Finance and Economics Discussion Series
Divisions of Research & Statistics and Monetary Affairs
Federal Reserve Board, Washington, D.C.

Monetary Policy and Inflation Dynamics

John M. Roberts

2004-62

Monetary Policy and Inflation Dynamics

by

John M. Roberts
Federal Reserve Board

October 2004

Abstract: Since the early 1980s, the United States economy has changed in some important ways: Inflation now rises considerably less when unemployment falls and the volatility of output and inflation have fallen sharply. This paper examines whether changes in monetary policy can account for these phenomena. The results suggest that changes in the parameters and shock volatility of monetary policy reaction functions can account for most or all of the change in the inflation-unemployment relationship. As in other work, monetary-policy changes can explain only a small portion of the output *growth* volatility decline. However, changes in policy can explain a large proportion of the reduction in the volatility of the output *gap*. In addition, a broader concept of monetary-policy changes—one that includes improvements in the central bank's ability to measure potential output—enhances the ability of monetary policy to account for the changes in the economy.

I am grateful to Flint Brayton, David Lebow, Dave Stockton, and participants at seminars at the Board of Governors, the Federal Reserve System's macroeconomics research committee, and the NBER Monetary Economics program for helpful discussions; to John Williams for providing his linearized version of the FRB/US model; and to Sarah Alves for able research assistance. The views expressed in this paper are those of the author and do not necessarily represent those of the Board of Governors of the Federal Reserve System or its staff.

In this paper, I assess the extent to which shifts in monetary policy can account for an important change in the relationship between unemployment and inflation: It appears that, in a simple reduced-form Phillips curve relationship between changes in inflation and the unemployment rate, the estimated coefficient on unemployment has been considerably smaller since the early 1980s than it was earlier (Atkeson and Ohanian, 2001; Staiger, Stock, and Watson, 2001). In addition, I look at the ability of monetary policy to account for changes in the reduction in the volatility of output and inflation that also dates from the early 1980s (McConnell and Perez-Quiros, 2000).

The notion that monetary policy should affect inflation dynamics is an old one, dating at least to Friedman's dictum that inflation is always a monetary phenomenon (1968). In his famous "Critique," Lucas (1975) showed how changes in monetary policy could, in principle, affect inflation dynamics. However, Lucas considered only very stylized monetary policies. The present exercise explores the effects of more realistic changes in policy on inflation dynamics.

I consider a number of ways in which monetary policy may have changed. First, monetary policy may have become *more reactive to output and inflation fluctuations* around the early 1980s (Clarida, Gali, and Gertler, 2000). In addition, monetary policy *may have become more predictable*, implying smaller shocks to a simple monetary-policy reaction function. Finally, Orphanides et al. (2000) argue that *policymaker estimates of potential output may have become more accurate*. Such improvements in estimates of potential output would constitute a change in monetary policy, as policy would be made on the basis of more accurate information.

I consider the effects of changes in policy on expectations formation, holding fixed the behavioral relationships in the economy. Although other relationships are unchanged, changes in policy can nonetheless affect the reduced-form relationship between inflation and economic activity by reducing the signal content of economic slack for future inflation. For example, if monetary policy acts more aggressively to stabilize the economy, then any given deviation in output from potential will contain less of a signal of future inflation. Similarly, a reduction in the persistence of potential output mismeasurement would mean that an increase in output resulting from a mis-estimate of potential output will not portend as much inflation because it is not expected to last as long.

I examine the predictions of these changes in policy for inflation dynamics and the economy's volatility using stochastic simulations of two macroeconomic models. One is a simple model composed of three equations, for inflation, the federal funds rate, and the output gap. The other is the Federal Reserve's large-scale FRB/US model. An advantage of looking at both models is that they represent points near the extremes of the range of complexity among models currently employed in policy analysis.[1]

Ball, Mankiw, and Romer (1988) have argued that changes in monetary policy may lead to changes in changes in the frequency of price adjustment, and thus changes in the parameters of the price-adjustment processes taken as structural here. In particular, they argue that the lower and more stable inflation that has marked the post-1982 period is likely to lead to less-frequent price adjustment. The Ball-Mankiw-Romer conjecture could thus provide an alternative explanation for the reduction in the slope of the reduced-form Phillips curve. In a recent empirical study, however, Boivin and Giannoni (2003) examined the sources of changes in the effects of monetary policy surprises on the economy. They found that the main source of changes in the effects of policy shocks was changes in the parameters of the policy reaction function rather than in the structural parameters of the economy, providing empirical support for the modeling strategy adopted here.

To summarize the results briefly, changes in monetary policy can account for most or all of the reduction in the slope of the reduced-form Phillips curve. Changes in policy can also account for a large portion of the reduction in the volatility of output *gap*, where the output gap is the percent difference between actual output and a measure of trend or potential output. However, as in other recent work (Stock and Watson, 2002; Ahmed, Wilson, and Levin, 2002), changes in policy account for a smaller proportion of changes in output *growth.*

---

[1] Rudebusch (2002) has also looked at the impact of changes in monetary policy on the slope of the Phillips curve. He also finds that changes in monetary policy can have an economically important effect on the estimated slope of the Phillips curve. He notes, however, that such a shift may be difficult to detect econometrically.

The ability to explain the reduction in inflation volatility is mixed: In the small-scale model, it is possible to explain all of the reduction in inflation volatility, whereas in FRB/US, the changes in policy predict only a small reduction in volatility. Finally, monetary policy's ability to account for changes in the economy is enhanced when changes in monetary policy are broadened to include improvements in the measurement of potential GDP.

1. The changing economy

1.1—Volatility of output and inflation

Table 1 presents standard deviations of: the annualized rate of quarterly GDP growth; core inflation (as measured by the annualized quarterly percent change in the price index for personal consumption expenditures other than food and energy); the civilian unemployment rate; and two measures of the output gap. The table compares standard deviations from two early periods—1960-1979 and 1960-1983—with a more recent period, 1984-2002. As others have noted (McConnell and Perez-Quiros, 2000; Blanchard and Simon, 2001), the economy has been much less volatile since 1983: The standard deviation of GDP growth has fallen by almost half and that of core inflation by a bit more than half. As discussed in McConnell and Perez-Quiros (2000), the drop in GDP growth volatility is statistically significant. For the unemployment rate, the drop in volatility is somewhat less sharp, and more dependent on the sample period: Relative to the 1960-79 period, the standard deviation of the unemployment rate has fallen by 20 percent, but relative to the period ending in 1983, the decline is almost 40 percent.

Two measures of the output gap are considered, one from the Federal Reserve's FRB/US model and one from the Congressional Budget Office.[2] For the FRB/US

---

[2] The output gap is defined as the percentage deviation of real GDP from an estimate of potential GDP. The FRB/US estimate of potential GDP is built up from a production function for business-sector output, where the current capital stock and estimates of structural multifactor productivity and labor input are the inputs. Structural MFP is estimated using Kalman-filter methods. Structural labor input is built up from: published population estimates; an estimate of the natural rate of unemployment that adjusts for estimated effects of changes in the demographic composition of the workforce and other labor-market developments; and Kalman-filter estimates of other trends, such as the

gap measure, the 1984-2002 standard deviation is 23 percent less than in the 1960-79 period and 42 percent less than in the 1960-1983 period. The declines in volatility are sharper for the CBO output gap, with a decline in standard deviation of 41 percent since the 1960-79 period and 51 percent since the 1960-1983 period.

1.2—The slope of the reduced-form Phillips curve

Figure 1 plots the over-the-year change in the four-quarter core PCE inflation rate against a four-quarter moving average of the unemployment rate. The panel on the left shows the scatter plot over the 1960-1983 period; on the right, over the 1984-2002 period. Each panel includes a regression line; the slope coefficients are shown in the first column of table 2. The regression run was:

$$(p_t - p_{t\text{-}4}) - (p_{t\text{-}4} - p_{t\text{-}8}) = \gamma_0 + \gamma_1 \left(\Sigma_{i=0,3}\, UR_{t\text{-}i}\right)/4 , \qquad (1)$$

where $(p_t - p_{t\text{-}4})$ indicates the four-quarter percent change in core PCE prices and UR is the civilian unemployment rate. As can be seen in the table, the slope coefficient of this reduced-form Phillips curve falls by nearly half between either of the earlier periods and the post-1983 period. Atkeson and Ohanian (2001) have also noted a sharp drop in the slope of a similar reduced-form relationship, as have Staiger, Stock, and Watson (SSW, 2001).[3]

Columns 2 and 3 of table 2 show the change in the slope coefficient in equation 1, using the FRB/US and CBO output gaps, respectively, in lieu of the unemployment rate. Results using the output gap provide a useful robustness check. In addition, the simple three-equation model used below includes the output gap rather than the unemployment rate. The reduction in the Phillips curve

workweek and labor force partipation. CBO's estimate of potential GDP is described in *CBO's Method for Estimating Potential GDP* (2001), available at www.cbo.gov.

[3] Figure 1.1 of SSW makes a similar point to figure 1 of this paper. SSW, however, argue that taking account of shifts in the NAIRU and in trend productivity growth can largely account for reductions in slope. Nonetheless, their results do indicate some time-variation in the slope (SSW, pp. 18-21), and the average slope coefficient is smaller in absolute value after 1983 than before (SSW, figure 1.5). Hence, the results of SSW are broadly consistent with those reported here.

slope is smaller using the output gap: For the FRB/US output gap, the reduction is between 30 and 40 percent, depending on the reference period, whereas for the CBO output gap, the reduction is only 12 to 23 percent. (As might be expected given typical Okun's law relationships, the coefficients on the output gap are about half the size of the coefficients in the corresponding equations using the unemployment rate—and, of course, they have the opposite sign.)

In table 3, I look at an alternative specification of the reduced-form Phillips curve, in which the quarterly change in inflation is regressed on three lags of itself and the level of the unemployment rate:

$$\Delta p_t = \gamma_0 + \gamma_1\, UR_t + \gamma_2\, \Delta p_{t-1} + \gamma_3\, \Delta p_{t-2} + \gamma_4\, \Delta p_{t-3} + (1 - \gamma_2 - \gamma_3 - \gamma_4)\, \Delta p_{t-4}, \qquad (2)$$

where Δp_t indicates the (annualized) one-quarter percent change in the core PCE price index. As in equation 1, the coefficients on lagged inflation are constrained to sum to one. I discuss the evidence for this restriction in section 1.3. For the unemployment rate, the results are qualitatively similar to those in table 2, although the magnitude of the reduction in the slope is a bit less, as the coefficient falls by 35 to 40 percent. In this regression, there is also a notable drop off in the statistical significance of the slope coefficient, with the *t*-ratio falling to 1.4 in the post-1983 sample, from levels around 2 or 3 in the earlier samples.

