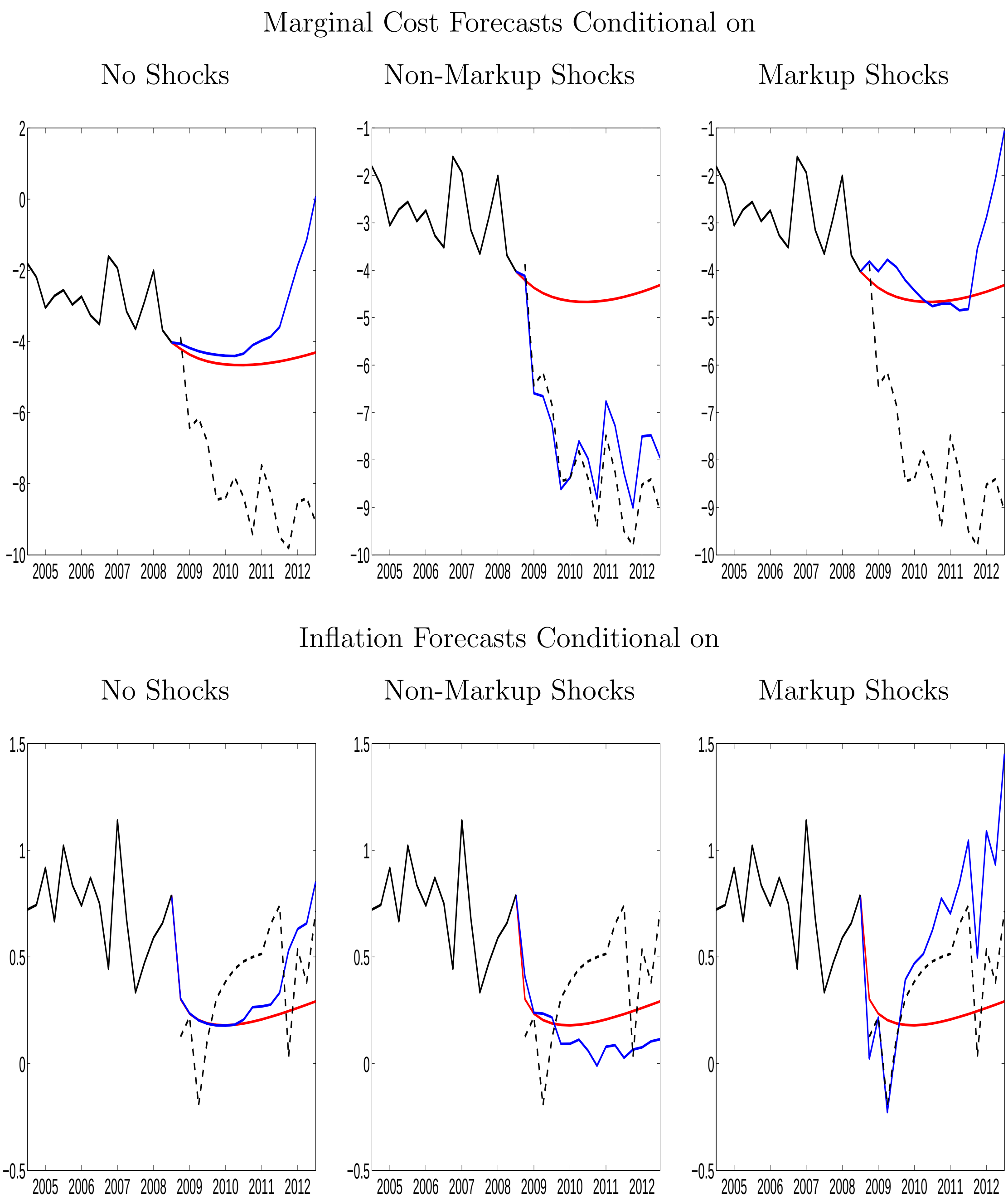
5 What Explains the Ex-post Forecast Errors?

We have argued that as of the end of 2008 the SWFF model could successfully predict the output and inflation behavior during the Great Recession and its aftermath. Marginal costs and interest rates, however, turned out to be substantially lower than had initially been forecast. Why is that? As we now discuss, this reflects both adverse shocks and considerable monetary policy accommodation. The policy accommodation sufficiently compensated for the averse shocks such that output growth and inflation did not differ too much, ex post, from their path predicted in 2008.

