Bank of Japan Working Paper Series

Structural Estimation of the Output Gap: A Bayesian DSGE Approach for the U.S. Economy

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No.07-E-24
November 2007

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This Version: November, 2007

Abstract

We estimate the output gap that is consistent with a fully specified DSGE model. Given the structural parameters estimated using Bayesian methods, we estimate the output gap that is defined as a deviation of output from its flexible-price equilibrium. Our output gap illustrates the U.S. business cycles well, compared with other estimates. We find that the main source of the output gap movements is the demand shocks, but that the productivity shocks contributed to the stable output gap in the late 1990s. The robustness analysis shows that the estimated output gap is sensitive to the specification for monetary policy rules.

Keywords: Output Gap, DSGE Models, Bayesian Estimation

JEL Classification: C11, C32, E31, E32

[*]We would like to thank Michel Juillard, Seisaku Kameda, Thomas Lubik, Nobuyuki Oda, Tomohiro Sugo, Kozo Ueda, and seminar participants at the International Department for insightful comments and discussions. The views expressed herein are those of the authors and do not necessarily reflect those of the Bank of Japan.

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1 Introduction

Macroeconomic analysis often takes account of the output gap, defined as a deviation of actual output from its trend or potential level. This is because the output gap is considered to be an important indicator of overall macroeconomic conditions and to play a significant role in the determination of inflation. A problem is that potential output is not observable, forcing researchers to rely on uncertain estimates. In this paper, we estimate the output gap based on a dynamic stochastic general equilibrium (DSGE) model using Bayesian techniques.

Various methods have been proposed to estimate the potential output. One of the easiest ways is to consider a certain univariate moving average of actual output as potential output. The HP filter, proposed by Hodrick and Prescott (1997), is widely used. The main drawback of such an approach is the lack of economic content. Another approach often employed is a production function approach. In this approach, an aggregate production function is estimated, and then "normal" amount of inputs are substituted in it to calculate the potential output. Examples are found in Clark (1979) and Congressional Budget Office (1995), among others. Although economic structure is considered, the output gap by this definition has only weak links to other economic relationships such as the Phillips curve for inflation. To incorporate a definition of the output gap into the Phillips curve relationship, Laxton and Tetlow (1992) extended the HP filter to a multivariate setting and computed potential output linked to inflation fluctuations. Also, Kuttner (1994) considered potential output as an unobserved stochastic trend and applied the Kalman filter to extract it, given simple output and inflation equations. These models exploit reduced-form equations and the output gaps obtained from their methods are a nonaccelerating-inflation or constant-inflation measure.

In contrast to these previous approaches, the output gap that is estimated in this paper is consistent with a fully specified New Keynesian DSGE model, which is derived from optimization problems of households and firms. Since the macroeconomic dynamics in this model are governed by deep parameters that are not affected by policy changes, our approach is designed to overcome the Lucus (1976) critique of reduced-form models for their lack of microfoundations. Moreover, the output gap in this framework is defined as a deviation of actual output from its flexible-price equilibrium level. As argued in Woodford (2003), an optimal monetary policy will replicate the flexible-price equilibrium that delivers more efficient allocation. Therefore, from a welfare perspective, the corresponding output gap should be a useful indicator for monetary policy.

Another feature of this paper is that the model is estimated using Bayesian methods. Bayesian estimation strategies help to estimate DSGE models with cross-equation restrictions, which cope well with misspecification and identification problems. In contrast to estimation of a single equation, estimation of the entire model in the full-information likelihood-based approach implicitly generates an optimal set of instruments for the structural parameters. In our approach, the potential output is extracted by using a Kalman filter algorithm, given the posterior distributions of the structural parameters. The fully specified DSGE model incorporated with data allows us to understand variability of the output gap, not only structurally but also historically.

The output gap we estimate in this paper is conceptually similar to the ones in Edge, Kiley, and Laforte (2007) for the U.S. and Smets and Wouters (2003) for the Euro area, who estimate larger-scale DSGE models with Bayesian techniques and extract the model-based output gaps.[1] They define potential output as the flexible-price-and-wage level of output attainable in the absence of the associated shocks. According to their estimates, the output gaps have been negative at all times since the middle of the 1990s, so that they might not be successful in illustrating the business cycles and overall macroeconomic conditions. In contrast, our estimate of the output gap exhibits the cyclical movements during the period and is considered to be a plausible measure of business conditions. In terms of modeling strategy, their models contain various kinds of shocks, even under flexible prices and wages, which complicate interpretation of the output gap variability. Our estimation of the output gap would be, on the other hand, a possible benchmark since it is based on a simple New Keynesian framework widely used in the recent monetary economics, which allows us to understand easily the driving forces of the output gap and other macroeconomic variables. Furthermore, we extensively document the sensitivity of our output gap estimates to alternative model specifications, choice of priors, and sample periods. While robustness of structural parameters has been carefully examined in the Bayesian DSGE literature, little attention has been paid to the sensitivity of the implied state transition of model variables. In this respect, this paper investigates the effect of

[1] Also, Walsh (2006) extracts the output gap using the DSGE model developed by Levin, Onatski, Williams, and Williams (2006), and points out that the estimated output gap has little relationship to the unemployment rate.

various estimation assumptions to the output gap movements.

This paper is structured as follows. The next section provides a simple variant of the prototypical New Keynesian model that is used for our analysis. Section 3 explains the Bayesian estimation strategies. In Section 4, our baseline estimation results are presented. Section 5 checks the robustness of our empirical analysis. Section 6 concludes the paper.

2 The Model

We consider a simple variant of the standard New Keynesian DSGE model. The model is consistent with optimizing behavior of households and monopolistically competitive firms that face price stickiness. Monetary policy follows an interest-rate feedback rule. Below is a brief description of the model. Note that all real variables below are detrended by a non-stationary trend component of the productivity process $\bar{A}_t$ with the constant growth rate γ^* to guarantee stationarity of the model.

2.1 The Representative Household

The representative household is infinitely lived and derives utility from a composite consumption good C_t, real money balances M_t/P_t, and leisure $1-N_t$. We introduce multiplicative consumption habit formation, as studied in Fuhrer (2000). The household maximizes the following expected utility function:

$$E_t \sum_{i=0}^{\infty} \beta^i D_{t+i} \left[\frac{1}{1-\tau} \left(\frac{C_{t+i}}{C_{t+i-1}^h} \right)^{1-\tau} + \frac{\mu}{1-b} \left(\frac{M_{t+i}}{P_{t+i}} \right)^{1-b} - \chi \frac{N_{t+i}^{1+\eta}}{1+\eta} \right],$$

where D_t is a preference shock that is interpreted as an IS or real demand shock, and C_{t-1}^h represents a habit stock with the habit persistence parameter $0 < h < 1$. $0 < \beta < 1$ is the discount factor, $\tau^{-1} > 0$ is the intertemporal substitution elasticity, $b > 0$ and $\eta > 0$ are associated with elasticities of substitution against consumption, and $\mu > 0$ and $\chi > 0$ are scale factors.

Given the aggregate price index, the budget constraint is:

$$C_t + \frac{M_t}{P_t} + \frac{B_t}{P_t} = \left(\frac{W_t}{P_t} \right) N_t + \frac{M_{t-1}}{P_t} + R_{t-1} \left(\frac{B_{t-1}}{P_t} \right) + \Pi_t,$$

where B_t is nominal government bonds that pay the nominal interest rate R_t, W_t/P_t is the real wage, and Π_t is real profits received from firms.