For the estimates with the output gap, in columns 2 and 3, the slope coefficients now change little between the early and late samples—indeed, for the CBO output gap, the coefficient even rises. However, in equation 2, the slope coefficient no longer summarizes the effect of unemployment on inflation, because the pattern of the coefficients on lagged inflation changes also matters. As can be seen in the bottom three rows of the table, there was an important change in these coefficients, with the coefficient on the first lag dropping from around one in the early samples to a bit less than 0.3 in the post-1983 sample. This change means that an initial impact of unemployment on inflation will have a much larger effect on inflation in the following quarter in the early period than in the later period. If the impact of unemployment on inflation is adjusted for this change in lag pattern, then the estimates in table 3 suggest that there has been a sharp reduction of the impact of the output gap on inflation, from 50 to

67 percent.[4] Because the slope coefficient in the simple model of equation 1 provides a single summary statistic for the change in the inflation dynamics, I will focus on changes in this coefficient in my work below.

As discussed in appendix A, there is also a substantial drop in the slope coefficient if more control variables are added to the equation and more general lag specifications are allowed. The results are sensitive to specification, with estimates of the drop in the slope varying from 15 to 70 percent. Nonetheless, the results presented in tables 2 and 3 are representative of the range of estimates.

1.3—Has U.S. inflation stabilized?

In the preceding subsection, it was assumed that the sum of coefficients on lagged inflation in the reduced-form Phillips curves remained equal to one. Of course, it is possible to imagine that if a central bank had managed to stabilize the inflation rate, inflation would no longer have a unit root, and the sum of lagged coefficients in the reduced-form Phillips curve would no longer equal one. Ball (2000) argues that, prior to World War I, inflation was roughly stable in the United States, and that the sum of lagged coefficients in reduced-form Phillips curves was less than one; Gordon (1980) makes a similar point.

It is not yet clear if inflation stability is once again a reality for the United States. Figure 2 plots the sum of lagged inflation coefficients from a rolling regression of U.S. core PCE inflation on four lags of itself, using windows of ten, fifteen, and twenty years. With a twenty-year window, the sum of lagged coefficients remains near 0.9 at the end of the sample, about where it was twenty years earlier. With a fifteen-year window, the sum is more variable, but here, too, it ends the sample at a high level. Using a ten-year window, there is more evidence that the persistence of inflation has fallen, as the sum of lagged coefficients drops to around 0.5.

The inflation data in the bottom panel helps explain these results. Inflation has moved down over the post-1983 period: Inflation as measured by core PCE prices

---

[4] In particular, I compute a "sacrifice ratio," which is the loss in output or unemployment required to obtain a permanent reduction of 1 percentage point in inflation.

averaged 4 percent from 1984 to 1987 but only 1-1/2 percent over the 1998-2002 period. In the most recent ten-year period, inflation has moved in a relatively narrow range, consistent with the small coefficient sum estimated over this period.

While the results with the ten-year window suggest that the United States may have entered a period of inflation stability, the evidence from the wider windows is less conclusive. Of course, a longer time series generally provides more convincing evidence than a shorter one. On net, the evidence would seem to suggest that inflation has remained highly persistent in the United States over the 1984-2002 period. I will return to the issue of inflation stability in section 6.

2. Changing monetary policy

2.1—Changes in the reaction function

One way to characterize the implementation of monetary policy is with a "dynamic Taylor rule" of the form:

$$ff_t = \rho\, ff_{t-1} + (1-\rho)\ \{r^* + (p_t - p_{t-4}) + \alpha\ xgap_t + \beta\ [(p_t - p_{t-4}) - \pi^*_t]\} + \epsilon_t, \qquad (3)$$

where ff is the federal funds rate, r^* is the equilibrium real interest rate, $(p_t - p_{t-4})$ is the four-quarter inflation rate, $xgap$ is the GDP gap, and π^* is the target inflation rate. A number of studies have found that such a rule characterizes monetary policy after 1983 quite well. Among others, these include Clarida, Gali, and Gertler (CGG, 2000) and English, Nelson, and Sack (ENS, 2003).

While the dynamic Taylor rule appears to be a good characterization of policy over the past two decades, its performance prior to 1980 is less impressive. For example, CGG find, in a similar model, very small estimates of the inflation parameter β—indeed, their point estimates put β less than zero over the 1960-to-1979 period. In this case, real interest rates will fail to rise when inflation is above target, which, as CGG discuss, can lead to an unstable inflation rate.

CGG emphasize the increase in the value of β as indicating an important shift in monetary policy in the early 1980s. They also provide evidence that policy has become more responsive to output fluctuations, reporting a large increase in α. Taylor (1999) and Stock and Watson (2002) also find a large increase in the coefficient on output in a similar monetary-policy rule.

Table A summarizes the assumptions about monetary-policy coefficients used in the simulations below. One set of parameters—labeled "aggressive"—is similar to the estimates of ENS for recent U.S. monetary policy. In the less-aggressive policy settings, the response to output is assumed to be half that in the aggressive setting, while the response to inflation is intended to be a minimal response that is consistent with stability. (The "least" aggressive policy in column 1 will be the base case; the "less" aggressive alternative in column 2 is used in cases where the policy in column 1 leads to numerical solution problems.)

Table A
Alternative Monetary Policy Rules

	Least aggressive policy	*Less aggressive policy*	*Aggressive policy*
ρ	0.7	0.7	0.7
α	0.5	0.5	1.0
β	0.0001	0.1	0.5

The reaction function in equation 1 includes an error term. One interpretation of such "shocks to monetary policy" is that they constitute changes to the objectives of monetary policy that are not fully captured by a simple econometric specification. Such an interpretation is perhaps most straightforward in a setting in which the long-run inflation objective of the central bank is not firmly established, as may have been the case for the United States in the pre-1980 period. In such a context, shocks to the reaction function could correspond to changes in the inflation target. Another interpretation—that the shocks represent errors in the estimation of the right-hand-side variables of the model—will be taken up shortly.

Table B **Volatility of the Fed Funds Rate** Standard deviations, percentage points		
	Change in funds rate	Residuals from reduced-form model
1984:Q1-2002:Q4	.56	.38
1960:Q1-1983:Q4	1.27	1.16
1960:Q1-1979:Q4	.92	.70

Table B presents some evidence that the variability of the error term in the reaction function has fallen. The first column presents the unconditional standard deviation of the change in the quarterly average funds rate, which falls by between 40 and 55 percent, depending on the early reference period. The second column reports the standard error of the residuals from simple reduced-form models of the funds rate, in which the funds rate is regressed on four lags of itself, the current value and four lags of the FRB/US output gap, and the current value and four lags of quarterly core PCE inflation. This residual is considerably less variable in the post-1983 period, with the standard deviation falling by between 45 and 67 percent. In the simulations in sections 4 and 5, I will consider a reduction in the standard deviation of the shock to a monetary-policy reaction function like equation 3 of a bit more than half, from 1.0 to 0.47.

2.2—Improvements in output gap estimation

As noted in the introduction, Orphanides et al. (2000) have suggested a specific interpretation for the error term—namely, that it reflects measurement error in the output gap. In particular, suppose that the monetary authorities operate under the reaction function:

$$ff_t = \rho\, ff_{t-1} + (1-\rho)\,\{r^* + (p_t - p_{t-4}) + \alpha\,(xgap_t + noise_t) + \beta\,[(p_t - p_{t-4}) - \pi^*_t]\}, \tag{4}$$

where,

$$noise_t = \phi\; noise_{t-1} + \epsilon_t\,. \tag{5}$$

Here, *noise* has the interpretation of measurement error in the output gap. Orphanides et al. (2000) estimate the time-series process for *ex post* errors in the output gap by comparing real-time estimates of the output gap with the best available estimates at the end of their sample. They find that there was an important shift in the time-series properties of the measurement error in the output gap. In particular, for the period 1980-1994, the serial correlation of output gap mismeasurement is 0.84, considerably smaller than the 0.96 serial correlation they find when they extend their sample back to 1966.[5]

The later period examined by Orphanides et al.—1980-1994—is earlier than the post-1983 period that has been characterized by reduced volatility and reduced responsiveness of inflation to the unemployment rate. It would thus be of interest to have an estimate of such errors for a more recent period. The paper by ENS suggests an indirect method of obtaining such an estimate. They estimate a monetary-policy reaction function similar to equation 3, but with a serially correlated error term. When estimated using current-vintage data, such a model can be given an interpretation in terms of the reaction function with noisy output gap measurement in equations 4 and 5. This can be seen by rewriting equation 4 as:

$$\begin{aligned} ff_t = \rho\, ff_{t-1} + (1-\rho)\ \{&r^* + (p_t - p_{t-4}) \\ &+ \alpha\, xgap_t + \beta\ [(p_t - p_{t-4}) - \pi^*_t]\} + u_t, \end{aligned} \qquad (6)$$

where $u_t \equiv \alpha\,(1-\rho)\, noise_t$, and is thus an AR(1) error process.

The results of English, Nelson, and Sack (2003) suggest that the noise process had a root of 0.7 over the 1987-2001 period. Estimates of a model similar to theirs suggest that the standard deviation of the shock to the noise process was

[5] It is reasonable to suppose that recent revisions to potential output will be smaller than revisions in the more-distant past owing simply to the passage of time: Estimates in the middle of the sample will be more accurate because future data as well as past data can be used to inform the estimate. To get some notion of the potential importance of this effect, I ran a Monte Carlo experiment on a Kalman filter model of trend output. I found that the reduction in revisions at the end of the sample was much smaller than what Orphanides et al. (2000) document. Hence, the reduction in revisions in Orphanides, et al., appears too large to be explained by the simple passage of time.

1.2 percentage points—about the same as Orphanides et al. (2000) found for both their overall and post-1979 samples.[6]

The preceding discussion suggests two extreme noise processes—the "worst case" process identified by Orphanides et al. (2000), with a serial correlation parameter of 0.96, and the process implicit in the serial correlation process of the error term from a reaction function estimated with recent data, where $\phi = 0.70$. I will also consider an intermediate case, with $\phi = 0.92$, which can be thought of as a less-extreme version of the Orphanides et al. worst case. Because there is little evidence for a shift in the standard deviation of the shock to the noise process, I assume the same value for all three processes, 1.10. These assumptions are summarized in table C.