Figure 8 shows the paths of inflation and marginal costs, comparing actuals (black), the baseline forecasts made in 2008Q4 and discussed in Section 3 (solid red), and forecasts that are computed conditional on the ZLB, the forward guidance provided after 2008 and, in addition, ex-post realized shocks (solid blue). Specifically, the blue lines in the left panels show the paths computed using the solution described in section 2.4.2 and setting all shocks to zero ("No Shocks"). The difference between these paths and the baseline forecasts are due to the fact that ex-post policy is different from the anticipated one. The other two

[15] It has been documented, e.g., in Schorfheide (2008) that DSGE model-based estimates of the slope of the Phillips curve can vary widely across studies. The variation can be caused by a combination of model specification, data set, and choice of the prior distribution. Del Negro and Schorfheide (2008) document that reasonable changes in the prior distribution can generate estimates of ζ_p ranging between 0.54 and 0.84, well within the range reported here. In addition, Herbst and Schorfheide (forthcoming) document that under a diffuse prior the SW model can generate a posterior distribution with two modes, one with $\zeta_p = 0.59$ and another one with $\zeta_p = 0.70$. Including the spread data as an additional observable contributes to shifting the posterior mass from one modal region to another.

Figure 8: Forecasts Conditional on (Ex-Post) Smoothed Shocks



Notes: Actual smoothed marginal cost $\mathbb{E}[mc_t|Y_{1:T_{full}},\hat{\theta}]$ and actual GDP deflator inflation until 2008Q3 (solid black); Actual smoothed marginal cost $\mathbb{E}[mc_t|Y_{1:T_{full}},\hat{\theta}]$ and actual GDP deflator inflation from 2008Q4 on (dashed black); unconditional forecasts based on $Y_{1:T_+}$ (solid red); forecasts conditional on $(\mathbb{E}[s_T|Y_{1:T_{full}},\hat{\theta}], y_{1,T+1}, \mathbb{E}[\epsilon_{j,T+1:T_{full}}|Y_{1:T_{full}},\hat{\theta}])$ where $j \in \{\text{No Shock}, \text{Markup}, \text{Non-Markup}\}$ (blue).

panels show the impact of the realized shocks. Given that one of the main question this paper wants to address is "Does the model need strong positive markup shocks in the post-recession period to explain why we did not observe deflation?" we focus our discussion on the effect of markup versus non-markup shocks. The forecasts conditional on realized shocks are obtained as follows. We condition on the full-sample smoothed vector of states $\mathbb{E}[s_T|Y_{1:T_{full}}, \hat{\theta}]$, the additional interest rate and spread information $y_{1,T+1}$ that is available at the end of 2008Q4, and the set of smoothed shock innovations $\mathbb{E}[\epsilon_{j,T+1:T_{full}}|Y_{1:T_{full}}, \hat{\theta}]$.[16] Here $\epsilon_{j,t}$ corresponds to either the markup shock or the vector of non-markup shocks. Because post-2008 policy is different from that assumed in the baseline forecasts, the contribution of markup and non-markup shocks does not add up to the difference between realized data and the baseline forecasts.

Our results are as follows: First, the two left panels of Figure 8 show that monetary policy has provided considerable accommodation through forward guidance, especially in the post-2010 period. In the absence of shocks this policy would have implied a sharp increase in marginal costs, relative to the baseline forecast, and an associated increase in inflation after 2010. Second, the sharp decline in marginal costs is almost completely explained by non-markup shocks (upper middle panel of Figure 8). This result is not surprising in view of the discussion in Section 4: given the high degree of estimated price rigidities in the SWFF model, marginal costs are largely endogenous and not very much affected by markup shocks. Third, non-markup shocks cause only a modest fall in inflation relative to the baseline forecast – about 20 basis points (quarter-on-quarter, lower middle panel). This finding is consistent with that shown in Figure 2: even conditional on a set of shocks that imply accurate predictions for marginal costs, the model does not predict a deflationary episode. The intuition behind this result is the one discussed in Section 3.2: by being accommodative, monetary policy is expected to push marginal costs up, which prevents inflation from declining too much. Fourth, ex-post markup shocks essentially explain all of the high frequency movements in inflation, but have little effect on marginal costs (upper and lower right panels of Figure 8). The model holds markup shocks responsible for the large but short-lived swings registered in inflation between 2009 and 2011. These swings

[16] Recall that the baseline forecast was conditioned on time T filtered states $\mathbb{E}[s_T|Y_{1:T}, \hat{\theta}]$ as well as $y_{1:T}$.

arguably reflect movements in energy prices, which collapsed in the last quarter of 2008 before jumping again in early 2011, during the Arab Spring.[17]

On balance, we conclude that the economy experienced generally negative shocks that pushed inflation, activity and marginal costs down. At the same time, monetary policy counteracted these shocks by deviating from the historical rule and providing more stimulus. This stimulus resulted in a much lower interest rate path than initially forecasted.