The first-order conditions for the household's optimization problem are:

$$\frac{U^*_{C,t}}{C_t} = \beta R_t E_t \left(\frac{U^*_{C,t+1}}{C_{t+1}} \frac{P_t}{P_{t+1}} \right), \tag{1}$$

$$\frac{D_t \mu \left(M_t/P_t\right)^{-b}}{U^*_{C,t}/C_t} = \frac{R_t - 1}{R_t}, \tag{2}$$

$$\frac{D_t \chi N_t^{\eta}}{U^*_{C,t}/C_t} = \frac{W_t}{P_t}, \tag{3}$$

where

$$U^*_{C,t} = D_t \left(C_t / C^h_{t-1} \right)^{1-\tau} - \beta h E_t \left[D_{t+1} \left(C_{t+1}/C^h_t \right)^{1-\tau} \right]. \tag{4}$$

Log-linear approximation of (1) and (4) around the steady state together with the equilibrium condition such that $C_t = Y_t$ yields the Euler equation:

$$u^*_{c,t} - y_t = E_t u^*_{c,t+1} - E_t y_{t+1} + r_t - E_t \pi_{t+1}, \tag{5}$$

with

$$u^*_{c,t} = \frac{(1-\tau)}{(1-\beta h)} \left[\left(1+\beta h^2\right) y_t - h y_{t-1} - \beta h E_t y_{t+1} \right] + \frac{1}{1-\beta h} d_t - \frac{\beta h}{1-\beta h} E_t d_{t+1}, \tag{6}$$

where the lower-case letters with time subscripts represent the percentage deviations from their steady-state values. Also, approximating (3) yields

$$d_t + \eta n_t - u^*_{c,t} + c_t = w_t - p_t. \tag{7}$$

2.2 The Firms

The final (composite) consumption good Y_t is produced using differentiated intermediate goods $Y_t(j)$, $j \in [0,1]$ produced by monopolistically competitive firms in the following technology:

$$Y_t = \left[\int_0^1 Y_t(j)^{\frac{\lambda_t - 1}{\lambda_t}} dj \right]^{\frac{\lambda_t}{\lambda_t - 1}},$$

where λ_t is the time-varying elasticity of demand for each intermediate good. The cost minimization problem of the final good sector gives the demand function for good j:

$$Y_t(j) = \left(\frac{P_t(j)}{P_t} \right)^{-\lambda_t} Y_t, \tag{8}$$

and the aggregate price index:

$$P_t = \left[\int_0^1 P_t(j)^{1-\lambda_t} dj \right]^{\frac{1}{1-\lambda_t}}. \tag{9}$$

Each monopolistically competitive firm faces a downward-sloping demand curve (8) for its differentiated product $Y_t(j)$. The production function is linear in labor input $N_t(j)$:

$$Y_t(j) = A_t N_t(j), \tag{10}$$

where A_t is an exogenous productivity disturbance.

Each firm's cost minimization problem, subject to the production function (10), is given by:

$$\min_{N_t} \left(\frac{W_t}{P_t}\right) N_t + \Phi_t \left(Y_t(j) - A_t N_t(j)\right),$$

where Φ_t is the firm's real marginal cost. The first-order condition provides:

$$\Phi_t = \frac{W_t/P_t}{A_t}. \tag{11}$$

Following Calvo (1983), the firms are assumed to have an opportunity to change their prices in a given period only with probability $1-\omega$. Each firm j chooses the price $P_t(j)$ to maximize expected discounted profits:

$$E_t \sum_{i=0}^{\infty} \omega^i Q_{t,t+i} \left[\left(\frac{P_t(j)}{P_{t+i}}\right) Y_{t+i}(j) - \Phi_{t+i} Y_{t+i}(j)\right],$$

where $Q_{t,t+i} = \beta^i \frac{U^*_{C,t+i}/C_{t+i}}{U^*_{C,t}/C_t}$ is the stochastic discount factor. Subject to the demand curve (8) with the equilibrium condition such that $C_t(j) = Y_t(j)$, the first-order condition for each firm implies the optimal price P_t^* chosen by all firms adjusting at time t:

$$\frac{P_t^*}{P_t} = Z_t \frac{E_t \sum_{i=0}^{\infty} \omega^i Q_{t,t+i} Y_{t+i} \Phi_{t+i} \left(\frac{P_{t+i}}{P_t}\right)^{\lambda_t}}{E_t \sum_{i=0}^{\infty} \omega^i Q_{t,t+i} Y_{t+i} \left(\frac{P_{t+i}}{P_t}\right)^{\lambda_t - 1}}, \tag{12}$$

where $Z_t = \frac{\lambda_t}{\lambda_t - 1}$ captures time-varying markup. From (9), the aggregate price is given by:

$$P_t = \left[\omega P_{t-1}^{1-\lambda_t} + (1-\omega) P_t^{*1-\lambda_t}\right]^{\frac{1}{1-\lambda_t}}.$$

Linear approximation around the steady state of P_t and P_t^* gives the New Keynesian Phillips curve:

$$\pi_t = \beta E_t \pi_{t+1} + \frac{(1-\beta\omega)(1-\omega)}{\omega} \varphi_t + \frac{1-\omega}{\omega} \left(z_t - \beta\omega E_t z_{t+1}\right), \tag{13}$$

where π_t denotes the inflation rate, $\varphi_t = w_t - p_t - a_t$ is the real marginal cost, and the time-varying markup z_t is interpreted as a cost-push shock to the firms' price setting. All of the variables are expressed as percentage deviations from their steady-state values.

2.3 Flexible-Price Equilibrium and the Output Gap

The output gap is defined as a deviation of the actual output from some measure of potential output. While previous studies have advocated various indexes of potential output, this paper focuses on the output gap that is defined as the deviation of actual output from its flexible-price equilibrium output that would prevail in the absence of cost shocks. As argued in Woodford (2003), an optimal monetary policy replicates the flexible-price equilibrium, which can be the first-best outcome under the assumption that the government offsets monopolistic distortions by appropriate subsidies. Thus, the output gap that is defined here should be a useful welfare measure for monetary policy makers.

Consider the case where all of the firms adjust their prices every period, abstracting from cost-push shocks. The flexible price setting is characterized when $\omega = 0$, $P_t^* = P_t$, and $Z_t = \bar{Z}$ in (12). Then, the definition of real marginal cost (11) implies:

$$\frac{W_t}{P_t} = \frac{A_t}{\bar{Z}}.$$

Combining this relationship with the first-order condition (3), which relates the real wage to the marginal rate of substitution between consumption and leisure, the flexible price equilibrium satisfies:

$$\frac{D_t \chi N_t^{\eta}}{U_{C,t}^*/C_t} = \frac{A_t}{\bar{Z}}.$$

Log-linear approximation around the steady state yields:

$$d_t + \eta n_t^f - u_{c,t}^{*f} + c_t^f = a_t, \tag{14}$$

where the superscript f means the flexible-price equilibrium. Similarly, the production function (10) can be linearized as:

$$y_t^f = n_t^f + a_t. \tag{15}$$

From (14) and (15), together with the equilibrium condition such that $y_t^f = c_t^f$, the flexible-price equilibrium output y_t^f can be written as:

$$y_t^f = a_t + \frac{1}{1+\eta} u_{c,t}^{*f} - \frac{1}{1+\eta} d_t, \tag{16}$$

with

$$u_{c,t}^{*f} = \frac{(1-\tau)}{(1-\beta h)} \left[\left(1+\beta h^2\right) y_t^f - h y_{t-1}^f - \beta h E_t y_{t+1}^f \right] + \frac{1}{1-\beta h} d_t - \frac{\beta h}{1-\beta h} E_t d_{t+1}. \tag{17}$$

Thus, fluctuations in the flexible-price equilibrium output depend not only on the productivity disturbance but also on the demand shock (specifically, the preference shock).

Then, the output gap is defined as:

$$gap_t = y_t - y_t^f,$$

which measures the percentage deviation of the actual output from the flexible-price equilibrium output.

2.4 Monetary Policy

The model is closed by specifying a monetary policy rule. The monetary policy rule is of the standard Taylor-type; that is, the central bank adjusts the nominal interest rate in response to the movement of inflation and the output gap from its respective target level. The log-linearized version of the policy rule is:

$$r_t = \rho_r r_{t-1} + (1-\rho_r)\left[\psi_\pi \pi_t + \psi_y \left(y_t - y_t^f\right)\right] + \varepsilon_{r,t}, \;\; \varepsilon_{r,t} \sim N(0, \sigma_r^2), \tag{18}$$

where $0 \leq \rho_r < 1$ determines the degree of interest rate smoothing, $\psi_\pi > 0$, and $\psi_y > 0$. $\varepsilon_{r,t}$ is an exogenous policy shock that can be interpreted as an unsystematic component of the monetary policy.

