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Abstract

The existing literature on U.S. monetary policy provides no sense of a cnsensus regarding the existence of a monetary policy regime. This paper explores the evolution of U.S. monetary policy regimes via the development of a Markov-switching model predicated on narrative and statistical evidence of a monetary policy regime. We identified five regimes for the period spanning 1956:I - 2005:IV and they roughly corresponded to the Chairman term of the Federal Reserve, except for the Greenspan era. More importantly, we demonstrate that the conflicting results regarding the response to inflation for the pre-Volcker period in the existing literature is not attributable to the different data but due to different samples, and also provided an insight regarding the Great Inflation—namely, that the near non-response to inflation in the early 1960s appears to have constituted the initial seed of the Great Inflation. We also find via analysis of the Markov-switching model for the U.S. real interest rate, that the regime changes in the real interest rate follow the regime changes in monetary policy within two years and that the evolution of real interest rate regimes provides a good explanation for the conflicting results regarding the dynamics of real interest rate.

Key Words: Monetary policy rule; Markov switching; Great Inflation; Real interest rate; Evolution

JEL Classification: E5; C32

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I. Introduction

Modeling the Fed's monetary policy strategies in terms of responses to economic development has long been a subject of great interest to Macroeconomists. Since Taylor (1993) specified a Fed's reaction function, wherein the real federal funds rate reacts to deviations in contemporaneous inflation from an inflation target and deviations in real output from its long-run potential level, a great deal of research has examined various versions of backward-looking and forward-looking Taylor rule for the U.S. monetary policy. Examples include the studies of Clarida, Gali and Gertler (1998, 2000), Judd and Rudebusch (1998), Taylor (1999), Orphanides (2001, 2002, 2004), Primiceri (2005, 2006), Boivin (2006), Kim and Nelson (2006), and Sims and Zha (2006), among others. Despite the substantial volume of useful research, however, there is far less of a consensus regarding the nature, evolution, or even the existence of monetary policy regime than should be the case.

Clarida *et al.* (2000) find that there are significant differences in the manner in which monetary policy was conducted pre- and post-late 1979 and the pre-Volcker rule that the Fed typically raised nominal rates by less than any increase in expected inflation permits greater macroeconomic instability than does the Volcker-Greenspan rule. Orphanides (2001) argues that estimating monetary policy rules based on *ex post* revised data, which were not available to policymakers in real-time, can generate a very distorted picture of historical monetary policy, and Orphanides (2004) shows, using real-time information, that there have been broad similarities in the monetary policy reaction function for the period prior to and after Volcker's appointment as chairman in 1979 and a strong reaction to inflation forecasts during both periods, in contrast to Clarida *et al.* (2000). Thus, the conflicting results of these studies of the pre-Volcker monetary policy are associated with the nature of *ex post* revised data vs. real-time data.

On the other hand, Sims and Zha (2006) employ the structural VAR models that explicitly allow for changes in the policy regime, and find that the best-fitting model is one that evidences only regime change in the variance of structural disturbances, but no change at all in the coefficients of the policy rule. Their results support the empirical practice of combining the samples prior to and after the Volcker period to estimate the model, so long as heteroscedasticity is properly taken into consideration. From the estimation of a time-varying structural VAR, Primiceri (2005) finds evidence of time variation in both systematic and non-systematic monetary policy; however, there appears to be little evidence for a causal link between changes in interest rate systematic responses and the high inflation and unemployment episodes, thereby indicating that within the range of policy parameters, different regimes were not sufficiently large to explain a substantial proportion of the fluctuations in inflation and unemployment.

Boivin (2006), however, finds that the response to inflation was relatively strong until around 1974, but then fell dramatically in the second half of the 1970s, thereby suggesting that a single regime does not appear to properly characterize the pre-Volcker conduct of monetary policy. He argues that the reason that Clarida *et al.* (2000) and Orphanides (2002, 2004) came up with the above conflicting results is the failure to properly account for the rich evolution of monetary policy, thereby reflecting more than a real-time data issue. Kim and Nelson (2006) consider a time-varying model for a forward-looking monetary policy rule based on a Heckman-type two-step procedure to deal with endogeneity in regressors and econometrically to take into consideration changing degrees of uncertainty associated with the Fed's forecasts of future inflation and GDP gap when estimating the model and find that the history of the Fed's conduct of monetary policy since the early 1970s can be divided into three subperiods: the 1970s, the 1980s, and the 1990s. Thus, whether or not systematic monetary policy actually changed remains a matter of some controversy.

While there is clearly some truth in all of these studies, they also seem to have some difficulties in addressing U.S. monetary policy. In this paper, we propose a reconciling story regarding the evolution of U.S. monetary policy. To this end, we consider the narrative evidence of Romer and Romer (2002a, 2004) who demonstrate that monetary policy has evolved in accordance with the Fed Chairman term, along with different beliefs regarding the manner in which the economy works and what monetary policy can accomplish, as well as Kim and Nelson's (2006) evidence that monetary policy rules have been different roughly according to the 1960s, the 1970s, the 1980s, and the 1990s. We also take into consideration the statistical evidence of Huizinga and Mishkin (1986), Bonser-Neal (1990), and Rapach and Wohar (2005), who demonstrate that the regime changes in real interest rates are associated with monetary policy regimes.

We employ a two-step MLE procedure to estimate a Markov-switching model with endogenous explanatory variables along with the regime-changing nature of coefficients and innovations for a Taylor-type forward-looking monetary policy rule. Kim (2004, 2009), Spagnolo, Psaradakis and Sola (2005), and Psaradakis, Sola and Spagnolo (2006) propose two steps estimation procedure to account for endogeneity in a Markov-switching framework. Kim (2004) considers a restricted case in which regimes in the first-step and second-step equations are perfectly correlated while Kim (2009) allows the possibility of imperfect correlation of regimes. Spagnolo *et al.* (2005) and Psaradakis *et al.* (2006) use some form of instrumental variable estimation, where the reduced-form equations relating the endogenous regressors to the instruments have state-dependent parameters as well as state-dependent variances. In this paper, one of the key features is that the instrumental variable equations are governed by two independent Markov-switching processes.

We find that our regime-switching model provides a good explanation of the evolution of U.S. monetary policy, and builds important insights on the existing literature. Specifically, our estimation identifies five regimes for U.S. monetary policy for the following periods: 1956:I to 2005:IV—1956:I - 1968:I; 1968:II - 1979:IV; 1980:I - 1985:I; 1985:II - 1997:I and 1997:II - 2005:IV. They correspond roughly to the narrative approach of the Chairman's term, with the exception of the Greenspan era. Moreover, we find that the changes in the Fed's responses to inflation and output gap, as well as changes in the variance of structural disturbance of policy play an important role in identifying these regimes.

Our results also show that the conflicting results reported by Clarida *et al.* (2000) and Orphanides (2004) concerning the Fed's response to inflation in the pre-Volcker period is not attributable to the nature of the real-time data, but rather is due to the use of different samples. More interestingly, we uncover key insights into the early stages of the evolution of the Great Inflation, namely that the near non-response of the Fed to inflation in the early 1960s due to new beliefs of policymakers (Romer and Romer 2004, Romer 2005) or institutional arrangements for policy coordination (Meltzer 2005) appears to have constitute the initial seed of the Great Inflation; thus, our results are consistent with the narrative evidence of Romer and Romer (2004) and Meltzer (2005).[1]

Analysis of the Markov-switching model for the U.S. real interest rate reveals that changes in the real interest rate are linked with regime changes in monetary policy rules and also that estimated break dates in the monetary policy rule and real interest rate nearly coincide within two years. Moreover, we find that when we consider the multiple structural breaks proposed by our model, the real interest rate is $I(0)$ over all regimes and that changes not only in the mean but also in the persistence of the real interest rate play an important role in describing the dynamics of the U.S. real interest rate. This result provides a good explanation for the different views of real interest rate dynamics in the existing literature.

The plan for this paper is as follows. Section II presents evidence of distinct monetary policy regimes in the U.S. from a narrative approach and from a statistical test and Section III models an evolution of monetary policy regimes and discusses the econometric methodology by which it can be estimated. The estimation results are reported and a reconciling story for the evolution of U.S. monetary policy is provided in Section IV. The evolution of the real interest rate linked with monetary policy regimes is discussed in Section V. A summary and concluding remarks are provided in Section VI.

[1] The Great Inflation refers to the long and pronounced run-up of inflation that occurred in the 1960s and 1970s. For details regarding the Great Inflation, see the special issue of the Federal Reserve Bank of the St. Louis *Review* Vol. 87 (2, Part 2) in March/April 2005 and Primiceri (2006).

II. Evidence of Distinct Monetary Policy Regimes in the U.S.

A. Evidence from a narrative approach

Recently, Romer and Romer (2002a, 2004) have studied the notion that policymakers' beliefs influence the carrying out of monetary policy. Romer and Romer (2002a) demonstrate that the fundamental source of changes in policy has been changes in policymakers' beliefs regarding the manner in which the economy functions, and find that while the basic objectives of policymakers have remained the same, the model or framework they employed to understand the economy has dramatically changed. They conclude that our economic understanding has evolved, and this evolution has manifested in distinct policy choices. Romer and Romer (2004) demonstrate that the key determinants of monetary policy success have been policymakers' views regarding the workings of the economy and what monetary policy can accomplish. This link between ideas and outcomes clearly implies that different beliefs can result in different policy actions and thereby to different outcomes. From this viewpoint, distinct monetary policy regimes might be considered as the result of the evolution of economic understanding and adopted policy.

Romer and Romer (2002a, 2004) provide specific descriptions for policymakers' beliefs and their policy actions under Federal Reserve chairmen since the post-World War II era. Such key beliefs and policy actions along with averages in the inflation rate (INF.), output gap (OG.), and *ex-post* real interest rate (INT.) are summarized in Table 1. The data we employ herein are quarterly data encompassing the period between 1956:I - 2005:IV. The interest rate is the average federal funds rate in the first-month of each quarter; inflation is the percentage change of the GDP deflator; the potential GDP is the series constructed by the Congressional Budget Office (CBO) and the output gap is the percentage deviation between the actual GDP and its potential level. The *ex post* real interest rate is calculated by subtracting the GDP deflator inflation from the three-month T-bill rate of the final month of a quarter, as reported by Campbell (1999).

As pointed out in Romer and Romer (2002a, 2004), Table 1 implies that policy actions are clearly linked to the beliefs of policymakers. Under Chairman William McChesney Martin Jr. in the 1960s, policymakers adopted the view that very low unemployment was an attainable long-run goal and that there was a permanent trade-off between inflation and unemployment; this view eventually led them to believe that expansionary policy could reduce unemployment permanently at relatively low cost. However, the average output gap in the Martin era of the 1960s (shown in Table 1) was highest among other four chairmen, thereby indicating that inflationary pressure was a relevant factor and that contractionary monetary policy may be required to lessen such inflationary pressures. In the 1970s, policymakers acknowledged a natural rate framework with a highly optimistic estimate of the natural rate of unemployment and a highly pessimistic estimate of the sensitivity of inflation to economic slack. As a consequence, policymakers continued to believe that further expansion would improve economic performance, even though a contractionary monetary policy prevailed for a short period. Under Paul Volcker in the 1980s, the Federal Reserve had a conviction that inflation has high costs and few benefits, together with realistic views regarding the sustainable level of unemployment and the determinants of inflation. As a consequence, extremely contractionary monetary policy was prevailing rule. In the late 1980s and early 1990s, policymakers continued to support the view that low inflation is critically important, along with holding output close to potential. The Federal Reserve has followed a moderate real interest rate policy but has never pursued extreme expansion or contraction. Romer and Romer (2004) point out that since the mid-1990s, the surprising behavior of inflation appears to have led Greenspan and some other members of the FOMC to change their views regarding the determinants of inflation; Greenspan argued that the economy has become much more competitive and that as a result, forces that would otherwise cause firms to raise prices could instead prompt them to find offsetting cost reductions.

