The Rise and Fall of U.S. Inflation Persistence*

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We estimate the path of inflation persistence in the United States over the last fifty years using an ARMA model of inflation with time-varying autoregressive parameter, motivated by the familiar New Keynesian framework. The estimated path of inflation persistence is consistent with a general reading of Federal Reserve history; inflation persistence is estimated to have declined substantially during Volcker and Greenspan's tenures from the high persistence of the 1970s. Interpreted in light of the theoretical framework, the results suggest that the Federal Reserve has placed increasing weight on inflation stability in recent decades.

JEL Codes: E52, E58.

1. Introduction

The policy preferences of central banks can be difficult to observe. Until recently, the Federal Reserve communicated neither a quantitative goal for the rate of inflation nor the speed at which it aims to close inflation gaps. Among central banks with explicit inflation targets, ambiguity often remains about the preference for inflation stability

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versus output stability.[1] This paper presents an approach to estimating the historical inflation objective of the Federal Reserve in conjunction with time-varying inflation persistence, which we interpret as an indicator of the relative preference for output stability. The idea that inflation persistence reflects the strength of the central bank's willingness to stabilize inflation relative to stabilizing output is at the core of monetary policy optimization theory. The relative preference for output stability, while difficult to observe, is a key determinant of the time for which inflation disequilibria persist and thus of the dynamics of inflation. The evolution of inflation persistence can thus offer some insight into how stabilization preferences have evolved.[2]

The theoretical framework consists of a stylized macroeconomy in which the central bank aims to minimize a quadratic loss function over inflation and the output gap. The solution to the central bank's optimization problem generates an autoregressive (AR) process for inflation. The speed of adjustment of this process—that is, inflation persistence—is determined by the central bank's relative preference for output stability as well as by the structural parameters of the macroeconomy. As the preference for output stability rises, so too does the persistence of inflation. The technique we apply is to specify a state-space model for the dynamics of inflation and employ the Kalman filter to estimate a time-varying AR parameter.

Our empirical findings are encouraging, returning reasonable estimates of inflation persistence and the Federal Reserve's inflation goal. The estimated path of inflation persistence is consistent with a general reading of Federal Reserve policy history. During the 1970s, inflation persistence was high, suggesting that the preference for inflation stability was weak relative to the goal of stabilizing output. A sharp decline in persistence in the early 1980s coincided with Volcker's chairmanship and suggests that the Federal Reserve became substantially more concerned with inflation stabilization around the time of the Volcker disinflation. Inflation and inflation persistence remained low during Greenspan's tenure, suggesting

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[1] Only a few self-declared inflation targeters even officially acknowledge a trade-off between inflation and output. Many prefer to emphasize inflation goals and downplay flexibility, according to Kuttner (2004).

[2] The idea that the dynamics of inflation are fundamentally related to the monetary regime is shared by Benati (2006, 2008).

continued strong preferences for inflation stability. Other factors in the economic environment may also have been at play, helping to drive inflation persistence lower from the 1980s and onwards. In particular, changes in the role of inflation expectations or the elasticity of inflation with respect to resource slack may have fostered speedier adjustment of inflation to its steady state.

Research into monetary policy preferences has largely followed two strands. The first has estimated reaction functions using policy interest rates to assess whether the inflation-stabilizing Taylor principle has been met. This approach, examples of which include Taylor (1993), Clarida, Galí, and Gertler (1998, 2000), Gerlach and Schnabel (2000), and Orphanides (2001), typically assumes parameter stability within a given sample and backs out the inflation objective by estimating an intercept and subtracting a real interest rate. The second strand has sought to estimate policy goals from inflation data. Kozicki and Tinsley (2005), Ireland (2007), and Leigh (2008) argue that the recent history of U.S. inflation can be reconciled with time variation in the Federal Reserve's implicit inflation target. The preference for output stability is assumed constant, so all three papers impute large swings to the target to match movements in the level of inflation since the 1960s. Other researchers, including Dennis (2006) and Primiceri (2006), estimate the inflation goal and the preference for output stability for pre- and post-1979 sub-samples.

Methodologically, rather than adopt the viewpoint of Kozicki and Tinsley (2005), Ireland (2007), and Leigh (2008) that historical inflation is best explained by a time-varying inflation objective, we interpret the data through the lens of time variation in the willingness to stabilize inflation. The competing viewpoints have different implications for the dynamics of inflation. Shifts in the inflation objective only impart shifts to the level of inflation. Shifts in the willingness to stabilize inflation change the dynamics of inflation. Specifically, a stronger willingness to stabilize inflation stabilizes the level and reduces the volatility and persistence of inflation.

Overall, our empirical analysis suggests that the undulations of inflation over the last fifty years are consistent with a model with time variation in the preference to achieve inflation stability. At times, that preference appears to have been sufficiently weak so as to undermine achieving the inflation goal. Naturally, the inflation objective may have changed over time and we allow for such variation in our framework.

The paper is organized as follows. Section 2 outlines the theoretical framework and the link between inflation persistence and the policy preferences of the central bank. Section 3 presents the estimation method, the data, and the results of our benchmark model for U.S. inflation. In section 4, sensitivity analysis is conducted. Section 5 considers the implications of our persistence estimates for policymakers' preferences and discusses alternative explanations for our findings. Section 6 concludes.

2. A Model of Time-Varying Inflation Persistence

We take as our starting point a popular, hybrid, New Keynesian model of the economy commonly used in monetary policy analysis. The model consists of a forward- and backward-looking Phillips curve (1) and an aggregate demand equation (2):

$$\pi_t - \pi^* = \phi(\pi_{t-1} - \pi^*) + (1-\phi)\beta E_t(\pi_{t+1} - \pi^*) + \alpha y_t + \varepsilon_t \quad (1)$$

$$y_t = \theta y_{t-1} + (1-\theta)E_t y_{t+1} - \varphi(i_t - r^* - E_t\pi_{t+1}) + \eta_t, \quad (2)$$

where π_t is inflation at time t, $E_{t-1}\pi_t$ is its expected value from $t-1$, π^* is the inflation objective of the central bank, y_t is the output gap, and i_t is the nominal policy rate. The shocks ε_t and η_t are unforecastable i.i.d. shocks.[3] The parameters ϕ and θ regulate the degree of backward-lookingness in the two equations, with the empirical literature tending to values close to one.

The central bank is assumed to minimize an intertemporal loss function of the following form,

$$\frac{1}{2}E_t\left(\sum_{\tau=t}^{\infty}\delta^{\tau-t}L(\pi_\tau, y_\tau)\right), \quad (3)$$

with quadratic period loss function $L(\pi_t, y_t) = (\pi_t - \pi^*)^2 + \lambda y_t^2$. The central bank's policy preferences are summarized by two parameters—an inflation objective, π^*, and the relative preference for output stability, λ. Strict inflation targeting coincides with $\lambda = 0$,

[3]These disturbances are sometimes modeled as AR(1) processes, mainly so that purely forward-looking models can match the persistence of the data. Since the hybrid setting we employ allows for intrinsic persistence, we see little need for this additional flexibility and prefer to keep the model as simple as possible.

flexible inflation targeting with $\lambda > 0$. Minimizing the loss function by treating $E_t y_{t+1}$ as the control variable, the optimizing first-order condition of the above problem for a central bank acting with discretion is

$$y_y = \frac{\lambda}{\alpha(1-\beta\rho)}(\pi_t - \pi^*), \tag{4}$$

which yields inflation dynamics

$$\pi_t - \pi^* = \rho(\pi_{t-1} - \pi^*), \tag{5}$$

where ρ, inflation persistence, is a function of λ, δ, β, α, and ϕ and $0 \leq \rho < 1$.[4]

When the central bank implements optimal discretionary policy according to equation (3), inflation persistence is rising in λ for given values of δ, β, α, and ϕ. This is the sense in which the dynamics of inflation are linked to the preferences of the monetary regime. (Note that ρ does not depend on parameters in the aggregate demand curve.) An analytical solution for ρ is not available, except for the special cases of ϕ equal to zero or one. The latter corresponds to the purely backward-looking, accelerationist Phillips curve addressed by Svensson (1997, 1999).[5] For values of ϕ between zero and one, numerical solutions for the AR parameter can be computed, which we do in section 5 when mapping our estimated values of ρ into implied policy preferences.