2.5 Exogenous Shock Processes and Equilibrium System

As sources of equilibrium dynamics, we assume that the demand shock d_t, the cost shock z_t, and the productivity shock a_t follow the stationary first-order autoregressive processes:

$$d_t = \rho_d d_{t-1} + \varepsilon_{d,t}, \;\; 0 \leq \rho_d < 1, \;\; \varepsilon_{d,t} \sim N(0, \sigma_d^2), \tag{19}$$

$$z_t = \rho_z z_{t-1} + \varepsilon_{z,t}, \;\; 0 \leq \rho_z < 1, \;\; \varepsilon_{z,t} \sim N(0, \sigma_z^2), \tag{20}$$

$$a_t = \rho_a a_{t-1} + \varepsilon_{a,t}, \;\; 0 \leq \rho_a < 1, \;\; \varepsilon_{a,t} \sim N(0, \sigma_a^2). \tag{21}$$

We now have a general equilibrium system that consists of the equations (5), (6), (7), (13), (16), and (17) together with the fundamental shock processes (19), (20), and (21).

3 Estimation Strategy

We apply Bayesian techniques in order to estimate structural parameters in the fully specified DSGE model. Bayesian estimation strategies help to estimate DSGE models with cross-equation restrictions, coping well with misspecification and identification problems. Given the estimated parameters, the potential output is estimated using a Kalman filter algorithm. In this section, we begin with a review about the Bayesian method. Next, we describe the data used for estimation and explain the prior distributions of the parameters.

3.1 Bayesian Estimation Methodology

In solving a rational expectations system, we follow the approach of Sims (2002).[2] To obtain a canonical form of the rational expectations system, we define the vector of the model variables $s_t = \left[y_t, \pi_t, r_t, u_t^*, y_t^f, u_t^{*f}, d_t, z_t, a_t, E_t y_{t+1}, E_t \pi_{t+1}, E_t y_{t+1}^f, E_t u_{t+1}^{*f}, y_{t-1}\right]'$,[3] the vector of exogenous fundamental disturbances $\varepsilon_t = [\varepsilon_{d,t}, \varepsilon_{z,t}, \varepsilon_{a,t}, \varepsilon_{r,t}]'$, and the vector of endogenous forecast errors $\eta_t = \left[(y_t - E_{t-1} y_t), (\pi_t - E_{t-1}\pi_t), (y_t^f - E_{t-1} y_t^f), (u_t^{*f} - E_{t-1} u_t^{*f})\right]'$. Then, the system of equations can be written in the canonical form:

$$\Gamma_0(\theta) s_t = \Gamma_1(\theta) s_{t-1} + \Psi_0(\theta)\varepsilon_t + \Pi_0(\theta)\eta_t, \tag{22}$$

where Γ_0, Γ_1, Ψ_0 and Π_0 are the conformable matrices of coefficients that depend on the structural parameters θ. The solution is of the form:[4]

$$s_t = \Gamma(\theta) s_{t-1} + \Psi(\theta)\varepsilon_t. \tag{23}$$

Let Y^T be a set of observable data. Since the rational expectations solution (23) and a set of measurement equations that relates data to the model variables s_t provide a state-space representation, the likelihood function $L(\theta|Y^T)$ can be evaluated using the Kalman filter. The Bayesian approach places a prior distribution $p(\theta)$ on parameters and updates the prior through the likelihood function. Bayes' Theorem provides the posterior distribution of θ:

$$p\left(\theta|Y^T\right) = \frac{L\left(\theta|Y^T\right) p(\theta)}{\int L\left(\theta|Y^T\right) p(\theta)\, d\theta}.$$

Markov Chain Monte Carlo methods are used to generate the draws from the posterior distribution. Based on the posterior draws, we can make inference on the parameters.[5] For

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[2]Sims' solution method generalizes the technique in Blanchard and Kahn (1980).

[3]Note that some of the variables are erased by combining equilibrium conditions. Also, y_{t-1} is added in the vector of the model variables s_t so that we can relate s_t to output growth data in the state-space representation explained below.

[4]We only consider the parameter space that leads to equilibrium determinacy.

[5]For our subsequent analysis, 500,000 draws are generated with a random-walk Metropolis Algorithm, and the first 50,000 draws are discarded.

details of its computational implementation, see Schorfheide (2000). The marginal data density, which assesses the overall fit of the model, is given by:[6]

$$p\left(Y^T\right) = \int L(\theta|Y^T)p(\theta)d\theta.$$

Our primary interest is to extract an estimate of the potential output, which is one of the state variables in the present model, so that the output gap can be calculated as a deviation of the actual output from the potential. Conditional on each draw of the parameters and a set of observables, the Kalman filter generates one-sided estimates of the state variables, based on previous observations, and the Kalman smoother computes two-sided estimates that incorporate data through the end of the sample. Throughout this paper, we consider the latter as the estimated state time series.

3.2 Data and Priors

The data used for estimation are the output growth rate (YGR_t), the inflation rate (INF_t), and the nominal interest rate (INT_t) in the U.S. economy. The output growth is calculated from real GDP, in per capita terms, divided by the labor force. The inflation rate is based on the CPI excluding food and energy, i.e., core CPI. The nominal interest rate is the Federal Funds Rate. The GDP and the CPI are seasonally adjusted. Inflation and the interest rate are annualized. All data are at quarterly frequencies from 1982:4 to 2006:4.[7] The measurement equations that relate the model variables s_t to the data is of the form:

$$\begin{bmatrix} YGR_t \\ INF_t \\ INT_t \end{bmatrix} = \begin{bmatrix} \gamma^* \\ \pi^* \\ r^* + \pi^* \end{bmatrix} + \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -1 \\ 0 & 4 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 4 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} s_t,$$

where γ^* is the steady-state growth rate of a nonstationary technology shock, while r^* and π^* are the annualized inflation and real interest rate at the steady state.

Priors for the structural parameters are summarized in Table 1. The inverse of intertemporal substitution elasticity τ, the habit persistence parameter h, and the probability ω that prices remain unchanged for the next period are in line with the estimates of a similar model that is reported in Lubik and Schorfheide (2004). The discount factor β is

[6] The marginal data densities are approximated using the harmonic mean estimator that is proposed by Geweke (1999).

[7] The beginning of the sample is determined to exclude the possibility of equilibrium indeterminacy, based on the finding in Lubik and Schorfheide (2004).

Table 1: Prior and posterior distributions of the parameters

			Prior		Posterior	
Parameter	Range	Density	Mean	90% interval	Mean	90% interval
τ	$\Re^+$	Gamma	1.86	[1.61, 2.11]	1.75	[1.51, 1.97]
h	$[0, 1)$	Beta	0.50	[0.25, 0.74]	0.59	[0.39, 0.79]
ω	$[0, 1)$	Beta	0.66	[0.58, 0.74]	0.82	[0.78, 0.86]
r^*	$\Re^+$	Gamma	3.00	[2.60, 3.42]	2.75	[2.42, 3.09]
η	$\Re^+$	Gamma	1.00	[0.58, 1.39]	0.79	[0.46, 1.11]
ψ_π	$\Re^+$	Gamma	1.50	[1.25, 1.74]	1.55	[1.29, 1.80]
ψ_y	$\Re^+$	Gamma	0.50	[0.34, 0.66]	0.69	[0.51, 0.86]
ρ_r	$[0, 1)$	Beta	0.50	[0.25, 0.75]	0.74	[0.67, 0.80]
ρ_d	$[0, 1)$	Beta	0.50	[0.25, 0.75]	0.79	[0.72, 0.86]
ρ_z	$[0, 1)$	Beta	0.50	[0.25, 0.75]	0.84	[0.76, 0.92]
ρ_a	$[0, 1)$	Beta	0.50	[0.25, 0.74]	0.90	[0.83, 0.98]
γ^*	$\Re^+$	Gamma	0.50	[0.00, 1.16]	0.43	[0.38, 0.48]
π^*	$\Re^+$	Gamma	3.36	[2.53, 4.16]	3.37	[2.87, 3.88]
σ_r	$\Re^+$	InvGamma	0.50	[0.22, 0.80]	0.14	[0.12, 0.16]
σ_d	$\Re^+$	InvGamma	0.50	[0.21, 0.79]	1.39	[1.05, 1.72]
σ_z	$\Re^+$	InvGamma	0.50	[0.21, 0.78]	0.45	[0.28, 0.62]
σ_a	$\Re^+$	InvGamma	0.50	[0.21, 0.79]	0.87	[0.64, 1.08]
$\ln p(Y^T)$					-287.60	

Note: The prior is truncated at the boundary of the determinacy region.

parameterized in terms of the steady-state real interest rate r^* so that the conversion is $\beta = [\exp(r^*/400)]^{-1}$. The prior means for r^* and π^* are based on historical averages of the actual data. The parameter η, which is associated with the substitution elasticity between consumption and labor, is distributed around one following standard calibration exercises in business cycle research. The monetary policy parameters ψ_π and ψ_y are set on the basis of Taylor (1993). The autoregressive coefficients of the shocks, ρ_d, ρ_z, and ρ_a, and the variances of the fundamental shocks, σ_r, σ_d, σ_z, and σ_a, are centered at 0.5, upon which we allow for relatively wide confidence intervals.