6 Conclusions

In this paper we examined the behavior of inflation forecasts generated from a standard, medium-sized DSGE model, augmented with a time-varying target inflation rate and financial frictions. The model embodies a New Keynesian Phillips curve relating current inflation to expected future 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 challenge this argument by showing that this observation can be reconciled with predictions of a standard DSGE model. As of 2008Q3 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 marginal cost forecasts turned out to be overly optimistic ex post, we show that even taking into account the ex-post realizations of marginal costs, the model does not imply deflation. We also document that our DSGE model generates a plausible measure of fundamental inflation for the post-1964 era which explains the low- to medium- frequency fluctuations of inflation and tracks core PCE inflation without relying on markup shocks.

[17] This is consistent with the findings of Coibion and Gorodnichenko (2013) who emphasize the rise in inflation expectations due to increases in oil prices during this time period.

References

Altig, D., L. J. Christiano, M. Eichenbaum, and J. Lindé (2011): "Firm-Specific Capital, Nominal Rigidities, and the Business Cycle," *Review of Economic Dynamics*, 14, 225–247.

Aruoba, S. B. and F. Schorfheide (2008): "Insights from an Estimated Search-Based Monetary Model with Nominal Rigidities," *Working Paper*.

——— (2013): "Macroeconomic Dynamics Near the ZLB: A Tale of Two Equilibria," *NBER Working Paper*, 19248.

Ball, L. and S. Mazumder (2011): "Inflation Dynamics and the Great Recession," *Brookings Papers on Economic Activity*, Spring, 337–402.

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

Bils, M. and P. J. Klenow (2004): "Some Evidence on the Importance of Sticky Prices," *Journal of Political Economy*, 112(5), 947–985.

Boivin, J., M. P. Giannoni, and I. Mihov (2009): "Sticky Prices and Monetary Policy: Evidence from Disaggregated US Data," *American Economic Review*, 99, 350–84.

Cagliarini, A. and M. Kulish (2013): "Solving Linear Rational Expectations Models with Predictable Structural Changes," *Review of Economics and Statistics*, 95, 328–336.

Chen, H., V. Curdia, and A. Ferrero (2012): "The Macroeconomic Effects of Large-scale Asset Purchase Programmes," *The Economic Journal*, 122, 1–34.

Christiano, L. J., M. Eichenbaum, and C. L. Evans (2005): "Nominal Rigidities and the Dynamic Effects of a Shock to Monetary Policy," *Journal of Political Economy*, 113, 1–45.

Christiano, L. J., M. Eichenbaum, and S. Rebelo (2011): "When Is the Government Spending Multiplier Large?" *Journal of Political Economy*, 119, 78–121.

Christiano, L. J., M. Eichenbaum, and M. Trabandt (2014a): "Understanding the Great Recession," *mimeo.*

Christiano, L. J., R. Motto, and M. Rostagno (2003): "The Great Depression and the Friedman-Schwartz Hypothesis," *Journal of Money, Credit and Banking*, 35, 1119–1197.

——— (2014b): "Risk Shocks," *American Economic Review*, 104, 27–65.

Coibion, O. and Y. Gorodnichenko (2013): "Is The Phillips Curve Alive and Well After All? Inflation Expectations and the Missing Disinflation," *NBER Working Paper*, 19598.

De Graeve, F. (2008): "The External Finance Premium and the Macroeconomy: US Post-WWII Evidence," *Journal of Economic Dynamics and Control*, 32, 3415 – 3440.

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

Del Negro, M. and F. Schorfheide (2008): "Forming Priors for DSGE Models (and How it Affects the Assessment of Nominal Rigidities)," *Journal of Monetary Economics*, 55, 1191–1208.

——— (2013): "DSGE Model-Based Forecasting," in *Handbook of Economic Forecasting, Volume 2*, ed. by G. Elliott and A. Timmermann, Elsevier.

Elsby, M. W. L., B. Hobijn, and A. Sahin (2013): "The Decline of the U.S. Labor Share," *Brookings Panel on Economic Activity*, Fall.

Erceg, C. J. and A. T. Levin (2003): "Imperfect Credibility and Inflation Persistence," *Journal of Monetary Economics*, 50, 915–944.

Fernández-Villaverde, J., G. Gordon, P. Guerrón-Quintana, and J. F. Rubio-Ramírez (2012): "Nonlinear Adventures at the Zero Lower Bound," *National Bureau of Economic Research Working Paper*.

Galí, J. and M. Gertler (1999): "Inflation Dynamics: A Structural Econometric Analysis," *Journal of Monetary Economics*, 44, 195–222.

Gilchrist, S. and E. Zakrajsek (2012): "Credit Spreads and Business Cycle Fluctuations," *American Economic Review*, 102, 1692–1720.

Greenwood, J., Z. Hercovitz, and P. Krusell (1998): "Long-Run Implications of Investment-Specific Technological Change," *American Economic Review*, 87, 342–36.

Gust, C., D. Lopez-Salido, and M. E. Smith (2012): "The Empirical Implications of the Interest-Rate Lower Bound," *Manuscript, Federal Reserve Board*.