Now consider a situation in which λ is time varying; that is, the period loss function exhibits changing preferences for output stability, λ_t,

$$L(\pi_t, y_t) = (\pi_t - \pi^*)^2 + \lambda_t y_t^2. \tag{6}$$

[4]Introducing control lags into the economy described by equations (1) and (2) alters the timing of the value function and optimality condition but does not affect the solution for the dynamics of inflation, which remains an AR(1) process. (For details on the setup of the optimization problem and its solution for both cases, the reader is referred to Clarida, Galí, and Gertler 1999.) Thus, control lags would not materially change the empirical specification we employ. Similarly, whether the model is linearized around a zero or non-zero steady-state rate of inflation does not affect our empirical specification. For a technical discussion of this issue, see Ascari (2004).

[5]Specifically, Svensson shows that in this case, $\rho = c(\lambda) = \lambda/(\lambda + \delta\alpha^2 k(\lambda))$, where $k(\lambda) = \frac{1}{2}\left[1 - \frac{\lambda(1-\delta)}{\delta\alpha^2} + \sqrt{\left(1 + \frac{\lambda(1-\delta)}{\delta\alpha^2}\right)^2 + \frac{4\lambda}{\alpha^2}}\right] \geq 1$.

Time variation in the preference for output stability can be motivated in a number of ways. First, an incoming chairman or committee member may hold views about the desired degree of output stability that differ from incumbents' opinions. Second, social or political pressure about the desirable degree of output volatility may be brought to bear at times, particularly when output losses are needed to offset inflationary shocks. Third, the central bank's perception of the relationships in the economy may change over time, prompting changes in λ_t. For example, as evidence accumulates that low and stable inflation is conducive to better economic outcomes, a central bank may develop a taste for stabilizing inflation more rapidly. This argument is related to the ideas of Primiceri (2006) and Sargent, Williams, and Zha (2006) that central bank learning has induced changes in policy strategy and thus inflation outcomes. However, our aim here is not to model potential interactions between central bank learning and the choice of λ_t. For our empirical exercise, λ_t is assumed to evolve independently of other parameters and variables in the economy.

We assume that the central bank optimizes as if the current value of λ_t will be constant going forward.[6] In this environment, the optimization problem boils down to a sequence of one-period discretionary optimizations, each of which yield a first-order condition akin to (4) but modified by a time subscript,

$$y_t = \frac{\lambda_t}{\alpha(1 - \beta\rho_t)}(\pi_t - \pi^*). \tag{7}$$

Inflation dynamics are now governed by a time-varying AR parameter, ρ_t,

$$\pi_t - \pi^* = \rho_t(\pi_{t-1} - \pi^*), \tag{8}$$

where ρ_t is a function of the parameters δ, β, α, and ϕ and the time-varying preference parameter λ_t.

[6]This is subtly different from a central bank that is aware that its preferences may change in the future but does not know to what value. In such a case, the central bank takes account of the changing persistence of future inflation outcomes, which raises the cost of an additional unit of future inflation in the value function. Specifically, the additional cost arises in the form of variance and covariance terms in the Lagrange multiplier of the intertemporal loss function. These terms do not appear when the central bank believes the current value of λ_t to be permanent.

The simplest theoretical framework presumes that the central bank has an inflation objective, π^*. This is a natural description of an explicit inflation-targeting central bank but also applies to an implicit inflation targeter whose objective is reasonably well understood by the public.[7] In practice, however, the objective may be time varying. Such time variation can be motivated in several ways; different preferences across Federal Reserve chairmen are one plausible candidate explanation (also discussed in Clarida, Galí, and Gertler 2000 and Erceg and Levin 2003).[8] In this paper, the empirical analysis is based on a period which spans five different chairmen. By interacting dummy variables for each chairman's tenure as follows,

$$\pi_t = (\pi^* + \varphi_1 D_M + \varphi_2 D_B + \varphi_3 D_{Mi} + \varphi_4 D_V)(1 - \rho_t) + \rho_t \pi_{t-1}, \quad (9)$$

we permit discrete shifts in the inflation objective. Greenspan's tenure is treated as the reference period, and the dummy variables take on the value one as follows (and zero otherwise): Martin (D_M) from 1955:Q1 to 1969:Q4, Burns (D_B) from 1970:Q1 to 1977:Q4, Miller (D_{Mi}) from 1978:Q1 to 1979:Q2, and Volcker (D_V) from 1979:Q3 to 1987:Q2. This specification will be our benchmark model, and we now turn to estimation.

3. Estimation and Results

3.1 The Estimation Framework

Our empirical strategy is to estimate the path of inflation persistence by estimating the AR process, treating inflation as an observable variable and the AR parameter as an unobserved state variable.

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[7]Several researchers take the view that the Federal Reserve fell into this category until recently. Giannoni and Woodford (2005) argue that the Federal Reserve's policy is well approximated by the solution to the above optimization problem. Mankiw (2002) and Goodfriend (2005) express similar views.

[8]Other explanations include accommodation of supply shocks through the inflation objective (Kozicki and Tinsley 2005), opportunistic disinflation (Kuttner 2004), and adaptation of the objective to lagged inflation (Gürkaynak, Sack, and Swanson 2005). In section 4, we address the first of these as the effect of oil price shocks is investigated.

The state-space setup differs markedly from the typical approach of estimating AR models with constant parameters over split or rolling samples. It is also an attractive alternative to the policy reaction-function literature in light of the critique by Rudebusch (2002a) and Söderlind, Söderström, and Vredin (2005) that potential model misspecification leads to unreliable coefficient estimates from estimated reaction functions. Our univariate framework is more robust to a range of economic specifications because the policy first-order condition which leads to equation (8) is essentially the same regardless of which state variables are in the macroeconomic model (Svensson 1997).

In its most general form, the model is characterized by an ARMA(1,q) process for inflation where the AR parameter is time varying. Specifically, it evolves as a random walk. To exemplify, the model with a constant target in equation (8) has the following state-space representation:

$$\xi_t = \mathbf{F}(\mathbf{x}_t)\xi_{t-1} + \mathbf{v}_t \tag{10}$$

$$\pi_t = \mathbf{A}(\mathbf{x}_t) + [\mathbf{H}(\mathbf{x}_t)]'\xi_t + \mathbf{w}_t, \tag{11}$$

where

$$\xi_t = \begin{bmatrix}1, & \rho_t, & u_t, & u_{t-1}, & \dots & u_{t-q}\end{bmatrix}', \tag{12}$$

$$\mathbf{x}_t = \begin{bmatrix}1, & \pi_{t-1}, & 1, & 1, & \dots & 1\end{bmatrix}', \tag{13}$$

$$\mathbf{F}(\mathbf{x}_t) = \begin{bmatrix}1 & 0 & 0 & 0 & 0 & \dots & 0\\ 0 & 1 & 0 & 0 & 0 & \dots & 0\\ 0 & 0 & 0 & 0 & 0 & \dots & 0\\ 0 & 0 & 1 & 0 & 0 & & 0\\ 0 & 0 & 0 & 1 & 0 & & 0\\ \vdots & \vdots & \vdots & & & \ddots & \vdots\\ 0 & 0 & 0 & \dots & 0 & 1 & 0\end{bmatrix}, \tag{14}$$

$\mathbf{A}(\mathbf{x}_t) = 0$, $[\mathbf{H}(\mathbf{x}_t)]' = \begin{bmatrix}\pi^*, & -\pi^* + \pi_{t-1}, & 1, & \theta_1, & \dots & \theta_q\end{bmatrix}$, $\mathbf{v}_t = \begin{bmatrix}0, & \omega_t, & u_t, & 0, & \dots, & 0\end{bmatrix}$, and $\mathbf{w}_t = 0$. The disturbance vector $\mathbf{v}_t$ is assumed to be independently normally distributed.