4 Empirical Results

In this section, we provide baseline results of our empirical analysis. We begin by explaining the posterior distribution of the structural parameters. Next, we present the estimated output gap and investigate its properties. Robustness of the estimates is examined in the next section.

4.1 Posterior Distribution of the Structural Parameters

The last two columns in Table 1 reports posterior distributions of the structural parameters. The posterior means for intertemporal substitution elasticity τ^{-1}, the habit persistence parameter h, the steady-state real interest rate r^*, the monetary policy coefficient on inflation rate ψ_π, the trend growth rate γ^*, and the steady-state inflation π^* are almost the same as their corresponding prior means. The parameter ω, the so-called Calvo parameter, is higher than its prior. The mean value 0.82 implies that firms set prices approximately every six quarters. The parameter η that relates to the elasticity for labor supply is smaller than the prior. The monetary policy coefficient on the output gap ψ_y is higher than the example in Taylor (1993), implying more importance of the output gap to the Fed's reaction function. The policy smoothing parameter ρ_r is higher than the prior, which is consistent with the empirical studies on the monetary policy rules.

The autoregressive coefficients for the fundamental shocks, ρ_d, ρ_z, and ρ_a, which represent persistency of the shocks, take remarkably high values. This result suggests that the stickiness observed in actual data is captured by the persistency of the shocks whereas the simple New Keynesian framework itself characterizes forward-looking behavior of the agents. While the variances of the demand shock σ_d and the productivity shock σ_a are larger than the priors, those of the policy shock σ_r and the cost shock σ_z are relatively smaller.

4.2 Propagation of the Fundamental Shocks

The primary interest of this paper is to extract the series of the output gap based on the estimated DSGE model and to investigate the background of the output gap fluctuations. Before proceeding to such analyses, it is useful to compute impulse responses and variance decompositions to understand the propagation mechanism of the structural shocks.

Figure 1 graphs impulse responses of output, inflation, the nominal interest rate, and

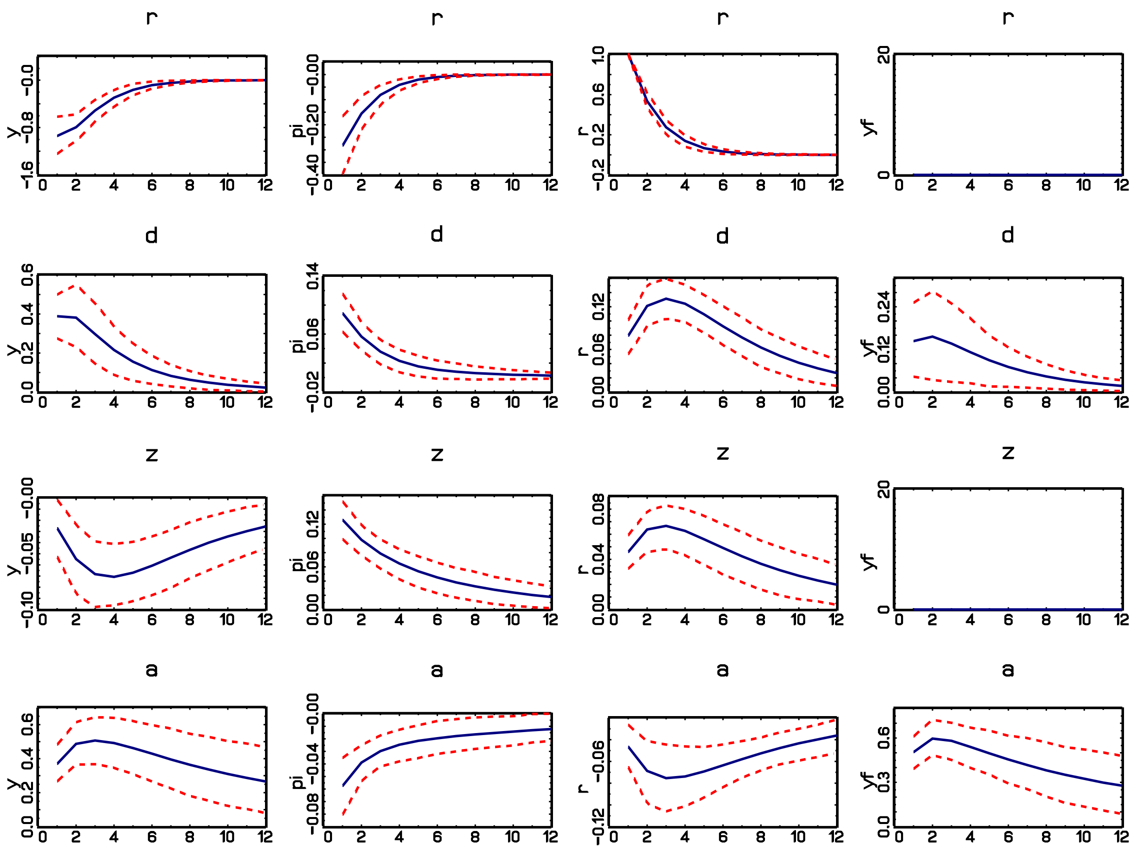

Figure 1: Impulse responses

the potential output to the following four shocks: demand, technology, marginal cost, and policy shock. Each graph plots the posterior mean (solid lines) and pointwise 90% posterior probability intervals (dashed lines) for the impulse response to one-standard-deviation shocks in terms of percentage deviation from the steady state. Since the model is based on a prototypical New Keynesian monetary DSGE framework with habit formation, the impulse responses here are quite standard. A positive demand shock (specifically, the preference shock) increases both actual output and potential output, but the increase in the potential output is less than the actual, so that inflation rises. In response to inflation, the central bank raises the interest rate. A positive technology shock boosts the potential output and has a negative effect on marginal cost and, hence, on inflation. Responding to low inflation, the central bank lowers the interest rate. Actual output also increases because of the high productivity and the low interest rate. A cost shock causes the monetary authority to raise the interest rate. The tightening monetary policy depresses

Table 2: Variance decompositions

Shock	Mean	90% interval	Shock	Mean	90% interval
Output			Inflation		
Demand	0.49	[0.25, 0.71]	Demand	0.19	[0.06, 0.30]
Productivity	0.46	[0.24, 0.68]	Productivity	0.15	[0.04, 0.25]
Cost	0.01	[0.00, 0.01]	Cost	0.64	[0.45, 0.85]
Policy	0.04	[0.01, 0.06]	Policy	0.02	[0.00, 0.04]
Interest rate			Potential output		
Demand	0.48	[0.34, 0.64]	Demand	0.09	[0.00, 0.21]
Productivity	0.27	[0.16, 0.39]	Productivity	0.91	[0.79, 0.99]
Cost	0.15	[0.06, 0.24]	Cost	0.00	[0.00, 0.00]
Policy	0.09	[0.05, 0.13]	Policy	0.00	[0.00, 0.00]

the economy. A positive monetary policy shock has a contractionary effect on both output and inflation. Notice that the cost and policy shocks have no effect on potential output.

Table 2 reports variance decompositions for output growth, inflation, the nominal interest rate, and potential output growth. To understand the variability of the output gap, the decompositions for actual and potential output are of particular importance. Actual output is driven by both demand and productivity shock while potential output movements are mainly due to productivity shock. For the two series, the contributions of the cost and policy shocks are negligible. Based on these findings together with the observation in the impulse response analysis, we historically evaluate the output gap variability in the next subsection.