Hall, R. E. (2011): "The Long Slump," *American Economic Review*, 101, 431–469.

Herbst, E. and F. Schorfheide (forthcoming): "Sequential Monte Carlo Sampling for DSGE Models," *Journal of Applied Econometrics*.

International Monetary Fund (2013): "World Economic Outlook (WEO). Hopes, Realities, and Risks. April 2013," .

Judd, K., L. Maliar, and S. Maliar (2010): "A Cluster-Grid Projection Method: Solving Problems with High Dimensionality," *NBER Working Paper*, 15965.

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

Nakamura, E. and J. Steinsson (2008): "Five Facts about Prices: A Reevaluation of Menu Cost Models," *The Quarterly Journal of Economics*, 123, 1415–1464.

Primiceri, G. (2006): "Why Inflation Rose and Fell: Policymakers Beliefs and US Postwar Stabilization Policy," *Quarterly Journal of Economics*, 121, 867–901.

Sargent, T. J. (1999): *The Conquest of American Inflation*, Princeton University Press, Princeton.

Sargent, T. J., T. Zha, and N. Williams (2006): "Shocks and Government Beliefs: The Rise and Fall of American Inflation," *American Economic Review*, 94, 1193–1224.

Sbordone, A. M. (2005): "Do Expected Future Marginal Costs Drive Inflation Dynamics?" *Journal of Monetary Economics*, 52, 1183–1197.

Schorfheide, F. (2008): "DSGE Model-Based Estimation of the New Keynesian Phillips Curve," *FRB Richmond Economic Quarterly*, Fall Issue, 397–433.

Sims, C. A. (2002): "Solving Linear Rational Expectations Models," *Computational Economics*, 20, 1–20.

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

——— (2007): "Shocks and Frictions in US Business Cycles: A Bayesian DSGE Approach," *American Economic Review*, 97, 586 – 606.

Stock, J. H. and M. W. Watson (2008): "Phillips Curve Inflation Forecasts," *NBER Working Paper*, 14322.

Woodford, M. (2003): *Interest and Prices*, Princeton University Press.

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

Marco Del Negro, Marc Giannoni, and Frank Schorfheide

A Data

Data on Real GDP (GDPC), the GDP deflator (GDPDEF), nominal personal consumption expenditures (PCEC), and nominal fixed private investment (FPI) are produced at a quarterly frequency by the Bureau of Economic Analysis, and are included in the National Income and Product Accounts (NIPA). Average weekly hours of production and nonsupervisory employees for total private industries (AWHNONAG), 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. Since our models are estimated on quarterly data, we take averages of the monthly data. Compensation per hour for the nonfarm business sector (COMPNFB) is obtained from the Labor Productvity and Costs release, and produced by the BLS at the quarterly frequency. All data are transformed following Smets and Wouters (2007). 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. Let Δ denote the temporal difference operator.

Then:

$$
\begin{aligned}
\text{Output growth} &= 100 * \Delta LN((GDPC)/LNSINDEX) \\
\text{Consumption growth} &= 100 * \Delta LN((PCEC/GDPDEF)/LNSINDEX) \\
\text{Investment growth} &= 100 * \Delta LN((FPI/GDPDEF)/LNSINDEX) \\
\text{Real Wage growth} &= 100 * \Delta LN(COMPNFB/GDPDEF) \\
\text{Hours worked} &= 100 * LN((AWHNONAG * CE16OV/100)/LNSINDEX) \\
\text{Inflation} &= 100 * \Delta LN(GDPDEF) \\
\text{FFR} &= (1/4) * FEDERAL\ FUNDS\ RATE
\end{aligned}
$$

Long-run inflation expectations are obtained from the Blue Chip Economic Indicators survey and the Survey of Professional Forecasters 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 1991Q4 onwards. Prior to 1991Q4, we use the 10-year expectations data from the Blue Chip survey to construct a long time series that begins in 1979Q4. 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

$$\text{10y Infl Exp} = (\text{10-YEAR AVERAGE CPI INFLATION FORECAST} - 0.50)/4.$$

where 0.50 is the average difference between CPI and GDP annualized inflation from the beginning of the sample to 1992. We divide by 4 to express the data in quarterly terms. Finally, 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:

$$\text{Spread} = (1/4) * (BaaCorporate\ -\ 10yearTreasury).$$

B Prior and Posterior Distributions

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: Long Run Inflation Expectations							
ρ_{π^*}	Beta	0.50	0.20	σ_{π^*}	InvG	0.03	6.00
Panel III: Financial Frictions (SWFF)							
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)'s original prior for π_* is Gamma(.62, .10). The following parameters are fixed in Smets and Wouters (2007): $\delta = 0.025$, $g_* = 0.18$, $\lambda_w = 1.50$, $\varepsilon_w = 10$, and $\varepsilon_p = 10$. In addition, for the model with financial frictions we fix the entrepreneurs' steady state default probability $\bar{F}_* = 0.03$ and their survival rate $\gamma_* = 0.99$. 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 DSGE Parameters