Our benchmark model takes its starting point in equation (9) in which the inflation target is allowed to vary by chairman of the Federal Reserve. The state space portrayed by equations (10) to (14) is appropriately augmented and the results are presented in section 3.2. We also estimate several variants of this model:

(i) assuming a constant inflation objective (section 4),
(ii) with oil price shocks (section 4),
(iii) a bivariate specification which allows interactions with the output gap (section 5.2), and
(iv) estimation with twelve-month-ended monthly inflation (see the appendix).

In all cases, the parameters of the model are estimated with maximum likelihood. The values of the AR parameter, $\{\hat{\rho}_t\}$, are estimated freely and not restricted to the $[0, 1)$ interval.[9] Enforcing the $[0, 1)$ restriction ex ante would require placing bounds on the state variable, such as the reflective barriers of Cogley and Sargent (2002, 2005) and Cogley, Morozov, and Sargent (2005). We prefer the unrestricted approach, as it enables us to assess whether the model returns plausible unrestricted estimates.

3.2 Benchmark Quarterly Model

We begin by estimating the following model with quarterly observations of annualized CPI inflation,

$$\pi_t = (\pi^* + \varphi_1 D_M + \varphi_2 D_B + \varphi_3 D_{Mi} + \varphi_4 D_V)(1 - \rho_t^q) + \rho_t^q \pi_{t-1} + u_t + \theta_1 u_{t-1}, \quad (15)$$

where π_t denotes the annualized rate of inflation from one quarter to the next, π^* is the central bank's inflation objective, and u_t is a disturbance term. The chairman dummy variables are those defined near the end of section 2. Equation (15) differs slightly from equation

[9]Diffuse priors (Koopman, Shephard, and Doornik 1999) are used for the initialization of the AR parameter.

(9) in that it models the disturbance as an MA(1) process, a common specification when modeling inflation. As Ang, Bekaert, and Wei (2007) and others before them have pointed out, if inflation is viewed as the sum of expected inflation and noise, as it typically is in the macroeconomics literature, and expected inflation follows an AR(1) process, then the reduced-form model of inflation is ARMA(1,1).[10] The AR parameter, ρ_t^q, is assumed to evolve as a random walk,

$$\rho_t^q = \rho_{t-1}^q + \omega_t, \tag{16}$$

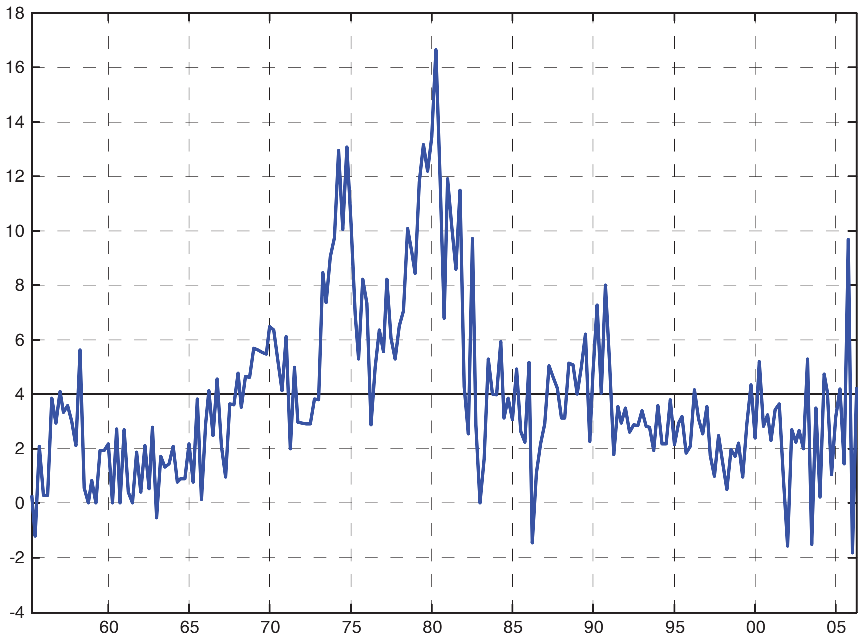
where $\omega_t \sim iid(0, \sigma_\omega^2)$.[11]

The model is estimated using data from 1955:Q1 to 2006:Q1, coinciding with the end of Chairman Greenspan's tenure. The data are shown in figure 1, and key parameter estimates and statistics are given in table 1. The first row of the table indicates that the inflation objective of the Federal Reserve under Greenspan's tenure was around 2.8 percent. During Martin's chairmanship (pre-1970), the objective was slightly lower but not significantly so. More notably, the target appeared to be substantially higher during the Burns and Miller periods (1970 to 1979). Under Burns, the target is estimated to have risen to just above 5 percent, and during Miller's short tenure to almost 13 percent, although the latter is estimated imprecisely. Volcker's tenure, beginning August 1979, is marked by a substantial decrease in the target to a level similar to that during Greenspan's tenure. Overall, the results lend some support to the idea that the Federal Reserve's inflation target has changed over time.

[10] Indeed, according to the information criteria, an ARMA(1,1) specification is preferred over ARMA(1,0) and ARMA(1,2) specifications for our data. Results are not reported but are available upon request.

[11] The random-walk assumption implies that there is no steady-state rate of persistence. While one alternative is to model the AR parameter as mean reverting, $\rho_t = \mu + \psi\rho_{t-1} + \chi_t$, upon estimation this yields a very similar path of inflation persistence (results available upon request). We prefer the more parsimonious random-walk specification, which brings less risk of overparameterization and is in line with specifications used elsewhere in the literature, such as in Cogley and Sargent's (2002, 2005) papers. This specification is also consistent with our assumption that the central bank believes the current value of λ_t will prevail in the future.

Figure 1. Annualized Quarterly CPI Inflation



Source: Bureau of Labor Statistics.

Despite allowing for shifts in the inflation objective, there is strong evidence for time-varying inflation persistence.[12] The estimated path of inflation persistence is plotted in figure 2, which reveals a pattern of time variation broadly consistent with a reading of Federal Reserve policy history. Inflation persistence was high and more volatile during the 1970s than in surrounding years. Inflation persistence declined in the years of the Volcker disinflation, consistent with the notion that the Federal Reserve became more focused upon inflation stabilization under Volcker's tenure. Persistence was comparatively low during the Greenspan years, 1987 to 2006, and tailed off toward the end of the sample. While substantial

[12]It can also be noted that the specification with time-varying persistence is preferred over one with chairman-specific targets but constant AR parameter. Results are not reported but are available upon request.

