POTENTIAL AND NATURAL OUTPUT

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ABSTRACT. We estimate a DSGE model with imperfectly competitive products and labor markets, and sticky prices and wages. We use the model to back out two counterfactual objects: *potential output*, i.e. the level of output that would prevail under perfect competition, and *natural output*, i.e. the level of output that would prevail with flexible prices and wages. We find that potential output is smooth, resulting in an output gap that closely resembles traditional measures of detrended output. Meanwhile natural output is extremely volatile, due to the very high variability of markup shocks. These disturbances, however, are very similar to measurement errors because they only explain price and wage inflation at very high frequencies. Under this alternative interpretation, potential and natural output move one-to-one.

1. INTRODUCTION

Is modeling imperfect competition, nominal rigidities and monetary policy important for our understanding of macroeconomic fluctuations? The objective of this paper is to provide a *quantitative* answer to this question. We do so by estimating a dynamic stochastic general equilibrium (DSGE) model with imperfectly competitive products and labor markets, and sticky prices and wages. The model is then used to back out two counterfactual objects:

- the *potential* (or *efficient*) level of output, i.e. the level of output that would prevail if products and labor markets were perfectly competitive;
- the *natural* level of output, i.e. the level of output that would prevail under imperfectly competitive markets, but with flexible prices and wages.

These are distinct objects because natural output reflects both the static distortion due to imperfect competition and the dynamic distortions due to exogenous time variation in the degree of markets competitiveness. In our case, the latter are modeled as shocks to desired markups in products and labor markets.

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According to our estimates, U.S. potential output has evolved quite smoothly in the postwar period. In other words, had markets been competitive, postwar business cycles would have been much less pronounced. A consequence of this finding is that the difference between actual and potential output, the *output gap*, closely resembles more traditional measures of detrended output, such as Hodrick-Prescott (HP) filtered output or the estimate produced by the Congressional Budget office (CBO).

Our second finding is that, on the contrary, natural output has been extremely volatile. The difference in volatility between natural and potential output is almost exclusively due to the high variability of wage markups shocks (Smets and Wouters (2007) and Chari, McGrattan, and Kehoe (2008)). A positive wage markup shock represents a negative shift of labor supply. When wages are sticky, the labor supply schedule is relatively flat. Hence, the drop in equilibrium hours and output can be moderate. On the other hand, with flexible wages the labor supply curve is substantially steeper. Hence, a positive markup shock produces a severe contraction in economic activity. This explains why potential output is estimated to be very volatile.

What is the interpretation of this finding? One interpretation is that, given the estimated volatility of mark-up shocks, output would have fluctuated enormously in the postwar period if prices and wages had been perfectly flexible. However, we regard this prediction of the model and interpretation of the results as unconvincing. In our model, in fact, the main role of price and wage markup shocks is to explain price and wage inflation at very high frequencies. Intuitively, this variation is unlikely to be due to exogenous high frequency changes in desired markups and more likely due, at least in part, to the presence of measurement error (Boivin and Giannoni (2006a)).

In order to investigate this possibility, we re-estimate our model replacing markup shocks simply with measurement errors in price and wage inflation. Not only does this specification yield a better fit of the data, but the inferred measurement errors are very similar to the "structural" mark-up shocks backed out from the baseline model. Moreover, both the estimates of the structural parameters and potential output are almost identical in the two specifications.

We draw three broad conclusions from our study:

(1) Our inferred measures of potential output indicate that the assumption of imperfectly competitive markets matters substantially for understanding business cycles. Put

another way, endogenous variations in price and wage markups generate important propagation mechanisms, which render the cyclical behavior of the economy quite different from the case in which markets are competitive and markups are zero.

(2) Our estimates of natural output in the baseline case (and of potential output in the model with measurement error) suggest caution in interpreting exogenous variations in markups as underlying structural shocks.

(3) From a more normative perspective, our analysis reveals that a simple estimated New-Keynesian model can deliver an output gap in line with measures of economic slack commonly referenced for the conduct of monetary policy (see, for example, Orphanides (2001), Laubach and Williams (2003) or Mishkin (2007)). This is of particular relevance considering the growing importance of this class of models for policy discussions (Gali and Gertler (2007)). On the other hand, our study also suggests a potentially ample role for monetary policy stabilization of real activity.

This paper is related to a large literature on the estimation of DSGE models (see, for instance, Rotemberg and Woodford (1997), Lubik and Schorfheide (2004), Boivin and Giannoni (2006b) or Smets and Wouters (2007)). Some of these papers explicitly assume that monetary policy responds to the difference between actual and potential output, but do not focus on the model predictions about the output gap. This issue is potentially important because a number of studies have shown that it is hard to obtain model-based estimates of the output gap that resemble detrended output (Levin, Onatski, Williams, and Williams (2005), Nelson (2005), Andrés, López-Salido, and Nelson (2005) and Edge, Kiley, and Laforte (2008)).

Similar to Levin, Onatski, Williams, and Williams (2005), Nelson (2005), Andrés, López-Salido, and Nelson (2005) and Edge, Kiley, and Laforte (2008), we explicitly take on the task of estimating the theory-based output gap. However, differently from these studies, our estimate of the output gap is in line with conventional views of the business cycles.

Our result that the output gap comoves with the business cycle is similar to Gali, Gertler, and Lopez-Salido (2007) and Sala, Soderstrom, and Trigari (2008). However, Gali, Gertler, and Lopez-Salido (2007) mainly study the gap between the consumption/leisure marginal rate of substitution and the marginal product of labor, which is proportional to the output gap only in particular cases. Moreover, we differ from Sala, Soderstrom, and Trigari (2008) because their paper focuses on optimal monetary policy issues, while our paper is positive in spirit. Another important difference between our paper and the rest of the literature is that we emphasize the difference between potential and natural output and the role of markup shocks in the flexible price economy. This relates our work to Chari, McGrattan, and Kehoe (2008), although they are not concerned with the estimation of the output gap.

The rest of the paper is organized as follows. Section 2 provides the details of the theoretical model. Section 3 builds up some intuition by analyzing a special case of this model. Section 4 describes the approach to inference and the procedure to estimate the potential and natural levels of output. Section 5 and 6 present the estimation results of the baseline model and our interpretation of them. Section 7 contains a number of robustness checks, while section 8 concludes.

2. The Model

This section outlines our baseline model of the U.S. business cycle. The model is similar to Christiano, Eichenbaum, and Evans (2005) and Smets and Wouters (2007), although we make the simplifying assumption that capital accumulation is exogenous.[1] We now present the optimization problems of all agents of our economy.

2.1. **Final goods producers.**

At every point in time t, perfectly competitive firms produce the final good Y_t combining a continuum of intermediate goods $Y_t(i)$, $i \in [0,1]$, according to the technology

$$Y_t = \left[\int_0^1 Y_t(i)^{\frac{1}{1+\Lambda_{p,t}}} di\right]^{1+\Lambda_{p,t}}.$$

We refer to $\Lambda_{p,t}$ as a price markup shock because it represents a disturbance to the desired markup of prices over marginal costs for the producers of intermediate goods. We assume that $\log(1+\Lambda_{p,t})$ is $i.i.d.N(0,\sigma_p^2)$.

Profit maximization and zero profit condition for the final goods producers imply the following relation between the price of the final good (P_t) and the prices of the intermediate goods ($P_t(i)$, $i \in [0,1]$)

$$P_t = \left[\int_0^1 P_t(i)^{-\frac{1}{\Lambda_{p,t}}} di\right]^{-\Lambda_{p,t}},$$

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[1] We will relax this assumption in section 7.

and the following demand function for the intermediate good i:

$$Y_t(i) = \left(\frac{P_t(i)}{P_t}\right)^{-\frac{1+\Lambda_{p,t}}{\Lambda_{p,t}}} Y_t.$$

2.2. **Intermediate goods producers.** A monopolistically competitive firm produces the intermediate good i with the production function

$$Y_t(i) = A_t L_t(i)^{\alpha}$$

where $L_t(i)$ denotes the labor input for the production of good i and A_t represents a productivity shock. We model A_t as nonstationary, with a growth rate ($z_t \equiv \log \frac{A_t}{A_{t-1}}$) evolving according to

$$z_t = (1-\rho_z)\gamma + \rho_z z_{t-1} + \varepsilon_{z,t},$$

with $\varepsilon_{z,t}$ $i.i.d.N(0, \sigma_z^2)$.

As in Calvo (1983), at each point in time, a fraction ξ_p of firms cannot re-optimize their prices. These firms set their prices following the indexation rule

$$P_t(i) = P_{t-1}(i)\pi_{t-1}^{\iota_p}\pi^{1-\iota_p},$$

where π_t is the gross rate of inflation and π denotes the steady state value of π_t. Re-optimizing firms choose instead their price, $\tilde{P}_t(i)$, by maximizing the expected present value of future profits:

$$E_t \sum_{s=0}^{\infty} \xi_p^s \beta^s \Lambda_{t+s} \left\{ \left[\tilde{P}_t(i)\left(\Pi_{j=0}^{s}\pi_{t-1+j}^{\iota_p}\pi^{1-\iota_p}\right)\right] Y_{t+s}(i) - W_t L_t(i) \right\},$$

where Λ_{t+s} is the marginal utility of consumption and W_t denotes the hourly nominal wage.