Table C
Alternative Assumptions about Gap Estimation Errors
Standard deviations in percentage points

	Serial correlation ϕ	Impact standard deviation	Unconditional standard dev'n
Worst case	.96	1.1	3.9
Intermediate	.92	1.1	2.8
Recent past	.70	1.1	1.5

2.3—Specification of the inflation target

As discussed in section 1.3, movements in inflation appear to have remained persistent in the 1983-2002 period. One reason for such persistence may be that the implicit inflation objective varied over this period. A specification that allows for inflation objectives to drift in response to actual events is:

$$\pi^*_t = \mu \, \pi^*_{t-1} + (1-\mu) \, \Delta p_t \, , \tag{7}$$

[6] The standard errors of the shocks to the estimated processes were similar in the two samples of Orphanides et al.: 1.09 and 0.97 percentage points in the longer and shorter samples, respectively.

where, as before, Δp_t represents annualized inflation. In equation 7, a fixed inflation target can be specified by setting $\mu = 1$. If $\mu < 1$, however, then the inflation target will be affected by past inflation experience, and inflation will possess a unit root. In most of the simulations that follow, I assume $\mu = 0.9$. In simulations of the FRB/US model, this value of μ allows the model to capture the historical relationship between economic slack and persistent changes in inflation. The results are not greatly affected by small changes in this parameter.[7]

3. Models

I examine the implications of changes in the conduct of monetary policy for output and inflation variability using two models. One is a variant of the "three-equation" macroeconomic model that has been used in many recent analyses of monetary policy (see, for example, Fuhrer and Moore, 1995; Rotemberg and Woodford, 1997; Levin, Wieland, and Williams, 1999; and Rudebusch, 2002). One appeal of the three-equation model is that it can be thought of as including the minimal number of variables needed to model the monetary-policy process: The monetary-policy reaction function is combined with equations for its independent variables, inflation and the output gap. In addition, the model's small size makes it straightforward to vary model parameters. The model is described more fully shortly.

The other model I use is the Federal Reserve's large-scale FRB/US model. FRB/US is described in detail in Brayton, et al. (1997) and Reifschneider, Tetlow, and Williams (1999). Among the key features of the FRB/US model are: the underlying structure is optimization-based; decisions of agents depend on explicit

---

[7] Specifying the inflation target as in equation 7 implies a particular interpretation of the disinflation of the early 1990s: According to equation 7, that disinflation was not the result of a conscious decision to reduce the inflation target but rather a decision to allow the reduction in inflation that occurred for other reasons to affect the target. Levin and Piger (2003) have argued that the early 1990s reduction in U.S. inflation is well characterized as an exogenous shift in the mean of inflation, an interpretation that is suggestive of an explicit change in the inflation target. Orphanides and Wilcox (2002, p. 51), however, provide evidence from the FOMC's minutes from 1989 that indicates that while a reduction in inflation would be welcome, a recession would not be. Furthermore, the Federal Reserve's 1992 *Annual Report* suggests that the weakness of the economy in 1991 and 1992 came as a surprise.

expectations of future variables; and the structural parameters of the model are estimated.

In both the three-equation model and FRB/US, economic agents are assumed to be at least somewhat forward-looking, and they form model-consistent expectations of future outcomes. As a consequence, their expectations will be functions of the monetary policy rule in the model. In this way, these models are—at least to some extent—robust to the Lucas critique, which argues that agents' expectations should change when the policy environment changes.

In addition to the monetary-policy reaction function described in section 2, the three-equation model also includes a New Keynesian Phillips curve and a simple "IS curve" that relates the current output gap to its lagged level and to the real short-term interest rate. The New Keynesian Phillips curve is:

$$\Delta p_t = E_t \Delta p_{t+1} + \kappa \, xgap_t + \eta_t , \qquad (8)$$

where η_t is an error term representing shocks to inflation. The microeconomic underpinnings of such a model are discussed in various places—see, for example, Roberts (1995). Because equation 8 can be thought of as having an explicit structural interpretation, it will be referred to as the "structural Phillips curve," in contrast to "reduced-form Phillips curves" such as equations 1 and 2.

One shortcoming of the New Keynesian Phillips curve under rational expectations is that it does a poor job of fitting some key macroeconomic facts (Fuhrer and Moore, 1995). A number of suggestions have been made for addressing its empirical shortcomings. Some recent work has focused on the possibility that inflation expectations are less than perfectly rational (Roberts, 1998; Mankiw and Reis, 2002). One way of specifying inflation expectations that are less than perfectly rational is:

$$E_t \Delta p_{t+1} = \omega \, M_t \, \Delta p_{t+1} + (1 - \omega) \, \Delta p_{t-1}, \qquad (9)$$

where the operator M indicates rational or "mathematical" expectations. An interpretation of this specification is that only a fraction ω of agents uses rational expectations while the remainder uses last period's inflation rate as a simple "rule of thumb" for forecasting inflation. Substituting equation 9 into equation 8 yields:

$$\Delta p_t = \omega M_t \Delta p_{t+1} + (1 - \omega) \Delta p_{t-1} + \kappa\, xgap_t + \eta_t . \quad (10)$$

Fuhrer and Moore (1995) and Christiano, Eichenbaum, and Evans (CEE, *forthcoming*) provide alternative microeconomic interpretations of equation 10. Fuhrer and Moore assume that agents are concerned with relative real wages. CEE argue that in some periods, agents fully re-optimize their inflation expectations, whereas in others, they simply move their wage or price along with last period's aggregate wage or price inflation. In their model, wages and prices are reset each period, and thus are only "sticky" for a very brief period. The only question is how much information is used in changing those wages and prices.[8]

The theoretical models of both Fuhrer and Moore and CEE suggest that $\omega = ½$. The results of Roberts (*forthcoming*) and Boivin and Giannoni (2003) provide empirical support for $\omega = ½$. I will therefore assume ω is about one-half in the simulations below.[9] I discuss other aspects of the calibration choice in section 5.

The IS curve is:

$$xgap_t = \theta_1\, xgap_{t-1} + (1 - \theta_1)\, E_t\, xgap_{t+1} - \theta_2 (r_{t-2} - r^*) + \nu_t , \quad (11)$$

where r is the real federal funds rate and ν_t is a random shock to aggregate demand. Rotemberg and Woodford (1997) discuss how an IS curve with $\theta_1 = 0$ can be derived from household optimizing behavior. Amato and Laubach (2001)

---

[8] Mankiw and Reis (2002) present an alternative model that also has the properties that prices are only trivially sticky and expectations are not re-optimized every period, although their assumption about what firms do in periods when they can't re-optimize is different.

[9] To be precise, I assume $\omega = 0.475$. I choose a value slightly less than ½ because with larger values, the model with an evolving inflation target often proved unstable—technically, it had too many large roots—when expectations formation was strongly forward-looking. This result suggests that with an evolving inflation target, stability is affected by the degree of forward-looking behavior. Technical issues aside, this result suggests an alternative reason why the economy may be highly volatile when there is not a firm commitment to an inflation target.

show how habit persistence can lead to a specification with lagged as well as future output. The lagged effect of interest rates on output can be justified by planning lags; Rotemberg and Woodford (1997) assume a similar lag. Again, details of the calibration are provided in section 5.

Stock and Watson (2002) also examine the effects of changes in monetary policy using a small macroeconomic model. Like this model, theirs also has a reduced-form output equation, a model of inflation with explicitly forward-looking elements, and a monetary-policy reaction function; in addition, they include an equation for commodity prices. But while Stock and Watson's model includes several explicitly calibrated parameters, it also includes a number of lag variables for which parameters are not reported, making a close comparison of their model with the present one difficult.

The three-equation model is, of necessity, limited in the detail it can provide. In particular, it is specified in terms of the output gap rather than overall output. Thus, for this model, only the variability of the output gap, and not output growth as well, can be reported. The more-elaborate FRB/US model includes estimates of output growth as well as output gap, which will facilitate comparisons with earlier work that only reports results for output growth.

4. Impulse responses

This section examines how the output and inflation effects of shocks to the model economy change under different monetary policies. Figure 3 shows the effects of a shock to the IS curve on output and inflation using the three-equation model discussed in the previous section. The top panel shows the effects of the shock under the least aggressive monetary policy, while the bottom panel shows the effects under the aggressive policy. In both panels, the shock initially raises output and inflation. Because the inflation target is affected by past inflation, there is a permanent increase in inflation in both panels. However, under the aggressive policy in the bottom panel, output returns more rapidly to its pre-shock value and the long-run increase in inflation is much smaller. Moreover, one to two years after the initial shock, the increase in inflation is notably smaller relative to output, suggesting a smaller reduced-form relationship between these variables under the aggressive policy.

Figure 4 looks at the effects of a reduction in the persistence of output gap estimation errors, holding fixed the responsiveness of monetary policy at the aggressive level. The top panel considers the worst-case estimate for error persistence ($\phi = 0.96$), while the bottom panel shows the recent-past case ($\phi = 0.7$). As can be seen, an initial 1 percentage point estimation error has much larger and more persistent effects on output and inflation in the top panel than in the bottom panel. Moreover, the impact of the shock on inflation over the first couple of years is much larger relative to the impact on inflation in the top panel, again suggesting a larger reduced-form slope.[10]

Of course, the simulations in figures 3 and 4 show only the effects of individual shocks. By contrast, the empirical reduced-form Phillips curve coefficients such as those discussed in section 1 reflect the effects of all shocks. A convenient way to consider the joint effect of a number of shocks on the reduced-form coefficients is stochastic simulation, the subject of the next section.

5. Stochastic simulations

5.1—Results with three-equation model

In this subsection, I use stochastic simulations of the three-equation model described in section 3 to assess the impact of changes in monetary policy on the volatility of output and inflation and on the reduced-form relationship between inflation and unemployment.

To calibrate the IS curve of the model, I first chose a weight on future output, θ_1, of ½, similar to the degree of forward-looking assumed in the structural Phillips

[10] Some notion of how the relationship between output and inflation changes between the top and bottom panels can be gleaned from changes in the "sacrifice-ratio," which, in terms of the figures, can be thought of as the integral of the output gap divided by the permanent change in inflation. In figure 3, the sacrifice ratio is 4.6 for the simulation in the top panel whereas it is 7.7 in the bottom panel. Hence, under the aggressive policy in the bottom panel, any given change in inflation is associated with a larger output gap, consistent with the expectation that an aggressive policy will limit the inflation consequences of any given movement in the output gap. In figure 4, the sacrifice ratio is 3.1 in the top panel and 4.7 in the bottom panel, again consistent with the idea that better monetary policy limits the responsiveness of inflation to output gaps.

curve discussed above. I then chose the IS-curve slope, θ_2, so as to match the effect of an identified monetary-policy shock on output in a VAR estimated over the 1960-to-2002 period, which implied $\theta_2 = 0.1$. I chose the slope of the structural Phillips curve and the standard errors of the shocks to the IS and structural Phillips curves so as to approximate the volatility of output, the volatility of inflation, and the slope of the simple reduced-form Phillips curve. This exercise resulted in standard deviations of the IS and Phillips curve shocks of 0.55 and 0.17 percentage point, respectively, and a structural Phillips curve slope of 0.005. Note that the model has been calibrated so that the volatility of the residuals is representative of the low-volatility period for the U.S. economy. The IS and Phillips-curve parameter estimates are in broad agreement with empirical estimates of New Keynesian models, such as Roberts (*forthcoming*) and Boivin and Giannoni (2003).

To carry out the stochastic simulations, I first solve the model under model-consistent expectations. I then use this solution to generate simulated data by taking random draws from the distribution of the model residuals. For each draw, a time series of 160 quarters is created. To reduce the influence of starting values, the first eighty quarters are discarded, and sample statistics are computed using the last eighty quarters. The shocks are drawn from a normal distribution.