Parameter	Posterior Mode				
	SWFF	SWπ	SW+Sp	SW	SW[2007]
α	0.178678	0.154830	0.214050	0.160809	0.190000
ζ_p	0.868025	0.654090	0.806292	0.707666	0.650000
ι_p	0.225859	0.209080	0.772076	0.290669	0.220000
Φ	1.526156	1.708648	1.642216	1.728323	1.610000
S''	3.043719	5.614790	5.233004	6.112120	5.480000
h	0.243997	0.708559	0.251476	0.708889	0.710000
ψ	0.188363	0.725931	0.733831	0.701683	0.540000
ν_l	2.673158	2.080374	2.165439	2.509971	1.920000
ζ_w	0.887520	0.787482	0.858637	0.803776	0.730000
ι_w	0.418745	0.557742	0.476646	0.570556	0.590000
r_*	0.133131	0.192898	0.136800	0.148262	0.160000
ψ_1	1.373653	1.969308	1.263218	2.047710	2.030000
ψ_2	0.018043	-0.005324	0.056610	0.087254	0.080000
ψ_3	0.239788	0.217532	0.245995	0.235958	0.220000
π^*	0.766193	0.687330	0.626823	0.693283	0.810000
σ_c	1.315895	1.328378	1.662724	1.452160	1.390000
ρ	0.674959	0.790865	0.762714	0.830549	0.810000
SP_*	1.908145	.	1.523782	.	.
$\zeta_{sp,b}$	0.044292	.	0.050000	.	.
γ	0.401155	0.336284	0.336667	0.374489	0.430000
$\bar{l}$	-45.478333	-45.444275	-43.745487	-42.520153	-42.500000

Note: See description of labels at the end of table below.

Table A-2: Posterior Mode for DSGE Parameters (cont.)

Parameter	Posterior Mode				
	SWFF	SWπ	SW+Sp	SW	SW[2007]
ρ_g	0.979327	0.998981	0.975821	0.998981	0.970000
ρ_b	0.944049	0.248741	0.992677	0.305477	0.180000
ρ_μ	0.643521	0.687660	0.699691	0.739313	0.710000
ρ_z	0.956351	0.982750	0.975633	0.969471	0.950000
ρ_{λ_f}	0.793946	0.867062	0.259992	0.871997	0.900000
ρ_{λ_w}	0.660922	0.993978	0.976975	0.977992	0.970000
ρ_{r^m}	0.067278	0.205791	0.040541	0.119415	0.120000
ρ_{σ_w}	0.989876	.	0.989877	.	.
ρ_{π^*}	0.990000	0.990000	.	.	.
σ_g	2.907965	2.921414	2.920280	2.928797	0.520000
σ_b	0.038367	0.224146	0.026477	0.217436	0.240000
σ_μ	0.503285	0.430473	0.428471	0.417726	0.450000
σ_z	0.496084	0.462921	0.465088	0.457645	0.450000
σ_{λ_f}	0.153534	0.148936	0.185276	0.141651	0.140000
σ_{λ_w}	0.256772	0.300435	0.274871	0.271245	0.240000
σ_{r^m}	0.291914	0.239621	0.243927	0.221767	0.240000
σ_{σ_w}	0.057474	.	0.052918	.	.
σ_{π^*}	0.029999	0.034894	.	.	.
η_{gz}	0.873709	0.834816	0.843962	0.832370	0.520000
η_{λ_f}	0.714342	0.725022	0.403510	0.746308	0.740000
η_{λ_w}	0.571991	0.967032	0.963266	0.941857	0.880000

Notes: SWFF refers to the baseline model, i.e., Smets and Wouters (2007)'s model with financial frictions and time-varying inflation target. SWπ is the SW model with time-varying inflation target but no financial frictions. SW+Sp represents the SW model estimated with the same observables as Smets and Wouters plus credit spread data. SW refers to the SW model estimated using the same observables as Smets and Wouters but with the 2012Q3 vintage of data. SW[2007] indicates the parameter estimates reported in Smets and Wouters (2007).