2.3. **Employment agencies.** Firms are owned by a continuum of households, indexed by $j \in [0,1]$. Each household is a monopolistic supplier of specialized labor, $L_t(j)$, as in Erceg, Henderson, and Levin (2000). Competitive employment agencies combines this specialized labor into a homogenous labor input sold to intermediate firms, according to

$$L_t = \left[\int_0^1 L_t(j)^{\frac{1}{1+\Lambda_{w,t}}} dj\right]^{1+\Lambda_{w,t}}.$$

We refer to $\Lambda_{w,t}$ as a wage markup shock because it represents a disturbance to the desired markup of wages over the marginal rate of substitution for wage setters. Notice that this shock has the same effect on the household's first order conditions as the preference shock analyzed by Hall (1997). This observational equivalence is important and we will return to this issue in section 6 and 7. We assume that $\log(1+\Lambda_{w,t})$ is $i.i.d.N(0,\sigma_w^2)$.[2]

Profit maximization by the perfectly competitive employment agencies implies the labor demand function

$$L_t(j) = \left(\frac{W_t(j)}{W_t}\right)^{-\frac{1+\Lambda_{w,t}}{\Lambda_{w,t}}} L_t,$$

where $W_t(j)$ is the wage received from employment agencies by the supplier of labor of type j, while the wage paid by intermediate firms for their homogenous labor input is

$$W_t = \left[\int_0^1 W_t(j)^{\frac{1}{\Lambda_{w,t}}} dj\right]^{\Lambda_{w,t}}.$$

2.4. **Households.** Each household maximizes the utility function

$$E_t \sum_{s=0}^{\infty} \beta^s b_{t+s} \left[\log\left(C_{t+s} - hC_{t+s-1}\right) - \varphi \frac{L_{t+s}(j)^{1+\nu}}{1+\nu}\right], \tag{2.1}$$

where C_t is consumption, h is the degree of internal habit formation and b_t is a "discount factor" shock affecting both the marginal utility of consumption and the marginal disutility of labor. This inter-temporal preference shock follows the stochastic process

$$\log b_t = \rho_b \log b_{t-1} + \varepsilon_{b,t},$$

with $\varepsilon_{b,t} \sim i.i.d.N(0,\sigma_b^2)$. Since technological progress is non stationary, we work with log utility to ensure the existence of a balanced growth path. Moreover, consumption is not indexed by j because the existence of state contingent securities ensures that in equilibrium consumption and asset holdings are the same for all households. In fact, the household budget constraint is given by

$$P_{t+s}C_{t+s} + T_t + B_{t+s} \leq R_{t+s-1}B_{t+s-1} + Q_{t+s-1}(j) + \Pi_{t+s} + W_{t+s}(j)L_{t+s}(j),$$

where T_t are lump-sum taxes and transfers, B_t denotes holding of government bonds, R_t is the gross nominal interest rate, $Q_t(j)$ is the net cash flow from participating in state contingent securities, and Π_t is the per-capita profit that households get from owning the firms.

Following Erceg, Henderson, and Levin (2000), in every period a fraction ξ_w of households cannot re-optimize their wages, but set their wages following the indexation rule

$$W_t(j) = W_{t-1}(j)\left(\pi_{t-1}e^{z_{t-1}}\right)^{\iota_w}\left(\pi e^{\gamma}\right)^{1-\iota_w}.$$

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[2] We have also experimented with a model with autocorrelated wage and price markup shocks. However, the estimated autocorrelation was fairly low and the results concerning potential and natural output were unchanged.

The remaining fraction of re-optimizing households set their wages by maximizing

$$E_t \sum_{s=0}^{\infty} \xi_w^s \beta^s b_{t+s} \left\{ -\varphi \frac{L_{t+s}(j)^{1+\nu}}{1+\nu} \right\},$$

subject to the labor demand function.

2.5. **Monetary and government policies.** Monetary policy sets the short term nominal interest rate following a Taylor type rule. In particular, the rule allows for interest rate smoothing, a systematic response to deviations of annual inflation from a time varying inflation target, and deviations of annual output growth from its steady state level:

$$\frac{R_t}{R} = \left(\frac{R_{t-1}}{R}\right)^{\rho_R} \left[\left(\frac{\left(\prod_{s=0}^{3} \pi_{t-s} \right)^{1/4}}{\pi_t^*} \right)^{\phi_\pi} \left(\frac{(Y_t/Y_{t-4})^{1/4}}{e^{\gamma}} \right)^{\phi_Y} \right]^{1-\rho_R} e^{\varepsilon_{R,t}},$$

where R is the steady state for the gross nominal interest rate and $\varepsilon_{R,t}$ is an *i.i.d.* $N(0, \sigma_R^2)$ monetary policy shock. The inflation target π_t^* evolves exogenously according to the process

$$\log \pi_t^* = (1-\rho_\pi) \log \pi + \rho_\pi \log \pi_{t-1}^* + \varepsilon_{\pi,t},$$

with $\varepsilon_{\pi,t} \sim i.i.d.N(0, \sigma_\pi^2)$. We also consider, and later discuss, an alternative specification of the policy rule, in which the monetary authority responds to the model-based output gap.[3]

3. The Output Gap in a Special Case

The objective of this paper is to provide a model-based estimate of the potential and natural levels of output. As mentioned in the introduction, potential output corresponds to the level of output under competitive markets, while natural output is defined as the level of output under flexible prices and wages. In general, both potential and natural output cannot be directly observed in the data, but must be inferred using the estimated DSGE model. We will follow this approach in sections 4 and 5. However, if we assume away habit formation, potential and natural output are a very simple function of some of the model's structural parameters and shocks. In order to build some intuition, in this section we follow Gali, Gertler, and Lopez-Salido (2007) and focus on this special case.

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[3] Fiscal policy is Ricardian, with the government budget constraint equal to $T_t + B_t \leq R_{t-1} B_{t-1}$.

Without habit formation, the evolution of natural output can be characterized by the following four equilibrium conditions:

$$0 = \lambda_{p,t} + w_t^n - \frac{1}{\alpha} a_t + \left(\frac{1}{\alpha} - 1 \right) y_t^n - \log \alpha \tag{3.1}$$

$$w_t^n = \nu l_t^n + c_t^n + \lambda_{w,t} \tag{3.2}$$

$$y_t^n = a_t + \alpha l_t^n \tag{3.3}$$

$$y_t^n = c_t^n, \tag{3.4}$$

where $\lambda_{p,t} \equiv \log(1 + \Lambda_{p,t})$, $\lambda_{w,t} \equiv \log(1 + \Lambda_{w,t})$, w_t is the logarithm of the real wage and the other lower case letters indicate the logarithm of the corresponding upper case letters.

If prices and wages are flexible, (this equilibrium is denoted by the superscript 'n' which stands for 'natural'), firms will set prices equal to a markup over marginal costs (equation (3.1)). Similarly, households will set the real wage equal to a markup over the marginal rate of substitution between hours and consumption (equation (3.2)). Finally, equation (3.3) and (3.4) correspond to the production function and the market clearing conditions respectively.

The combination of equations (3.1)-(3.4) yields

$$y_t^n = \underbrace{a_t + \frac{\alpha}{1+\nu} \log \alpha}_{y_t^p} \quad - \quad \underbrace{\frac{\alpha}{1+\nu} (\lambda_{p,t} + \lambda_{w,t})}_{d_t}, \tag{3.5}$$

according to which the evolution of the natural level of output is a function of two components. The first component corresponds to potential output, y_t^p, and is related to the path of productivity. Potential output describes how output would evolve under perfect competition. The second component, d_t, corresponds instead to the output distortion due to imperfect competition. The mean of this distortion is positive, which implies that natural output is on average lower than potential output. Moreover, natural output is also more volatile than potential output because the exogenous markup shocks make this distortion time varying.

The evolution of these markup shocks can be inferred only by estimating the entire DSGE model. Therefore, natural output cannot be directly extracted from the data in an easy way. However, potential output is just a simple function of productivity. Since the production function implies that $a_t = y_t - \alpha l_t$, we can measure productivity and, therefore, potential output using data on GDP and per-capita hours.[4]

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[4] We set $\alpha = 0.65$ and $\nu = 1$, which are standard values in the literature. See section 4 for the details about the parameterization of the model.

Figure 1*a* plots this measure of potential output as well as actual output. Notice that potential output corresponds to a smoother version of actual output, in line with the usual decomposition of output into trend and cycle obtained with common reduced-form, statistical methods. This emerges even more clearly from figure 1*b*, which plots the difference between the two lines. For comparison, figure 1*b* also reproduces HP-detrended output, which we use as one possible indicator of business cycle fluctuations (we will consider additional measures later on). Notice that the output gap fluctuations approximately correspond to output deviations from the HP trend. In other words, under perfect competition, output would evolve quite smoothly and we would not observe the typical patterns of business cycles. It is worth stressing that this result is independent of the details of the sticky prices and wages economy.

What do we learn, from this simple derivation? First, the evolution of productivity in a frictionless model is not sufficient to generate realistic business cycles. To preview our findings, this is true even in the model with endogenous capital accumulation that we will consider in section 7 as a robustness check. Therefore, the propagation generated by the price and wage stickiness is *potentially* important. Second, the derivation illustrates that potential output coincides with the productivity process only in the special case analyzed above.

In the more general case of habit formation in consumption, preference shocks also contribute to the evolution of potential output. In that case, the computation of the output gap is more involved and requires the estimation of the DSGE model. In principle, the inclusion of these frictions and additional disturbances could result in a substantially more volatile measure of potential output (Woodford (2003) and Gali (2008)) and, therefore, a very different characterization of the output gap. Furthermore, the estimation of the model is necessary to back out our second object of interest, i.e. the natural level of output. We take on this task in the next sections.

4. Model Solution and Estimation

This section describes how we solve and estimate the model in order to compute potential and natural output in the general case.