Figures- 1.a, 1.b, and 1.c plot the behavior of the inflation rate, the behavior of the output gap, and the *ex post* real interest rate beginning in the first quarter in 1956, respectively.

The vertical lines show the quarters in which each chairman's tenure began.[2] As indicated in Figures 1.a and 1.b, the values and movements of the inflation rate and the output gap vary significantly over different chairman eras. In particular, the *ex post* real interest rates, as shown in Figure 1.c, appear to differ fairly substantially in different chairman eras.

Taken together, our analysis of economic beliefs and policy outcomes over the five chairmen's tenures on the basis of Romer and Romer's (2002a, 2004) narrative approach demonstrates that economic understanding has evolved, and this evolution has resulted in a variety of U.S. monetary policy regimes.

B. Evidence from a statistical test

Huizinga and Mishkin (1986) show evidence suggesting that monetary policy regime change has been a crucial source of shifts in the behavior of the real interest rate in the late 1970s and the early 1980s. Bonser-Neal (1990) shows, in the study of four countries, that real rates have not proven constant across monetary regimes while the characteristics of the real rate process shifts vary across countries. According to the test for multiple structural breaks in the mean of the U.S. real interest rate, Perron (1990), Garcia and Perron (1996), and Bai and Perron (2003) find significant evidence of multiple structural breaks over the 1961:I - 1986:III period, and Hamilton (1994) demonstrates that three different regimes of the U.S. real interest rate over 1960:I - 1992:IV are characterized by average real interest rates. Caporale and Grier (2000) and Rapach and Wohar (2005) have also identified structural breaks in the U.S. real interest rate, while they considered different sources of structural breaks. Caporale and Grier (2000) focus on changes in the party control of the presidency or either branch of Congress. On the other hand, Rapach and Wohar (2005) consider regime changes in the process governing the inflation rate as a potential source, and find that the dates for the inflation and real interest rate regime changes are quite close to one another. They suggest that changes in

[2] There was a Chairman, William Miller, from March 1978 to August 1979. However, as the Miller era was quite short relative to other chairman eras, it would be difficult for one to identify unique policy actions and their effects within such a brief period.

the monetary regime can bring about persistent changes in the real interest rates, given the assumption that breaks in inflation rates are determined by exogenous shifts in the nature of the monetary regime.

Given the argument that the real interest rate is the most fundamental indicator of the stance of monetary policy, such test results for multiple structural breaks in the U.S. real interest rate also imply that U.S. monetary policy regimes have indeed evolved.

In summary, the results of our analysis of both the narrative record for five chairmen eras and the test results regarding multiple structural breaks in the real interest rates significantly indicate a distinct evolution in U.S. monetary policy regime. In the following sections, we consider a Markov-switching model in order to address the changes that have occurred in U.S. monetary policy.

III. Modelling an Evolution of Monetary Policy Regimes

A. Model specification

The forward-looking version of monetary policy rule with regime changes considered in this paper takes the following form:

$$r_t^* = \beta_{0,S_t}^* + \beta_{1,S_t}(E_t(\pi_{t,k}) - \pi_t^*) + \beta_{2,S_t} E_t(g_{t,k}), \tag{1}$$

$$\begin{aligned} S_t &= j \ if \ \tau_{j-1} < t \leq \tau_j, \ j = 1, 2, ..., J, \ t = 1, 2, ..., T, \\ \tau_0 &= 0, \ \tau_J = T, \end{aligned} \tag{2}$$

where r_t^* is the target nominal federal funds rate; π_t^* is the target inflation rate; $\pi_{t,k}$ is the percent change in the price level between time t and $t+k$; $g_{t,k}$ is a measure of the average output gap between time t and $t+k$; E_t is the expectational operator conditional on information up to time t, at which the target interest rate is determined; β_{0,S_t}^* is the desired nominal federal funds rate when both inflation and output are at their target level; β_{1,S_t} and β_{2,S_t} are the response of the funds rate to the expected inflation and output gap, respectively. These coefficients depend on the Fed's stance on monetary policy summarized by the unobserved regime indicator variable S_t.

As documented by Clarida *et al.* (2000), Sack and Wieland (2000) and a host of others, each period the Fed sets the actual funds rate in a way that eliminates only a fraction of the gap between its current target level and its lagged value, thereby resulting in a smoothing of the interest rate. To accommodate this, we adopt the following specification for the actual federal funds rate:

$$\begin{aligned} r_t &= (1-\beta_{3,S_t})r_t^* + \beta_{3,S_t} r_{t-1} + \varepsilon_t, \\ 0 &< \beta_{3,S_t} < 1, \end{aligned} \tag{3}$$

where β_{3,S_t} is the smoothing parameter that measures the degree of interest rate smoothness and undergoes structural breaks and ε_t is a random disturbance term. Combining Eqs. (1) and (3) yields the following empirical model of the monetary policy rule:

$$r_t = (1-\beta_{3,S_t})[\beta_{0,S_t} + \beta_{1,S_t}\pi_{t,k} + \beta_{2,S_t} g_{t,k}] + \beta_{3,S_t} r_{t-1} + e_t, \;\; e_t \sim N(0, \sigma^2_{e,S_t}), \tag{4}$$

where $\beta_{0,S_t} = \beta^*_{0,S_t} - \beta_{1,S_t}\pi^*_t$, and the regressors $\pi_{t,k}$ and $g_{t,k}$ replace $E_t(\pi_{t,k})$ and $E_t(g_{t,k})$ in Eq. (1), respectively, and are therefore correlated with the new error term $e_t = \varepsilon_t + (1 - \beta_{3,S_t})[\beta_{1,S_t}(\pi_{t,k} - E_t(\pi_{t,k})) + \beta_{2,S_t}(g_{t,k} - E_t(g_{t,k}))]$.

In order to estimate Eq. (4), two issues must be considered. First of all, we postulate that there are J monetary policy regimes that shift permanently, equivalently stating that there exist $J-1$ structural breaks in the conduct of monetary policy: $S_t = 1$ for $0 < t \leq \tau_1$, $S_t = 2$ for $\tau_1 < t \leq \tau_2, ..., S_t = J$ for $\tau_{J-1} < t \leq T$, where $\tau_1, \tau_2, ..., \tau_{J-1}$ are the unknown structural break dates. According to Chib's (1998) methodology, S_t is modeled as a first-order Markov switching process governed by the following transitional probabilities:

$$\widetilde{\mathbf{P}} = \begin{pmatrix} p_{11} & 0 & 0 & \cdots & 0 & 0 \\ 1-p_{11} & p_{22} & 0 & \cdots & 0 & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ 0 & 0 & 0 & \cdots & p_{J-1J-1} & 0 \\ 0 & 0 & 0 & \cdots & 1-p_{J-1J-1} & 1 \end{pmatrix}, \tag{5}$$

where $p_{ij} = \Pr(S_t = j|S_{t-1} = i)$ is the probability of switching to regime j at time t from the regime i at time $t-1$. Note that some restrictions are imposed on the probabilities to reflect the properties of structural breaks: the restriction $p_{jj} + p_{jj+1} = 1,\ j = 1, ..., J-1$, means that if we are in a regime, it is only possible to either remain within the same regime or to shift to the next regime in the next period; the restriction $p_{JJ} = 1$ shown in the last column means that once we are in the last regime, we remain forever in the regime. When structural breaks are modeled as above, the break date parameters can be estimated using the expected regime durations—for example, the j-th break date $\tau_j = \sum_{k=1}^{j} 1/(1-p_{kk})$ where $1/(1-p_{kk})$ is the expected duration of the k-th regime.

Secondly, owing to the existence of endogenous regressors, the Markov-switching model of Eq. (4) cannot be consistently estimated by the conventional Hamilton (1989) filter. We adopt Kim's (2009) maximum likelihood estimation procedure to consistently estimate the model[3]. To illustrate this procedure, let us first assume that the endogenous regressors are related to the vector of instrumental variables, $\mathbf{z}_t$, in the following manner:

[3]Note that a general method of moment (GMM) cannot be applied to the model with the unknown break dates.

$$
\begin{aligned}
\pi_{t,k} &= \mathbf{z}_t'\boldsymbol{\delta}_{1,S_{1t}} + v_{1t}, & (6)\\
g_{t,k} &= \mathbf{z}_t'\boldsymbol{\delta}_{2,S_{2t}} + v_{2t}, & (7)\\
\mathbf{v}_t &= [v_{1t}\ v_{2t}]' \sim i.i.d.N(\mathbf{0}_2, \boldsymbol{\Sigma}_{\mathbf{v},S_{1t},S_{2t}}), & (8)\\
\boldsymbol{\Sigma}_{\mathbf{v},S_{1t},S_{2t}} &= \begin{pmatrix} \sigma^2_{v_1,S_{1t}} & \rho_{v_{12}}\sigma_{v_1,S_{1t}}\sigma_{v_2,S_{2t}} \\ \rho_{v_{12}}\sigma_{v_1,S_{1t}}\sigma_{v_2,S_{2t}} & \sigma^2_{v_2,S_{2t}} \end{pmatrix}, & (9)\\
S_{1t} &= m\ if\ \tau_{1,m-1} < t \leq \tau_{1,m},\ m = 1,2,...,M,\ \tau_{1,0} = 0,\ \tau_{1,M} = T,\\
S_{2t} &= q\ if\ \tau_{2,q-1} < t \leq \tau_{2,q},\ q = 1,2,...,Q,\ \tau_{2,0} = 0,\ \tau_{2,Q} = T,
\end{aligned}
$$

where the instrumental variables Eqs. (6) for inflation and (7) for output gap are subject to $M-1$ structural breaks governed by S_{1t} and subject to $Q-1$ structural breaks governed by S_{2t}, respectively. Following Spagnolo et al. (2005) and Psaradakis et al. (2006), we consider a structural break not only in variances, $\boldsymbol{\Sigma}_{\mathbf{v},S_{1t},S_{2t}}$, but also in the slope coefficients, $\boldsymbol{\delta}_{1,S_{1t}},\ \boldsymbol{\delta}_{2,S_{2t}}$. The associated unknown break dates are $\tau_{1,1},\ \tau_{1,2},...,\tau_{1,M-1}$ for Eq. (6) and $\tau_{2,1},\ \tau_{2,2},...,\tau_{2,Q-1}$ for Eq. (7). S_{1t} and S_{2t} follow a first-order Markov switching process governed by the constrained transition probabilities, $\tilde{\mathbf{p}}_1,\ \tilde{\mathbf{p}}_2$, as in the transition probabilities of S_t. We assume that S_{1t} and S_{2t} are not correlated with one another, but their potential correlation with S_t cannot be ruled out.