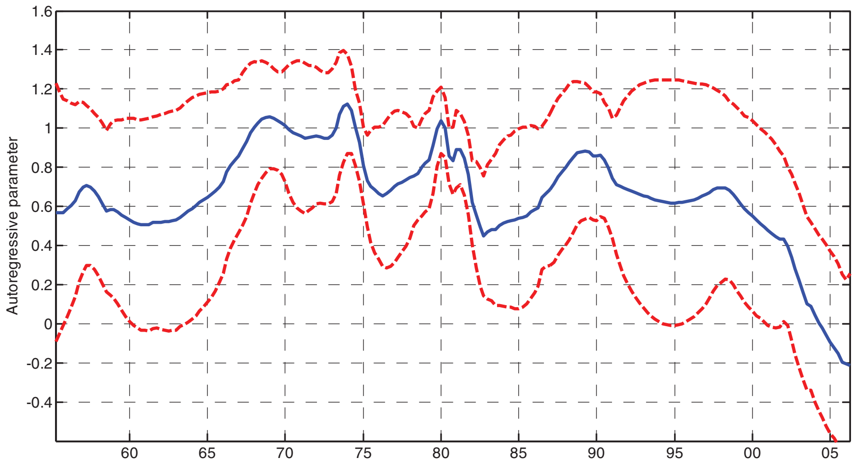
Table 1. Estimation Results for Annualized Quarterly CPI Inflation

	Benchmark	Constant Inflation Objective	Oil Dummies
π^*	2.823**	2.799**	2.916**
	(0.220)	(0.173)	(0.204)
D_M	−1.158**	—	—
	(0.344)		
D_B	2.406**	—	—
	(0.797)		
D_{Mi}	10.020**	—	—
	(3.335)		
D_V	0.626	—	—
	(0.447)		
D_{73}	—	—	1.964
			(3.254)
D_{79}	—	—	8.395**
			(1.032)
D_{90}	—	—	0.838
			(3.144)
$\hat{\sigma}_u^2$	3.059	2.979	3.119
$\hat{\sigma}_\omega^2$	1.274×10^{-2}	8.403×10^{-3}	4.374×10^{-3}
AIC	4.369	4.340	4.291
SIC	4.499	4.405	4.405
ARCH-LM	3.72	3.56	4.83

Notes: * (**) denotes significance at the 5 (1) percent level. Standard errors are in parentheses. $\hat{\sigma}_\omega^2$ is the error variance for the persistence parameter state equation and $\hat{\sigma}_u^2$ is the error variance of the observation equation for π_t. AIC is the Akaike information criterion. SIC is the Schwarz information criterion. The ARCH-LM test was conducted with four lags. All models are estimated from first-quarter 1955 to first-quarter 2006 with MA(1) disturbances.

uncertainty attends the point estimates, the low estimates near the end of the sample are broadly in line with results reported by Benati (2008) for the United Kingdom during the latter part of its inflation-targeting regime. The implied decline of the half-life of inflation shocks from the 1970s to the 1990s dwarfs the changes late in the sample.

Figure 2. Estimate of $\{\rho_t^q\}$ from Benchmark Model Using Annualized Quarterly CPI Inflation



Notes: The model is estimated using data from 1955:Q1 to 2006:Q1 with MA(1) disturbances. Dashed bands are ±2 root mean squared errors reflecting filter uncertainty. (The fact that only filter uncertainty is taken into account means that the bands in this figure are likely to underestimate the true uncertainty somewhat; see, for example, Rodríguez and Ruiz 2012 for a discussion.)

Briefly during the late 1960s and 1970s, when inflation was at its most volatile, the point estimate of persistence exceeds one, which should be the reasonable upper limit for stabilizing monetary policy. Several factors may contribute to this result. Poorly anchored inflation expectations may have ratcheted up during inflationary episodes, as in the adaptive learning mechanism described in Orphanides and Williams (2005). Alternatively, the central bank's inflation objective may have risen during those years, distorting our estimate of persistence. For example, the Federal Reserve may have accommodated inflationary cost-push shocks, such as oil price shocks, by raising the inflation objective to alleviate the output trade-off. We address this possibility in section 4.

The model's diagnostics are encouraging, and residuals from the model are well behaved. The null hypothesis that no ARCH(4) effects are present cannot be rejected by an ARCH-LM test at conventional significance levels, a finding that speaks in favor of modeling inflation with time-varying persistence. Heteroskedastic errors are not needed to capture time variation of inflation volatility.[13]

4. Sensitivity Analysis

In this section, we investigate the sensitivity of our results with respect to the specification of the Federal Reserve's inflation target. Specifically, we consider two alternative empirical models—one with a constant inflation target and one where the target is assumed to have been adjusted in response to oil price shocks.

We estimate the following model which restricts the inflation objective to a constant over the whole sample:

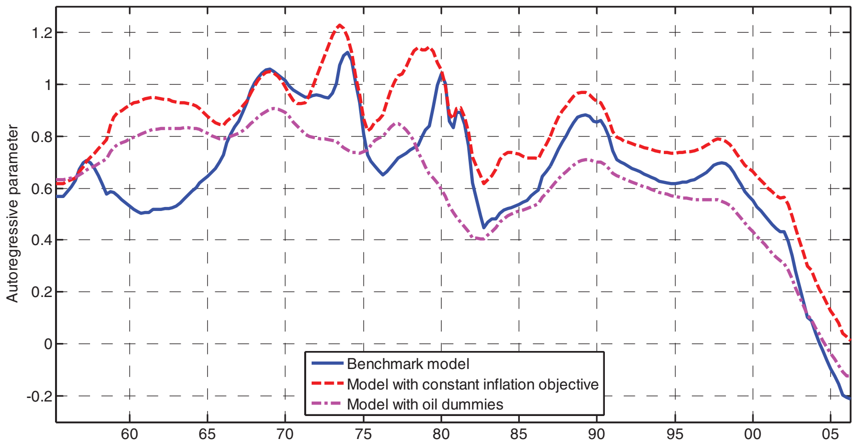
$$\pi_t - \pi^* = \rho_t^q(\pi_{t-1} - \pi^*) + u_t + \theta_1 u_{t-1}. \tag{17}$$

As with the benchmark model, the disturbances are modeled as MA(1). Key parameter estimates are given in table 1, with the inflation target estimated as 2.8 percent during the sample. The estimated path of inflation persistence is presented in figure 3 and largely tells the same story as that of the benchmark model. The most notable difference is during the late 1950s and early 1960s when the model with a constant inflation target estimates that persistence rose to fairly high levels whereas the benchmark model reports that persistence fell during this period. Interestingly, both information criteria prefer the more parsimonious model with a constant target over that with chairman-specific targets.

The estimation results also show an important point in an intuitive way: Time-varying persistence enables the model to capture periods of high inflation volatility and simultaneously allows inflation to be far from its stationary mean. In contrast, shifts in the inflation objective can only capture changes in the level of inflation and not its volatility.

[13]The absence of ARCH effects in the residuals suggests that it is unlikely that the estimated time variation in inflation persistence is due to heteroskedastic error terms. To do so would require a highly specific one-to-one mapping between persistence and heteroskedasticity. Moreover, our estimated path for the AR parameter is qualitatively similar to that found in both Cogley and Sargent (2002) and Cogley and Sargent (2005), where the former paper does not allow for time-varying volatility but the latter does. As pointed out by Cogley and Sargent (2005), allowing for time-varying volatility does little to alter estimates of inflation persistence.

Figure 3. Estimate of $\{\rho_t^q\}$ from Benchmark and Alternative Models Using Annualized Quarterly CPI Inflation



Note: All models are estimated using data from 1955:Q1 to 2006:Q1 with MA(1) disturbances.