The first step of the model solution consists of rewriting the equilibrium conditions in terms of deviations of the real variables from the non-stationary technology process A_t. The collection of equilibrium conditions can then be represented by

$$E_t\left[f\left(\xi_{t+1},\xi_t,\xi_{t-1},\varepsilon_t,\theta\right)\right]=0, \tag{4.1}$$

where ξ_t is a properly defined $k \times 1$ vector of endogenous variables, which also includes all the variables necessary to characterize both the perfect competition and the flexible prices and wages equilibria, ε_t is the $n \times 1$ vector of exogenous i.i.d. disturbances and θ is a $p \times 1$ vector of structural unknown coefficients. We then log-linearize (4.1) around the non-stochastic steady state and solve the linear system of rational expectations equations by standard methods (for example Sims (2001)). This procedure delivers the following system of transition equations

$$\hat{\xi}_t = G(\theta)\,\hat{\xi}_{t-1} + M(\theta)\,\hat{\varepsilon}_t, \tag{4.2}$$

where the "hat" denotes log deviations from the steady state and $G(\theta)$ and $M(\theta)$ are conformable matrices whose elements are functions of θ.

4.1. **Observables and data.** We estimate the model using five series of U.S. quarterly data. More precisely, we specify the observation equation

$$x_t = H\hat{\xi}_t + d, \tag{4.3}$$

where $x_t \equiv [\Delta \log Y_t, \log L_t, \Delta \log \frac{W_t}{P_t}, \pi_t, R_t]$. Notably, our choice of observable variables implies that labor productivity and the labor share are also observed. This is important because it makes our analysis consistent with the literature focusing on productivity shocks as sources of sizable business cycles and the literature emphasizing the role of the labor share as a driving force of inflation (see, for example, Gali and Gertler (1999) and Sbordone (2002)).

The sample for our dataset spans from 1954:IV to 2006:III. We construct real GDP by dividing nominal GDP (Haver Analytics) by population (age 22 to 65) and the GDP Deflator (also from Haver). For hours we use a measure for the total economy (as opposed to just the non-farm business sector) following Francis and Ramey (2006). This is also our source for the population series. Real wages corresponds to nominal compensation of employees from NIPA, divided by hours and the GDP deflator. Inflation is measured as the quarterly log difference in the GDP deflator, while for nominal interest rates we use the effective Federal Funds rate. We do not demean or detrend any series.

4.2. **Bayesian inference and priors.** We use Bayesian methods to characterize the posterior distribution of the structural coefficients of the model (see An and Schorfheide (2007) for a survey). The posterior distribution combines the likelihood function with prior information.[5] The likelihood function can be evaluated by applying the Kalman Filter to the linear and Gaussian state space model represented by equations (4.2) and (4.3). In the rest of this section we briefly discuss the specification of the priors, which is reported in table 1.

We fix the steady state price and wage markups (λ_p and λ_w) to 10 and 25 percent respectively and the Frisch elasticity of labor supply to 1. These parameters only enter the slope of the price and wage Phillips curves and are not separately identified from the the degree of price and wage stickiness. Moreover, we set α equal to 0.65, which implies a steady state labor share of $\alpha/(1+\lambda_p) \approx 0.59$, consistent with our data.

We place weakly informative priors on the remaining coefficients. For instance, the prior on the degree of habit formation is centered at 0.6 and the 95 percent prior interval is wide enough to include most values used in the literature. Similarly, consistent with the literature, the coefficients of the policy rule imply considerable inertia and substantial interest rate reaction to inflation.

For the autocorrelation coefficients of the shock processes we use Beta priors. Our prior is centered at 0.4 for the persistence of the growth rate of productivity and 0.6 for the persistence of the inter-temporal preference shock. As for the inflation target shock, we fix the autocorrelation coefficient to 0.995 because we want this shock to capture the very low frequency behavior of inflation for which the DSGE model might not provide a good description (see, for example, Cogley and Sargent (2005), Primiceri (2006) or Ireland (2007)).

The price and wage markup shocks are normalized to enter with a unit coefficient in price and wage inflation equations respectively (see Smets and Wouters (2007) and appendix A). The priors on the innovations' standard deviations are quite disperse and chosen in order to generate volatilities for the endogenous variables broadly in line with the data. Finally, the covariance matrix of the innovations is assumed to be diagonal.

We conclude our description of the prior with an analysis of its implications for the volatility of the output gap. In this respect, our prior is quite disperse: the 90 percent prior interval for the standard deviation of the output gap spans from 0.34 to 3.21. The median of this distribution is 0.91, well below the variability of the commonly used statistical measures of detrended output that we will consider in the next section.

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[5] In section 7 we show that results are robust to estimating the model by maximum likelihood (i.e. with flat priors).

5. Potential Output and the Output Gap in the Estimated Model

This section presents the estimation results of the baseline model, as well as our estimates of potential output and the output gap. Table 1 reports the posterior median and 90 percent posterior intervals for the unknown coefficients. The data are generally quite informative about the model parameters. In particular, wages are re-optimized less frequently than prices. Moreover, monetary policy exhibits a substantial degree of activism, with interest rates responding more than 2 to 1 to inflation and 0.5 to 1 to output growth. The only case of weak identification seems to be the habit formation parameter, for which the posterior distribution does not deviate much from the prior.

Figure 2*a* plots the observed level of output relative to the model implied measure of potential. Meanwhile, figure 2*b* plots the posterior median and 90 percent posterior interval for the model-implied output gap, i.e. the difference between actual and potential output. These estimates are obtained by applying the Kalman Smoother to the state space form given by equations (4.2) and (4.3), for each draw generated by our posterior simulator.

For comparison, figure 3 plots the model implied gap together with three possible measures of the business cycle. These include HP-detrended output, following the Real Business Cycle tradition (King and Rebelo (1999)), and the deviation of log output from a linear trend and the CBO estimate of potential. Overall the DSGE based output gap captures cyclical fluctuations very well, closely resembling HP-detrended output and the CBO output gap in particular. The positive interpretation of this finding is that potential output is rather smooth, which is perhaps surprising since it is now being influenced by additional disturbances compared to the simple example considered in section 3. Furthermore, it suggests that, had products and labor markets been perfectly competitive, the postwar period would have experienced much less pronounced business cycles. Therefore, modeling explicitly the nominal and monetary part of the economy seems important for understanding cyclical fluctuations.

In particular, observe that the deep recession of the early 1980s is almost entirely driven by a collapse in the output gap. This confirms the anecdotal evidence about the importance of “nominal” and monetary factors during that historical period. Finally, our estimate of the output gap is particularly high during the 1990s, implying that the steady rise of output of the 1990s is considerably larger than the observed surge in productivity. One possible explanation for this finding is that we have not considered potential changes in the average growth rate of productivity in the 1990s (Edge, Laubach, and Williams (2007)). Another possibility is related to demographics, changes in labor force participation and other factors that may have driven the low frequency variation in hours. We will investigate this further in section 7.

In sum, we find that our theory-based estimate of the output gap resembles quite closely conventional measures of detrended output. This result is in contrast with the typical conclusion of the estimated DSGE literature (Mishkin (2007)), which has for the most part suggested very small output gaps and hence a volatile process for potential (Levin, Onatski, Williams, and Williams (2005), Andrés, López-Salido, and Nelson (2005) and Edge, Kiley, and Laforte (2008)). For this reason section 7 conducts an extensive set of robustness checks, including the estimation of a model with endogenous capital accumulation. As will become clear, none of these modifications will substantially affect our results.

Our finding that the output gap moves over the business cycle is consistent with the analysis of the efficiency gap of Gali, Gertler, and Lopez-Salido (2007) and the normative study of Sala, Soderstrom, and Trigari (2008). However, in contrast with both of these papers and the rest of the literature, we also provide a characterization of the natural level of output and the role of markup shocks. We turn to this next.

6. Natural Output and the Role of Markup Shocks

In this section we present our estimates of natural output. There are several reasons to look at the natural level of output, in addition to potential output. First, the difference between actual and natural output reflects the quantitative importance of nominal rigidities in isolation. The output gap, instead, summarizes the relevance of the imperfect competition assumption, i.e. the combined importance of nominal rigidities and the exogenous variation in markups. In other words, markup shocks open up a wedges between potential and natural output. Therefore, looking at natural output forces us to study the properties of these shocks, which have received considerable attention in the literature on optimal monetary policy due to the trade-off that they entail for the policymakers' objectives.

Figure 4*a* plots the model-based natural level of output. Our estimates are quite striking: had prices and wages been flexible, output would have been extremely volatile. As a result, the gap between actual and natural GDP (figure 4*b*) would have also been very volatile, fluctuating between approximately +100 and −100 percent.

The excess volatility of natural output relative to potential output is mainly due to the role of wage markup shocks. This is evident in figures 4*c* and 4*d*, that plot the gap between actual output and output under flexible prices and wages, when we shut down price and wage markup shocks respectively.[6]

An obvious question is why wage markup shocks have such a large effect on output when prices and wages are flexible? There are two explanations: first, under flexible wages, the labor supply schedule is much steeper than with sticky wages. As a consequence, the contraction of labor supply induced by a positive markup shock produces a more severe drop in equilibrium hours and output. The second explanation is that wage markup shocks are very volatile. Recall, in fact, that we have followed the usual normalization of these shocks, such that they have unit impact in the price and wage Phillips' curves (appendix A). This normalization involves multiplying the shock by the slope of the Phillips curve, which is generally tiny. Therefore, for a given volatility of the normalized shocks, this implies a very large volatility of the original shock with a structural interpretation.[7]

How can we interpret these results? One interpretation is that wage markups over marginal rates of substitution fluctuate enormously for exogenous reasons. Therefore, had prices and wages been perfectly flexible, output would have also varied by implausibly large amounts. However, we regard this prediction of the model and interpretation of the results as unconvincing. For example, the variance decomposition of our model reveals that price mark-up shocks explain the high frequency variation in price inflation but play a very limited role in the variability of the remaining observables. This is evident in table 2, that reports the share of variance of the 1,2,4 and 8 step-ahead forecast error attributed to price mark-up shocks. As for wage mark-up shocks, these disturbances also explain the bulk of the high frequency variability in real wages although retain a more prominent role for this series at longer horizons. Notice however that neither of these disturbances significantly influence output or hours.