Having specified the instrumental variables, we are now able to address the problem of endogeneity, based on the control function approach of Heckman and Robb (1985). The key to the approach is the Cholesky decomposition of the variance-covariance matrix of $[v^*_{1t}\ v^*_{2t}\ e_t]'$ where $[v^*_{1t}\ v^*_{2t}]' = \boldsymbol{\Sigma}^{-1/2}_{\mathbf{v},S_{1t},S_{2t}}[v_{1t}\ v_{2t}]'$:

$$
\begin{bmatrix} \mathbf{v}_t^* \\ e_t \end{bmatrix} \sim \begin{bmatrix} \mathbf{I}_2 & \mathbf{0}_2 \\ \boldsymbol{\rho}'_{S_t}\sigma_{e,S_t} & \sqrt{(1-\boldsymbol{\rho}'_{S_t}\boldsymbol{\rho}_{S_t})}\sigma_{e,S_t} \end{bmatrix} \begin{bmatrix} \boldsymbol{\omega}_{1t} \\ \omega_{2t} \end{bmatrix}, \tag{10}
$$

$$
\begin{bmatrix} \boldsymbol{\omega}_{1t} \\ \omega_{2t} \end{bmatrix} \sim i.i.d.N\left(\begin{pmatrix} \mathbf{0}_2 \\ 0 \end{pmatrix}, \begin{pmatrix} \mathbf{I}_2 & \mathbf{0}_2 \\ 0 & 1 \end{pmatrix} \right), \tag{11}
$$

where $\mathbf{v}_t^* = [v_{1t}^* \ v_{2t}^*]'$, $\boldsymbol{\rho}_{S_t} = [\rho_{1,S_t} \ \rho_{2,S_t}]'$, and $\boldsymbol{\omega}_{1t}$ and ω_{2t} are independent standard normal random variables. Thus, Eq. (4) can be rewritten as:

$$
\begin{aligned}
r_t &= (1-\beta_{3,S_t})[\beta_{0,S_t} + \beta_{1,S_t}\pi_{t,k} + \beta_{2,S_t}g_{t,k}] + \beta_{3,S_t}r_{t-1} \\
&\quad + \gamma_{1,S_t}v_{1t}^* + \gamma_{2,S_t}v_{2t}^* + \omega_t^*, \qquad (4') \\
\omega_t^* &\sim i.i.d.N(0, \sigma^2_{\omega,S_t}),
\end{aligned}
$$

where $\gamma_{1,S_t} = \rho_{1,S_t}\sigma_{e,S_t}$, $\gamma_{2,S_t} = \rho_{2,S_t}\sigma_{e,S_t}$, and $\sigma^2_{\omega,S_t} = (1-\boldsymbol{\rho}'_{S_t}\boldsymbol{\rho}_{S_t})\sigma^2_{e,S_t}$. The disturbance term ω_t^* is now uncorrelated with the regressors $\pi_{t,k}$, $g_{t,k}$, r_{t-1}, v_{1t}^*, and v_{2t}^* so that Eq. (4') is free from endogeneity and can be consistently estimated since v_{1t}^* and v_{2t}^* function as bias-correcting terms.

B. Two-step estimation procedure

Kim (2009) proposes a joint estimation procedure and a two-step estimation procedure for the estimation of a Markov-switching model with endogenous explanatory variables such as Eq. (4')[4]. The joint procedure allows us to estimate Eqs. (4'), (6), and (7) along with the transition probabilities provided in Eq. (5) and the transition probabilities for S_{1t} and S_{2t} based on the Hamilton (1989) filter. Even though the joint estimation procedure is

[4] Kim (2004) proposes an estimation procedure for a Markov-switching model in the presence of endogenous explanatory variables with limited use. If S_t is perfectly correlated with S_{1t} and S_{2t}−that is, $S_t = S_{1t} = S_{2t}$−our model can be estimated by Kim's (2004) procedure.

asymptotically most efficient, it may not always be feasible, as it is subject to the curse of dimensionality as the result of too many parameters in the transition matrix[5]. A reasonable alternative to the joint estimation procedure is the two-step procedure summarized below which is relatively free from the curse of dimensionality.

In the first step, we apply the Hamilton (1989) filter to the model provided by Eqs. (6)-(8) and the transition probabilities to obtain consistent estimates of $\boldsymbol{\theta}_{12} = [\boldsymbol{\delta}_1' \ \boldsymbol{\delta}_2' \ \boldsymbol{\sigma}_{v_1}' \ \boldsymbol{\sigma}_{v_2}' \ \rho_{v_{12}} \ \tilde{\mathbf{p}}_1' \ \tilde{\mathbf{p}}_2']'$ where $\boldsymbol{\delta}_1 = [\delta_{1,1}' \ \delta_{1,2}' \ \cdots \delta_{1,M}']'$, $\boldsymbol{\delta}_2 = [\delta_{2,1}' \ \delta_{2,2}' \ \cdots \delta_{2,Q}']'$, $\boldsymbol{\sigma}_{v_1} = [\sigma_{v_{1,1}} \ \sigma_{v_{1,2}} \ \cdots \sigma_{v_{1,M}}]'$, $\boldsymbol{\sigma}_{v_2} = [\sigma_{v_{2,1}} \ \sigma_{v_{2,2}} \ \cdots \sigma_{v_{2,Q}}]'$, $\tilde{\mathbf{p}}_1 = [p_{1,11} \ p_{1,22} \ \cdots p_{1,M-1M-1}]'$, $\tilde{\mathbf{p}}_2 = [p_{2,11} \ p_{2,22} \ \cdots p_{2,Q-1Q-1}]'$, and standardized residuals

$$\begin{pmatrix} \hat{v}_{1t}^* \\ \hat{v}_{2t}^* \end{pmatrix} = \hat{\boldsymbol{\Sigma}}_{\mathbf{v},S_{1t},S_{2t}}^{-\frac{1}{2}} \begin{pmatrix} \pi_{t,k} - \mathbf{z}_t'\hat{\boldsymbol{\delta}}_{1,S_{1t}} \\ g_{t,k} - \mathbf{z}_t'\hat{\boldsymbol{\delta}}_{2,S_{2t}} \end{pmatrix}, \tag{12}$$

and the smoothed probabilities of S_{1t} and S_{2t} : $f(S_{1t}|\tilde{\mathbf{X}}_T;\hat{\boldsymbol{\theta}}_{12})$, and $f(S_{2t}|\tilde{\mathbf{X}}_T;\hat{\boldsymbol{\theta}}_{12})$ where $\tilde{\mathbf{X}}_T = [\mathbf{x}_2 \ \mathbf{x}_3 \ \cdots \mathbf{x}_{T+1}]'$, $\mathbf{x}_t = [\pi_{t+1,k} \ g_{t+1,k}]'$. It is worth noting that in making inferences regarding S_{1t} and S_{2t}, their potential correlation with S_t is ignored because consistency can be achieved at the cost of efficiency.

In the second step, using the Hamilton (1989) filter, we estimate Eq. (4') along with Eq. (3), after replacing v_{1t}^* and v_{2t}^* by $\hat{v}_{1t}^*$ and $\hat{v}_{2t}^*$ obtained from the first step, respectively. The estimated equation is:

$$\begin{aligned} r_t &= (1-\beta_{3,S_t})[\beta_{0,S_t} + \beta_{1,S_t}\pi_{t,k} + \beta_{2,S_t}g_{t,k}] + \beta_{3,S_t}r_{t-1} \\ &\quad +\gamma_{1,S_t}\hat{v}_{1t}^* + \gamma_{2,S_t}\hat{v}_{2t}^* + u_t, \qquad\qquad (4") \\ u_t &\sim i.i.d.N(0,\sigma_{u,S_t}^2). \end{aligned}$$

As indicated by Pagan (1984), the covariance matrix of estimators from the second step

[5] As will be discussed later, $J = 5$ for S_t, $M = 3$ for S_{1t}, and $Q = 2$ for S_{2t} are selected. In this case, the transition matrix of the joint estimation has a dimension of 30×30.

regression is biased as the result of the use of the generated regressors $\hat{v}_{1t}^{*}$ and $\hat{v}_{2t}^{*}$. The appendix provides the correct covariance matrix that accounts for the generated regressors problem. Details of the construction of the log likelihood functions for step 1 and step 2 are also provided in the appendix.

IV. Empirical Results

A. Estimation of monetary policy rule

The data are quarterly time series spanning the period 1956:I - 2005:IV[6]. The data regarding inflation, output gap and *ex post* real interest rates are the same as in Section II. The instruments include three lags of the federal funds rate, GDP gap, inflation, commodity price changes, and spread between the long-term bond rate and the three-month Treasury Bill rate. All series are downloaded from the FRED dataset in the Federal Reserve Bank of St. Louis.

In order to determine the characteristic of structural breaks in the first step estimation for inflation and output gap, we consider Spagnolo *et al.* (2005), Psaradakis *et al.* (2006), Sims and Zha (2006), Kim and Nelson (1999), McConnell and Perez-Quiros (2000), and Kang, Kim, and Morley (2009). On the one hand, Sims and Zha (2006) demonstrate that the best fitted multivariate regime-switching model for U.S. monetary policy allows for time variations in disturbance variances only, and the regime-switching model with coefficients allowed to change are not sufficiently large to account for the movements in inflation occurring in the 1970s and 1980s. On the other hand, Spagnolo *et al.* (2005) and Psaradakis *et al.* (2006) consider both state-dependent parameters and state-dependent variances to explain the rejection of the unbiased forward exchange rate hypothesis and to test the generalized Expectations Hypothesis. Kang *et al.* (2009) found, using the GDP deflator for the sample

[6] The initial period of our sample differs slightly from that used in the study of Clarida *et al.* (2000), which begins in 1960:I. The reason for this is that we attempt to avoid the small sample of the first regime resulting from giving up the initial four quarters' data due to lagged regressors. Nevertheless, both results based on the sample 1956:I - 2005:IV and on the sample 1960:I - 2005:IV are qualitatively similar.

period of 1959-2006, that U.S. inflation underwent two sudden permanent regime shifts, both of which corresponded to changes in persistence. Based on Spagnolo *et al.* (2005), Sims and Zha (2006), and Kang et al. (2009), only two structural breaks are allowed in the parameters and the variance of inflation in the first step estimation. Additionally, Kim and Nelson (1999) and McConnell and Perez-Quiros (2000) reported that since the first quarter of 1984, the volatility of U.S. real GDP has decreased significantly. Based on these literature, we consider one structural break in the parameters and in the variance of the output gap.

Figures 2 and 3 show the smoothed probabilities of inflation regimes and output gap regimes, respectively. The two structural break dates identified in the inflation estimations are 1973:I and 1984:II, and these are nearly close to the break dates reported by Kang *et al.* (2009) who identified 1970:III and 1984:IV as two break dates over the sample period of 1959-2006. With regard to the output gap, a structural change is estimated to have occurred in 1983:I while Kim and Nelson (1999) and McConnell and Perez-Quiros (2000) identified 1984:I. Overall, the estimation results in the first step appear to be fairly consistent with the existing literature.

In order to determine how many structural changes occurred at unknown dates in the monetary policy rule during the sample, we use the narrative evidence regarding possible monetary policy regimes. In Section II, the narrative approach suggests that U.S. monetary policy regimes have evolved with different Fed Chairmen since the 1950s. Given the four chairmen over the period of 1956 − 2005, we select five regimes because we consider the possibility of different regimes for Chairman Alan Greenspan due to changes in inflation behavior occurring in the mid–1990s[7].

We allow four unknown structural changes, which are endogenously estimated by the latent Markov-switching model outlined by the equation (4") in Section III. The target horizon is assumed to be one-quarter for both inflation and the output gap (i.e. $k = 1$). The

[7] To determine how many structural changes occurred at unknown dates in the monetary policy rule during the sample, we also use the sequential procedure test proposed recently by Qu and Perron (2007). The results of Qu and Perron's test indicate four unknown structural changes. The results are available upon request.

estimation results are reported in Table 2. The estimated coefficients for the bias correction term for inflation, γ_{1,S_t}, are negative over five regimes and statistically significant in regime 2, regime 4 and regime 5 while those of the bias correction term for GDP gap, γ_{2,S_t}, are negative over five regimes and statistically significant in all regimes except regime 5. This result confirms the results reported by Kim (2004) and Kim and Nelson (2006), in which ignoring the endogeneity in the regressors of the forward-looking policy rule in equation (4) would result in serious bias in the estimation of the time-varying coefficients. The degree of interest rate smoothing is quite low in the early 1980s, but fairly high in the late 1980s, the 1990s, and the early 2000s.