4.3 Output Gap

Figure 2 plots the posterior mean of the two-sided smoothed estimate of the output gap (thick solid line) and its 90 percent confidence intervals (dashed lines). Deviation of output from its HP trend[8] is also presented for the purpose of comparison (thin solid line). The shaded areas indicate recessions as dated by the National Bureau of Economic Research (NBER).

Our model-consistent output gap had been positive during the late 1980s, but turned to be negative in the first half of the 1990s, reflecting the severe concern in financial sectors.

[8]The smoothing parameter of the HP filter is set at 1600.

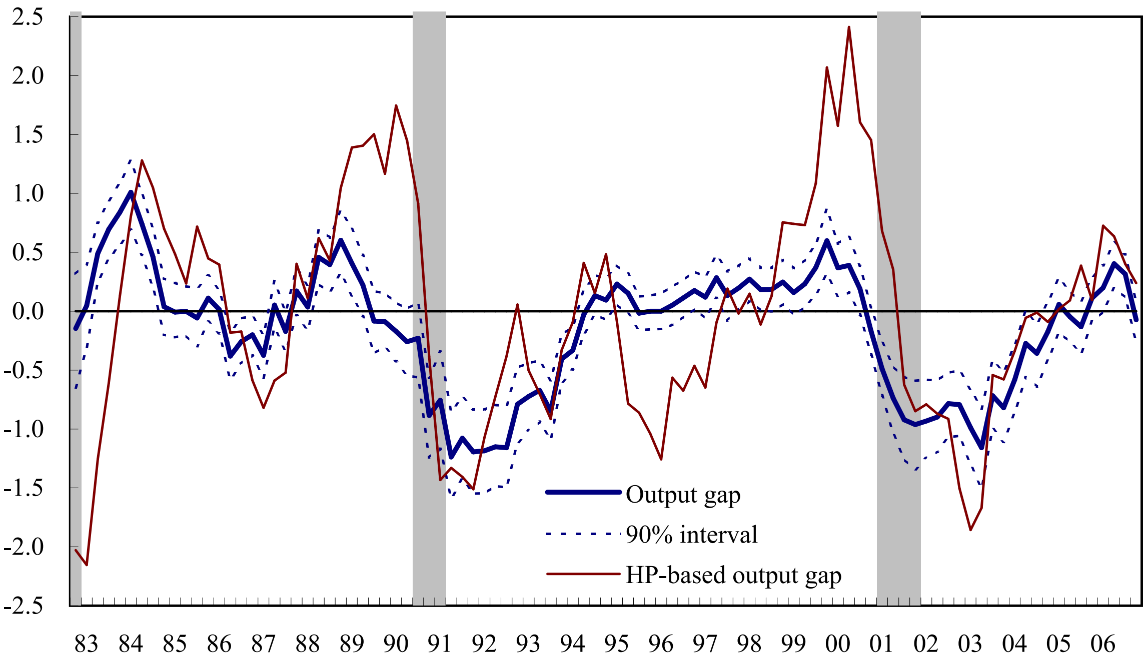

Figure 2: Output gaps

As the economy boomed in the latter half of the 1990s, the gap exceeded its desired level and attained the high level toward 2000. After the collapse of the so-called IT bubbles at the beginning of 2001, the output gap dropped to be negative, and has been around the neutral level since 2005. A remarkable characteristic of our model-based output gap is that the periods when it sharply fell to be negative correspond well to the dates of recessions published by the NBER and that the gap had recovered from the bottom or stayed positive during the boom. This property suggests that the output gap can be a reasonable indicator for overall macroeconomic conditions. The HP-based output gap is, however, inconsistent with the boom in the middle of the 1990s; that is, it dropped during the booms in 1993 and 1995 owing to temporary stagnation of the actual output since the potential output is assumed to evolve smoothly at all times. In contrast, our model-based output gap takes account of the steadily high inflation rate during the period, so that it exhibits few changes in 1993 and 1995.

According to Edge, Kiley, and Laforte (2007), who exploit a larger model for the U.S. economy and estimate the output gap that is conceptually similar to ours, their output gap has been negative at all times since the middle of the 1990s. On the other hand, our estimate of the output gap exhibits cyclical movements during the period and is successful

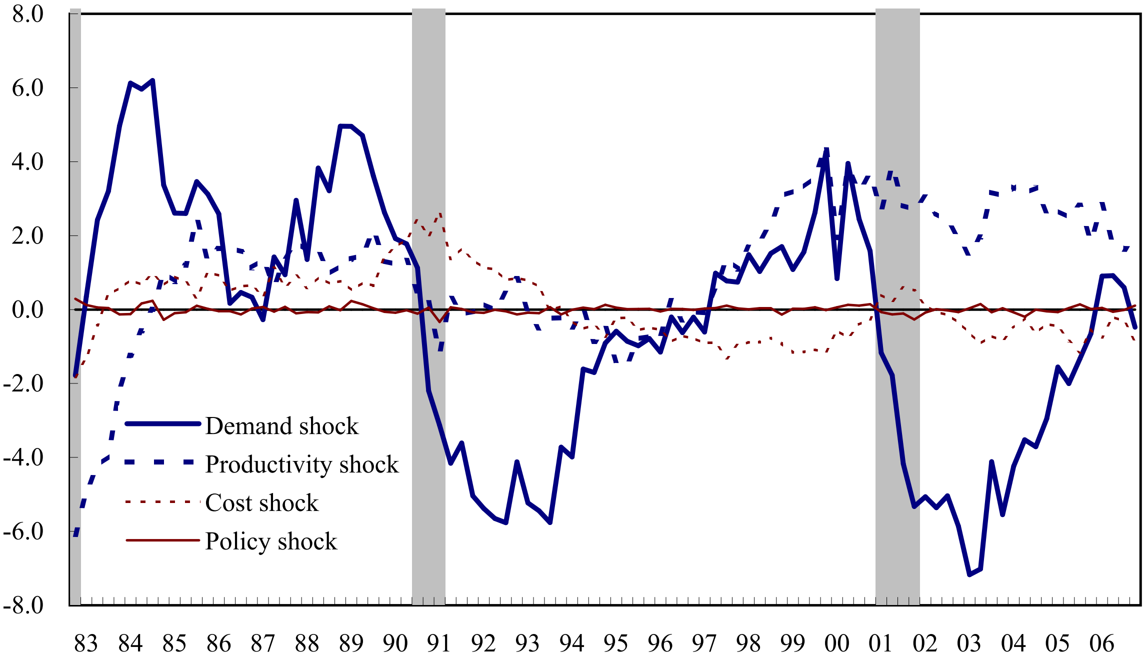

Figure 3: Historical estimates of the shocks

in illustrating the business cycles. A possible interpretation of this difference is that their output gap has less correlation with actual output and, hence, a relatively closer link to inflation, so that the gap captures downward trend in inflation. The weak link between their output gap and actual output is ascribed to the richness of their model; that is, their model contains various kinds of shocks, even under flexible prices and wages, and these shocks have substantial effects on potential output in the same direction as actual output, which results in a weak relationship between the output gap and actual output.

An important advantage of the DSGE-based output gap is that we can infer the driving forces of the output gap and the relevant macroeconomic variables structurally. Figure 3 depicts the historical mean estimates of the fundamental shocks: demand shocks d_t (thick solid line), productivity shocks a_t (thick dashed line), cost shocks z_t (thin dashed line), and policy shocks $\varepsilon_{r,t}$ (thin solid line), and Figure 4 graphs the contributions of each shock to the output gap historically.[9] The figures show that the large swings in the demand shocks are the main source of the output gap movements. In particular, both of the two

[9]The total of the stacked column tends not to be equal to our estimate of the output gap in a few periods from the beginning of the sample. This is because the series of the output gap and the fundamental shocks are the Kalman smoothed estimates while the contributions of each shock are computed by substituting the historical estimates of the shocks into the structural moving average representation.