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[6] Notice that, as mentioned in section 2, wage markup shocks are observationally equivalent to the intratemporal preference shocks of Hall (1997) in our framework. Under this alternative interpretation, these disturbances would influence the perfect competition economy and potential output. Hence, the output gap would correspond to the volatile process plotted in figure 4*c*. We will return to this issue in section 7.

[7] We have also tried to estimate the model without the normalization. This leaves all our conclusions intact since it delivers standard deviations of 14.62 and 199.47 for price and wage mark-up shocks respectively.

Intuitively, this high frequency variability seems unlikely to be due to exogenous high frequency changes in desired markups but perhaps due to the presence of measurement error. To assess whether this alternative interpretation alters our results, we have re-estimated our model replacing the two markup shocks with measurement error. Table 3 reports the posterior median and 90 percent posterior interval for the unknown coefficients (second column). Interestingly, none of the estimates change substantially relative to the baseline case (repeated in the first column), with the exception of the degree of price stickiness, which is substantially lower here. In addition, figure 5*a* plots the estimate of the output gap, which is almost identical to the one in the baseline model.

To summarize, our results suggest caution in interpreting exogenous variations in markups as underlying structural shocks. This is made clear in figure 5*b* and *c* which shows a very close correspondence between the "structural" markup shocks in the baseline model and their counterparts when treated as measurement errors. For price markup shocks this is consistent with work by Boivin and Giannoni (2006a) using rich datasets. As for wages, it is also well known that alternative data sources (e.g. NIPA, CES, CPS) can produce large discrepancies (see, for example, Abraham, Spletzer, and Stewart (1999), Bosworth and Perry (1994), or Aaronson, Rissman, and Sullivan (2004)). Nonetheless, given the large share of wage variability explained by wage markup shocks, the measurement error interpretation of these disturbances is likely to be only part of the story. Shedding light on the role and interpretation of these shocks seems a priority for future research.

7. Robustness

7.1. **Maximum likelihood.** In our baseline exercise, we follow the recent literature on Bayesian estimation of DSGE models and use the prior information reported in table 1. To verify that the priors are not responsible for our main results, we re-estimate the model by maximum likelihood. Maximizing the likelihood is numerically more challenging than maximizing the posterior, since the use of weakly informative priors ameliorates the problems related to the presence of flat areas of the likelihood function and of multiple local modes. However, as illustrated in figure 6*a*, the output gap based on the MLE estimates is almost identical to the one in the baseline model.

7.2. **Output gap in the policy rule.** We also estimate a model in which we allow the policy rule to respond directly to the output gap, rather than annual output growth, since both specifications are quite common in the literature. Once again, this modification barely affects the quantitative results (figure 6*b*).

7.3. **Labor supply shocks.** An important assumption of our baseline model is the absence of "labor supply" shocks. In general these shocks are observationally equivalent to wage mark-up shocks. In our baseline however, wage markup disturbances are white noise and were shown not to explain a meaningful share of the variability of output and hours. This does not rule out however, the presence of a persistent component of "labor supply" shock which, as suggested by Hall (1997), could play a central role in business cycle fluctuations. Here we demonstrate the robustness of our results to the presence of these shocks. Incorporating this disturbances is an important extension because labor supply shocks directly affect potential output and, therefore, might shift to potential output some of the variability of output that is now attributed to the output gap.

Following Hall (1997), we model labor supply shocks as intra-temporal preference shocks, i.e. disturbances affecting the marginal rate of substitution between consumption and hours. More precisely, we assume that the parameter φ in the utility function (2.1) is time varying and follows an exogenous AR(1) process:

$$\log \varphi_t = \left(1 - \rho_\varphi\right) \log \varphi + \rho_\varphi \log \varphi_{t-1} + \varepsilon_{\varphi,t},$$

with $\varepsilon_{\varphi,t} \sim i.i.d.N(0, \sigma_\varphi^2)$. For the estimation, as in the case of the inter-temporal preference shock, our prior on ρ_φ is centered at 0.8, implying a substantial degree of persistence. As for the standard deviation of the innovations, σ_φ, we impose a prior that favors more time variation than other shocks. This seems an appropriate strategy if we are interested in assessing the robustness of our results to the presence of these new disturbances.[8]

Figure 6*c* plots the estimate of the output gap implied by the model with labor supply shocks, which is very similar to the one of the baseline model. This is not surprising, given the fact that labor supply shocks are inferred to be very persistent and to absorb only some of the low frequency fluctuations in hours and output (see Justiniano, Primiceri, and Tambalotti (2008) for a careful assessment of this result). As a consequence, if anything, the output gap in figure 6*c* resembles even more closely both HP-detrended output. This is because labor supply shocks boost potential in the late 1990s, perhaps capturing changes in labor force participation or demographics affecting the low frequency component of hours.

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[8] Our prior on σ_φ is an Inverse-Gamma with mean equal to 4 and standard deviation equal to 2.

7.4. **A larger scale model.** Another simplifying assumption of our baseline model is the absence of endogenous capital accumulation and the related frictions and shocks typical of larger scale models. As for labor supply shocks, these features might affect our estimates of potential output and the output gap. Therefore, in order to check the robustness of our results, we have also estimated a larger scale model, along the lines of Christiano, Eichenbaum, and Evans (2005), Smets and Wouters (2007) and Justiniano, Primiceri, and Tambalotti (2008).

When capital accumulation is endogenous, the production function of intermediate firms becomes

$$Y_t(i) = \max\left\{A_t^{\alpha} L_t(i)^{\alpha} K_t(i)^{1-\alpha} - A_t F; 0\right\}, \tag{7.1}$$

where $K_t(i)$ denotes the amounts of effective units of capital inputs of firm i and F is a fixed cost of production, which we choose so that profits are zero in steady state. In this new economy, households own the capital stock, so that their budget constraint becomes

$$P_t C_t + P_t I_t + T_t + B_t \leq R_{t-1} B_{t-1} + Q_{t-1}(j) + \Pi_t + W_t(j) L_t(j) + r_t^k u_t \bar{K}_{t-1} - P_t a(u_t) \bar{K}_{t-1},$$

where I_t stands for investment. Following Christiano, Eichenbaum, and Evans (2005), households also choose the capital utilization rate, u_t, which transforms physical capital ($\bar{K}_t$) into effective capital according to

$$K_t = u_t \bar{K}_{t-1}.$$

Effective capital is then rented to firms at the rate r_t^k. The cost of capital utilization is $a(u_t)$ per unit of physical capital. We assume $u_t = 1$ in steady state, $a(1) = 0$ and define $\chi \equiv \frac{a''(1)}{a'(1)}$.

The physical capital accumulation equation is

$$\bar{K}_t = (1-\delta)\bar{K}_{t-1} + \mu_t \left(1 - S\left(\frac{I_t}{I_{t-1}}\right)\right) I_t,$$

where δ is the depreciation rate. The function S captures the presence of adjustment costs in investment, as in Christiano, Eichenbaum, and Evans (2005). We assume that, in steady state, $S = S' = 0$ and $S'' > 0$. As in Greenwood, Hercowitz, and Krusell (1997), the investment shock μ_t is an exogenous disturbance to the rate of transformation of today's one unit of forgone consumption into tomorrow's physical capital. We assume that it follows the stochastic process

$$\log \mu_t = \rho_\mu \log \mu_{t-1} + \varepsilon_{\mu,t},$$

where $\varepsilon_{\mu,t}$ is $i.i.d.N(0,\sigma_\mu^2)$. Incorporating this shock in the analysis might be important since Justiniano, Primiceri, and Tambalotti (2008) argue that this disturbance is responsible for most business cycle fluctuations in the US economy.

In this larger scale model we also assume that public spending is determined exogenously as a time-varying fraction of GDP

$$G_t = \left(1 - \frac{1}{g_t}\right) Y_t,$$

where the government spending shock g_t follows the stochastic process

$$\log g_t = (1-\rho_g)\log g + \rho_g \log g_{t-1} + \varepsilon_{g,t},$$

with $\varepsilon_{g,t} \sim i.i.d.N(0,\sigma_g^2)$.

Finally, the aggregate resource constraint becomes

$$C_t + I_t + G_t + a(u_t)\bar{K}_{t-1} = Y_t,$$

which can be derived by combining the government and the households' budget constraints with the zero profit condition of the final goods producers and the employment agencies. Finally, as in section 7.3, we also assume the presence of an intra-temporal preference shock affecting the marginal rate of substitution between consumption and hours. The rest of the model is identical to the baseline model of section 2.

We estimate this version of the model using also data on consumption and investment and the prior specification reported in table 4. These priors are identical to the priors of our baseline model for the coefficients common to the two models. As for the additional coefficients appearing in the model with capital, we adopted the prior specification of Justiniano, Primiceri, and Tambalotti (2008).[9]

While the parameter estimates are similar to values obtained by the existing literature, here we draw particular attention to our estimate of potential output and the output gap. Figure 7 reports the posterior median of the output gap and, for comparison, our three measures of the business cycle: HP-detrended output and output deviations from a linear trend and the CBO estimate of potential. There are a few things to notice. First, even in this larger scale model with more shocks potentially buffeting potential output, the output gap is not small. Moreover, as for the baseline case, the output gap closely resembles conventional measures

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[9] In the model with capital, we also estimate ν and λ_p because these coefficients are now identified.

of the business cycle. We view these results as an important assessment of robustness of our main findings.