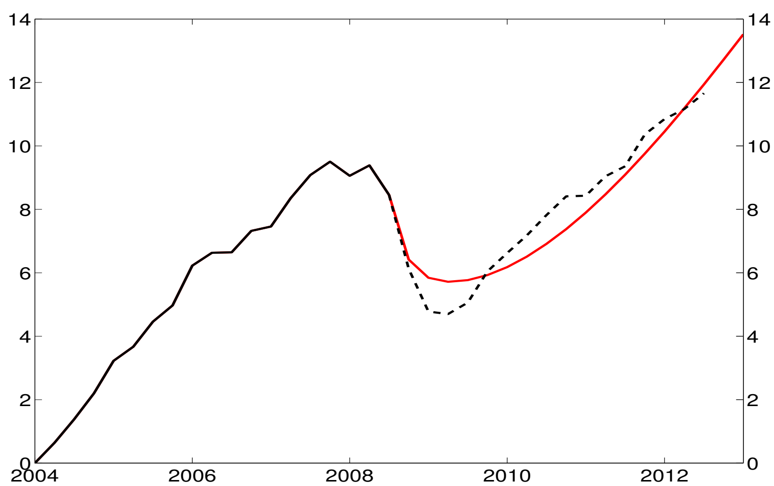
C Additional Tables and Figures

C.1 Section 3

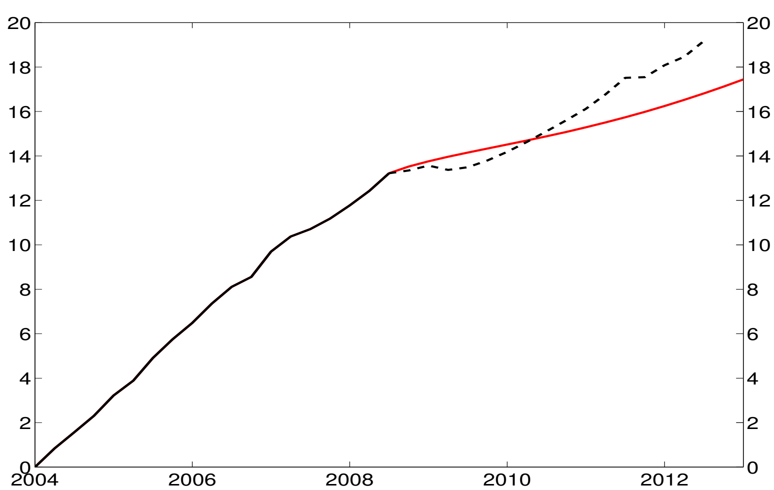
Figure A-1 depicts cumulative output growth and inflation forecasts.

Figure A-1: Cumulative Forecasts of Output Growth and Inflation

Log Output



Log Prices

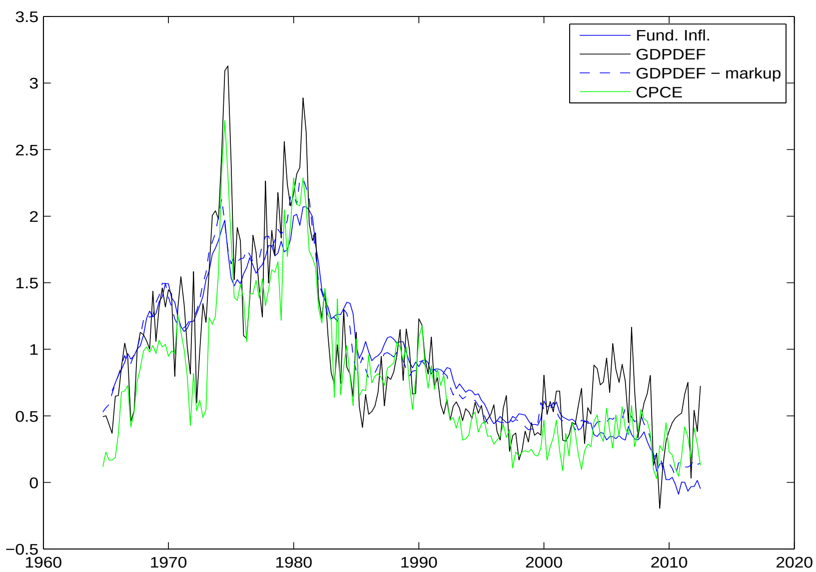


Notes: Log levels for 2004Q1 are normalized to zero. Actual data (solid black); Forecast paths (solid red); actual data (dashed black).

C.2 Section 4.2

Figure A-2 shows SWFF fundamental inflation $\tilde{\pi}_t$, core PCE inflation (since a core measure for the GDP Deflator is not available), as well as a measure of fundamental inflation stripped of the indirect effect that arises from the impact of markup shocks on the evolution of marginal costs ($\pi_t^{no\ mkup}$). $\tilde{\pi}_t$ and $\pi_t^{no\ mkup}$ are close to one another and track core inflation even better than they track the GDP deflator inflation. The comparison between core and actual inflation is also revealing: differences between core and headline inflation usually reflect abrupt changes in commodity prices, as in the latest period or in the mid-2000s, and these changes are captured by markup shocks in the model. But markup shocks also have an effect on marginal costs: positive markup shocks depress economic activity and make fundamental inflation lower, opening a gap between $\tilde{\pi}_t$ and $\pi_t^{no\ mkup}$.