B. Monetary policy regimes

Four structural changes are estimated to have occurred and thus five regimes for U.S. monetary policy over the 1956:I - 2005:IV period are identified: 1956:I - 1968:I for regime 1, 1968:II - 1979:IV for regime 2, 1980:I - 1985:I for regime 3, 1985:II - 1997:I for regime 4 and 1997:II - 2005:IV for regime 5. The estimation of parameters for a forward-looking monetary policy rule with regime switching is summarized in Table 2. Figure 4 depicts smoothed probabilities ($\Pr[S_t = j|\tilde{\mathbf{y}}_T]$) where $\tilde{\mathbf{y}}_T = [r_1 \ r_2 \ \cdots r_T]'$ for five identified regimes. These estimated regimes correspond roughly to the Fed Chairman eras in Section II, and this finding is consistent with the views of Judd and Rudbusch (1998) and Romer and Romer (2004), with the exception of the era of chairman Alan Greenspan[8]. According to Romer and Romer (2004), since the mid-1990s, there has been a qualitative change in inflation behavior. Interestingly, our model does appear to identify exactly such a change, and considers the Greenspan era as two distinct regimes.

Figures 5a and 5b show the regime-shifting Fed's response to inflation and to the output gap along with their 90% confidence bands throughout the entire sample, respectively. Several

[8] From 1956 to 2005, there were actually five Federal Reserve chairmen. However, since the era of chairman William Miller was short (March 1978 - August 1979) and his belief about economic understanding along with a low natural rate of unemployment was similar to the era of chairman Arthur Burns, our estimation appears not to consider this period as a unique regime.

points to note stand out from Figure 5a with regard to the Fed's response to inflation. First of all, the value of the estimated coefficient on inflation in regime 1 (1960s) is significantly below unity and does not differ statistically significantly from zero. The response to inflation in regime 1 appears to differ substantially from those of all other regimes. As pointed out by Romer and Romer (2002a, 2004) and in Section II, this result shows that the Fed has barely responded to inflation in the 1960s although inflation was rising during this period, as is shown in Figure 1a. Secondly, the values of the estimated coefficient on the response to inflation in regimes 2, 3, 4, and 5 are relatively high. This result implies that since 1968:II, the Fed appears to have responded strongly to inflation in an effort to stabilize the economy. This result is consistent with Orphanides (2004), who demonstrated the strong response of the Fed to inflation over the period 1966:I - 1979:II. Thirdly, the Fed's response to inflation in regime 5 (since the mid-1990s) appears not to be strong relative to that of the early Greenspan period. This result implies that the Fed appears to have realized the qualitative change in inflation behavior occurring in the mid-1990s; as a result, their response to inflation changed to an easier stance. Additionally, this result appears to support the argument that the Fed provided plenty of liquidity for a stimulation of the U.S. economy in the early 2000s.

In Figure 5b, the response to the output gap evidences quite a different pattern across five regimes. First of all, the magnitude of the Fed's response to the output gap in regime 1 (1960s) is significantly greater than zero, but small relative to regime 2 (1970s), regime 4 (early 1990s), and regime 5 (since the mid-1990s). Combining this result with that for response to inflation supports Romer and Romer (2004), and Romer (2005), who argued that in the 1960s, policymakers' beliefs in a long-run trade-off between inflation and unemployment and a flawed model by a natural rate framework with a very low natural rate and an extreme insensitivity of inflation to slack resulted in a highly expansionary monetary and fiscal policy and policy inaction to cure inflation. We will discuss this issue in more detail in the following subsection.

Secondly, the Fed seems not to respond to the output gap in regime 3, which is consistent with Romer and Romer (2002a) and Kim and Nelson (2006). As demonstrated by Kim and Nelson (2006), it can be concluded that during the 1980s (regime 3), the Fed paid closer attention to inflation than to real economic activities, resulting in the stabilization of inflation. Thirdly, since the late 1980s, the Fed's response to the output gap appears to increase significantly. This result is interpreted to mean that once inflation has been reduced to a lower stable level, the Fed could have more room to actively react to the real output gap. The much narrower confidence band in the late Greenspan period (regime 5) demonstrates that the Fed's response to the output gap was statistically significant relative to the early Greenspan period (regime 4), to boost the economy in the early 2000s. Fourthly, the estimated coefficients on the Fed's response to output gap in regimes 1 (1960s) and 2 (1970s) are 0.5697 and 1.1440 respectively, which reflect a strong response to the output gap. This result shows that the Fed reacted actively to real economic conditions even during the Great Inflation and is consistent with the findings of Orphanides (2004), who argues that policy appears to have been activist in nature during the Great Inflation.

We summarize five estimated U.S. monetary policy regimes in terms of both regime changes in the Fed's responses to inflation and to the output gap in Table 3. In regime 1 (roughly the 1960s, William Martin as Fed's Chairman), the Fed appears to have only minimally responded to inflation but to have responded with moderate vigor to the output gap. In regime 2 (the 1970s, Arthur Burns as Fed's Chairman), the Fed seems to have responded firmly to both inflation and the output gap. The Fed appears to have responded firmly to inflation but not to the output gap in regime 3 (the 1980s, Paul Volcker as Fed's Chairman). In regime 4 (early 1990s, early Alan Greenspan as Fed's Chairman), the Fed appears to have reacted tightly to inflation and to have responded firmly to the output gap. However, in regime 5 (since the mid-1990s, late Alan Greenspan as Fed's Chairman), the Fed has responded to inflation with moderate vigor due to very stable inflation behavior, and has responded firmly to the output gap, probably as the result of the recession in 2001. Overall, the stance of monetary policy based on our five regimes appears quite consistent with Romer and Romer (2004), who summarize the policy stances based on beliefs and policy actions under the Federal Reserve Chairman since the post-world war II, with the exception of the era of Chairman Alan Greenspan.

Sims and Zha (2006) show that the best fit among a variety of regime-switching models for monetary policy is the one with time variations only in disturbance variances, but not the one with changes in coefficients, even though their results leave room for those with strong beliefs that monetary policy changed substantially. However, consistent with the narrative approach by Romer and Romer (2002a, 2004), our results suggest that changes in monetary policy regimes play an important role in characterizing the evolution of U.S. monetary policy, and thus our results appear to go beyond the findings of Sims and Zha (2006).

C. Ex-post data vs. Real-time data

If our presented model characterizes the evolution of U.S. monetary policy regime appropriately, one might anticipate that our estimation results might provide a consistent explanation for conflicting results in the existing literature. The first relevant issue is whether or not one takes into account the nature of real-time data. Clarida *et al.* (2000) found, using *ex post* data from 1960:I to 1996:IV, that the estimated coefficient in the Fed's response to inflation is less than unity in the pre-Volcker years (1960:I - 1979:III) and interpreted this to mean that the Fed typically raised nominal rates by less than any increase in expected inflation, thereby resulting in greater macroeconomic instability for the pre-Volcker period than during the time of Volcker-Greenspan rule. On the other hand, Orphanides (2004) demonstrated, using real-time data from 1966:I to 1995:IV, that the estimated response to inflation exceeds one in both the pre-Volcker (1966:I - 1979:II) and Volcker-Greenspan periods (1979:III - 1995:IV) and also argued that the estimated weaker reaction to inflation asserted by Clarida *et al.* (2000) for the pre-Volcker period results from failure to take into consideration information that was available to the FOMC in real time. Thus, the conflicting results in both studies are attributed to different data sets (i.e., ex-post data vs. real-time data).

Our results with the regime-switching model, however, suggest that this is not an issue of the nature of the data, but rather of the different samples used in the two studies. In the study of Clarida *et al.* (2000), the estimated coefficient of the Fed's response to inflation for the period 1960:I - 1979:III, β_1, was 0.83, whereas in the study of Orphanides (2004), it was 1.49 for the period 1966:I - 1979:II. Note that the sample used in Clarida *et al.*'s (2000) includes the first half of the 1960s, whereas Orphanides's (2004) sample does not cover it; however, both studies regard the pre-Volcker period as simply a one-monetary policy regime. This sample difference implies that as we include the first half of 1960s, as did Clarida *et al.*, the estimated response to inflation is diminished but because we leave out the first half of the 1960s like Orphanides, the response to inflation is significantly high.

Our estimate of the regime-switching model clearly implies this. There are two different regimes for the pre-Volcker period, and the Fed's response to inflation differs fairly substantially over the two regimes. The estimated coefficient of the Fed's response to inflation in regime 1 (1957:I - 1968:I) is -0.2605 ($\beta_{1,1}$), which is not statistically different from zero at a conventional significance level, whereas that of regime 2 (1968:II - 1979:IV) is 1.4740 ($\beta_{1,2}$). Note that the period of our regime 2 is quite close to that utilized by Orphanides' (2004) pre-Volcker sample, and the estimated coefficients on both studies are almost identical, although our study employs *ex post* data.

On the other hand, if we consider the pre-Volcker period as one monetary policy regime, as did Clarida *et al.* (2000) and thus take an average of the estimated coefficients for both regime 1 and regime 2, the average is 0.6068, which is close to that of Clarida *et al.* (2000). This means that when we include the first-half of the 1960s in the pre-Volcker sample, the estimated coefficient of the Fed's response to inflation is closer to that of Clarida *et al.* This implies that the estimated weak response of the Fed to inflation for the pre-Volcker period in Clarida *et al.* (2000) is the result of the ignorance of two different monetary policy regimes.

From this perspective, our results indicate that the conflicting results between Clarida *et al.* (2000) and Orphanides (2004) are not the result of the differences in the data (i.e., *ex post* data vs. real-time data), but are rather due to different samples. Additionally, our results appear to support the findings of a study recently conducted by Bernanke and Boivin (2003), who demonstrated that the forecasting performance by the Fed in a data-rich environment does not appear to be dependent on the use of the finally revised (as opposed to "real-time") data.

D. Great Inflation

Our result may also provide some insights into the evolution of Great Inflation. Romer and Romer (2002a, 2002b, 2004) demonstrated that the monetary policymakers of the 1950s had a deep-seated antipathy toward inflation and acted to control it like the central bankers of the 1990s; however, there was a radical turn in the economic framework in the beginning of the 1960s and the FOMC and Kennedy and Johnson administrations adopted it. A key element of these new beliefs was a long-run trade-off between unemployment and inflation along with modest inflation and rather low levels of unemployment. They argue that such a view exerted a major impact on monetary policy in the 1960s; thus, despite rapid output growth, high resource use, and rising inflation, the FOMC did not tighten. Meltzer (2005) stressed the role of leadership and beliefs of Federal Reserve policymakers, particularly the Chairman, and argued that during the early 1960s, Chairman Martin placed excessive emphasis on reaching consensus among FOMC members prior to changing policy, resulting in unfortunate delays in taking prompt action for anti-inflation at the early stages of the Great Inflation and that policy coordination between fiscal and monetary policy compromised the Fed's independence and kept the Fed from taking timely and effective disinflationary action during the 1960s.

Romer and Romer (2004) have pointed out that another shift in views occurred at the very end of Chairman Martin's tenure, which is the belief that there was no long-run inflation-unemployment trade-off, that the natural rate framework works, and that the Fed began to tighten substantially beginning in late 1968. Nevertheless, policymakers did have optimistic estimates of the natural rate—a rate lower than the growth rate of potential output—and their estimate appears to have made them feel that there was no conflict between expansionary policy and their goal of lowering actual inflation to validate the reduced expectations prevailing in the early 1970s.