The standard deviation of output growth, the output gap, and inflation are calculated for each draw and the summary statistics are averaged over the draws. Similarly, the slope of the reduced-form Phillips curve is estimated for each draw. I present the slope coefficients from two models. One is the simple reduced-form Phillips curve of equation 1, modified to use the output gap rather than the unemployment rate:

$$(p_t - p_{t-4}) - (p_{t-4} - p_{t-8}) = \gamma_0 + \gamma_1 (\Sigma_{i=0,3}\, xgap_{t-i})/4 . \qquad (12)$$

Presenting results for this simple model has the advantage that the results are directly comparable to the simple relations illustrated in figure 1; also, the results focus attention (and econometric power) on the slope coefficient.[11] I also consider the slightly more elaborate reduced-form Phillips curve:

$$\Delta p_t = \gamma_0 + \gamma_1\, xgap_t + \gamma_2\, \Delta p_{t-1} + \gamma_3\, \Delta p_{t-2} + \gamma_4\, \Delta p_{t-3} + \gamma_5\, \Delta p_{t-4}\,. \qquad (13)$$

Equation 13 is similar to equation 2 except that here, the sum of the lagged inflation coefficients is not constrained to sum to one. Estimates of this equation can thus allow for the possibility that the changes in policy under consideration may have reduced the sum of lag coefficients.

In table 4, I consider the effects of changes in the coefficients of the reaction function and changes in the volatility of a simple *i.i.d.* error term added to the reaction function. These changes in policy are similar to those that Stock and Watson (2002) have considered. I later turn to the possibility that the serial correlation of errors in the measurement of the output gap may have fallen. Initially, to isolate the effects of these changes in policy from the possibility that target inflation has become better anchored, I assume that target inflation is updated using equation 7 with a parameter $\mu = 0.9$.

Comparing columns 1 and 2 shows the effects of moving to a more-aggressive monetary policy. This policy shift leads to an important reduction in the volatility of both the output gap and inflation: The standard deviation of the gap falls by about a quarter while the standard deviation of inflation falls by half. The reduction in the volatility of the output gap is at the low end of the range of the historical decline between early and later periods while the reduction in inflation volatility is in line with that seen historically.

The slope of the simple reduced-form Phillips curve falls by about one-third, in line with historical reductions in the Phillips curve slope as measured with the output gap, although somewhat short of the reductions in the coefficient on the unemployment rate. Also, the *t*-statistic on the slope of the simple Phillips curve falls from 2.9 to 1.6, suggesting that these changes in monetary policy may also have affected the apparent statistical robustness of the simple Phillips curve

---

[11] The reported coefficient standard errors are based on the simulated distributions, and so are not affected by the serial correlation induced by the overlapping left-hand-side variable.

relationship. The more-elaborate Phillips curve shows a similar reduction in slope while the sum of coefficients on lagged inflation remains high.

Column 3 introduces an additional change in monetary policy, a reduction in the volatility of the shock to policy. In this model, this additional change has very little effect on the results: The volatility of the output gap and inflation fall somewhat more, but the estimated Phillips-curve slopes are very similar to those in column 2.

Column 4 looks at the implications of the switch to a fixed inflation target, under the assumption of an aggressive monetary policy and small shocks to the reaction function, as in column 3. This shift in policy has only small effects on the results: The volatility of the output gap actually rises a bit while that of inflation falls by about 15 percent. The slope of the reduced-form Phillips curve rises a bit. Perhaps surprisingly, the persistence of inflation falls only slightly, and inflation remains highly persistent. In section 6, I return to the question of how the behavior of the economy might change if the central bank were to adopt a strict inflation target.

Table 5 considers the model with persistent gap errors, along the lines suggested by Orphanides et al. (2000). Column 1 shows Orphanides et al.'s "worst-case scenario," in which output-gap estimation errors have a quarterly autocorrelation of 0.96. In column 1, a weak response of monetary policy to output and inflation errors is assumed. In this case, the volatility of the output gap is at the high end of historical estimates while that of inflation is far greater than was the case historically. In columns 2 and 3, I therefore consider two ways of reducing the influence of persistent output gap errors. In column 2, I assume the more-aggressive policy reaction function parameters along with a fixed inflation target.[12] With this policy, the volatility of the output gap is about in line with historical values for the 1960-1979 period and inflation is much closer to the historical range. The slope of the simple reduced-form Phillips curve is just above the historical range. Inflation is highly persistent, with a root of 0.97. These results are consistent with the argument made in Orphanides (2001), that

[12] A fixed inflation target is assumed because of numerical problems with the solution under an evelving target. Inflation is nonetheless highly persistent in this case.

poor estimation of potential output, rather than weak response of monetary policy to output and inflation, was responsible for volatile and persistent inflation in the pre-1984 period.

In column 3, I consider an alternative in which the monetary-policy reaction remains weak but output gap errors are somewhat less persistent than in columns 1 and 2. This adjustment cuts the standard deviation of inflation by more than half, bringing it closer to the range that was seen historically. Both columns 2 and 3 provide plausible candidate characterizations of the high-volatility period.

Column 4 considers the implications of a reduction in the persistence of the shock to the reaction function, so that $\rho = 0.7$, under the assumption of an aggressive monetary policy. As can be seen by comparing column 4 with column 2, reducing the persistence of the shock to the reaction function while holding the parameters of the reaction function fixed has important effects on the volatility of output and the slope of the Phillips curve. The standard deviation of the output gap falls by 30 per cent and the volatility of inflation by almost half. The slope of the simple Phillips curve falls by about a third. As in table 4, there is a marked reduction in the statistical significance of the Phillips curve slope, as the *t*-ratio falls from more than 3 to just 1.7. Inflation remains highly persistent, with an autoregressive root of 0.94.

Comparing column 4 with column 3 gives an alternative view of the change in monetary policy—namely, that it represented a combination of more aggressive policy and better estimation of potential output. The story on output volatility is about the same as for column 2. The reduction in the slope of the simple reduced-form Phillips curve is greater in this case, at around one-half.

The final column of table 5 adds the assumption of a fixed inflation target. The volatility of inflation falls somewhat further while that of the output gap actually rises a bit. Estimates of the slope of the Phillips curve are little changed. As in table 4, the adoption of a fixed inflation target has surprisingly little effect on the persistence of inflation in this model.

5.2—Results with FRB/US

In this section, I work with the Federal Reserve's FRB/US model of the U.S. economy. In the simulations, I solve a linearized version of the FRB/US model under model-consistent expectations. The draws for the stochastic simulations are taken from a multivariate normal distribution using the variance-covariance matrix of residuals from the FRB/US model estimated over the 1983-2001 period. Hence, the volatility of the residuals is representative of the low-volatility period for the U.S. economy. Because the FRB/US model includes the unemployment rate, here, the reduced-form Phillips curve results are based on this variable, as in equations 1 and 2.

Columns 1, 2, and 3 of table 6 consider the effects of first increasing the parameters of the reaction function and then reducing the volatility of the (not-serially correlated) shock to the reaction function. As in table 4, it is primarily the change in the reaction function parameters that affects the volatility of output; there is only a smaller further reduction from reducing the volatility of the reaction-function shock. Between column 1 and column 3, the standard deviation of the GDP *gap* falls by about 30 percent, somewhat more than with the three-equation model. However, the standard deviation of GDP *growth* falls by only about 10 percent. The reduction in the volatility of the output gap is in the range of the historical decline between the 1960-1979 and 1983-2002 periods. But the reduction in GDP growth volatility is considerably smaller than what actually occurred, a finding similar to those reported in Stock and Watson (2002).

Increasing the reaction-function parameters only leads to a reduction of about 10 percent in the slope of the simple reduced-form Phillips curve; the slope of the more-elaborate Phillips curve, however, falls by more than 40 percent. Inflation is highly persistent in both columns 1 and 2, with an autoregressive root around 0.9. With the reduction in the volatility of the monetary-policy shock in column 3, the slope of the simple Phillips curve relative to column 1 is now about one-third smaller. The slope of the more-elaborate Phillips curve also declines further, and the total reduction is now almost 60 percent. As in the three-equation model, these changes in monetary policy can account for most or all of the reduction in the slope of the reduced-form Phillips curve.

Column 4 looks at the implications of the switch to a fixed inflation target, under the assumption of an aggressive monetary policy and small shocks to the reaction function, as in column 3. In contrast to the three-equation model, there is now a large reduction in inflation persistence with the switch to a fixed inflation target, a result perhaps more in line with prior expectations.

Table 7 considers the implications of reduced serial correlation in output gap estimation errors as well as changes in the responsiveness of policy. Assuming the "worst-case" output-gap estimation errors along with a weak response of monetary policy to output and inflation, column 1, leads to volatilities of output and inflation that are far greater than was the case historically. For inflation, this result is similar to that in table 5; for the output gap, the excess volatility is much greater. Columns 2 and 3 repeat the two solutions to this excess volatility used with the three-equation model: assuming a more-aggressive policy, and assuming somewhat smaller persistence of estimation errors. Both solutions reduce the volatility of output and inflation, and both lead to plausible characterizations of the earlier period.

Column 4 considers the implications of a reduction in the persistence of the shock to the reaction function, so that $\rho = 0.7$, under the assumption of an aggressive monetary policy. As can be seen by comparing column 4 with column 2, reducing the persistence of the shock to the reaction function while holding the parameters of the reaction function fixed has large effects on the volatility of the output gap and the slope of the Phillips curve. The standard deviation of the output gap falls by almost half, at the high end of the range of the historical decline. However, the reduction in the standard deviation of output *growth* is only about 20 percent. The slope of the simple Phillips curve falls by two-thirds—even more than the declines that have been seen historically. Inflation remains highly persistent, with an autoregressive root of 0.92. The comparison of column 4 with column 3 yields similar results for output volatility. The reduction in the slope of the simple reduced-form Phillips curve is less sharp in this case, but it is still around 40 percent.

While the FRB/US model predicts reductions in output gap volatility and the slope of the Phillips curve that are consistent with historical changes, it does not suggest that monetary policy had much to do with the reduction in inflation volatility. Looking across tables 6 and 7, changes in policy lead to reductions of the standard deviation of inflation of at most 10 percent, well short of the historical reductions.

The final column of table 7 adds the assumption of a fixed inflation target. As might be expected, the persistence of inflation drops further, as does the slope of the simple Phillips curve. The standard deviation of inflation also drops, and is now in the historical range. However, this reduction in inflation volatility occurs only when the persistence of inflation is considerably lower than was the case for the 1983-2002 period.