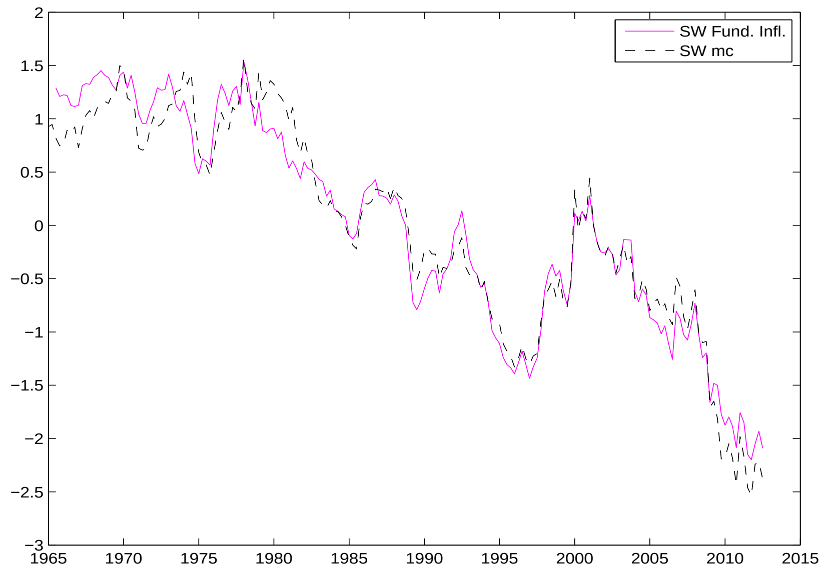
Figure A-2: Inflation, Fundamental Inflation, Counterfactual Inflation without Markup Shocks, and Core Inflation



Notes: GDP deflator inflation (solid black); core PCE inflation (solid green); $\tilde{\pi}_t$ from SWFF model (solid blue); counterfactual GDP deflator inflation $\pi_t^{no\ mkup}$ without markup shocks (dashed blue).

Figure A-3 compares SW fundamental inflation and SW marginal costs. The two series look almost identical, illustrating that for low ζ_p fundamental inflation tracks marginal costs.

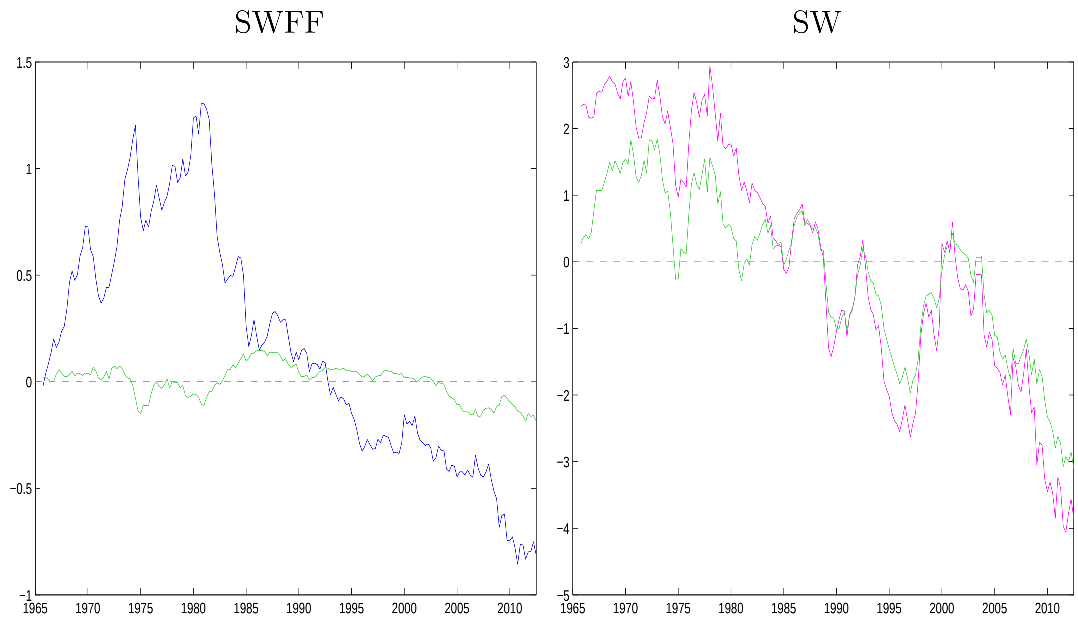
Figure A-3: SW Fundamental Inflation and SW Marginal Costs



Notes: Smoothed marginal costs from SW model (dashed black); fundamental inflation from SW model (solid purple). Both series are standardized (demeaned and divided by their respective standard deviation).

Figure A-4 shows that the fraction of fundamental inflation attributable to markup shocks is very small for the SWFF model, whereas markup shocks explain most of fundamental inflation in the SW model.