8. Conclusions

[TBW]

Appendix A. Normalization of the Shocks

As in Smets and Wouters (2007), we normalize some of the exogenous shocks by dividing them by a constant term. For instance, one of our log-linearized equilibrium conditions is the following Phillips curve:

$$\hat{\pi}_t = \frac{\beta}{1+\beta\iota_p} E_t \hat{\pi}_{t+1} + \frac{1}{1+\beta\iota_p} \hat{\pi}_{t-1} + \kappa \hat{s}_t + \kappa \hat{\lambda}_{p,t},$$

where $\kappa \equiv \frac{\left(1-\beta\xi_p\right)\left(1-\xi_p\right)}{(1+\iota_p\beta)\xi_p\left(1+\frac{1-\alpha}{\alpha}(1+\frac{1}{\lambda_p})\right)}$, s_t is the model-implied real marginal cost and the "hat" denotes log deviations from the non-stochastic steady state. The normalization consists of defining a new exogenous variable, $\hat{\lambda}^*_{p,t} \equiv \kappa \hat{\lambda}_{p,t}$, and estimating the standard deviation of the innovation to $\hat{\lambda}^*_{p,t}$ instead of $\hat{\lambda}_{p,t}$. We do the same for the wage markup shock, for which we use the following normalizations:

$$\hat{\lambda}^*_{w,t} = \left(\frac{\left(1-\beta\xi_w\right)\left(1-\xi_w\right)}{\left(1+\beta\right)\xi_w \left(1+\nu(1+\frac{1}{\lambda_w})\right)} \right) \hat{\lambda}_{w,t}$$

These normalizations are chosen in such a way that these shocks enter the inflation and wage equations with a unity coefficient. In this way it is easier to choose a reasonable prior for their standard deviation. Moreover, the normalization is a practical way to impose correlated priors across coefficients, which is desirable in some cases. For instance, imposing a prior on the standard deviation of the innovation to $\hat{\lambda}^*_{p,t}$ corresponds to imposing prior that allow for correlation between κ and the standard deviation of the innovations to $\hat{\lambda}_{p,t}$. Often, these normalizations improve the convergence properties of the MCMC algorithm.

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Table 1: Prior densities and posterior estimates for baseline model

		Prior			Posterior		
Coefficient	Description	Prior Density [1]	Mean	Std	Median	Std	[5 , 95]
γ	SS technology growth rate	N	0.5	0.025	0.49	0.02	[0.46 , 0.53]
$100(\pi\text{-}1)$	SS quarterly inflation	N	0.625	0.1	0.62	0.10	[0.47 , 0.78]
$100(\beta^{-1}\text{-}1)$	Discount factor	G	0.25	0.1	0.15	0.05	[0.08 , 0.26]
h	Consumption habit	B	0.6	0.1	0.63	0.03	[0.58 , 0.68]
ξ_p	Calvo prices	B	0.66	0.1	0.74	0.02	[0.71 , 0.78]
ξ_w	Calvo wages	B	0.66	0.1	0.91	0.02	[0.88 , 0.93]
ι_p	Price indexation	B	0.5	0.2	0.28	0.07	[0.16 , 0.40]
ι_w	Wage indexation	B	0.5	0.2	0.06	0.03	[0.02 , 0.13]
Φ_p	Taylor rule inflation	N	1.7	0.3	2.35	0.16	[2.08 , 2.62]
Φ_y	Taylor rule output	G	0.3	0.2	0.51	0.08	[0.37 , 0.64]
ρ_R	Taylor rule smoothing	B	0.6	0.2	0.65	0.04	[0.58 , 0.70]
ρ_z	Neutral Technology growth	B	0.4	0.2	0.57	0.04	[0.51 , 0.63]
ρ_b	Intertemporal preference	B	0.6	0.2	0.95	0.01	[0.92 , 0.96]
$logL^{ss}$	SS leisure	N	339.45	0.5	339.51	0.44	[338.79 , 340.24]
$100\ \sigma_{mp}$	Monetary policy	I	0.15	1	0.22	0.01	[0.20 , 0.24]
$100\ \sigma_z$	Neutral Technology growth	I	1	1	0.78	0.04	[0.72 , 0.85]
$100\ \sigma_p$	Price mark-up	I	0.15	1	0.17	0.01	[0.15 , 0.19]
$100\ \sigma_{\pi*}$	Inflation Target	I	0.04	0.02	0.06	0.01	[0.05 , 0.07]
$100\ \sigma_b$	Intertemporal preference	I	1	1	3.45	0.77	[2.46 , 4.95]
$100\ \sigma_w$	Wage mark-up	I	0.15	1	0.30	0.02	[0.27 , 0.32]

Calibrated coefficients: $\nu=1$, $\lambda_p=0.1$, $\lambda_w=0.25$, $\rho_{\pi*}=0.995$, $\alpha=0.65$

[1] N stands for Normal, B Beta, G Gamma and I Inverted-Gamma1 distribution

[2] Median and posterior percentiles from 4 chains of 50,000 draws generated using a Random walk Metropolis algorithm, where we discard the initial 20,000 and retain one in every 5 subsequent draws.

Table 2: Share of the forecast error variance explained by price and wage mark-up shocks

Panel A: Price Mark-up shocks

Horizon (quarters) ***Series***	**1**	**2**	**4**	**8**
Output growth	0.01	0.01	0.01	0.01
Inflation	0.67	0.45	0.28	0.19
Interest Rates	0.03	0.07	0.12	0.07
Real Wage growth	0.10	0.09	0.08	0.07
Hours	0.05	0.05	0.04	0.02

Panel B: Wage Mark-up shocks

Horizon (quarters) ***Series***	**1**	**2**	**4**	**8**
Output growth	0.02	0.02	0.02	0.02
Inflation	0.01	0.02	0.02	0.02
Interest Rates	0.00	0.00	0.00	0.01
Real Wage growth	0.82	0.73	0.64	0.58
Hours	0.06	0.08	0.10	0.11

[1] Obtained using the posterior baseline model parameters reported in Table 1.

Table 3: Estimates for three alternative specifications

		Baseline	**Measurement Error Specification**				**Baseline**
Coefficient	Description	Median [1]	Median [2]	Std	[5	95]	MLE [3]
γ	SS technology growth rate	0.49	0.49	0.02	0.46	0.53	0.50
$100(\pi-1)$	SS quarterly inflation	0.62	0.63	0.10	0.47	0.79	0.88
$100(\beta^{-1}-1)$	Discount factor	0.15	0.12	0.04	0.06	0.20	0.00
h	Consumption habit	0.63	0.61	0.04	0.55	0.67	0.63
ξ_p	Calvo prices	0.74	0.62	0.03	0.56	0.67	0.76
ξ_w	Calvo wages	0.91	0.91	0.01	0.88	0.93	0.93
ι_p	Price indexation	0.28	0.32	0.11	0.14	0.52	0.22
ι_w	Wage indexation	0.06	0.08	0.04	0.03	0.15	0.00
Φ_p	Taylor rule inflation	2.35	2.45	0.18	2.17	2.77	2.65
Φ_y	Taylor rule output	0.51	0.48	0.09	0.35	0.63	0.59
ρ_R	Taylor rule smoothing	0.65	0.68	0.03	0.63	0.73	0.64
ρ_z	Neutral Technology growth	0.57	0.46	0.05	0.37	0.55	0.57
ρ_b	Intertemporal preference	0.95	0.89	0.02	0.84	0.92	0.96
$logL^{ss}$	SS leisure	339.51	339.46	0.43	338.75	340.16	339.11
$100\,\sigma_{mp}$	Monetary policy	0.22	0.23	0.01	0.21	0.25	0.21
$100\,\sigma_z$	Neutral Technology growth	0.78	0.75	0.04	0.69	0.81	0.78
$100\,\sigma_p$	Price mark-up	0.17	0.20	0.01	0.18	0.22	0.17
$100\,\sigma_{\pi*}$	Inflation Target	0.06	0.06	0.01	0.05	0.07	0.06
$100\,\sigma_b$	Intertemporal preference	3.45	2.26	0.30	1.86	2.80	4.73
$100\,\sigma_w$	Wage mark-up	0.30	0.55	0.03	0.51	0.60	0.29

[1] Baseline model as reported in table 1

[2] Model with measurement errors

[3] Maximum likelihood estimates for baseline model

Table 4: Prior densities and posterior estimates for the model with capital

		Prior			Posterior[2]		
Coefficient	Description	Prior Density[1]	Mean	Std	Median	Std	[5 , 95]
α	Capital Share	N	0.3	0.05	0.16	0.01	[0.15 , 0.17]
ι_p	Price indexation	B	0.5	0.15	0.46	0.08	[0.31 , 0.59]
ι_w	Wage indexation	B	0.5	0.15	0.08	0.03	[0.04 , 0.13]
γ	SS technology growth rate	N	0.5	0.025	0.49	0.02	[0.45 , 0.53]
h	Consumption habit	B	0.6	0.1	0.74	0.06	[0.66 , 0.84]
λ_p	SS mark-up goods prices	N	0.15	0.05	0.30	0.04	[0.23 , 0.36]
$logL^{ss}$	SS leisure	N	0.33	0.025	0.33	0.03	[0.29 , 0.37]
$100(\pi-1)$	SS quarterly inflation	N	0.625	0.1	0.63	0.10	[0.46 , 0.79]
$100(\beta^{-1}-1)$	Discount factor	G	0.25	0.1	0.12	0.04	[0.06 , 0.19]
ν	Inverse Frisch elasticity	G	2	0.75	2.25	0.77	[1.26 , 3.73]
ξ_p	Calvo prices	B	0.66	0.1	0.91	0.01	[0.89 , 0.93]
ξ_w	Calvo wages	B	0.66	0.1	0.76	0.04	[0.68 , 0.83]
χ	Elasticity capital utilization costs	G	5	1	4.49	0.96	[3.12 , 6.23]
S''	Investment adjustment costs	G	4	1	4.61	0.74	[3.55 , 5.94]
Φ_p	Taylor rule inflation	N	1.7	0.3	2.46	0.21	[2.12 , 2.81]
Φ_{dy}	Taylor rule output growth	G	0.4	0.3	1.08	0.17	[0.84 , 1.39]
ρ_R	Taylor rule smoothing	B	0.6	0.2	0.76	0.04	[0.70 , 0.81]