Our estimations of a monetary policy rule in these periods appear to be fairly compatible with the above history. As shown in the estimated coefficients on the response to inflation in regimes 1 and 2, the Fed appears to have responded very minimally to inflation until the late 1960s, whereas it appears to have reacted to inflation quite vigorously in the late 1960s and 1970s, although inflation was rising in the early 1960s. Additionally, the estimated coefficient on output gap response in regime 2 was 1.1440, which is fairly firm response to the output gap and consistent with the findings of Orphanides (2004), who demonstrated that the Fed's responses to inflation and output gap were quite strong in the late 1960s and 1970s, even using real-time information, and argued that policy appears to have been activist during the Great Inflation. Overall, our estimation results provide a remarkably consistent explanation for what happened during the period of the Great Inflation.

V. Monetary Policy Regimes and Real Interest Rate

Huizinga and Mishkin (1986), Bonser-Neal (1990), and Rapach and Wohar (2005) find that the regime changes in the real interest rate are related to the monetary policy regime. If the real interest rate is the most fundamental indicator of the stance of monetary policy, our regime-switching model to explain the evolution of U.S. monetary policy results in a regime-switching model for the real interest rate, and suggests the occurrence of coincidental regime changes in monetary policy and real interest rates.

In order to characterize this relationship, we model the real interest rate as an AR (1) process with regime changes:

$$
\begin{aligned}
(rr_t - \mu_{D_t}) &= \phi_{D_t}(rr_{t-1} - \mu_{D_{t-1}}) + e_t, \qquad (13)\\
e_t &\sim N(0, \sigma^2_{e,D_t}),\\
D_t &= l \; if \; \tau_{D,l-1} < t \leq \tau_{D,l}, \; l = 1, 2, \cdots, L, \; \tau_{D,0} = 0, \; \tau_{D,L} = T,
\end{aligned}
$$

where rr_t is the ex-post real interest rate, ϕ_{D_t} is the regime dependent AR coefficient, σ^2_{e,D_t} captures the regime-switching variance and D_t is the regime indicator variable, which follows a first-order Markov process with constrained transition probabilities as in Eq. (5). We allow for structural breaks in the parameters $\boldsymbol{\psi} = [\mu \; \phi \; \sigma^2_e]'$. If the regime changes in the real interest rate are related closely to the regime changes in monetary policy, it may be sensible for one to assume that there are the same number of regimes in the real interest rate and that the timing of regime changes in the real interest rate can be correlated with the timing of regime changes in the monetary policy rule.

We estimate Eq. (13), allowing the same number of structural breaks (five regimes) in the real interest rate[9]. The real interest rate is taken as the difference between the three-month T-bill rate and the inflation of the GDP deflator, which is the exact ex-post real interest rate as shown in Section II. The estimation results are shown in Table 4 and the smoothed probabilities of the real interest rate regimes are plotted in Figure 6. The four estimated break dates are 1970:IV, 1981:I, 1986:I, and 2001:I. It is worth noting that the estimated break dates of the real interest rate follow the break dates of monetary policy within approximately two years, with the exception of the date of 2001:I (1997:I for monetary policy). This result implies that given the notion of some leads and lags between the conduct of monetary policy and its effect on the economy, these break dates of the real interest rate are quite close to those of the monetary policy rule. As the ex-post real interest rate began to fall significantly beginning in late 2000 as shown in Figure 1c, our model may have selected this date as a

[9]The result of Qu and Perron's (2007) test for structural breaks in the real interest rate also indicates four structural breaks over the sample.

structural change in the real interest rate. This reduction in the real interest rate coincides roughly with the decline in output gap, as shown in Figure 1b. This result is consistent with Zhang, Osborn and Kim (2008), who find in the test for structural changes in the New Keynesian Phillips Curve for the period 1960 - 2005 that there was a break at around 2001, and suggested that this was associated with U.S. monetary policy during that period.

Figure 7a plots the mean real interest rate with 90% confidence bands over five regimes. These estimated means of the real interest rate over five regimes, μ_l, $l = 1, 2, ..., 5$, are $1.245,\ -0.3712,\ 5.0525,\ 2.8463$, and -0.3126, and appear rather close to those of each chairman period's real interest rate, $1.097,\ -0.535,\ 4.178,\ 2.755$ and -0.585, as described in Table 1[10]. Hence, these results appear to support the view that there has been an evolution in monetary policy and the real interest rate is the most fundamental indicator of the stance of U.S. monetary policy.

Additionally, the change in the persistence of real interest rate is an important point to address. Walsh (1987) and Rose (1988) found that the real interest rate was $I(1)$ whereas Perron (1990) and Garcia and Perron (1996) argued that the U.S. real interest rate is more accurately described as a stationary process around an infrequently shifting mean and such infrequent regime changes in the mean real interest rate make it difficult to reject the unit root null hypothesis for the real interest rate. As shown in Table 4, the estimated mean real interest rates over five regimes, μ_l, are fairly different and the estimated parameters for persistence measure, ϕ_l, are significantly less than unity. This is again demonstrated in Figure 7b. Figure 7b shows the estimated persistence parameters of the real interest rate with 90% confidence bands. Persistence clearly rose since the mid-1980s. This result demonstrates that considering changes not only in the mean of the real interest rate but also in the persistence of real interest rate is important for characterizing the dynamics of the U.S. real interest rate.

In summary, the dynamics of the real interest rate has been linked to the evolution

[10] -0.535 is the mean of the *ex post* real interest rate over the Burns and Miller era, given the similar beliefs of two chairmen as pointed out in the previous section. Additionally, 2.755 and -0.585 are the mean real interest rates over regimes 4 and 5 of the Greenspan era.

of monetary policy. When we allowed the same number of breaks in the estimate of the real interest rate, we found that the estimated break dates of real interest rates are nearly identical to those of the monetary policy rule. Additionally, there have clearly been regime changes in the mean real interest rates and the persistence of the real interest rate appears to have increased since the mid-1980s. Thus, such regime changes in the mean and in the persistence of the real interest rates play an important role in describing the dynamics of the U.S. real interest rate, and may provide another explanation for the conflicts in existing studies regarding the process of the real interest rate.

VI. Conclusions

Both narrative and statistical evidences have been presented demonstrating that U.S. monetary policy has changed since the late 1950s. Romer and Romer (2002a, 2004) show that monetary policy regime corresponds roughly to terms of different Federal Reserve chairmen, along with different views as to how the economy works and what monetary policy can accomplish. Kim and Nelson (2006) show that U.S. monetary policy can be divided into the 1960s, the 1970s, the 1980s, and the 1990s. Additionally, Huizinga and Mishkin (1986), Bonser-Neal (1990), and Rapach and Wohar (2005) demonstrate that the regime changes in the real interest rates are related to monetary policy regimes.

Considering such narrative and statistical evidence regarding changes in U.S. monetary policy, we evaluate the evolution of monetary policy regimes by employing a regime-switching model in which policy changes are non-recurrent and monotonic but probabilistic, and in which we take into consideration endogeneity in the regressor, as in the study of Kim and Nelson (2006). We find that five regimes for U.S. monetary policy for the period 1956:I - 2005:IV are identified: 1956:I - 1968:I; 1968:II - 1979:IV; 1980:I - 1985:I; 1985:II - 1997:I; 1997:II - 2005:IV. The finding that the Greenspan era was divided into two different regimes— focusing on the strong response to inflation in the early term but structural changes in inflation since the mid-1990s—is an interesting point to be explored further in the future. We also find that not only the changes in the response of the Fed to inflation, and to the output gap, but also the changes in the structural variances of monetary policy perform a crucial function in identifying the regimes. This appears to be important finding beyond that of Sims and Zha (2006).

Our results provide two important insights to explain the conflicting issues in the existing literature. First of all, we demonstrate that the conflicting results between Clarida *et al.* (2000) and Orphanides (2004) regarding the Fed's response to inflation in the pre-Volcker period is not attributable to different data (*ex post* data vs. real-time data) but rather the result of different samples. When we consider the pre-Volcker period as two different regimes, we can consistently explain the issue. Secondly, our results provide key insights into the evolution of the Great Inflation. Romer and Romer (2002a, 2004), Romer (2005), and Meltzer (2005) argue that the Fed has responded only minimally to inflation in the early 1960s owing to the beliefs of policymakers or to institutional arrangements for policy coordination, although the inflation was rising significantly. Our estimation results demonstrate this argument precisely, and are thus consistent with the narrative evidence provided by Romer and Romer (2004) and Meltzer (2005).

Given the assertion that the real interest rate is the most fundamental indicator of the stance of monetary policy, we investigated whether regime changes in the U.S. real interest rate are linked to regime changes in U.S. monetary policy. We find that the estimated break dates for the real interest rate are nearly coincidental to those of monetary policy. For a different perspective on real interest rate dynamics we consulted the existing literature, and find that when we consider multiple structure breaks in the real interest rate, the real interest rate is $I(0)$ over all regimes and that changes not only in the mean but also in the persistence of the real interest rate are critically important in describing the dynamics of the U.S. real interest rate.

As admitted by Sims and Zha (2006), it may prove difficult to predict policy actions;

additionally, if shifts occurred in the systematic components of policy, they were of a sort that is rather difficult for us to track precisely. Nevertheless, this paper suggests that one may learn some lessons from the exploration of the evolution of U.S. monetary policy regimes by our regime-switching model regarding changes occurring in U.S. monetary policy since the 1960s.

1 Appendix. Two-step estimation procedure

This appendix provides a detailed discussion of the modified two-step estimation procedure of Kim (2009). For the purposes of notational convenience, we redefine the variables and parameters in Eqs. (6)-(8) and the transition probabilities as $\mathbf{x}_t = [\pi_{t,k}\ g_{t,k}]'$, $\mathbf{Z}_t = \mathbf{I}_2 \otimes \mathbf{z}_t$, $\boldsymbol{\delta} = [\boldsymbol{\delta}'_{1,S_1}\ \boldsymbol{\delta}'_{2,S_2}]'$ and those in Eqs. (4') and (5) as $y_t = r_t$, $\boldsymbol{\theta} = [\boldsymbol{\beta}'_0\ \boldsymbol{\beta}'_1\ \boldsymbol{\beta}'_2\ \boldsymbol{\beta}'_3\ \boldsymbol{\gamma}'_1\ \boldsymbol{\gamma}'_2\ \boldsymbol{\sigma}^{2\prime}_u\ \tilde{\mathbf{p}}']'$ where $\boldsymbol{\beta}_k = [\beta_{k,1}\ \beta_{k,2}\ \cdots \beta_{k,J}]'$, $k = 0, 1, 2, 3$, $\boldsymbol{\gamma}_g = [\gamma_{g,1}\ \gamma_{g,2}\ \cdots\ \gamma_{g,J}]'$, $g = 1, 2$, $\boldsymbol{\sigma}^2_u = [\sigma^2_{u,1}\ \cdots\ \sigma^2_{u,J}]'$, $\tilde{\mathbf{p}} = [p_{11}\ \cdots p_{J-1J-1}]'$, and $\boldsymbol{\theta}_{12} = [\boldsymbol{\delta}'\ vec(\boldsymbol{\Sigma}_{\mathbf{v},m,q})'\ vec(\tilde{\mathbf{p}}_1)'\ vec(\tilde{\mathbf{p}}_2)']'$, where $vec(\boldsymbol{\Sigma}_{\mathbf{v},m,q}) = [vec(\boldsymbol{\Sigma}_{\mathbf{v},1,1})'\ vec(\boldsymbol{\Sigma}_{\mathbf{v},1,2})' \cdots vec(\boldsymbol{\Sigma}_{\mathbf{v},M,Q})']'$, $\tilde{\mathbf{p}}_1 = [p_{1,11}\ \cdots p_{1,M-1M-1}]'$, $\tilde{\mathbf{p}}_2 = [p_{1,11}\ \cdots p_{1,Q-1Q-1}]'$ and $\tilde{\mathbf{p}}_1$ and $\tilde{\mathbf{p}}_2$ are transitional probabilities for S_{1t} and S_{2t} respectively.