Figure A-4: Movements in Fundamental Inflation $\tilde{\pi}_t$ Attributable to Markup Shocks

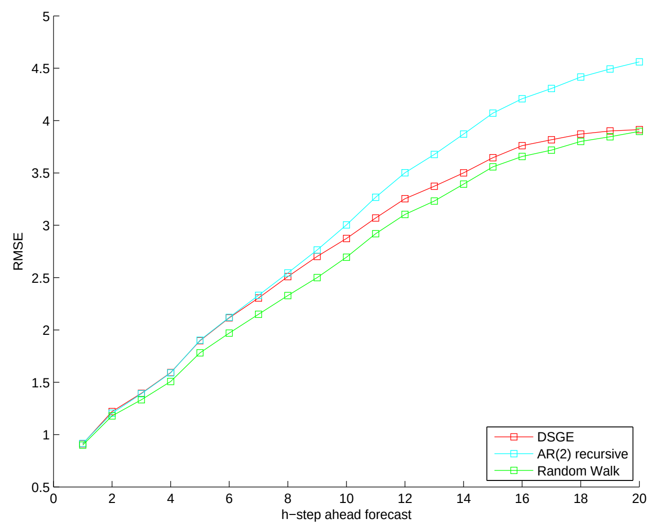


Notes: Left panel: fundamental inflation from SWFF model (solid blue); movements in fundamental inflation attributable to markup shocks (solid green). Right panel: fundamental inflation from SW model (solid purple); movements in fundamental inflation attributable to markup shocks (solid green).

C.3 Section 4.3

Figure A-5 compares RMSEs for marginal cost $\mathbb{E}[mc_t|Y_{1:T_{full}}, \hat{\theta}]$ forecasts from the SWFF model.

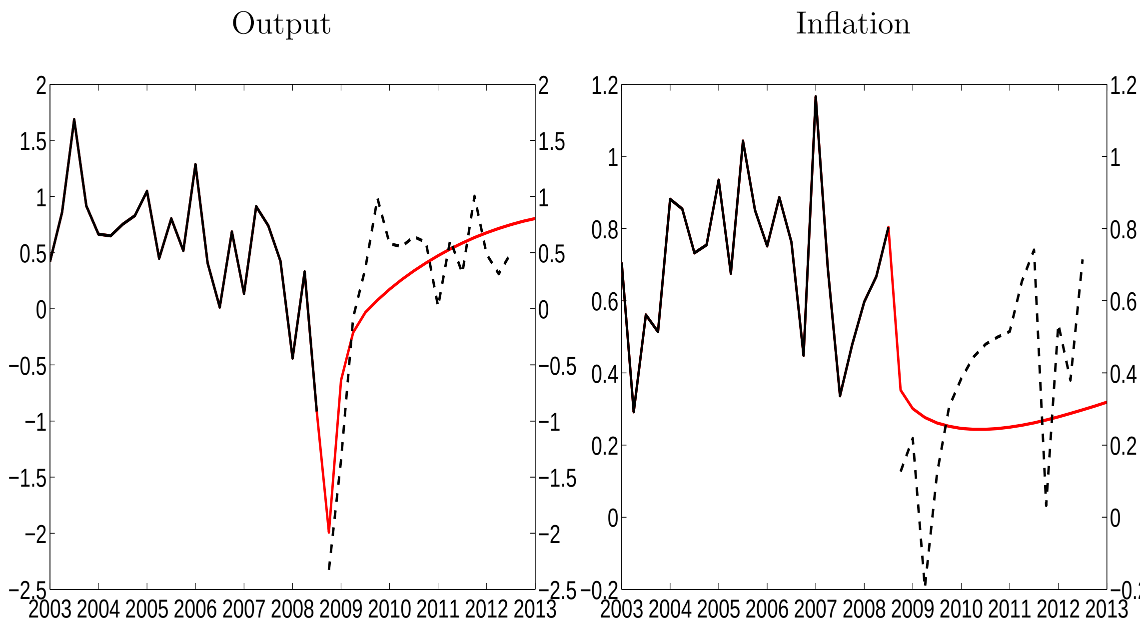
Figure A-5: RMSE of Marginal Cost Forecasts



Notes: The figure shows the RMSE of marginal costs forecasts from the SWFF model (red line), a random walk (green) and an AR(2) model estimated recursively on past marginal cost data (light blue) for the period 1989Q4-2012Q3.

Figure A-6 depicts output growth and inflation forecasts that are obtained by replacing real wage growth with the growth rate of detrended real wages. We do not re-estimate the DSGE model parameter; we only re-run the Kalman filter to generate the forecasts.

Figure A-6: Forecasts of Output Growth and Inflation Based on Detrended Wages



Notes: Output growth and inflation: actuals until 2008Q3 (solid black); forecast paths (solid red); actuals starting 2008Q4 (dashed black).