The following are some conclusions looking across both the FRB/US and three-equation model results:

- Changes in monetary policy imply large reductions in output gap volatility in both FRB/US and in the simple three-equation model, in the range of what has been seen historically. The reductions are somewhat larger in FRB/US.
- While changes in monetary policy can explain the reduction in output *gap* volatility, they cannot explain much of the reduction in the volatility of GDP *growth* in FRB/US. One possible reconciliation of these findings is that in addition to changes in monetary policy, there were also reductions in the volatility of the "supply side" of the economy, which would affect the volatility of GDP growth but not the volatility of the output gap. Under this hypothesis, monetary policy is an adequate explanation for the greater stability of aggregate demand in the economy but some additional explanation is needed to explain the greater stability of aggregate supply.[13]
- For inflation, changes in monetary policy can account for most or all of the standard-deviation reduction in the three-equation model, but not in FRB/US.

---

[13] Another factor that may have affected changes in GDP more than output gaps is the reduced frequency of strikes and other labor disputes, which were much less common in the 1980s and 1990s than in 1960s and 1970s. Strikes of, for example, autoworkers formerly led to notable, and short-lived, effects on aggregate output, a phenomenon missing from the recent U.S. experience. Because these disruptions were generally brief, they would have had a more marked effect on changes than on levels.

- In both models, changes in monetary policy predict large reductions in the slope of the simple reduced-form Phillips curve—of between 30 and 40 percent in the three-equation model, and up to two-thirds in FRB/US. Thus, according to these models, monetary policy appears to be able to account for the reduction in the slope of the reduced-form Phillips curve.
- The predicted changes in the economy are greater if improvements in monetary policy are broadened to include the ability of the central bank to estimate potential output, along the lines suggested by Orphanides et al. (2000).

6. How might the economy behave under a fixed inflation target?

As the evidence in figure 2 suggested, the evidence for a drop in inflation persistence is, thus far, inconclusive. However, estimates limited to the past decade are suggestive that inflation may have become more stable. In this section, I use the three-equation model to consider how the behavior of the economy may change in a regime of inflation stability.

Expectations formation is central to the question of how inflation dynamics are likely to change in a regime of inflation stability. In the simulations considered so far, equation 9 has been used as the model of expectations formation. In equation 9, "non-optimizing" agents rely on past inflation as an indicator of future inflation. Similarly, under CEE's interpretation of the model, agents find it useful to use lagged inflation to index prices in periods when they do not re-optimize. It is most useful to use lagged inflation as an predictor of future inflation when inflation is highly persistent; if inflation were not persistent, lagged inflation would not be a good indicator of future inflation. It is reasonable to assume, therefore, that if inflation were to be stabilized, agents would change their inflation forecasting rules. Here, I consider one characterization of how agents might change the way they set expectations as inflation dynamics change. In particular, I consider the following generalization of equation 9:

$$E_t\, \Delta p_{t+1} = \omega\, M_t\, \Delta p_{t+1} + (1 - \omega)\, \lambda\, \Delta p_{t-1}\,, \qquad (14)$$

where the parameter λ is chosen so as to give the best "univariate" forecast of inflation. (For simplicity, the implicit inflation target is assumed to be zero.)

Thus, in equation 9, $\lambda = 1$ was the best univariate forecast under the assumption—which has heretofore been close to accurate—that inflation had a unit root.

Suppose that the central bank adopts a fixed inflation target. According to column 4 of table 4, in the three-equation model with $\lambda = 1$, this change would result in an inflation process with a root of 0.92. We can then ask what would happen if agents adopted a univariate inflation forecast with $\lambda = 0.92$. A simulation under this assumption shows that inflation will have a root of 0.79. But then, agents will want to update their forecasting rule to be consistent with this new assessment of the serial correlation of inflation. Doing so, however, further reduces the persistence of inflation. Following this process to its logical conclusion suggests that a "fixed point" for univariate expectations formation is approximately zero autocorrelation (actually, the fixed point is $\lambda = 0.02$).

According to this model, then, the long-run consequences of a policy of a fixed inflation target is inflation that is not only stationary but actually uncorrelated. Of course, this evolution is based on a particular assumption about expectations formation. But there is some historical precedent for such an outcome. Ball (2000) argues that in the 1879-1914 period, when the United States was on the gold standard, the "best univariate forecast" for inflation was zero: Under the gold standard, inflation was not expected to persist. Ball (2000) and Gordon (1980) argue that allowing perceived inflation dynamics to change with the policy regime can go a long way to allowing the expectations-augmented Phillips curve—which works well in the second half of the twentieth century—to account for the performance of inflation in the gold standard period.

If a central bank were to adopt a fixed inflation target, how quickly might a transition to stable inflation take place? Based on simulations with the baseline three-equation model, it could take a while for agents to catch on. In table 4, for example, inflation is predicted to have an autoregressive root of 0.92 even under a fixed inflation target. In the twenty-year sample underlying these simulations, the *t*-ratio of the hypothesis that this coefficient is still one is only 1.6, well short of Dickey-Fuller critical values. So even if agents with univariate expectations were good time-series econometricians, they may see little need to change the way they form their expectations. FRB/US, however, is more sanguine: Switching to a fixed inflation target leads to a large reduction in the persistence of inflation, and the largest root of inflation falls to 0.77 (table 6, column 4 and table 7, column 5). If this were the case, the transition to stable inflation could occur more rapidly.

7. Conclusions

- As in other recent work, I find that changes in the parameters of the monetary-policy reaction function and reductions in the variance of shocks to the reaction function can explain only a small fraction of the reduction in the standard deviation of the *growth rate* of output. However, I find that changes in monetary policy can explain most or all of the reduction in the standard deviation of the output *gap*; the effects are especially strong in the FRB/US model.
- One interpretation of this result is that improvements in monetary policy can account for a large proportion of the reduction in aggregate demand volatility; a reduction in aggregate supply volatility would be required to account for the remaining reduction in the volatility of output growth.
- The monetary policy changes considered here predict large declines in the slope of the reduced-form relationship between the change in inflation and the unemployment rate, both in the large-scale FRB/US model and in the small three-equation model.
- The results for inflation volatility are mixed: In the three-equation model, changes in monetary policy can account for most or all of the reduction in the standard deviation of inflation. By contrast, in FRB/US, these monetary-policy changes predict only a small reduction in inflation volatility.
- The change in the setting of monetary policy suggested by Orphanides et al. (2000)—that policymakers may have improved their methods for estimating potential GDP—strengthens the ability of monetary policy changes to explain changes in the economy, implying greater reductions in volatility and in the slope of the reduced-form Phillips curve.

Table 1
The U.S. Economy's Changing Volatility
Standard deviations, percentage points

	GDP growth[a]	Core inflation[a]	Unemploy-ment rate	Output gap, FRB/US	Output gap, CBO
1984:Q1-2002:Q4	2.22	1.18	1.09	2.08	1.54
1960:Q1-1983:Q4	4.32	2.56	1.77	3.57	3.17
1960:Q1-1979:Q4	3.98	2.42	1.36	2.71	2.61

Notes: a. Quarterly percent change, annual rate.

Table 2 **Evidence of a Shift in the Slope of the Reduced-Form Phillips Curve, Simple Model** $(p_t - p_{t-4}) - (p_{t-4} - p_{t-8}) = \gamma_0 + \gamma_1 (\Sigma_{i=0,3} UR_{t-i})/4$			
	Unemployment rate	FRB/US output gap	CBO output gap
1984:Q1-2002:Q4	-.201 (.056)	.092 (.032)	.159 (.038)
1960:Q1-1983:Q4	-.389 (.085)	.154 (.050)	.207 (.043)
1960:Q1-1979:Q4	-.378 (.155)	.130 (.095)	.180 (.080)

Notes: Standard errors, shown in parentheses, are adjusted for serial correlation of equation residuals using Newey-West procedure.

Table 3 **Evidence of a Shift in the Slope of the Reduced-Form Phillips Curve, More Complex Model** $\Delta p_t = \gamma_0 + \gamma_1 UR_t + \gamma_2 \Delta p_{t-1} + \gamma_3 \Delta p_{t-2} + \gamma_4 \Delta p_{t-3} + (1-\gamma_2-\gamma_3-\gamma_4) \Delta p_{t-4}$			
	Unemployment rate	FRB/US output gap	CBO output gap
Slope coefficient (γ_1)			
1984:Q1-2002:Q4	-.098 (.069)	.051 (.036)	.091 (.048)
1961:Q1-1983:Q4	-.154 (.052)	.066 (.026)	.084 (.028)
1961:Q1-1979:Q4	-.157 (.075)	.056 (.038)	.076 (.038)
Coefficient on first inflation lag (γ_2)			
1984:Q1-2002:Q4	.29 (.12)	.29 (.12)	.28 (.12)
1961:Q1-1983:Q4	1.02 (.10)	1.05 (.11)	1.02 (.10)
1961:Q1-1979:Q4	1.01 (.11)	1.04 (.12)	1.02 (.10)

Table 4
The Effects of Changes in Monetary Policy on Volatility and the Slope of the Reduced-Form Phillips Curve: Three-Equation Model
5000 draws

	(1)	(2)	(3)	(4)
Inflation target: M-policy shock: α and β:	Evolving S.D. = 1.0 0.5 and 0.0001	Evolving S.D. = 1.0 1.0 and 0.5	Evolving S.D. = 0.47 1.0 and 0.5	Fixed S.D. = 0.47 1.0 and 0.5
Volatility:				
S.D. (gap)	2.32	1.82	1.79	1.84
S.D. (inflation)	2.36	1.20	1.19	1.02
Phillips curves:				
Simple; slope	.213 (.073)	.139 (.084)	.139 (.086)	.146 (.085)
With lags; slope	.062 (.024)	.041 (.026)	.041 (.026)	.040 (.026)
Sum lag coefs.	.98 (.03)	.94 (.06)	.94 (.06)	.93 (.06)
Inflation, largest root	.97 (.03)	.94 (.05)	.94 (.05)	.92 (.05)

Notes: Numbers in parentheses are standard errors.
"Sum lag coefs." indicates the sum of the coefficients on lagged inflation.

Table 5
The Effects of Changes in the Persistence of Potential Output Errors on Volatility and the Slope of the Reduced-Form Phillips Curve: Three-Equation Model
5000 draws

	(1)	(2)	(3)	(4)	(5)
Error persistence:	0.96	0.96	0.92	0.7	0.7
Inflation target:	Evolving	Fixed	Evolving	Evolving	Fixed
α and β:	0.5 & 0.1	1.0 & 0.5	0.5 & 0.1	1.0 & 0.5	1.0 & 0.5
Volatility:					
S.D. (gap)	3.51	2.64	2.68	1.82	1.88
S.D. (inflation)	6.71	2.37	3.31	1.22	1.05
Phillips curves:					
Simple; slope	.289	.221	.239	.145	.150
	(.066)	(.068)	(.070)	(.085)	(.082)
With lags: slope	.069	.059	.064	.043	.043
	(.024)	(.022)	(.023)	(.026)	(.026)
Sum lag coefs.	.99	.97	.98	.94	.93
	(.02)	(.03)	(.03)	(.06)	(.06)
Inflation, largest root	.99	.97	.98	.94	.93
	(.02)	(.03)	(.03)	(.05)	(.05)

Notes: Numbers in parentheses are standard errors.
“Sum lag coefs.” indicates the sum of the coefficients on lagged inflation.