During a few brief episodes, the estimates of $\hat{\rho}_t$ from the benchmark and constant-objective models exceed one. These episodes coincide reasonably well with the oil price shocks centered around 1973 and 1979. Such cost-push shocks may have brought about temporary changes in the steady-state rate of inflation, perhaps by being partially accommodated to ease the monetary policy trade-off, and could bias our persistence estimates upwards. We hence modify our benchmark specification to include dummy variables for these episodes which interact in the same manner as the chairman dummy variables:

$$\pi_t = (\pi^* + \varphi_1 D_{73} + \varphi_2 D_{79} + \varphi_3 D_{90})\,(1 - \rho_t^q) \\ + \rho_t^q \pi_{t-1} + u_t + \theta_1 u_{t-1}. \quad (18)$$

The dummy variables take on the value one as follows (and zero otherwise): D_{73} from 1973:Q2 to 1974:Q3, D_{79} from 1978:Q2 to 1981:Q3, and D_{90} from 1990:Q3 to 1991:Q2.

Coefficient estimates are shown in the third column of table 1; the benchmark inflation objective over the whole sample is estimated to be 2.9 percent, while each of the oil-shock dummies attracts a positive coefficient, implying a temporarily higher goal level of inflation during those periods. However, only the 1979 dummy is significant. The estimates of the AR parameter, $\{\hat{\rho}_t^q\}$, are plotted alongside those from the other models in figure 3. The path of inflation persistence resembles that of the other specifications, but importantly, the point estimates no longer breech one. This specification with oil dummies is preferred by the Akaike information criterion over both the benchmark specification and that with a constant inflation objective; it is also preferred over the benchmark model according to the Schwarz information criterion. However, the odds ratios are close to one, suggesting that there are not marked differences in the models' ability to fit the data. Further sensitivity analysis conducted using monthly data indicates that our findings are robust to data frequency—see the appendix for details.

5. Time Variation in Other Structural Parameters

In this section we canvass several sources of change that may have contributed to lower inflation persistence since the early 1980s. Given its stylized nature, the sources of variation within the model are few; inflation persistence is a function of δ, β, α, and ϕ and the preference parameter λ. In this section we focus on policymakers' stabilization preferences and time variation in the parameters of the Phillips curve. Factors outside of the model abound, some of which we touch on at the end of the section.

5.1 Policymakers' Preference for Output Stability

Our framework was motivated by the observation that a central bank's willingness to stabilize inflation should have tangible effects on inflation persistence. What, then, do our estimates of inflation persistence imply about this willingness? We first gauge a rough range of values for λ by calibrating other parameters of the model. The exercise is illustrative and intended only to give an impression of how the Federal Reserve's policy preferences might have evolved were it the primary source of parameter change in the model.

Table 2 gives an overview of the parameter assumptions. We make the standard assumption that the central bank discounts slowly, $\delta = 0.99$, and—following Clarida, Galí, and Gertler (1999)—

Table 2. Parameter Assumptions for Mapping Persistence to Preferences

Parameter	Value
δ	0.99
β	0.99
α	0.1, 0.3
ϕ	0.3, 0.6, 0.9

set β to the same value. With respect to the output elasticity in the Phillips curve, α, estimates in the literature range from 0.3 (Rudebusch 2002b) to 0.15 (Dennis 2006) to 0.05 (Galí, Gertler, and López-Salido 2001). We consider calibrations for two values of α, namely 0.1 and 0.3. The hybrid New Keynesian Phillips curve in equation (1) encompasses a wide range of views about the degree of backward-lookingness, ϕ. Empirical estimates, such as those of Rudebusch and Svensson (1999), Rudebusch (2002b), and Rudd and Whelan (2005) tend to find most weight attached to lagged variables, but the issue remains disputed (see Henry and Pagan 2004 and Galí, Gertler, and López-Salido 2001 for diverse opinions). To accommodate these viewpoints, we map inflation persistence to λ conditional on four different values of ϕ, ranging from strongly forward looking $\phi = 0.3$ to completely backward looking, $\phi = 1$.

For each value of α and ϕ, ρ is mapped into a value of λ. Figures 4 and 5 represent the two different assumptions for α. Within each chart the contour lines represent different values of ϕ.

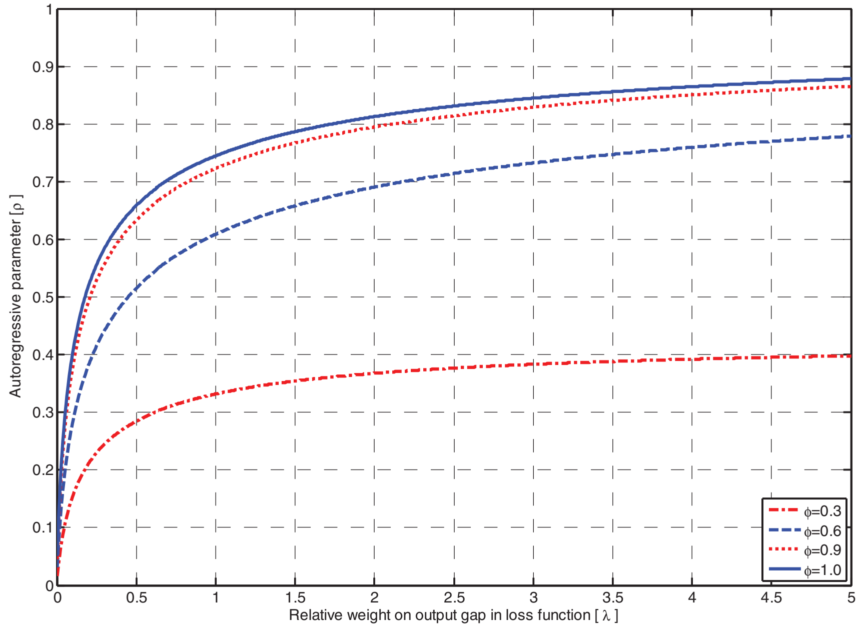
The figures convey two intuitive properties:

(i) Inflation persistence increases monotonically with the weight that the central bank places on output stability.

(ii) Higher lines correspond to more inflation persistence for a given value of λ, confirming the intuition that inflation is more slowly mean reverting when the Phillips curve is more backward looking.

Relating figures 4 and 5 to our empirical results summarized in figure 3, it can first be noted that the estimated AR parameter from the specification with a constant target is 1.0 on average during

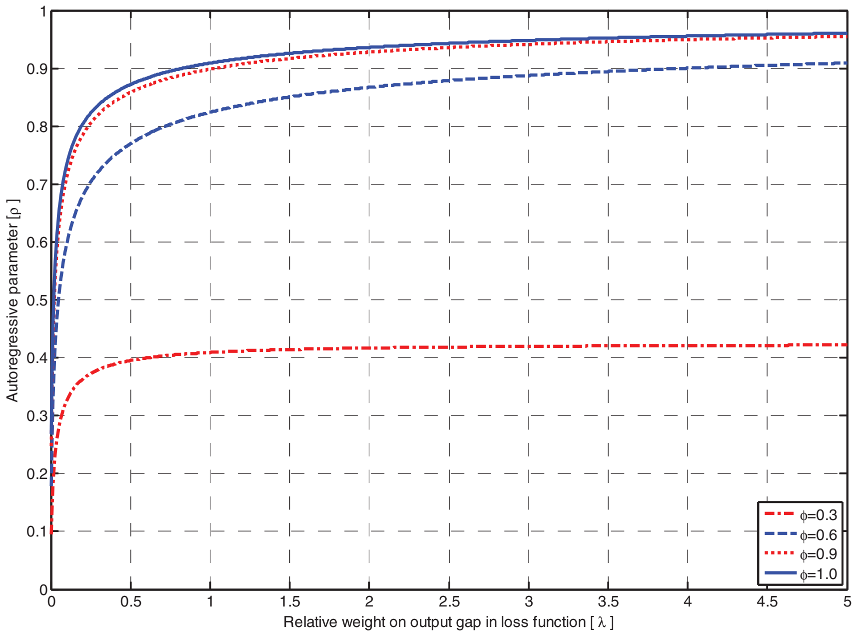
Figure 4. Calibrated Mapping between ρ and λ when $\alpha = 0.3$