(Continued on the next page)

Table 4: Prior densities and posterior estimates for the model with capital *(continued)*

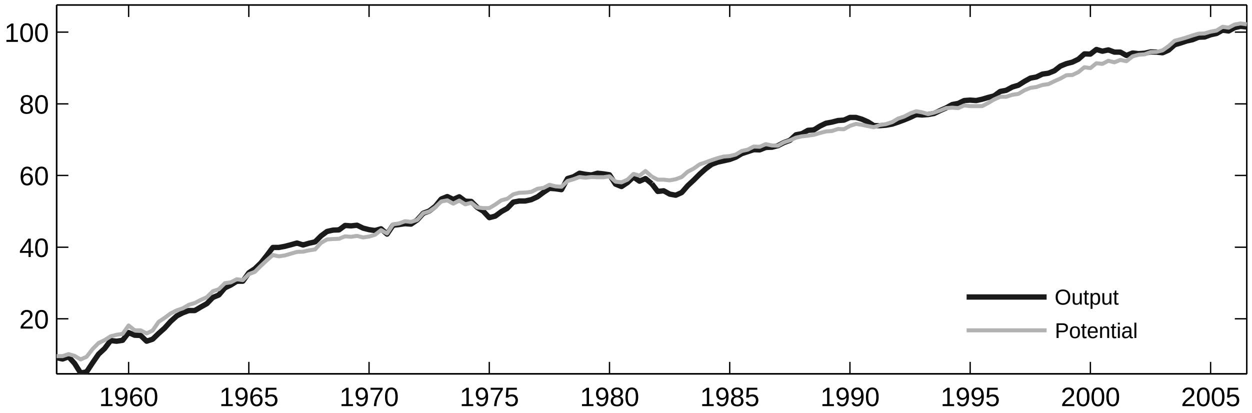
		Prior			Posterior[2]		
Coefficient	Description	Prior Density[1]	Mean	Std	Median	Std	[5 , 95]
ρ_z	Neutral Technology growth	B	0.4	0.2	0.08	0.04	[0.02 , 0.16]
ρ_g	Government spending	B	0.6	0.2	0.99	0.00	[0.99 , 0.99]
ρ_μ	Investment	B	0.6	0.2	0.55	0.06	[0.45 , 0.64]
ρ_L	Labor Disutility	B	0.8	0.15	0.98	0.01	[0.96 , 1.00]
ρ_b	Intertemporal preference	B	0.6	0.2	0.74	0.10	[0.50 , 0.84]
$100\,\sigma_{mp}$	Monetary policy	I	0.15	1	0.22	0.01	[0.20 , 0.24]
$100\,\sigma_z$	Neutral Technology growth	I	1	1	0.92	0.05	[0.85 , 1.01]
$100\,\sigma_g$	Government spending	I	0.5	1	0.37	0.02	[0.34 , 0.40]
$100\,\sigma_\mu$	Investment	I	0.5	1	11.02	1.87	[8.50 , 14.73]
$100\,\sigma_p$	Price mark-up	I	0.15	1	0.17	0.01	[0.15 , 0.19]
$100\,\sigma_L$	Labor Disutility	I	1	1	2.03	0.86	[1.14 , 3.86]
$100\,\sigma_b$	Intertemporal preference	I	0.1	1	0.03	0.01	[0.02 , 0.06]
$100\,\sigma_w$	Wage mark-up	I	0.15	1	0.30	0.02	[0.28 , 0.33]
$100\,\sigma_{\pi*}$	Inflation Target	I	0.05	0.025	0.05	0.01	[0.04 , 0.06]

Calibrated coefficients: depreciation rate (δ) is 0.025, g implies a SS government share of 0.22, λ_w=0.25, $\rho_{\pi*}$=0.995

[1] N stands for Normal, B Beta, G Gamma and I Inverted-Gamma1 distribution

[2] Median and posterior percentiles from 4 chains of 140,000 draws generated using a Random walk Metropolis algorithm, where, for each chain, we discard the initial 40,000 and retain one in every 10 subsequent draws.

Figure 1: Potential and Output Gap in a Special Case


Observed and Potential Levels of Output

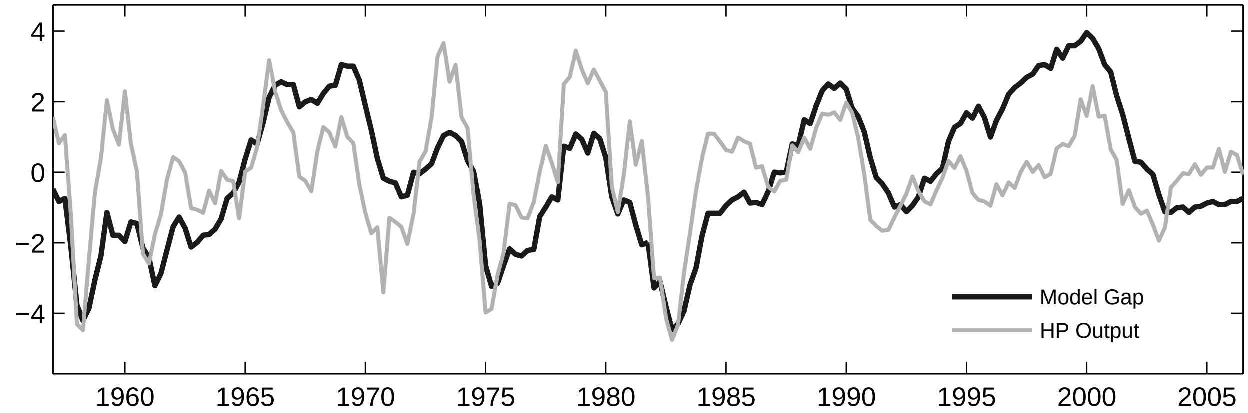
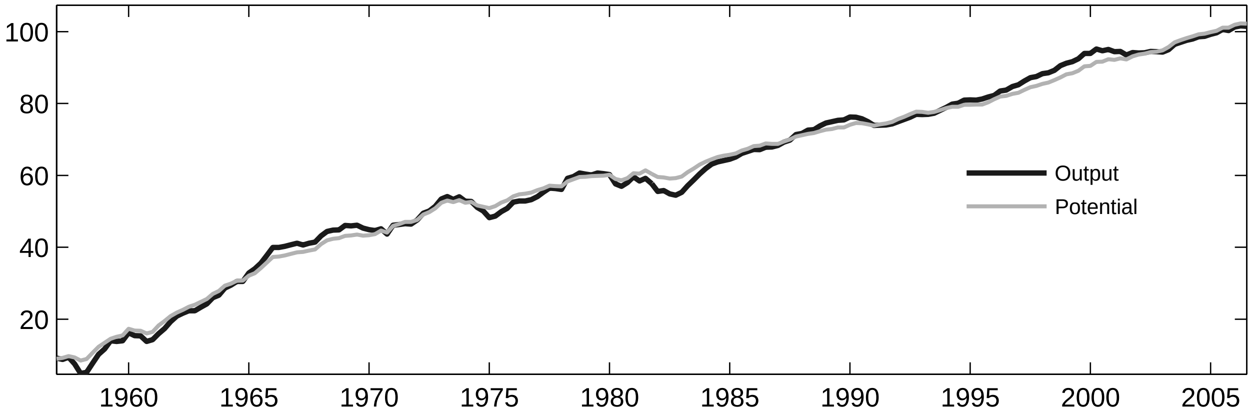