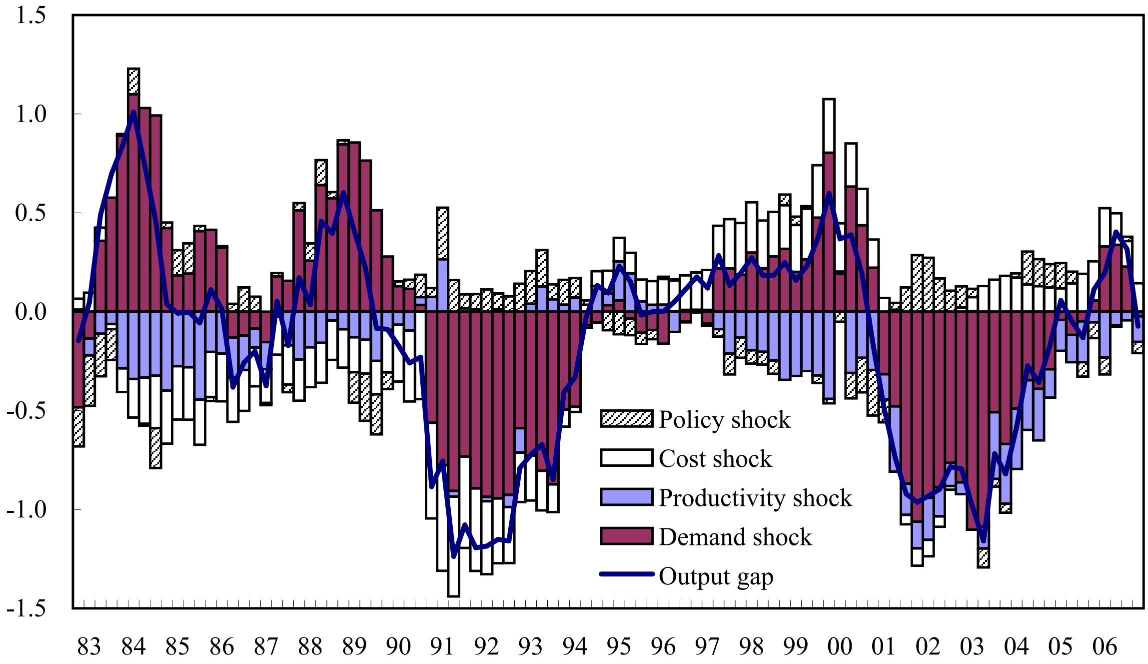

Figure 4: Historical decomposition of the output gap

recessions are triggered by the sharp drops in the demand disturbances. Our estimates, however, reveal a stark difference between the two recession periods. Whereas productivity had been sluggish under the first recession in the early 90s, it had exhibited high growth and had negative impact on the output gap in the second recession after the collapse of the IT bubbles. We can also see that the cost shocks negatively affected the output gap in and after the first recession due to the high interest rate responding to inflation. Another finding is that, during the latter half of the 90s, the demand and productivity expanded simultaneously, which gave rise to the stable output gap and, hence, stable inflation. This finding contributes to the recent discussions on the "good luck" hypothesis that explains the recent stable inflation regime; the literature typically documents decreasing volatilities of the associated shocks,[10] our analysis rests on tracking the comovements of the fundamental shocks.

[10]See, for instance, Canova, Gambetti, and Pappa (2005) and Sims and Zha (2006).

5 Robustness Analysis

The DSGE-consistent output gap we have computed is conditional on the modeling framework and the estimation assumptions. In this section, we investigate the robustness of our baseline results by considering modifications with respect to the model specification, the priors, and the estimation sample.

5.1 Alternative Model Specifications

While an advantage of the full-information likelihood-based approach is to implicitly generate an optimal set of instruments for the coefficients of the equations, a weakness is that it is potentially sensitive to model misspecification. In this subsection, we check the robustness of our baseline estimates by exploiting alternative specifications to the baseline model.

We first consider the case where the utility function for the representative household is specified without habit formation, i.e., $h = 0$ in the baseline system of equations. Then, the model is reduced to the prototypical New Keynesian model described in Walsh (2003) or Woodford (2003).

Galí and Gertler (1999) suggest that postwar U.S. inflation dynamics is consistent with a simple hybrid variant of the New Keynesian Phillips curve that allows for a fraction of firms that use a backward-looking rule to set prices. Let λ denote a fraction of the firms that set their prices using a simple rule of thumb that is based on the recent history of aggregate price. Then, the hybrid New Keynesian Phillips curve is of the following form:

$$\pi_t = \frac{\lambda}{\phi}\pi_{t-1} + \frac{\beta\omega}{\phi}E_t\pi_{t+1} + (1-\lambda)\left[\frac{(1-\beta\omega)(1-\omega)}{\phi}\varphi_t + \frac{1-\omega}{\phi}(z_t - \beta\omega E_t z_{t+1})\right], \quad (24)$$

with $\phi = \omega + \lambda[1-\omega(1-\beta)]$. The prior for λ is distributed according to a Beta-distribution with mean 0.5 and standard deviation 0.1.

As for the monetary policy, the monetary policy rule specified as (18) assumes that the monetary authority have complete information on the output gap when they make their decision. Orphanides, Porter, Reifschneider, Tetlow, and Finan (2000), however, show that it may be preferable for the policy to respond to output growth rather than the output gap when the measurement errors of the output gap are taken into account. Thus, we consider the following reaction function that reacts to the actual output growth rate instead of the output gap:

$$r_t = \rho_r r_{t-1} + (1-\rho_r)(\psi_\pi \pi_t + \psi_y \Delta y_t) + \varepsilon_{r,t}. \quad (25)$$

Table 3: Parameter estimation results based on alternative specifications

	Without habit		Hybrid Phillips curve		Output growth rule	
Parameter	Mean	90% interval	Mean	90% interval	Mean	90% interval
λ			0.47	[0.28, 0.66]		
τ	1.76	[1.53, 1.99]	1.81	[1.57, 2.04]	1.68	[1.45, 1.92]
h			0.82	[0.68, 0.95]	0.37	[0.21, 0.52]
ω	0.80	[0.76, 0.85]	0.76	[0.70, 0.82]	0.82	[0.77, 0.86]
r^*	2.74	[2.40, 3.08]	2.68	[2.36, 2.98]	2.67	[2.34, 2.99]
η	0.87	[0.52, 1.23]	0.84	[0.50, 1.18]	0.85	[0.51, 1.20]
ψ_π	1.61	[1.36, 1.87]	1.50	[1.27, 1.73]	1.81	[1.59, 2.02]
ψ_y	0.71	[0.53, 0.90]	0.67	[0.49, 0.84]	0.57	[0.41, 0.72]
ρ_r	0.72	[0.66, 0.79]	0.72	[0.66, 0.78]	0.72	[0.67, 0.78]
ρ_d	0.83	[0.78, 0.89]	0.69	[0.58, 0.80]	0.89	[0.85, 0.94]
ρ_z	0.83	[0.74, 0.93]	0.47	[0.25, 0.69]	0.49	[0.22, 0.76]
ρ_a	0.96	[0.93, 0.99]	0.72	[0.58, 0.88]	0.96	[0.93, 0.99]
γ^*	0.42	[0.38, 0.47]	0.47	[0.43, 0.50]	0.44	[0.38, 0.50]
π^*	3.52	[3.01, 4.04]	3.36	[2.94, 3.79]	3.56	[3.08, 4.05]
σ_r	0.15	[0.13, 0.18]	0.14	[0.12, 0.16]	0.18	[0.16, 0.21]
σ_d	1.42	[1.09, 1.74]	1.24	[0.86, 1.61]	1.17	[0.85, 1.47]
σ_z	0.42	[0.27, 0.57]	1.22	[0.43, 1.99]	0.36	[0.21, 0.50]
σ_a	0.75	[0.62, 0.89]	1.06	[0.61, 1.50]	0.88	[0.71, 1.06]
$\ln p(Y^T)$	-292.36		-302.21		-289.17	

Table 3 summarizes posterior distributions of the parameters based on the alternative specifications above. Without habit formation, i.e., $h = 0$, the changes in the estimated parameters are quite marginal from the baseline case. With the hybrid Phillips curve (24), while a fraction of the rule-of-thumb price setters λ has a similar distribution to the prior, the autoregressive coefficient for the cost shock ρ_z becomes smaller as a result of the internal dynamic structure that is embedded in the hybrid Phillips curve. The other parameters are, by and large, in line with the baseline estimates. In the case with the alternative monetary policy rule specified as (25), the habit persistence parameter h and the autoregressive coefficient on the cost shock ρ_z take smaller values, reflecting the additional lag structure by including the output growth $y_t - y_{t-1}$ in the policy rule. Notice that each marginal data density $\ln p(Y^T)$ indicates that alternative specifications considered here do not contribute