Note: $\delta = \beta = 0.99$.

the 1970s, implying an infinite weight on stabilizing output. For the quarterly model with oil dummies, the estimated persistence is lower and ranges between roughly 0.6 and 0.9 during the 1970s. For the range of calibration assumptions, persistence of 0.6 to 0.9 is consistent with very wide ranges of λ. An AR parameter of 0.6 is consistent with a value of λ as low as 0.04 for an inelastic and completely backward-looking Philips curve ($\alpha = 0.1$ and $\phi = 1$) but also as high as infinity for a more forward-looking Phillips curve. Quarterly persistence of 0.9 implies values for λ between 0.83 and infinity. Interestingly, a very forward-looking Phillips curve is incompatible with inflation persistence as high as in the 1970s. For example, for $\phi = 0.3$ inflation persistence can be no higher than about 0.4 regardless of the central bank's preferences over output stability. Thus our calibration exercise does not lend support to a strongly forward-looking Phillips curve, consistent with the econometric evidence presented in Lindé (2005) and Rudd and Whelan (2005).

Figure 5. Calibrated Mapping between ρ and λ when $\alpha = 0.1$



Note: $\delta = \beta = 0.99$.

The Volcker-Greenspan era represents a marked difference; from all specifications, the estimated AR parameter is substantially lower on average and falling over time. All three models estimated on quarterly data suggest that the AR parameter has been less than 0.3 since the middle of 2003, which implies that λ has to be a very small value indeed; for $\phi \geq 0.6$, λ is less than 0.1 and often close to zero. That λ has to be very close to zero in recent years to match U.S. inflation data is broadly in line with the findings of other researchers; see, for example, Favero and Rovelli (2003) and Söderlind, Söderström, and Vredin (2005).

Summing up this exercise, the inflation persistence of the 1970s implies a wide range of quite high values for λ. The lower values and narrower ranges for λ in more recent years are indicative of stronger preferences for inflation stability. As emphasized above, this exercise should only be seen as illustrative given the uncertainty around point estimates and the assumption that other parameters were static.

With that in mind, we consider some other sources of time variation in the model.

5.2 Did the Parameters of the Phillips Curve Change?

Could time variation in ϕ and α also help account for the decline in inflation persistence post-1979? The general consensus in the literature that the trade-off between inflation and output has been stable or even flattened works in the wrong direction to explain declining inflation persistence. But more forward-looking pricing behavior may have contributed modestly to the decline in inflation persistence. We address the two issues in turn.

As is evident by comparing the contour lines of figures 4 and 5, a decrease in the elasticity of inflation with respect to the output gap (lower α), all else constant, increases inflation persistence. Macroeconometric evidence generally points toward stability or a slight decrease of this elasticity over our sample. Using econometric techniques similar to those we employ, Staiger, Stock, and Watson (2001) find little time variation in the slope of the Phillips curve. Fernández-Villaverde and Rubio-Ramírez (2008) estimate the Calvo probability governing firms' price setting and find evidence of growing price-setting rigidity after the 1970s, similarly implying a lessening of the trade-off between inflation and output.

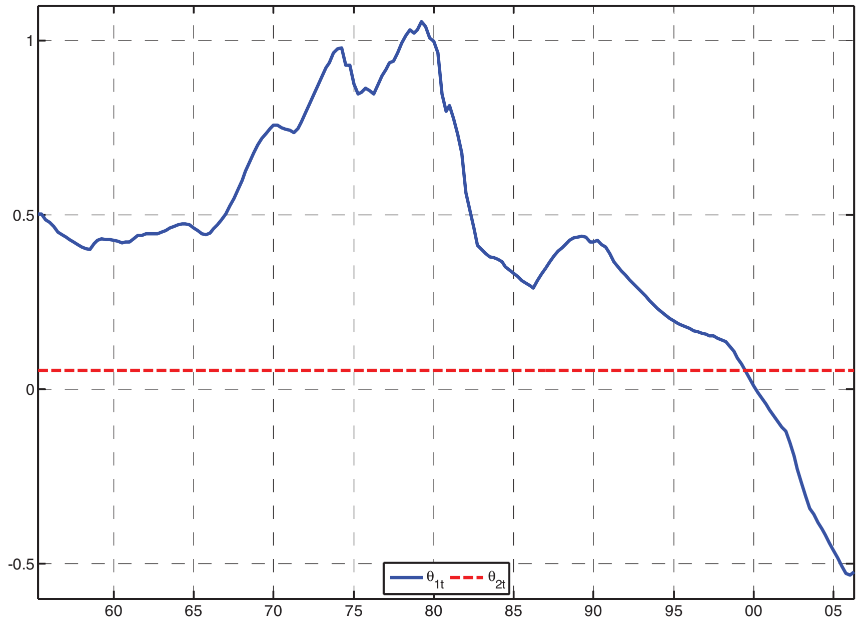
To assess the role of time variation in the relationship between inflation and the output gap within our own framework, we extend the model with a constant inflation objective in equation (8) to a bivariate model including the output gap. Consistent with the literature described above, the exercise yields weak evidence for a decline in the inflation-output trade-off yet does not detract from the primary finding of a decline in the AR properties of inflation itself.

We estimate two extensions of the quarterly model with a constant target which allow the output gap to enter the dynamic process for inflation with a time-varying coefficient. We employ the Congressional Budget Office's (CBO's) publicly available estimate of the output gap for estimation, although similar results obtain throughout using an output gap created as an HP filter of actual output.

We first estimate the following backward-looking Phillips curve:

$$\pi_t - \pi^* = \theta_{1t}(\pi_{t-1} - \pi^*) + \theta_{2t} y_t + e_t, \tag{19}$$

Figure 6. Estimates of $\{\theta_{1t}\}$ and $\{\theta_{2t}\}$ from Backward-Looking Phillips-Curve Model Using Annualized Quarterly CPI Inflation



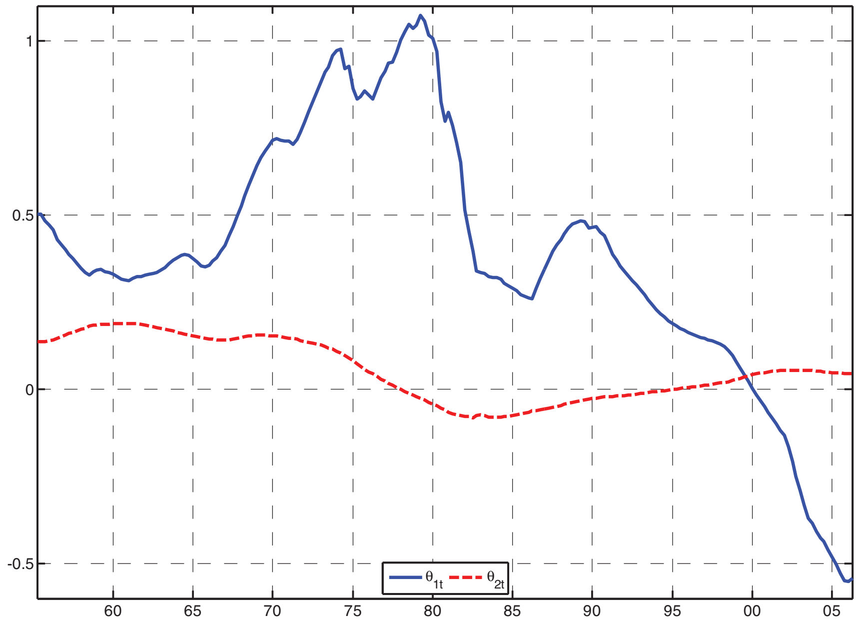
Notes: Estimates are from equation (19), using the CBO output gap. The model is estimated using data from first-quarter 1955 to first-quarter 2006.

where $\theta_{1t} = \theta_{1t-1} + \omega_{1t}$, $\theta_{2t} = \theta_{2t-1} + \omega_{2t}$, and $\omega_{it} \sim iid(0, \sigma^2_{\omega_i})$ for $i = 1, 2$. The time-varying coefficients are estimated by maximum likelihood as unobserved state variables with random-walk transition equations. The coefficient estimates are plotted in figure 6. Ample variation in the AR parameter on inflation remains, but estimation concludes that θ_{2t} is constant over time.