Model Output Gap and HP filtered Output

Figure 2: Potential and Output Gap in Baseline Estimated Model

Observed and Potential Levels of Output



Model Output Gap and 90% posterior bands

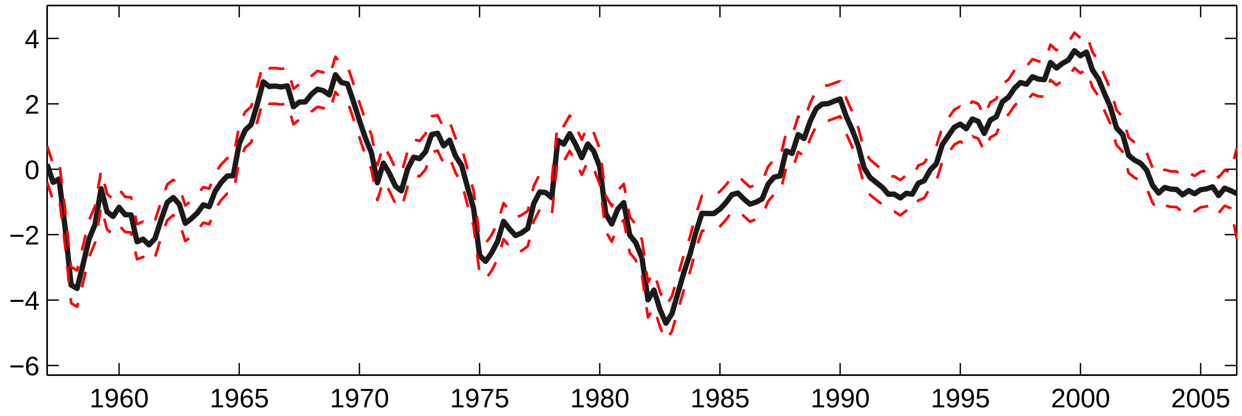


Figure 3: Output Gap and Various Measures of the Business Cycle

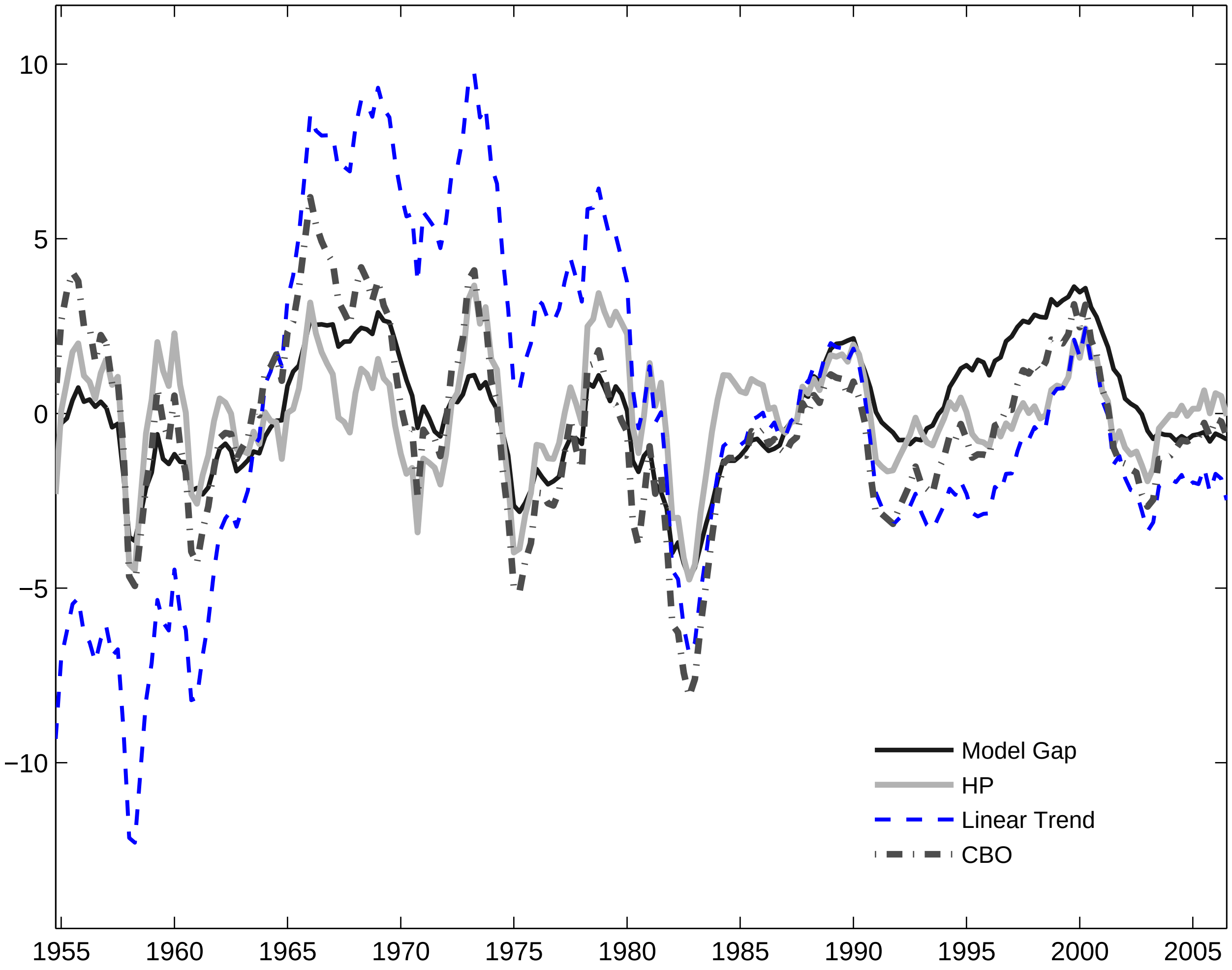
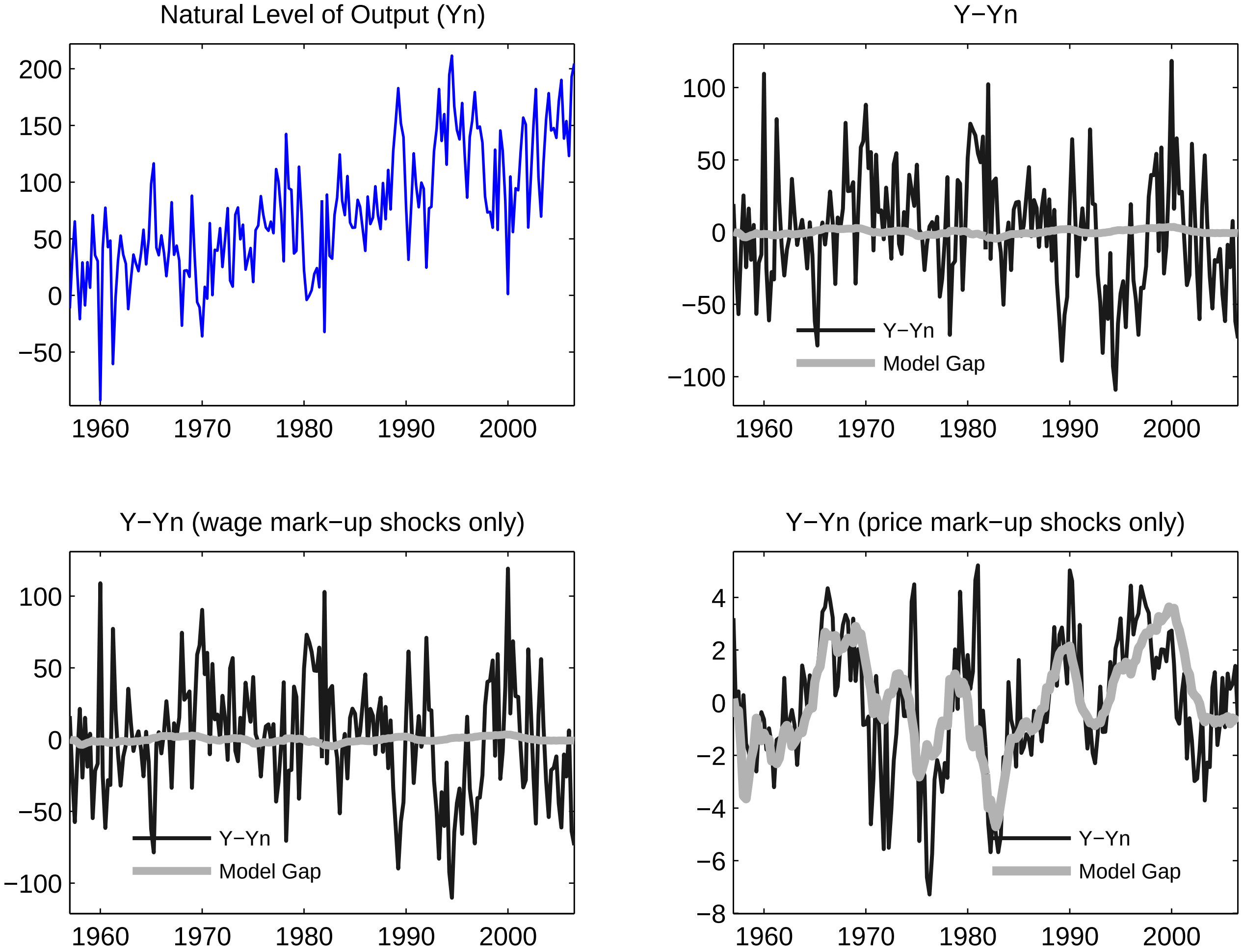


Figure 4: Natural Level of Output and individual contribution of wage and price mark−up shocks



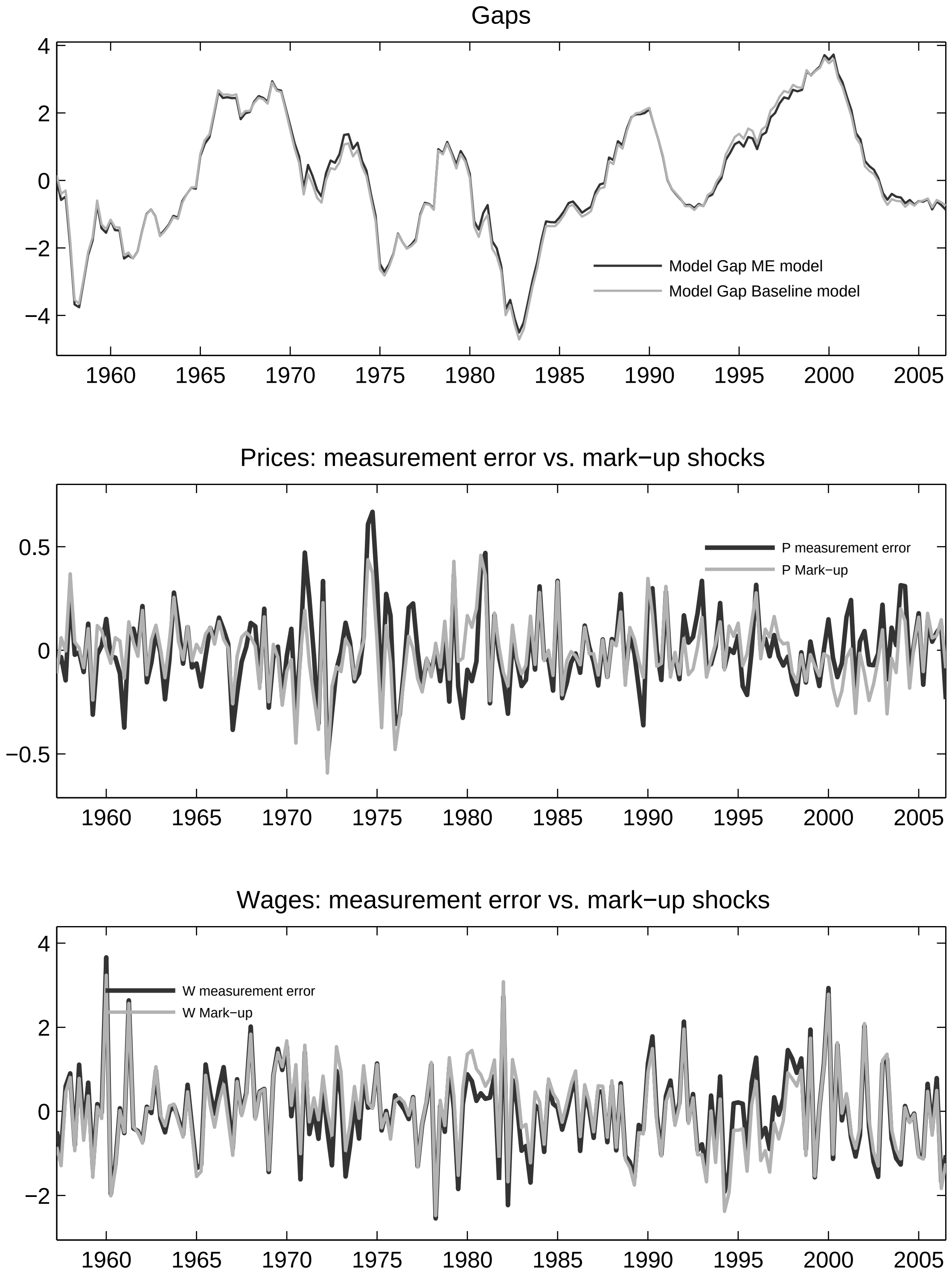
Natural Level of Output (Yn)