Table 6
The Effects of Changes in Monetary Policy on Volatility and the Slope of the Reduced-Form Phillips Curve: FRB/US
2000 draws

	(1)	(2)	(3)	(4)
Inflation target: M-policy shock: α and β:	Evolving S.D. = 1.0 0.5 and 0.0001	Evolving S.D. = 1.0 1.0 and 0.5	Evolving S.D. = .47 1.0 and 0.5	Fixed S.D. = .47 1.0 and 0.5
Volatility:				
S.D. (gap)	2.4	1.8	1.7	1.9
S.D. (GDP growth)	3.5	3.2	3.2	3.1
S.D. (inflation)	2.8	3.2	3.2	1.6
Phillips curves:				
Simple; slope	-.186 (.279)	-.176 (.394)	-.129 (.409)	-.081 (.278)
With lags; slope	-.130 (.179)	-.074 (.198)	-.054 (.205)	-.081 (.181)
Sum lag coefs.	.84 (.12)	.89 (.10)	.89 (.10)	.71 (.20)
Inflation, largest root	.89 (.07)	.92 (.07)	.92 (.07)	.77 (.11)

Notes: Numbers in parentheses are standard errors.
“Sum lag coefs.” indicates the sum of the coefficients on lagged inflation.

Table 7
The Effects of Changes in the Persistence of Potential Output Errors on Volatility and the Slope of the Reduced-Form Phillips Curve: FRB/US
2000 draws

	(1)	(2)	(3)	(4)	(5)
Error persistence:	0.96	0.96	0.90	0.70	0.70
Inflation target:	Evolving	Fixed	Evolving	Evolving	Fixed
α and β:	0.5 & 0.1	1.0 & 0.5	0.5 & 0.1	1.0 & 0.5	1.0 & 0.5
Volatility:					
S.D. (gap)	6.1	3.4	3.5	1.8	1.9
S.D. (GDP growth)	5.8	4.0	4.1	3.2	3.1
S.D. (inflation)	6.3	3.6	3.7	3.3	1.7
Phillips curves:					
Simple; slope	-.47	-.50	-.33	-.17	-.102
	(.16)	(.20)	(.22)	(.41)	(.26)
With lags; slope	-.37	-.35	-.22	-.070	-.093
	(.18)	(.16)	(.17)	(.21)	(.18)
Sum lag coefs.	.83	.84	.84	.89	.71
	(.09)	(.09)	(.11)	(.11)	(.20)
Inflation, largest root	.94	.92	.92	.92	.77
	(.04)	(.06)	(.05)	(.07)	(.11)

Notes: Numbers in parentheses are standard errors.
“Sum lag coefs.” indicates the sum of the coefficients on lagged inflation.

Appendix A —Additional Phillips curve estimates

In this appendix, I consider some broader Phillips curve models that permit controls for additional factors. In particular, I consider including measures of supply shocks such as relative import and food and energy prices; allowing for longer lags of inflation; allowing for shifts in the NAIRU; and allowing for an influence of productivity growth in the model, as in Ball and Moffitt (2001).

I consider the relationship between inflation and the unemployment rate using the following reduced-form model:

$$\Delta p_t = - c_1 \, (UR_t - NR_t) + c_2(L) \, \Delta p_{t-1} + c_3 \, X_t + \epsilon_t \, . \qquad \text{(A.1)}$$

where Δp_t is the (annualized) inflation rate, RU is the unemployment rate, NR is an estimate of the NAIRU, $c_2(L)$ is a lag polynomial that indicates that multiple lags of inflation are included, and X is a vector of other variables that will be discussed shortly. As before, the measure of inflation I use is the price index for consumer prices other than food and energy.

$c_2(L)$ differs from the simple models considered earlier. In the simple model of equation 2, the lag polynomial is simply four lags of inflation. $c_2(L)$ in equation A.1 is assumed to involve sixteen lags with the coefficients constrained to lie on a second-order polynomial. See Brayton, Roberts, and Williams (1999) for a discussion of the role of lag polynomials in reduced-form models of inflation. As before, the sum of lagged coefficients is constrained to be one; this restriction easily passes statistical muster in both models and all sample periods considered.

In this appendix, I allow the NAIRU (NR) to vary over time. First of all, I allow for a break in the constant term across the two estimation samples, which, in addition to letting the coefficient on the unemployment rate vary over times, effectively allows for different NAIRU estimates in the two samples. Second, I allow the changing demographic composition of the labor force to shift the

NAIRU over time.[14] Finally, a number of authors have noted developments in the labor market that may have shifted the NAIRU in recent years. For example, Katz and Krueger (1999) have cited increases in the incarceration rate and in the use of temporary help services while Autor and Duggan (2003) have emphasized increases in disability insurance roles. To allow for these factors as well as other developments cited by Katz and Krueger and CBO (2002), I also consider the sensitivity of the estimates to a reduction in the NAIRU of 3/4 percentage point that occurs linearly between 1985 and 2000, beyond the movements in demographic factors already mentioned.

The vector X includes controls for shifts in the relative prices of food and energy, as discussed in Brayton, Roberts, and Williams (1999). Ball and Moffitt (2001) have recently argued that the productivity acceleration of the 1990s may also have affected the NAIRU. They argue that an acceleration in productivity relative to recent trends in real wage growth can have an important damping effect on inflation. I report results that include adding such a variable to the vector of supply-shock controls.[15]

Table A.1 reports results using the specification in equation A.1. Column 1 reports results including import and food and energy prices in the vector X, but not the Ball-Moffitt productivity-acceleration variable or the 1985-2000 NAIRU shift variable. Column 2 adds the NAIRU shift; column 3 adds the productivity-acceleration variable; and column 4 adds both. In the top panel of the table, I allow all of the parameters to shift between the two periods, as in tables 2 and 3. The estimates in this panel suggest a reduction in the slope of the reduced-form Phillips curve of between 15 and 33 percent. The smallest reduction in the slope

[14] I adjust for the changing demographic composition of the labor force by using fixed 1993 labor force weights to weight together the unemployment rates for teenagers and two age groups each for men and women, 20-to-24 and 25-and-older.

[15] In particular, I include the difference between the four-quarter percent change in output per hour in the nonfarm business sector, and, a weighted average of past annualized quarterly real hourly compensation gains, where the weights decline geometrically at a rate of 4 percent per quarter, where real hourly compensation is measured as compensation per hour in the nonfarm business sector divided by the price index for nonfarm business sector output.

comes in the specifications in columns 2 and 4 that allow for a gradual reduction in the NAIRU over the 1985-2000 period.

The specification in equation A.1 is highly parameterized. There is thus a danger of overfitting, especially in short samples. To guard against this risk, the bottom panel of the table constrains all of the parameters, except the intercept and the coefficient on the unemployment rate, to be the same across the two periods. This procedure yields much sharper reductions in the estimated slope parameter: Even controlling for both the shift in the NAIRU and the productivity-acceleration term as in column 4, the coefficient on the unemployment rate drops by more than half. Moreover, the drop is statistically significant at the 10 percent level, and the *t*-ratio on the slope drops to 1.5 in the post-1983 period.[16]

[16] Rudebusch (2002) demonstrates that changes in the parameters of the Phillips curve induced by changes in monetary policy may be very difficult to detect econometrically, even when they are economically important.

Table A.1
Evidence of Shifts in the Slope of the Inflation-Unemployment Trade-off: Broader Models

	(1)	(2) w/ NAIRU shift	(3) w/ productivity effect	(4) w/ both
Approach A: Allow all parameters to shift				
Slope, 61-83	-.340 (.057)	-.340 (.057)	-.339 (.057)	-.339 (.057)
Slope, 84-02	-.227 (.100)	-.290 (.112)	-.239 (.100)	-.289 (.112)
Percent change	-33	-15	-29	-15
Approach B: Allow only constant and slope to shift				
Slope, 61-83 Slope, 84-02	-.339 (.052) -.106 (.086)	-339 (.052) -.148 (.100)	-.337 (.052) -.115 (.087)	-.338 (.052) -.153 (.100)
P-value for change in slope	.018	.082	.025	.094
Percent change	-69	-56	-66	-55

Note: Numbers in parentheses are standard errors.