Step 1:

We maximize the following log likelihood function with respect to $\boldsymbol{\theta}_{12}$:

$$
\begin{aligned}
& \ln L_2(\boldsymbol{\theta}_{12}; \tilde{\mathbf{X}}_T) \\
= & \ln \left[f(\tilde{\mathbf{X}}_T; \boldsymbol{\theta}_{12}) \right] \\
= & \sum_{t=1}^{T} \ln \left[f(\mathbf{x}_t | \tilde{\mathbf{X}}_{t-1}; \boldsymbol{\theta}_{12}) \right] \\
= & \sum_{t=1}^{T} \ln \left[\sum_{S_{1t}=1}^{M} \sum_{S_{2t}=1}^{Q} f(\mathbf{x}_t | \tilde{\mathbf{X}}_{t-1}, S_{1t}, S_{2t}; \boldsymbol{\theta}_{12}) f(S_{1t}, S_{2t} | \tilde{\mathbf{X}}_{t-1}; \boldsymbol{\theta}_{12}) \right] && \text{(A.1)} \\
= & \sum_{t=1}^{T} \ln \left[\sum_{S_{1t}=1}^{M} \sum_{S_{2t}=1}^{Q} f(\mathbf{x}_t | \tilde{\mathbf{X}}_{t-1}, S_{1t}, S_{2t}; \boldsymbol{\theta}_{12}) f(S_{1t} | \tilde{\mathbf{X}}_{t-1}; \boldsymbol{\theta}_{12}) f(S_{2t} | \tilde{\mathbf{X}}_{t-1}; \boldsymbol{\theta}_{12}) \right] && \text{(A.2)}
\end{aligned}
$$

where $\tilde{\mathbf{X}}_t = [\mathbf{x}_1\ \mathbf{x}_2\ ...\mathbf{x}_t]'$, $f(S_{1t}|\tilde{\mathbf{X}}_{t-1}; \boldsymbol{\theta}_{12})$ and $f(S_{2t}|\tilde{\mathbf{X}}_{t-1}; \boldsymbol{\theta}_{12})$ are the filtered probabilities of S_{1t} and S_{2t}, respectively and

$$
\begin{aligned}
& f(\mathbf{x}_t|\tilde{\mathbf{X}}_{t-1}, S_{1t}, S_{2t}; \boldsymbol{\theta}_{12}) \\
= \quad & (2\pi)^{-1} \left|\boldsymbol{\Sigma}_{v,S_{1t},S_{2t}}\right|^{-1/2} \times \exp\left\{\frac{-1}{2}(\mathbf{x}_t - \mathbf{Z}_t'\boldsymbol{\delta})'\boldsymbol{\Sigma}^{-1}_{v,S_{1t},S_{2t}}(\mathbf{x}_t - \mathbf{Z}_t'\boldsymbol{\delta})\right\}. \qquad \text{(A.3)}
\end{aligned}
$$

The equation (A.2) holds since S_{1t} and S_{2t} are independent of one another. The application of the Hamilton (1989) filter yields a consistent estimate of $\hat{\boldsymbol{\theta}}_{12}$ and the smoothed probabilities $f(S_{1t}|\tilde{\mathbf{X}}_T; \boldsymbol{\theta}_{12})$, and $f(S_{2t}|\tilde{\mathbf{X}}_T; \boldsymbol{\theta}_{12})$ to be used in Step 2.

It is worth noting that the model considered in the study of Kim (2009) differs slightly from that described herein. In Kim (2009), regime changes in the instrumental variable equations are shown to be governed only by one Markov-switching process, whereas the equations in this paper are governed by two independent Markov-switching processes. Hence, the Step 1 regression is duly modified.

Step 2:

Conditional on $\hat{\boldsymbol{\theta}}_{12}, f(S_{1t}|\tilde{\mathbf{X}}_T; \hat{\boldsymbol{\theta}}_{12})$, and $f(S_{2t}|\tilde{\mathbf{X}}_T; \hat{\boldsymbol{\theta}}_{12})$, the following log likelihood function is maximized with respect to $\boldsymbol{\theta}$:

$$
\begin{aligned}
& \ln L_1(\boldsymbol{\theta}; \tilde{\mathbf{Y}}_T, \tilde{\mathbf{X}}_T) = \ln\left[f(\tilde{\mathbf{Y}}_T|\tilde{\mathbf{X}}_T; \boldsymbol{\theta}, \hat{\boldsymbol{\theta}}_{12})\right] \\
= \quad & \sum_{t=1}^{T} \ln[f(y_t|\tilde{\mathbf{Y}}_{t-1}, \tilde{\mathbf{X}}_T; \boldsymbol{\theta}, \hat{\boldsymbol{\theta}}_{12})] \\
= \quad & \sum_{t=1}^{T} \ln[\sum_{S_t=1}^{J} f(y_t, S_t|\tilde{\mathbf{Y}}_{t-1}, \tilde{\mathbf{X}}_T; \boldsymbol{\theta}, \hat{\boldsymbol{\theta}}_{12})] \qquad \text{(A.4)} \\
= \quad & \sum_{t=1}^{T} \ln[\sum_{S_t=1}^{J} f(y_t|S_t, \tilde{\mathbf{Y}}_{t-1}, \tilde{\mathbf{X}}_T; \boldsymbol{\theta}, \hat{\boldsymbol{\theta}}_{12}) f(S_t|\tilde{\mathbf{Y}}_{t-1}, \tilde{\mathbf{X}}_T; \boldsymbol{\theta}, \hat{\boldsymbol{\theta}}_{12})], \qquad \text{(A.5)}
\end{aligned}
$$

where $\tilde{\mathbf{Y}}_t = [y_1 \ y_2 \ \cdots y_t]'$ and

$$
\begin{aligned}
&f(y_t|S_t, \tilde{\mathbf{Y}}_{t-1}, \tilde{\mathbf{X}}_T; \boldsymbol{\theta}, \hat{\boldsymbol{\theta}}_{12}) \\
= &\sum_{S_{1t}=1}^{M} \sum_{S_{2t}=1}^{Q} f(y_t|S_t, S_{1t}, S_{2t}, \tilde{\mathbf{Y}}_{t-1}, \tilde{\mathbf{X}}_T; \boldsymbol{\theta}, \hat{\boldsymbol{\theta}}_{12}) f(S_{1t}, S_{2t}|S_t, \tilde{\mathbf{Y}}_{t-1}, \tilde{\mathbf{X}}_T; \boldsymbol{\theta}, \hat{\boldsymbol{\theta}}_{12}), \quad \text{(A.6)}
\end{aligned}
$$

and

$$
f(y_t|S_t, S_{1t}, S_{2t}, \tilde{\mathbf{Y}}_{t-1}, \tilde{\mathbf{X}}_T; \boldsymbol{\theta}, \hat{\boldsymbol{\theta}}_{12}) = \frac{1}{\sqrt{2\pi\sigma^2_{u,S_t}}} \exp(-\frac{1}{2\sigma^2_{u,S_t}} u_t^2), \quad \text{(A.7)}
$$

where

$$
u_t = r_t - [(1 - \beta_{3,S_t})(\beta_{0,S_t} + \beta_{1,S_t}\pi_{t,k} + \beta_{2,S_t} g_{t,k}) + \beta_{3,S_t} r_{t-1} + \gamma_{1,S_t}\hat{v}^*_{1t} + \gamma_{2,S_t}\hat{v}^*_{2t}]. \quad \text{(A.8)}
$$

To complete the evaluation of the log likelihood function L_1, we require the probability term $f(S_{1t}, S_{2t}|S_t, \tilde{\mathbf{Y}}_{t-1}, \tilde{\mathbf{X}}_T; \boldsymbol{\theta}, \hat{\boldsymbol{\theta}}_{12})$. We replace it with the smoothed probability:

$$
f(S_{1t}, S_{2t}|\tilde{\mathbf{X}}_T; \hat{\boldsymbol{\theta}}_{12}) = f(S_{1t}|\tilde{\mathbf{X}}_T; \hat{\boldsymbol{\theta}}_{12}) f(S_{2t}|\tilde{\mathbf{X}}_T; \hat{\boldsymbol{\theta}}_{12}), \quad \text{(A.9)}
$$

where the equality holds as the result of the independence of S_{1t} from S_{2t}. If S_t is independent of S_{1t} and S_{2t}, the replacement is relatively straightforward. Even though S_t is potentially correlated with S_{1t} and S_{2t}, correct inferences regarding S_{1t} and S_{2t} is possible at the cost of efficiency, and thus consistent estimation of the second step regression is guaranteed, as documented by Kim (2009).

The use of the generated regressors $\hat{v}^*_{1t}$ and $\hat{v}^*_{2t}$ in the second step regression renders biased the covariance matrix of $\hat{\boldsymbol{\beta}} = [\hat{\boldsymbol{\beta}}_0' \ \hat{\boldsymbol{\beta}}_1' \ \hat{\boldsymbol{\beta}}_2' \ \hat{\boldsymbol{\beta}}_3']'$ obtained as the negative of the inverse of the Hessian matrix. The adjusted covariance matrix to account for the effects of the generated regressors is obtained from the $(6 \times J : 6 \times J) - th$ block of:

$$\hat{Cov}(\hat{\boldsymbol{\theta}}) = \left[-\frac{\partial^2 \ln L_1(\boldsymbol{\theta})}{\partial \boldsymbol{\theta} \partial \boldsymbol{\theta}'} | \boldsymbol{\theta} = \hat{\boldsymbol{\theta}}^* \right]^{-1}, \tag{A.10}$$

where $\hat{\boldsymbol{\theta}}^* = [\hat{\boldsymbol{\beta}}_0' \ \hat{\boldsymbol{\beta}}_1' \ \hat{\boldsymbol{\beta}}_2' \ \hat{\boldsymbol{\beta}}_3' \ \hat{\boldsymbol{\gamma}}_1' \ \hat{\boldsymbol{\gamma}}_2' \ (\boldsymbol{\sigma}_u^2 + \hat{\gamma}_1^2 + \hat{\gamma}_2^2)' \ \widehat{\tilde{\mathbf{p}}}']'$, $\hat{\boldsymbol{\gamma}}_g^2 = [\hat{\gamma}_{g,1}^2 \ \hat{\gamma}_{g,2}^2 \ \cdots \hat{\gamma}_{g,J}^2]'$, $g = 1, 2$.