An alternative to the reduced-form Phillips curve is to envisage a bivariate vector autoregression between the inflation gap and the output gap with time-varying coefficients, the first equation of which is

$$\pi_t - \pi^* = \theta_{1t}(\pi_{t-1} - \pi^*) + \theta_{2t} y_{t-1} + e_t, \tag{20}$$

Figure 7. Estimates of $\{\theta_{1t}\}$ and $\{\theta_{2t}\}$ from Bivariate Vector Autoregression Model Using Annualized Quarterly CPI Inflation



Notes: Estimates are from equation (20), using the CBO output gap. The model is estimated using data from first-quarter 1955 to first-quarter 2006.

where once again $\theta_{1t} = \theta_{1t-1} + \omega_{1t}$ and $\theta_{2t} = \theta_{2t-1} + \omega_{2t}$. The estimated series $\{\hat{\theta}_{1t}\}$ and $\{\hat{\theta}_{2t}\}$ are plotted in figure 7. There is some evidence for time variation in the coefficient of the output gap on inflation—the coefficient declines modestly around the middle of the sample—but the variation is minor and does not line up well with the movements in inflation persistence. Results using an output gap created as a standard HP filter of actual output are very similar (results available upon request).[14]

Comparing models with (i) constant parameters, (ii) time variation only in the coefficient on lagged inflation, (iii) time variation in

[14]The inflation objective is estimated to be around 2.7 to 2.8 percent across all of these model variations.

only the coefficient on the (lagged) output gap, and (iv) time variation in both coefficients, model (ii) is preferred according to the information criteria. And as figures 6 and 7 show, even when the relationship between the inflation gap and output gap is permitted to evolve in our framework, variation in inflation's own AR dynamics remains substantial. This exercise makes us more confident that the evolution of inflation persistence cannot be attributed to the slope of the Phillips curve and that ample scope for competing explanations remains.

Finally, we turn to the degree of forward-looking behavior of the inflation relationship. In microfounded derivations of the hybrid New Keynesian Phillips curve, wage- and price-setting behavior regulate the degree of forward-lookingness of the aggregate relationship. Were such behavior to change, so too would the persistence of inflation. Using aggregate data for the U.S. macroeconomy, Benati (2008) finds marginally lower values of ϕ—that is, more forward-lookingness in the Phillips curve—for a sample after the Volcker stabilization than in a long sample spanning the last fifty years. Such a change works in the right direction to reduce inflation persistence, but the magnitude seems insufficient to be the sole explanation.

5.3 Factors Outside the Model

There are naturally factors outside the scope of our stylized model that could affect inflation persistence. As pointed out by Svensson (1999), model uncertainty—in particular, uncertainty about the natural rate—and interest rate smoothing could both give rise to more gradual adjustment of conditional inflation forecasts back to the target. It is difficult to assess how the degree of model uncertainty has changed over the course of our sample; if the degree of uncertainty about the natural rate has remained roughly constant, then inference about the direction of change in the Federal Reserve's preferences is unaffected. If model uncertainty has in fact declined, this may account for some of the decline in inflation persistence.

Regarding interest rate smoothing, we observe less inflation persistence during the last fifteen years of the sample, but many economists believe these years were a time when greater emphasis was placed on the smooth adjustment of interest rates. The observed decline in inflation persistence could either imply that (i) there has been minimal movement toward interest rate smoothing or that (ii) the decline in the relative preference for output stability has been even more pronounced, offsetting the effect of a shift toward interest rate smoothing on inflation persistence. Lastly, growing credibility of the central bank's nominal anchor may have facilitated faster mean reversion of the public's inflation expectations following shocks and contributed to the estimated decline in persistence.

6. Conclusions

Inflation persistence has varied substantially over the last fifty years, and the Federal Reserve's willingness to stabilize inflation has likely played a key role. A standard New Keynesian model motivates a clear linkage between the central bank's stabilization preferences and inflation persistence, and we use such a model to motivate estimating an ARMA(1,q) model of inflation with time-varying AR parameter. Our empirical results for inflation persistence and the implied inflation target are plausible and intuitive. Consistent with the general opinion that inflation stability was given more focus during and after Volcker's chairmanship, inflation persistence fell during the 1980s and continued to do so during Greenspan's term.

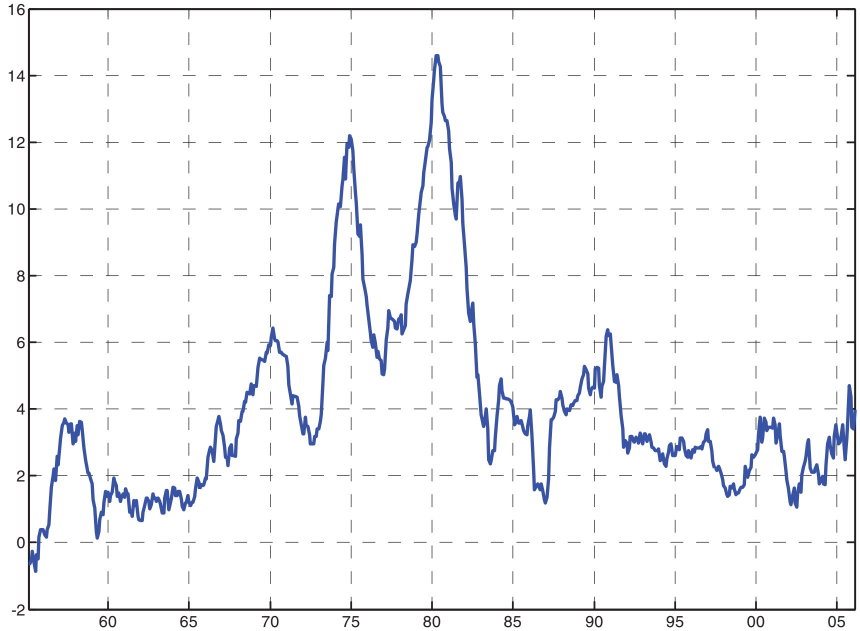
According to our benchmark model, the inflation target was likely higher during the 1970s than in other decades. There is also some empirical support for a model with a constant target level. Importantly though, both models deliver the result that inflation persistence has risen and fallen, strengthening the case that the central bank's willingness to stabilize inflation around its inflation objective has evolved over time. The evidence for high levels of inflation persistence suggests that high inflation of the past was due in part to an unwillingness to stabilize inflation. By the same logic, inflation goals were reached during the 1990s because of a greater willingness to stabilize inflation at the cost of output stability.

An overall low inflation target paired with time-varying inflation persistence is also consistent with the stylized facts of the falling *level* and *volatility* of inflation during the last two decades. Modeling the inflation process with shifts in its target or intercept, as in Levin and Piger (2002) and Kozicki and Tinsley (2005), explains changes in the level of inflation but not its variance. In contrast, the period of declining inflation persistence we identify coincides with the lower level and volatility of inflation toward the end of the sample. Whilst there is evidence in the literature that the variance of shocks to inflation has declined since the 1970s, we do not actually need heteroskedastic disturbances in this model in order to match the data. Our results differ from those who have found inflation persistence to be stable based on split samples and rolling regressions, such as Pivetta and Reis (2007). By retaining the whole sample in a unified estimation, we hope our approach is better able to detect gradual change in inflation persistence.