Figure 1

Change over the Year in 4-quarter Core PCE Inflation vs. Unemployment

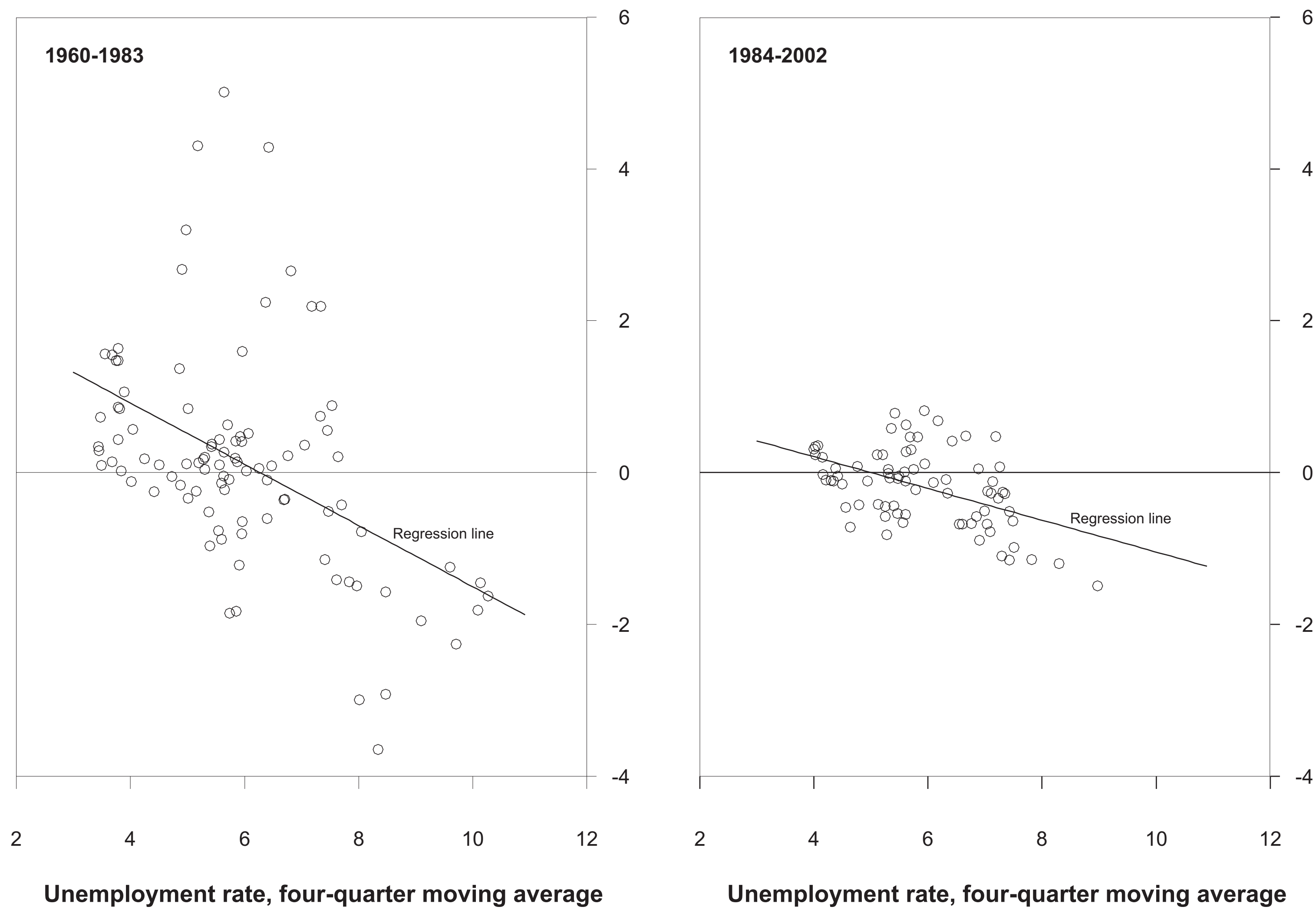
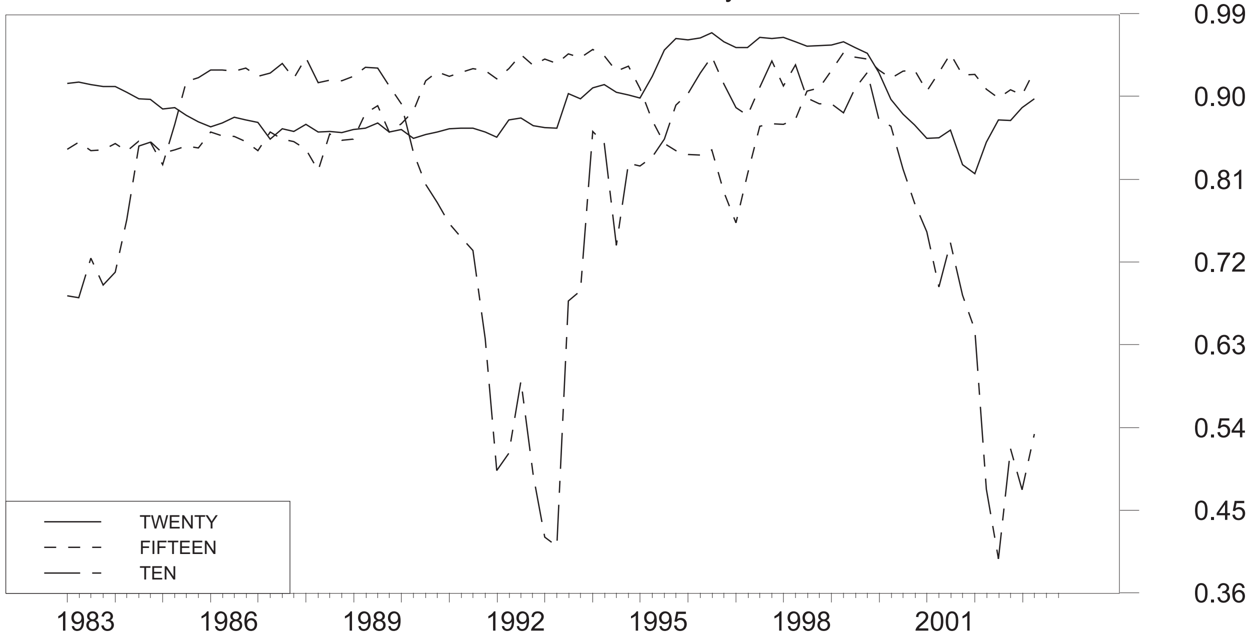


Figure 2

Has Inflation Stabilized?

Rolling regression results: Sum of four own-lag coefficients

Series labels indicate number of years in window.



Core PCE Inflation

Four-quarter percent change

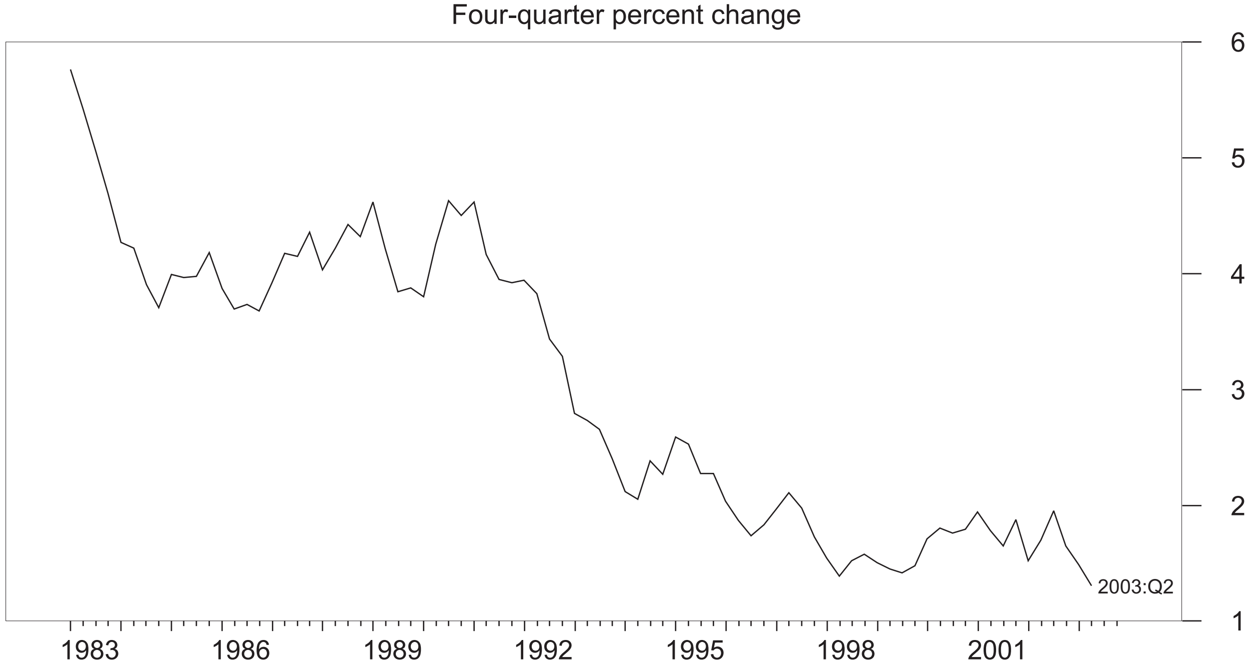


Figure 3

Implications of a More-Aggressive Monetary Policy for the Effects of an IS Shock

Three Equation Model

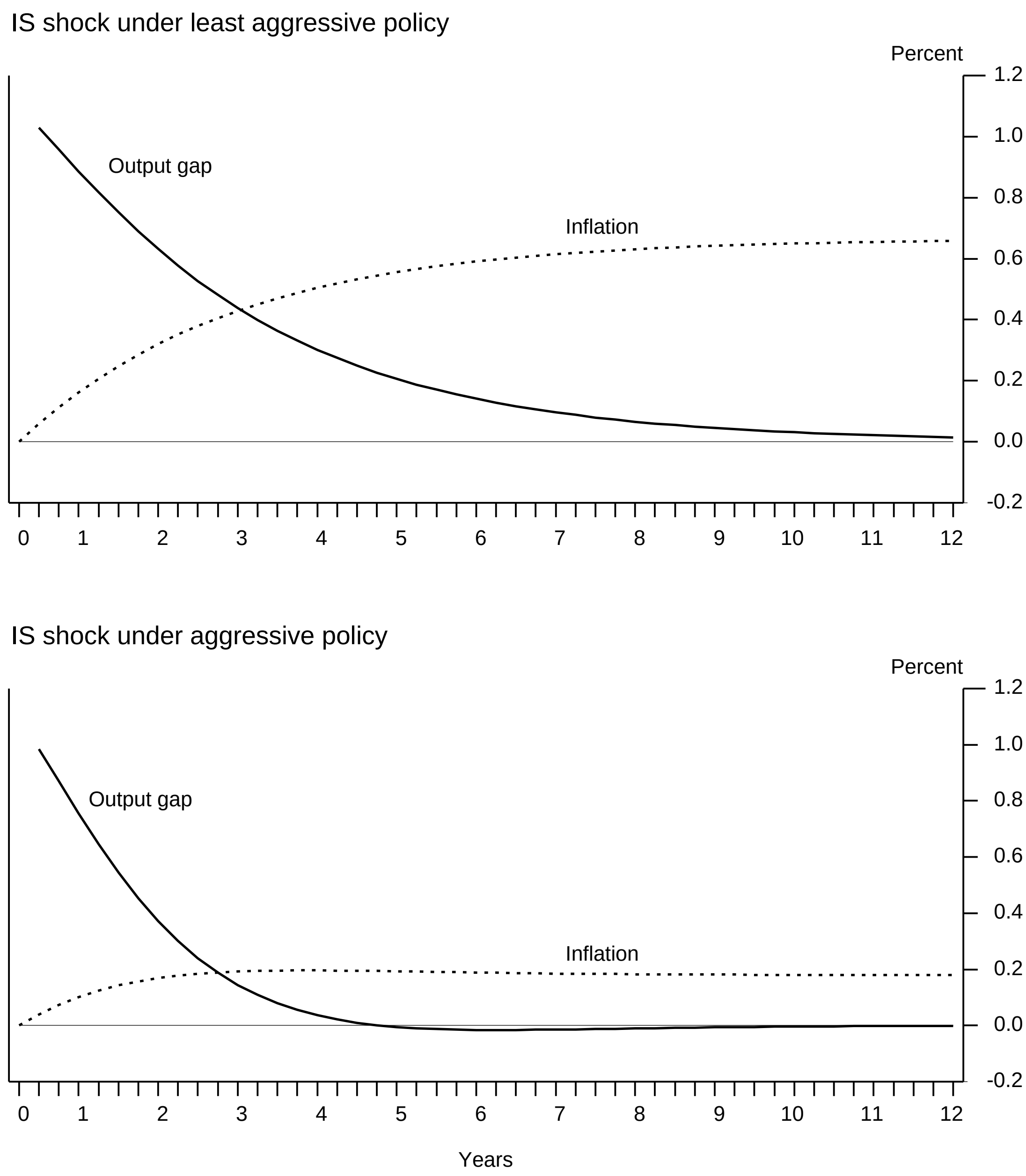
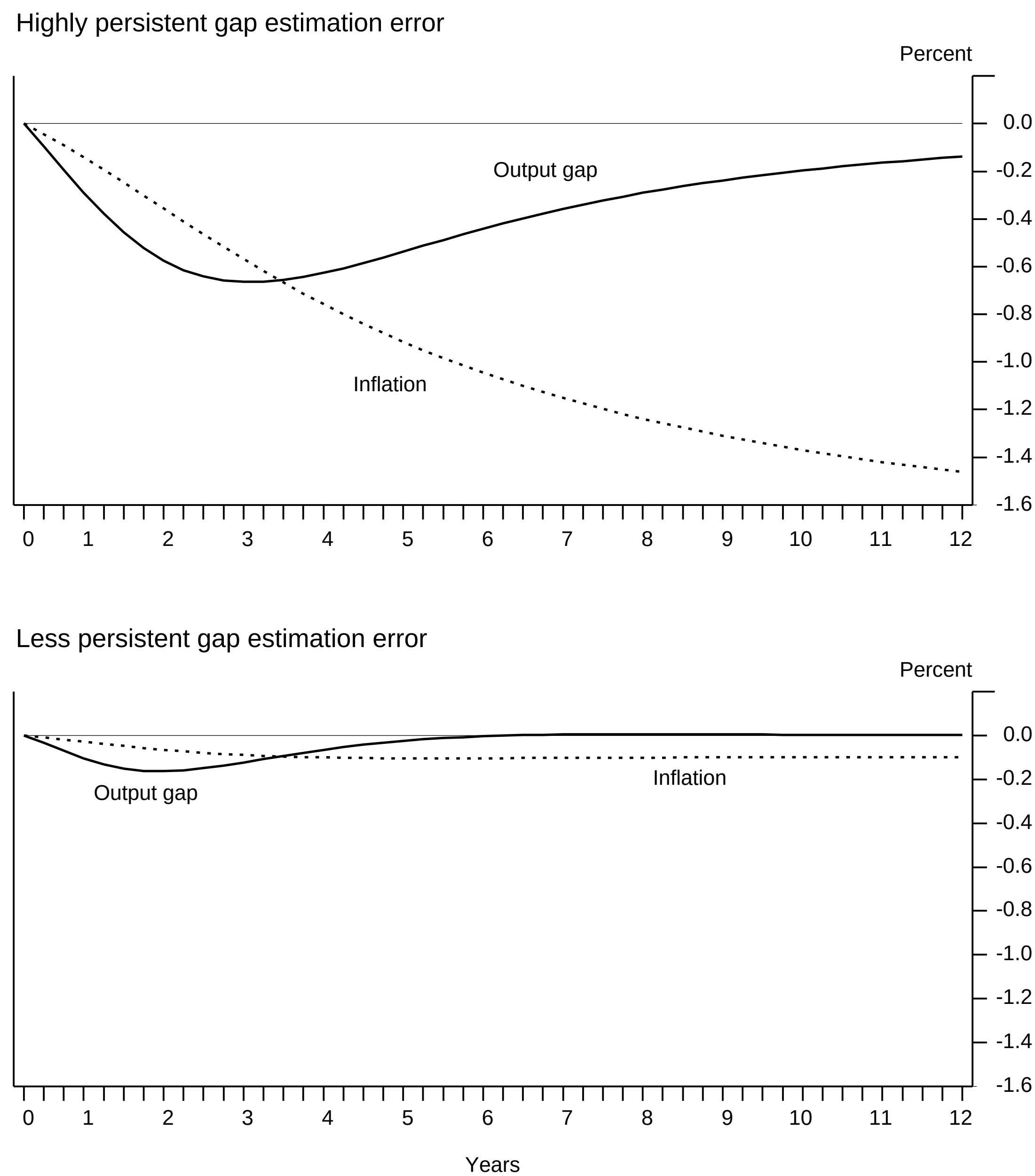