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Table 1. Beliefs, Policy Actions, and Key Variables Under Federal Reserve Chairmen since 1958

Chairman	Key beliefs/Policy actions	Key variables		
		INF.	OG.	INT.
W. M. Martin	**Late 1950s and 1960s (1958-1969):**	2.434	0.896	1.097
(1951:04 - 1970:01)	1. Permanent unemployment-inflation tradeoff			
	2. Economy's capacity: low prudent unemployment (4%)			
	3. At the very end, natural rate framework with a very low natural rate			
	Policy actions:			
	Expansion and accommodating monetary policy despite rising inflation			
	Mild tightening in 1969 to reduce inflation			
A. Burns	**Early 1970s (1970 - 1973):**	6.205	-0.782	-0.629
(1970:02 - 1978:01)	1. Natural rate framework with a very low natural rate (3.8%)			
	2. New emphasis on expected inflation			
	3. More pessimistic about the downward responsiveness of inflation to slack			
	4. The role of other factors but not monetary policy for the change in inflation			
	Policy action:			
	Expansion in 1970 - 1973			
	Middle 1970s (1974 - 1977):			
	1. Renewed belief that conventional aggregate demand restraint could reduce inflation			
	2. High natural rate (4.9%)			
	Policy action:			
	Contractionary monetary policy in 1974 but modest expansion in 1976			

Table 1. Beliefs, Policy Actions, and Key Variables Under Federal Reserve Chairmen since 1958: Continued

Chairman	Key beliefs/Policy actions	Key variables		
		INF.	OG.	INT.
W. Miller	1. Relatively low natural rate	7.915	0.999	-0.018
(1978:03 - 1979:08)	2. Resurgence of the view that slack would have little impact on inflation			
	Policy actions:			
	Expansion despite high and rising inflation,			
	Advocacy of various nonmonetary policies			
P. Volcker	1. Critical importance of low inflation: Inflation is very harmful	4.774	-2.599	4.178
(1979:08 - 1987:08)	2. Inflation responds to the output gap.			
	3. No substitute for aggregate demand restraint in controlling inflation			
	4. Relatively high estimate of the natural rate			
	Policy action:			
	Extremely contractionary policy			
A. Greenspan	1. Fundamentally same with Volcker about price stability in late 1980s and early 1990s	2.429	-0.457	1.886
(1987:08 - 2006:01)	2. Relatively low natural rate of unemployment since mid-1990s			
	3. Innovations limit inflation since mid-1990s			
	Policy action:			
	Moderate tightening to reduce mild inflation			
	In response to 1990-1991 recession, active expansion			

Note: INF., OG., and INT. denote the average of inflation rate, the output gap, and the ex-post real interest rate over the term of each chairman respectively.

Table 2. Estimation of parameters for a forward-looking monetary policy rule with regime switching

Parameters	$j=1$		$j=2$		$j=3$		$j=4$		$j=5$	
$\beta_{0,j}$	3.4830	(0.5748)	-1.9120	(2.3200)	6.0830	(3.0700)	2.5560	(1.7310)	0.7420	(1.5110)
$\beta_{1,j}$	-0.2605	(0.4813)	1.4740	(0.3791)	1.2630	(0.4117)	1.8020	(0.5184)	1.3250	(0.6687)
$\beta_{2,j}$	0.5697	(0.1335)	1.1440	(0.4880)	0.1481	(0.4451)	1.8110	(0.5243)	1.3810	(0.2262)
$\beta_{3,j}$	0.5393	(0.1117)	0.7358	(0.0888)	0.2044	(0.2548)	0.7958	(0.0393)	0.7808	(0.0654)
$\gamma_{1,j}$	0.0666	(0.0902)	-0.2467	(0.1335)	-1.0590	(0.8607)	-0.3597	(0.0805)	-0.1714	(0.0774)
$\gamma_{2,j}$	-0.3424	(0.0804)	-0.5303	(0.1452)	-1.2410	(0.7645)	-0.1755	(0.0622)	-0.1114	(0.0742)
$\sigma_{\omega^*,j}$	0.3567	(0.0385)	0.7126	(0.0758)	2.1890	(0.3464)	0.3655	(0.0381)	0.3050	(0.0373)
p_{jj}	0.9778	(0.0219)	0.9787	(0.0211)	0.9518	(0.0471)	0.9792	(0.0206)		
τ_j	1968:I		1979:IV		1985:I		1997:I			
$\ln(L)$	-156.90									

Note: j denotes the status of regime j. τ_j is the break date of regime j. Figures in the parentheses are standard errors. $\ln(L)$ is the value of log likelihood.

Table 3. Inferred monetary policy regimes

Responses	Regime 1	Regime 2	Regime 3	Regime 4	Regime 5
	(1956:I - 1968:I)	(1968:II - 1979:IV)	(1980:I - 1985:I)	(1985:II - 1997:I)	(1997:II -2005:IV)
Inflation	-0.2605 (0.4813)	1.4740 (0.3791)	1.2630 (0.4117)	1.8020 (0.5184)	1.3250 (0.6687)
Output gap	0.5697 (0.1335)	1.1440 (0.4880)	0.1481 (0.4451)	1.8110 (0.5243)	1.3810 (0.2262)
Inferred response	None to inflation	Firm to inflation	Firm to inflation	Firm to inflation	Moderate to inflation
	Moderate to output gap	Firm to output gap	None to output gap	Firm to output gap	Firm to output gap

Note: Figures in the third and fouth rows are estimated responses to inflation and output gap and figures in the parentheses are standard errors for each regime.

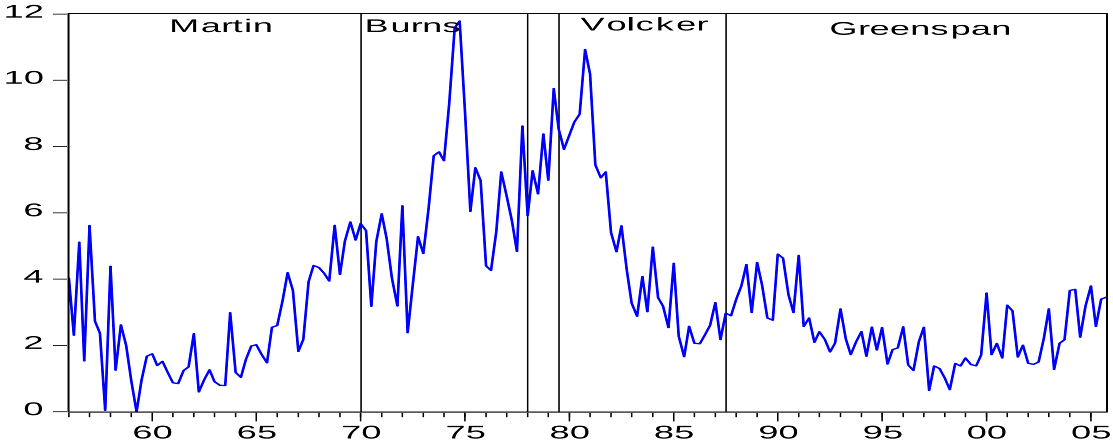
Table 4. Parameter estimates of AR(1) model of real interest rate with four structural breaks

Parameters	$l=1$		$l=2$		$l=3$		$l=4$		$l=5$	
μ_l	1.2450	(0.2030)	-0.3712	(0.4427)	5.0525	(0.3343)	2.8463	(0.3161)	-0.3126	(0.5851)
ϕ_l	0.2236	(0.1351)	0.4086	(0.1455)	0.1345	(0.2400)	0.6491	(0.1010)	0.6423	(0.1874)
$\sigma_{u,l}$	1.1385	(0.1125)	1.6245	(0.1839)	1.1688	(0.1889)	0.8808	(0.0828)	0.9447	(0.1576)
q_{ll}	0.9822	(0.0176)	0.9755	(0.0243)	0.9494	(0.0497)	0.9835	(0.0164)	-	-
$\tau_{D,l}$	1970:IV		1981:I		1986:I		2001:I			
$\ln(L)$	-312.09									

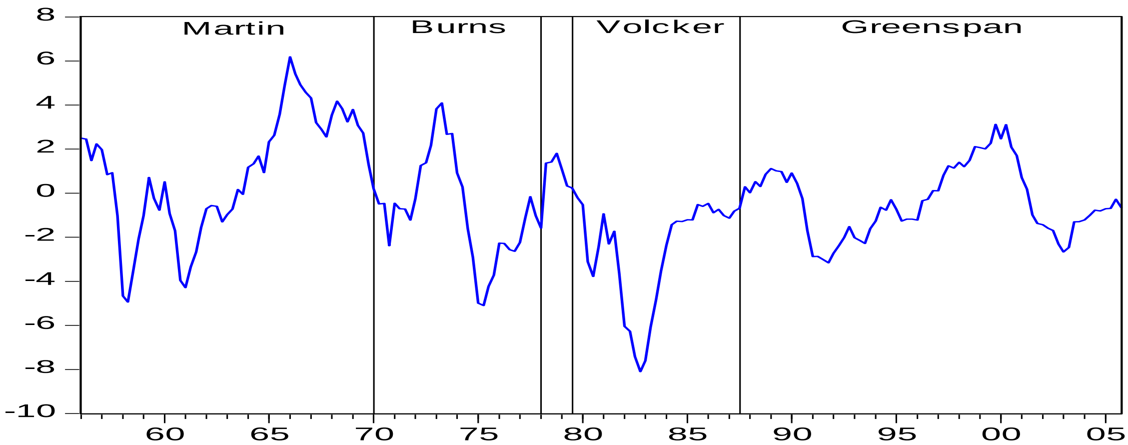
Note: l denotes the status of regime l. Figures in the parentheses are standard errors. $\tau_{D,l}$ is the break date of regime l. $\ln(L)$ is the value of log likelihood.

Figure 1. Key variables

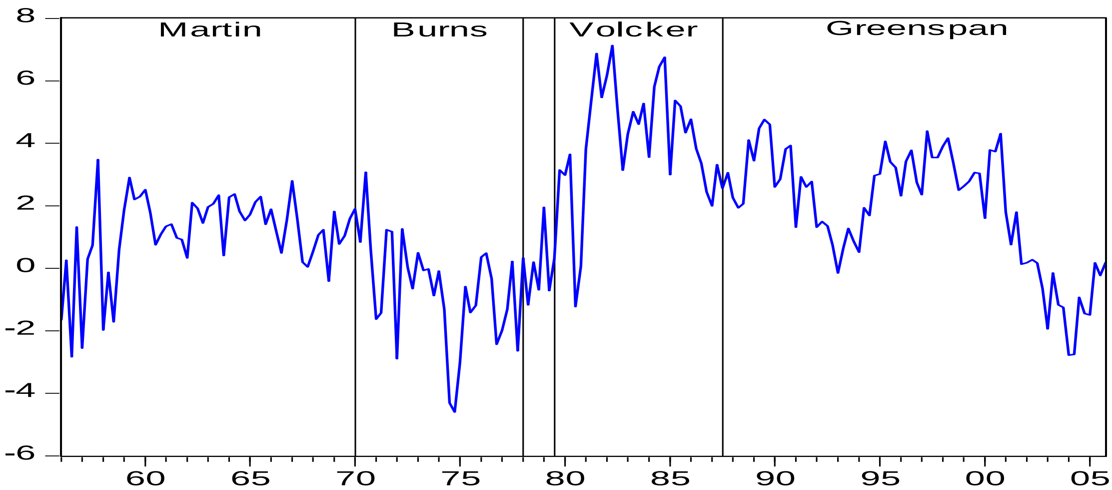
a. Inflation rate



b. Output gap



c. Ex post real interest rate



Note: The vertical lines indicate the quarter when a chairman's tenure begins.