The results are consistent with the interpretation of Clarida, Galí, and Gertler (2000) and Boivin (2006) who, among others, argue that the typically larger coefficients on inflation in reaction functions estimated over more recent samples indicate a greater willingness to stabilize inflation at the cost of output. Our results also echo the findings of Primiceri (2006), that steady-state inflation rates and the target have been low and stable since the 1960s. We differ from Primiceri's interpretation, however, that prolonged periods of high inflation were due to central bank misunderstandings about the natural rate and parameters of the Phillips curve; in our model, prolonged inflation results from a high preference for output stability. Reconciling these two interpretations is a topic for future research.

From a broader perspective, our results are relevant to the literature on the empirical time-series properties of inflation. The approach we employ is sufficiently flexible to permit the properties of inflation to change between integrated and mean reverting over the sample, unlike the traditional dichotomy in the unit-root literature of classifying inflation as I(0) or I(1). This raises a fundamental difference between our approach and that of Cogley and Sargent (2002, 2005); while the pattern of inflation persistence we estimate resembles their results, they define persistence as the speed of mean reversion of the transitory component of inflation. As a result, inflation in Cogley and Sargent's framework possesses a unit root over their whole sample. Moreover, our approach takes its motivation from a model of the macroeconomy, allowing an intuitive interpretation of the relationship between monetary policy and inflation persistence which is not afforded by their framework.

Figure 8. Twelve-Month-Ended CPI Inflation



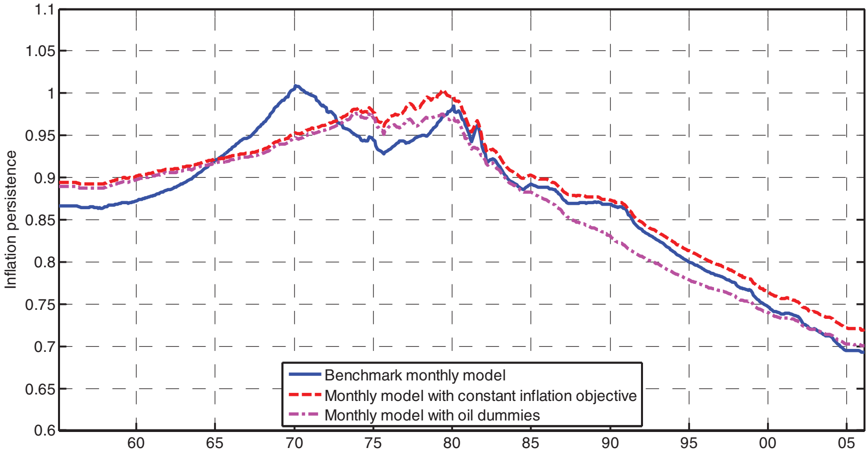
Source: Bureau of Labor Statistics.

Appendix

To assess whether our models are robust to data frequency, we estimate them using monthly CPI inflation, which offers higher-frequency data and thus more observations. Annualized monthly inflation rates yield a very noisy series of inflation, so we construct a twelve-month-ended rate spanning January 1955 to January 2006, shown in figure 8. The twelve-month-ended series is smoother but induces a higher-order MA structure that needs to be taken into account in the estimation. Accordingly, we estimate the following model which is similar to, but less parsimonious than, the quarterly benchmark model:

$$\pi_t = (\pi^* + \varphi_1 D_M + \varphi_2 D_B + \varphi_3 D_{Mi} + \varphi_4 D_V)(1 - \rho_t^m) + \rho_t^m \pi_{t-1} + u_t + \sum_{j=1}^{12} \theta_j u_{t-j}. \quad (21)$$

Figure 9. Estimate of $\{\rho_t^m\}$ from Benchmark and Alternative Models Using Twelve-Month-Ended CPI Inflation



Note: All models are estimated using data from January 1955 to January 2006 with MA(12) disturbances.

Recall that year-ended data observed k times per year introduces an MA$(k-1)$ structure. Thus twelve-month-ended data impart an MA(11) structure. However, as was the case for the quarterly data, an additional MA term seems to be preferred in the empirical specification.[15] Like its quarterly counterpart, the state variable ρ_t^m is assumed to evolve as a random walk,

$$\rho_t^m = \rho_{t-1}^m + \eta_t, \tag{22}$$

where $\eta_t \sim iid(0, \sigma_\eta^2)$.

The estimated series of the AR parameter $\{\hat{\rho}_t^m\}$ from the ARMA(1,12) specification is plotted in figure 9, alongside estimates of the monthly models with a constant target and oil dummies described in section 4. The profile of inflation persistence is smoother than that from the annualized quarterly data; peaks and troughs are

[15]Judging from information criteria, the MA(12) process for the errors is preferred over the MA(11) specification as well as over higher-order processes. Results are not reported but are available upon request.

Table 3. Estimation Results for Twelve-Month-Ended CPI Inflation

	Benchmark	Constant Inflation Objective	Oil Dummies
π^*	2.890**	2.826**	2.848**
	(0.371)	(0.356)	(0.324)
D_M	−0.916	—	—
	(0.610)		
D_B	4.242**	—	—
	(1.289)		
D_{Mi}	5.659**	—	—
	(1.343)		
D_V	0.149	—	—
	(0.913)		
D_{73}	—	—	0.162
			(1.656)
D_{79}	—	—	4.149**
			(1.494)
D_{90}	—	—	1.951
			(1.580)
$\hat{\sigma}_u^2$	0.048	0.049	0.049
$\hat{\sigma}_\omega^2$	6.983×10^{-5}	4.839×10^{-5}	4.597×10^{-5}
AIC	0.309	0.302	0.296
SIC	0.446	0.410	0.426
ARCH-LM	25.13*	25.04*	21.74*

Notes: * (**) denotes significance at the 5 (1) percent level. Standard errors are in parentheses. $\hat{\sigma}_\omega^2$ is the error variance for the persistence parameter state equation and $\hat{\sigma}_u^2$ is the error variance of the observation equation for π_t. AIC is the Akaike information criterion. SIC is the Schwarz information criterion. The ARCH-LM test was conducted with twelve lags. All models are estimated from January 1955 to January 2006 with MA(12) disturbances.

smoothed out and the number of occasions on which $\hat{\rho}_t^m$ exceeds one (in the benchmark model and the model with a constant inflation target) is reduced. As was the case with the quarterly data, allowing the inflation objective to rise during oil price shocks tempers the estimates of inflation persistence. The Schwarz information criterion slightly prefers the specification with a constant target over the benchmark and oil-dummy specifications, but the differences are minor.

Overall, the broad pattern of inflation persistence closely resembles that in figure 3; persistence begins at a moderate level in the 1950s and 1960s, rises to values around one during the 1970s, and then steadily declines during the Volcker and Greenspan tenures. (Note that the coefficients shown in figure 9 need to be compounded by three to be comparable to the quarterly estimates shown in figures 2 and 3.) The estimated inflation objective for Greenspan's tenure in the benchmark model is almost identical to that based on quarterly data; see table 3. Similarly, the unique target level in the model with a constant target is 2.8 percent regardless of frequency used for estimation.[16] Our findings appear robust to data frequency.

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[16] As was true for the quarterly data, the monthly model with time-varying persistence is preferred over an ARMA model with constant parameters according to information criteria. That is, time variation in inflation persistence is econometrically preferred over the static alternative. Results are not reported but are available upon request.

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