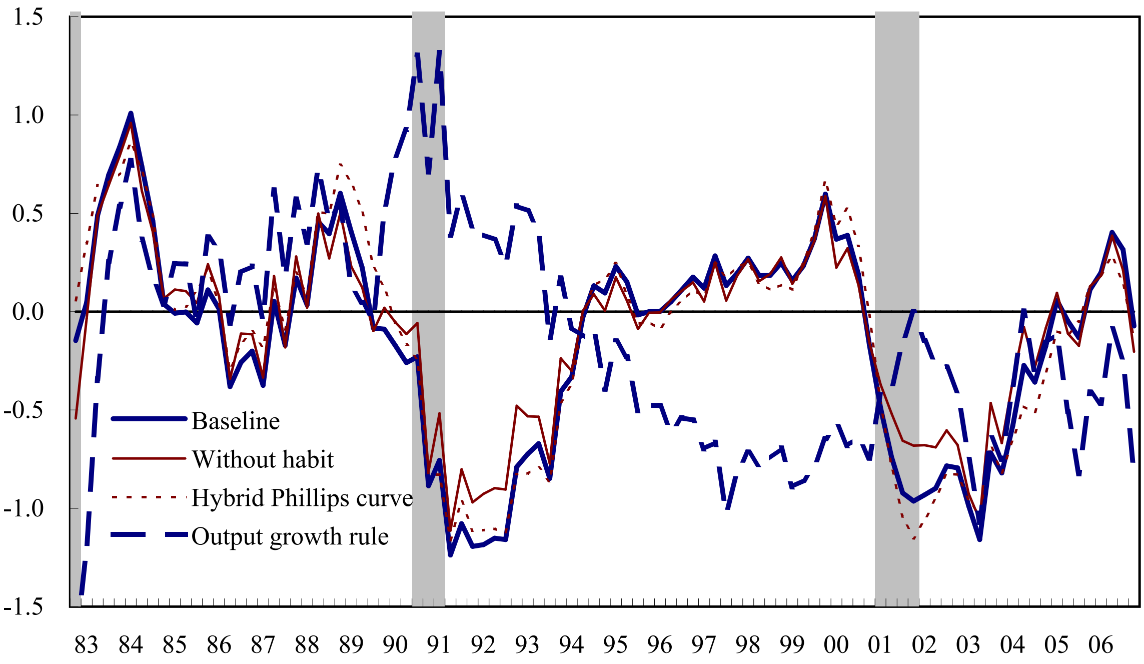

Figure 5: Output gaps based on different model specifications

to a better fit of the model. This finding, in turn, validates our baseline specification in an empirical sense.

Figure 5 compares the mean estimates of the output gaps extracted from the alternative model specifications. The output gap without habit formation (thin solid line) and that with the hybrid Phillips curve (thin dashed line) is almost the same as that in the baseline case (thick solid line). This is considered as a result that the differences of the estimated parameters are marginal and that overall model properties remain unchanged. As for the case with the output growth rule (thick dashed line), however, the output gap is dramatically different from the baseline estimate. In particular, the series of the output gap under the alternative policy rule is quite similar to that of inflation throughout the sample. This is because the DSGE-based output gap has a close link to inflation. When the output gap is included in the policy rule, the movements of the gap directly affect the nominal interest rate and are, then, transmitted to actual output through the Euler equation. Thus, in the process of estimation, more information on the interest rate and output data is used to determine the evolution of the output gap. Under the output growth rule, in contrast, the output gap is linked to the interest rate and output only through the inflation channel, and, hence, the connection between the output gap and inflation becomes

Table 4: Parameter estimation results based on alternative priors

	Loose prior		Tight prior	
Parameter	Mean	90% interval	Mean	90% interval
τ	1.57	[1.18, 1.93]	1.82	[1.69, 1.94]
h	0.81	[0.60, 0.99]	0.48	[0.37, 0.59]
ω	0.85	[0.80, 0.89]	0.75	[0.71, 0.78]
r^*	2.45	[1.95, 2.94]	2.87	[2.69, 3.06]
η	0.71	[0.19, 1.20]	0.91	[0.72, 1.10]
ψ_π	1.50	[1.03, 1.96]	1.59	[1.47, 1.72]
ψ_y	0.92	[0.55, 1.30]	0.55	[0.46, 0.65]
ρ_r	0.76	[0.69, 0.83]	0.70	[0.64, 0.77]
ρ_d	0.75	[0.57, 0.89]	0.79	[0.71, 0.87]
ρ_z	0.84	[0.76, 0.93]	0.77	[0.54, 0.94]
ρ_a	0.82	[0.69, 0.96]	0.97	[0.95, 0.99]
γ^*	0.45	[0.41, 0.50]	0.38	[0.32, 0.45]
π^*	3.08	[2.47, 3.68]	3.56	[3.22, 3.91]
σ_r	0.14	[0.12, 0.16]	0.17	[0.14, 0.20]
σ_d	1.13	[0.51, 1.68]	1.07	[0.85, 1.30]
σ_z	0.54	[0.28, 0.79]	0.30	[0.20, 0.39]
σ_a	1.00	[0.57, 1.47]	0.83	[0.69, 0.96]
$\ln p(Y^T)$	-279.77		-300.39	

strong. The last finding sheds light on an important property of system-based estimates of the output gap since most of the previous studies only consider Phillips curve relationships to estimate the output gap.

5.2 Alternative Priors

Bayesian estimation strategies allow likelihood functions to be weighted by prior distributions, which play important roles to estimate fully specified DSGE models. The prior provides information that is not contained in the data, and helps to avoid identification problems. However, since changes in the prior distributions affect a shape of the corresponding posterior, Bayesian estimation results might be changed depending on the priors. To assess the sensitivity of our estimates to the choice of priors, we reestimate the baseline model under two alternative priors: the "loose" prior and the "tight" prior. In principle,

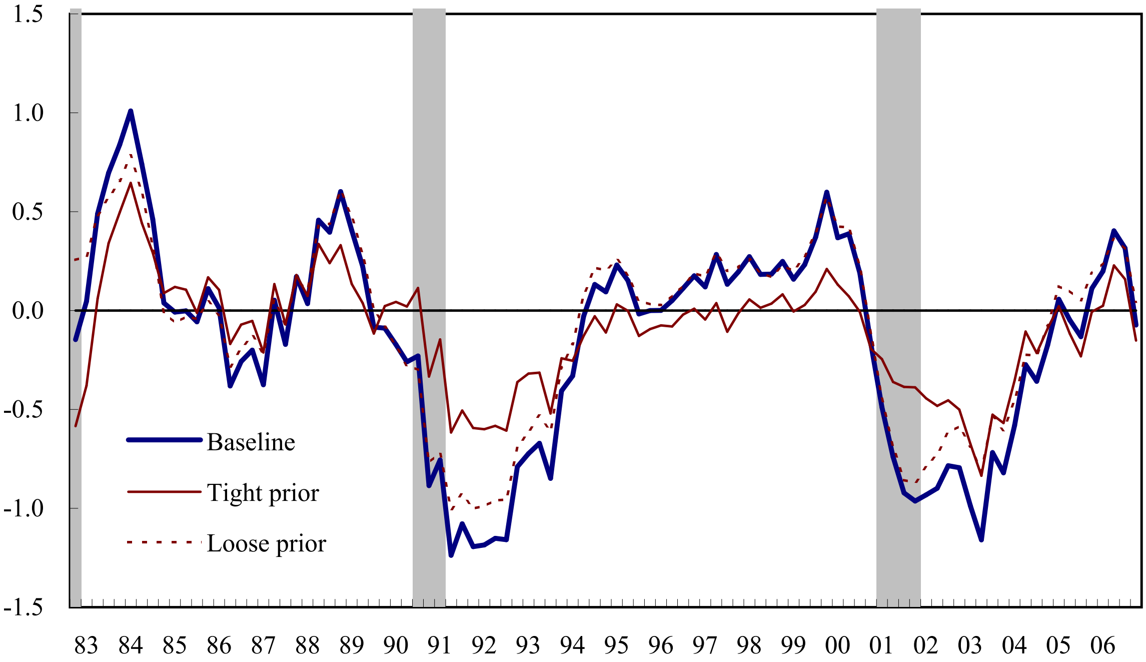

Figure 6: Output gaps based on different priors

the loose priors exploit more information on data, and the tight priors reflect more beliefs of researchers. The loose and tight prior modify the baseline prior so that the standard deviations for a subset of the parameters, $\{\tau, h, \omega, r^*, \eta, \psi_\pi, \psi_y, \gamma^*, \pi^*\}$, become doubled and half, respectively.