Figure 4

Effects of an Output Gap Estimation Error
Three Equation Model



References

Ahmed, Shaghil, Andrew Levin, and Beth Anne Wilson (2002) "Recent U.S. Macroeconomic Stability: Good Policies, Good Practices, or Good Luck?" Federal Reserve Board International Finance Discussion Paper no. 730 (June).

Amato, Jeffrey D., and Thomas Laubach (2001) "Implications of Habit Formation for Optimal Monetary Policy," Federal Reserve Board FEDS working paper no. 2001-58 (May).

Atkeson, Andrew, and Lee H. Ohanian (2001) "Are Phillips Curves Useful for Forecasting Inflation?" *Federal Reserve Bank of Minneapolis Quarterly Review* 25, 2-11.

Autor, David H., and Mark G. Duggan (2003) "The Rise in Disability Rolls and the Decline in Unemployment," *Quarterly Journal of Economics* 118.

Ball, Laurence (2000) "Near-Rationality and Inflation in Two Monetary Regimes," NBER Working Paper no. 7988 (October).

_______, and Robert Moffitt (2001) "Productivity Growth and the Phillips Curve," in Alan B. Krueger and Robert M. Solow, eds., *The Roaring 1990s: Can Full Employment Be Sustained?* Russell Sage Foundation: 61-90.

_______, N. Gregory Mankiw, and David Romer (1988) "New Keynesian Economics and the Output-Inflation Trade-Off," *Brookings Papers on Economic Activity* 1988:1, 1-82.

Blanchard, Olivier, and John Simon (2001) "The Long and Large Decline in U.S. Output Volatility," *Brookings Papers on Economic Activity* 2001:1, 135-64.

Blinder, Alan S. and Janet L. Yellen (2001) "The Fabulous Decade: Macroeconomic Lessons from the 1990s," in Alan B. Krueger and Robert M. Solow, eds., *The Roaring 1990s: Can Full Employment Be Sustained?* Russell Sage Foundation: 91-156.

Brayton, Flint, Eileen Mauskopf, David Reifschneider, Peter Tinsley, and John C. Williams (1997) "The Role of Expectations in the FRB/US Macroeconomic Model," *Federal Reserve Bulletin* 83, 227-24.

_______, John M. Roberts, and John C. Williams (1999) "What's Happened to the Phillips Curve?" Federal Reserve Board FEDS working paper no. 1999-49 (September).

Boivin, Jean, and Marc Giannoni (2003) "Has Monetary Policy Become More Effective?" NBER Working Paper no. 9459 (January).

Christiano, Lawrence J., Martin Eichenbaum, and Charles L. Evans (*forthcoming*) "Nominal Rigidities and the Dynamic Effects of a Shock to Monetary Policy," *Journal of Political Economy*.

Clarida, Richard, Jordi Gali, and Mark Gertler (2000) "Monetary Policy Rules and Macroeconomic Stability: Evidence and Some Theory," *Quarterly Journal of Economics* 115, 147-80.

Congressional Budget Office (2002) "The Effect of Changes in Labor Markets on the Natural Rate of Unemployment," available at www.cbo.gov (April).

English, William B., William R. Nelson, and Brian P. Sack (2003) "Interpreting the Significance of Lagged Interest Rates in Estimated Monetary Policy Rules," *Berkeley Electronic Press Journal of Macroeconomics* 3.

Estrella, Arturo and Jeffrey C. Fuhrer (2003) "Monetary Policy Shifts and the Stability of Monetary Policy Models," *Review of Economics and Statistics* 85, 94-104.

Friedman, Milton (1968) "Inflation: Causes and Consequences," in *Dollars and Deficits* (Englewood Cliffs, N.J.: Prentice-Hall), 21-60.

Fuhrer, Jeff and George Moore (1995) "Inflation Persistence," *Quarterly Journal of Economics* 110, 127-59.

Gordon, Robert J. (1980) "A Consistent Characterization of a Near-Century of Price Behavior," *American Economic Review* 70, 243-49.

Greenspan, Alan (1996) Testimony before the U.S. Senate Committee on Banking, Housing, and Urban Affairs, July 18 (http://www.federalreserve.gov/boarddocs/hh/1996/july/testimony.htm).

Katz, Lawrence F., and Alan B. Krueger (1999) "The High-Pressure U.S. Labor Market of the 1990s," *Brookings Papers on Economic Activity* 1999:1, 1-87.

Levin, Andrew T., and Jeremy M. Piger (2003) "Is Inflation Persistence Intrinsic in Industrial Economies?" Federal Reserve Bank of St. Louis working paper no. 2002-23.

_______, Volker Wieland, and John C. Williams (1999) "Robustness of Simple Monetary Rules under Model Uncertainty," in John B. Taylor, ed., *Monetary Policy Rules*, University of Chicago Press.

Lucas, Robert E. (1975) "Econometric Policy Evaluation: A Critique," *Carnegie-Rochester Conference Series* 1, 19-46.

Mankiw, N. Gregory, and Ricardo Reis (2002) "Sticky Information versus Sticky Prices: A Proposal to Replace the New Keynesian Phillips Curve," *Quarterly Journal of Economics* 117, 1295-1328.

McConnell, Margaret M., and Gabriel Perez-Quiros (2000) "Output Fluctuations in the United States: What Has Changed Since the Early 1980s?" *American Economic Review* 90, 1464-76.

Orphanides, Athanasios (2001) "Monetary Policy Rules Based on Real-Time Data," *American Economic Review* 91, 964-85.

_______, Richard D. Porter, David Reifschneider, Robert Tetlow, and Frederico Finan (2000) "Errors in the Measurement of the Output Gap and the Design of Monetary Policy," *Journal of Economics and Business* 52, 117-41.

Reifschneider, David, Robert Tetlow, and John C. Williams (1999) "Aggregate Disturbances, Monetary Policy, and the Macroeconomy: The FRB/US Perspective," *Federal Reserve Bulletin* 85, 1-19.

Roberts, John M. (1995) "New Keynesian Economics and the Phillips Curve" *Journal of Money, Credit, and Banking* 27, 975-84.

_______ (1998) "Inflation Expectations and the Transmission of Monetary Policy" Federal Reserve Board *FEDS* working paper no. 1998-43 (October).

_______ (*forthcoming*) "How Well Does the New Keynesian Sticky-Price Model Fit the Data?" *Berkeley Electronic Press Contributions in Macroeconomics.*

Rotemberg, Julio J. and Michael J. Woodford (1997) "An Optimization-Based Econometric Framework for the Evaluation of Monetary Policy," in Ben S. Bernanke and Julio J. Rotemberg, eds., *NBER Macroeconomics Annual 1997*, MIT Press, 297-345.

Rudebusch, Glenn D. (2002) "Assessing the Lucas Critique in Monetary Policy Models," working paper, Federal Reserve Bank of San Francisco (February).

Staiger, Douglas, James H. Stock, and Mark W. Watson (2001) "Prices, Wages, and the U.S. NAIRU in the 1990s," in Alan B. Krueger and Robert M. Solow, eds., *The Roaring 1990s: Can Full Employment Be Sustained?* Russell Sage Foundation, 3-60.

Stock, James H., and Mark W. Watson (2002) "Has the Business Cycle Changed and Why?" working paper, Harvard University (August).

Taylor, John B. (1999) "A Historical Analysis of Monetary Policy Rules," in John B. Taylor, ed., *Monetary Policy Rules*, University of Chicago Press, 319-41.