Y−Yn

Y−Yn (wage mark−up shocks only)

Y−Yn (price mark−up shocks only)

Figure 5: Output Gap and Measurement Errors (ME)



Gaps

Prices: measurement error vs. mark−up shocks

Wages: measurement error vs. mark−up shocks

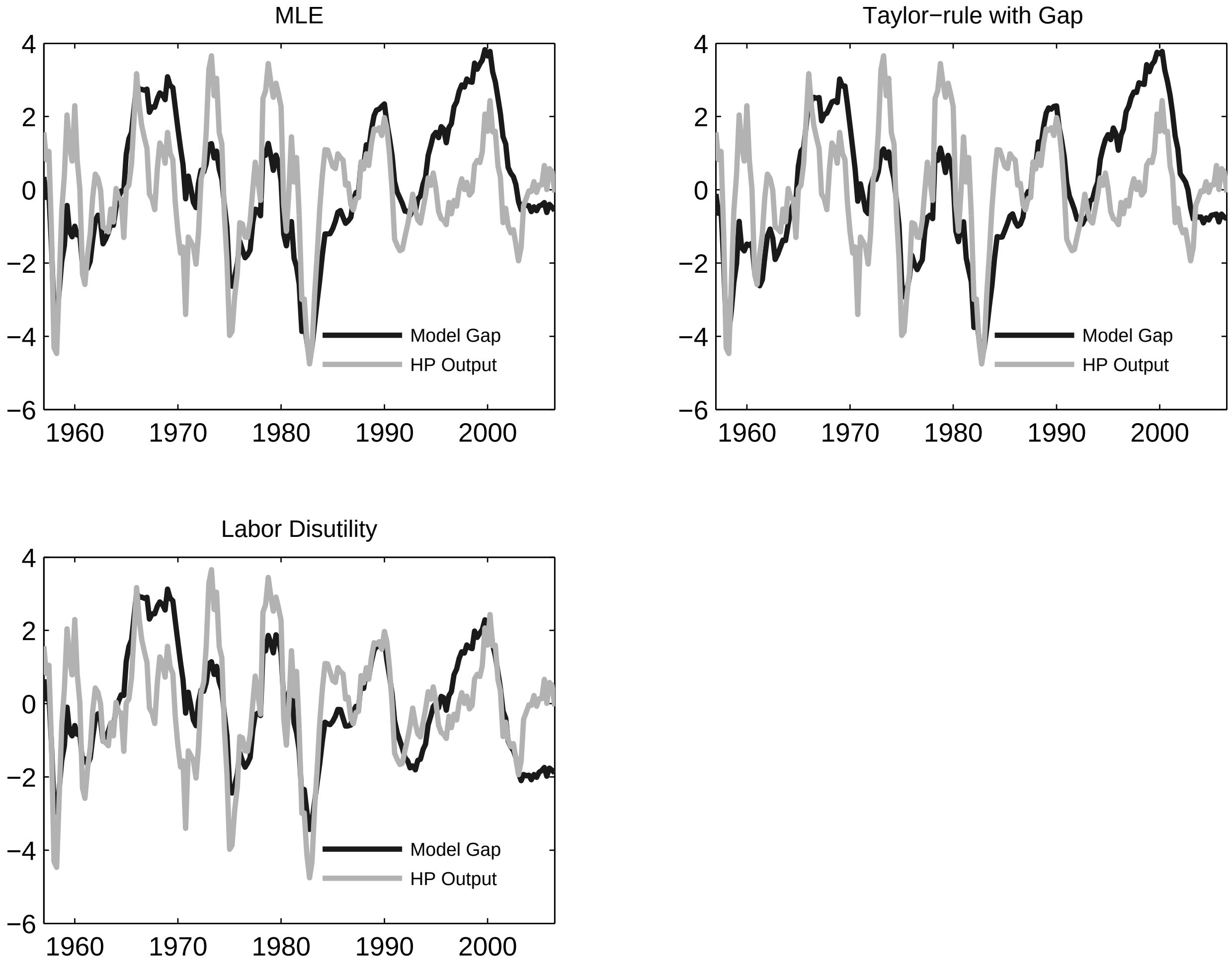


Figure 6: Output Gap for Alternative Specifications

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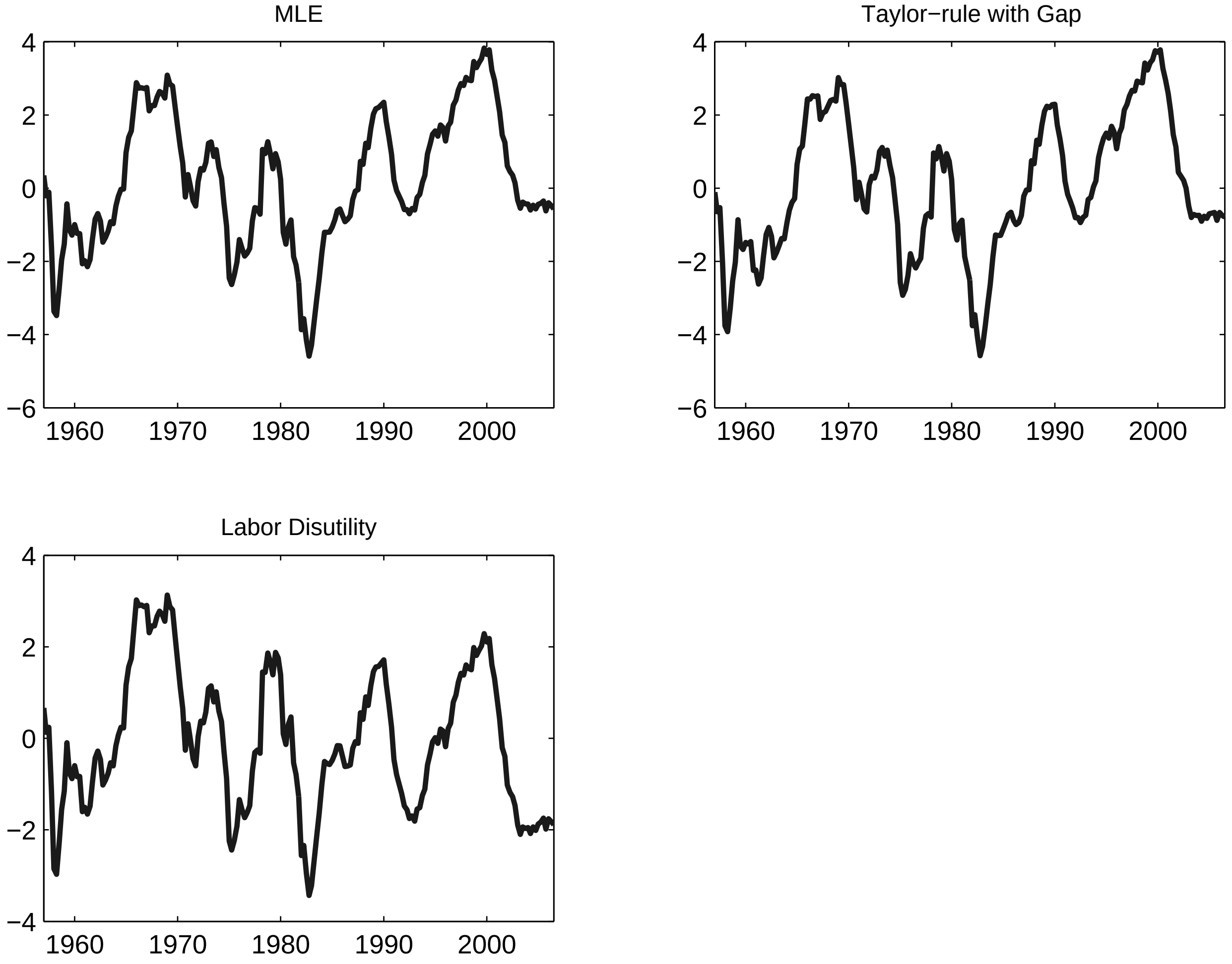

Figure 7: Output Gap in Estimated Model with Capital