The resulting posterior distributions under different priors are summarized in Table 4. As expected, for most of the parameters, deviations of the posterior estimates from the prior means are remarkable under the loose prior, and the tight prior delivers the estimates close to the prior. Figure 6 depicts the corresponding estimates of the output gap. We can see that the output gap under the tight prior (thin solid line) exhibits smaller volatility. This result is due to the smaller values of the habit persistence parameter h and the Calvo parameter ω under the tight prior, which reduces the endogenous volatilities generated by the shocks. On the other hand, the gap under the loose prior (dashed line) is almost the same as the baseline (thick solid line), implying that the baseline estimates have already exploited enough information contained in the data.

Table 5: Parameter estimation results based on different samples

	1982Q4–2003Q4		1982Q4–2000Q4	
Parameter	Mean	90% interval	Mean	90% interval
τ	1.74	[1.51, 1.97]	1.72	[1.48, 1.94]
h	0.59	[0.39, 0.81]	0.58	[0.35, 0.82]
ω	0.82	[0.78, 0.86]	0.80	[0.75, 0.85]
r^*	2.78	[2.43, 3.12]	2.88	[2.52, 3.22]
η	0.79	[0.46, 1.11]	0.81	[0.47, 1.15]
ψ_π	1.55	[1.30, 1.81]	1.58	[1.33, 1.85]
ψ_y	0.68	[0.50, 0.85]	0.64	[0.46, 0.81]
ρ_r	0.71	[0.63, 0.78]	0.70	[0.62, 0.79]
ρ_d	0.77	[0.69, 0.86]	0.76	[0.68, 0.86]
ρ_z	0.84	[0.76, 0.92]	0.85	[0.77, 0.93]
ρ_a	0.91	[0.84, 0.98]	0.92	[0.84, 0.99]
γ^*	0.42	[0.36, 0.48]	0.45	[0.39, 0.51]
π^*	3.45	[2.90, 3.99]	3.48	[2.91, 4.05]
σ_r	0.15	[0.12, 0.17]	0.15	[0.13, 0.18]
σ_d	1.36	[1.02, 1.70]	1.19	[0.87, 1.50]
σ_z	0.45	[0.28, 0.61]	0.41	[0.26, 0.56]
σ_a	0.88	[0.65, 1.10]	0.83	[0.62, 1.04]
$\ln p(Y^T)$	-261.79		-223.71	

5.3 Effect of Data Accumulation

Actual real-time analysis is conducted through reestimating the structural parameter and reextracting the state variables when new data are available. This subsection especially considers the effect of data accumulation to the smoothed estimates of the output gap.

While the Kalman filter generates one-sided estimates of the potential output, the Kalman smoother computes two-sided estimates by reevaluating one-sided estimates backward from the end of the sample. This implies the possibility that the smoothed estimate of the output gap is revised, every time when new data are added, not only at the end of the sample but also throughout the sample. In particular, a relatively large revision may occur toward the end of the sample. Also, since the state variables are evaluated given each draw of structural parameters, changes in the estimated parameters may cause substantial changes in the output gap if extension in the sample size coincides with some structural

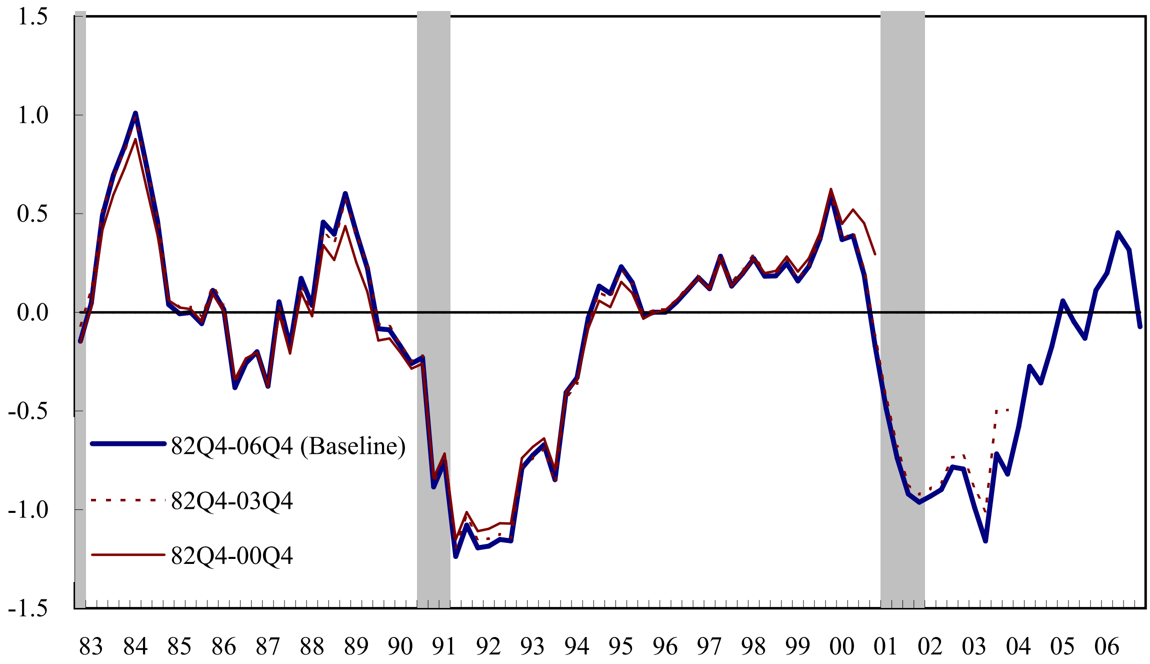

Figure 7: Effect of data accumulation

changes. This causes a serious problem when policy makers try to measure the output gap accurately and use the measurement in making a real-time assessment of business conditions. Below, we examine how the sample addition affects the estimate of the output gap.[11]

Table 5 reports the parameter estimation results based on different samples, i.e., 1982Q4–2003Q4 and 1982Q4–2000Q4. The structural parameters are fairly stable against addition to the sample, and, hence, the effect of changes in parameters to the estimates of the output gap should be negligible. Figure 7 shows how sample addition affects the two-sided smoothed estimates of the output gap. The revision at the end of each sample is more than 0.3 percent, which should not be ignored on account of the scale of the series. In particular, the gap estimated through 2000Q4 (thin solid line) becomes positive while the baseline (thick solid line) has negative values. Although substantial revisions are made only for a few periods near the end of the sample, minor revisions are found throughout the sample. This finding together with the result of parameter stability implies that the effect of data accumulation is ascribed to the smoothing procedure that reevaluates one-sided estimates

[11]See Orphanides and van Norden (2002) for comprehensive analysis of real-time estimates for a variety of output gaps.

backward from the end of the sample.

6 Conclusion

In this paper, we estimated the output gap that is consistent with the fully specified DSGE model. The model-based estimation of the output gap has several advantages. First, the output gap is a useful measure for welfare since the model is derived from optimizing behavior of households and firms. Second, based on our Bayesian estimation results, the output gap is a plausible indicator for macroeconomic conditions. Third, the structural parameters and fundamental shocks provide an economic interpretation for movements of the estimated output gap.

According to our robustness analysis, however, researchers need to be careful in assessing the estimated output gap since our estimation procedure is subject to model specifications, choice of priors, and data accumulation. Our analysis particularly shows that the result is sensitive to the alternative specification for the monetary policy rule, which is relevant to an information assumption on the central bank. Therefore, it could be an extension to consider an alternative information assumption on households and firms or introduce learning expectations for the agents, and, then, examine the implied output gaps.

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