Figure 2. Smoothed probabilities of inflation regimes

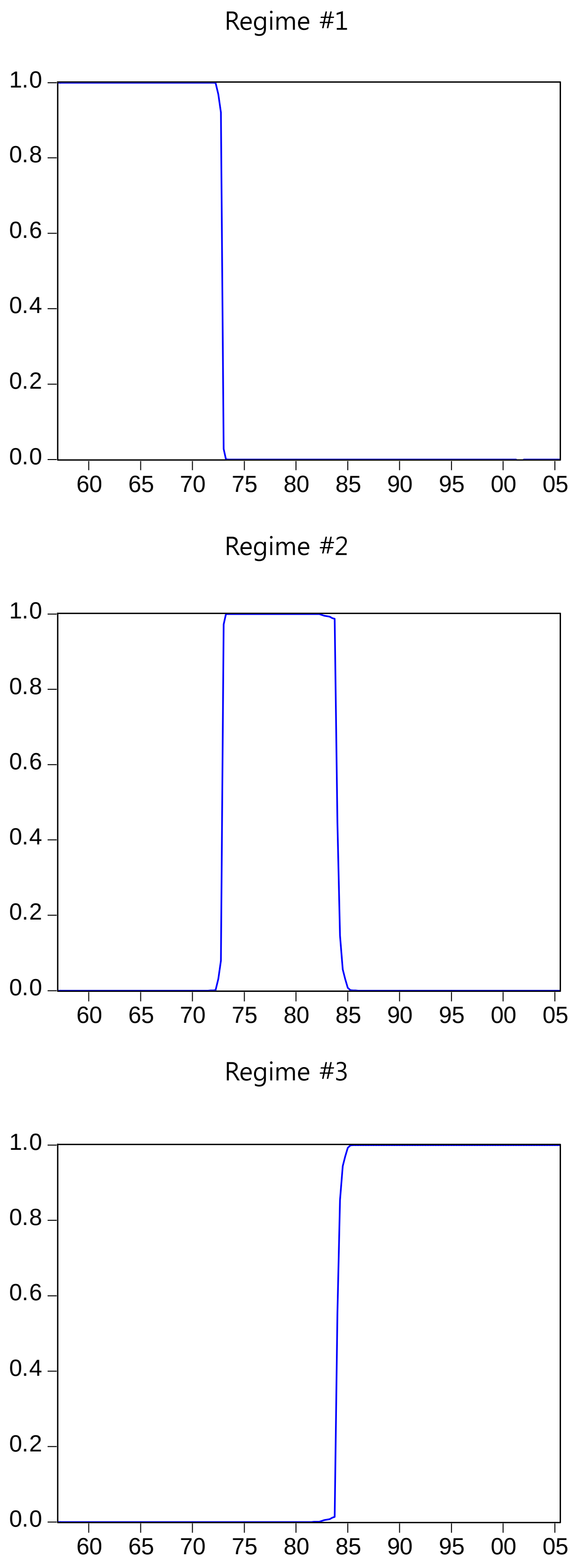


Figure 3. Smoothed probabilities of output gap regimes

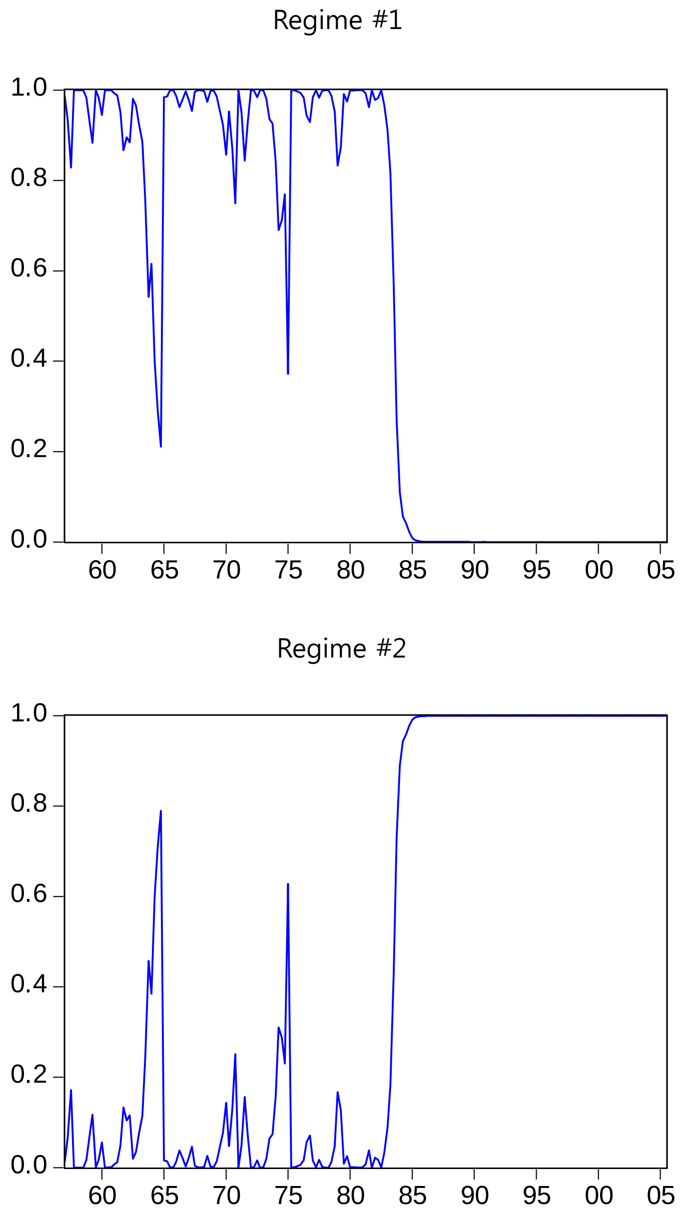


Figure 4. Smoothed probabilities of monetary policy regimes

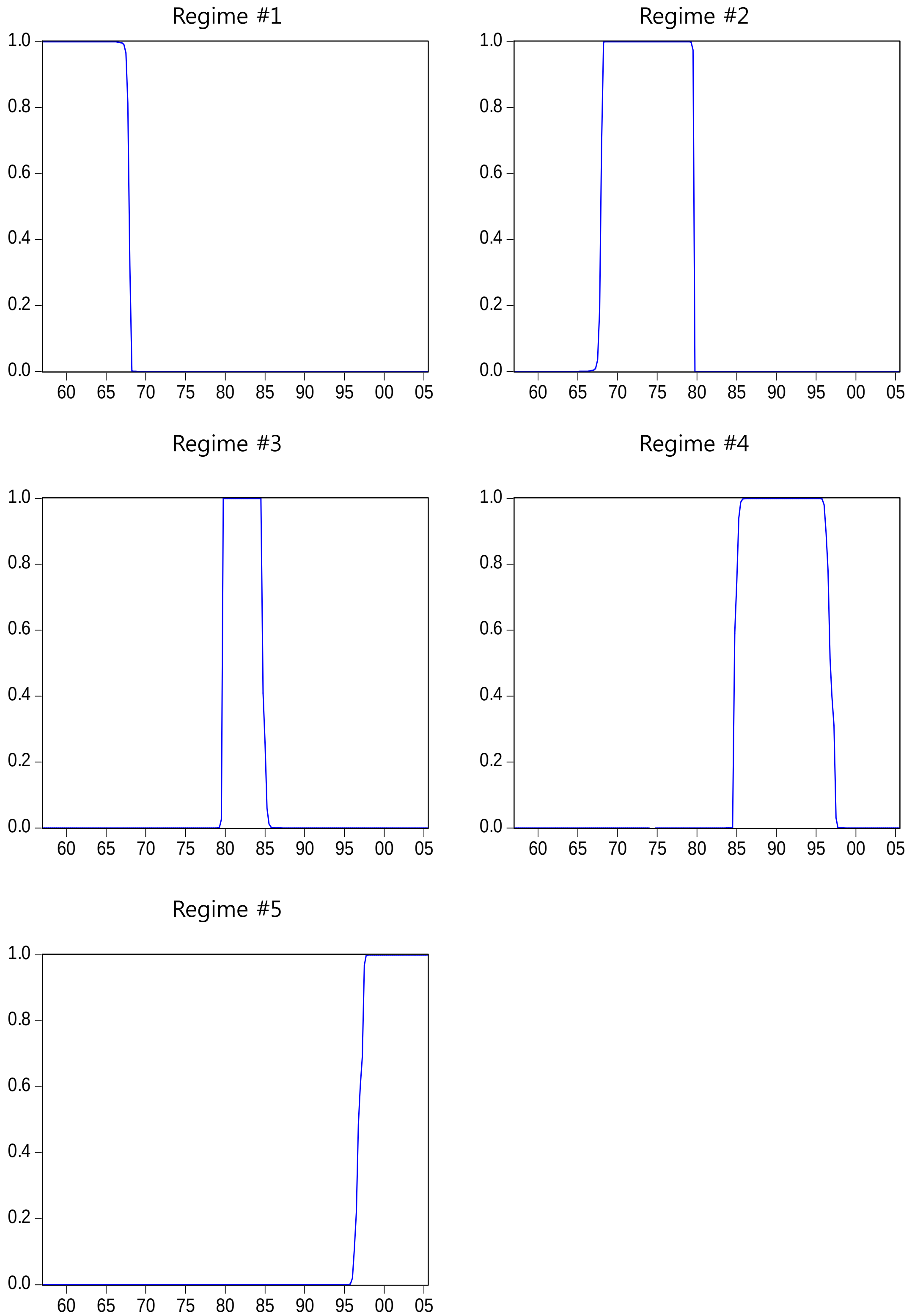


Figure 5a. Regime-switching response of federal funds rate to expected inflation and 90% confidence bands

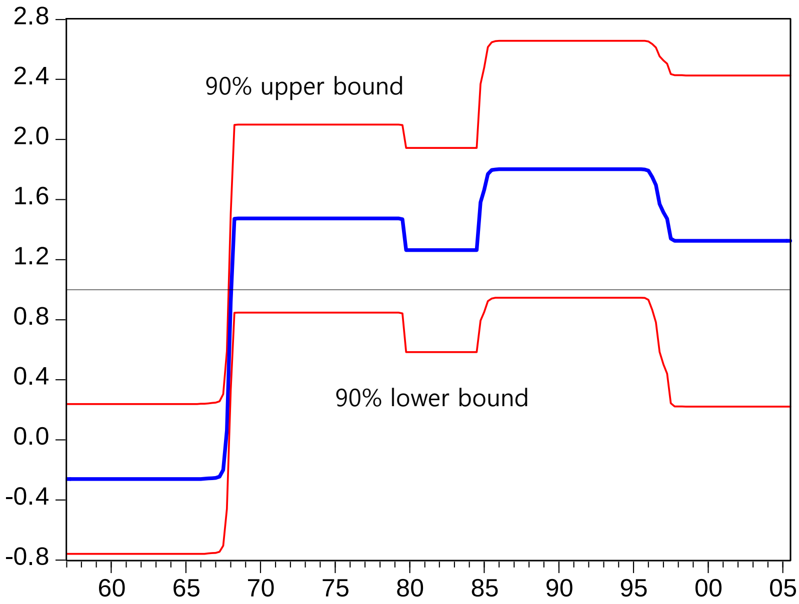


Figure 5b. Regime-switching response of federal funds rate to expected output gap and 90% confidence bands

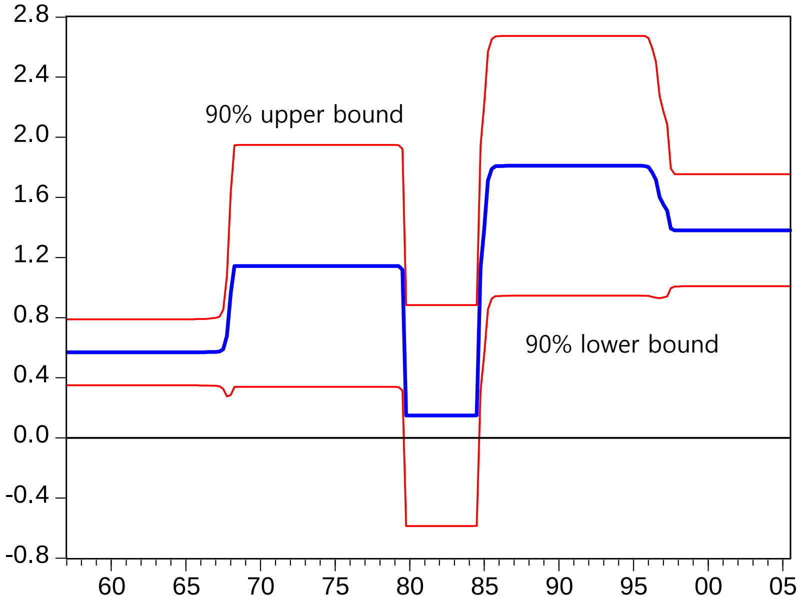


Figure 6. Smoothed probabilities of real interest rate regimes

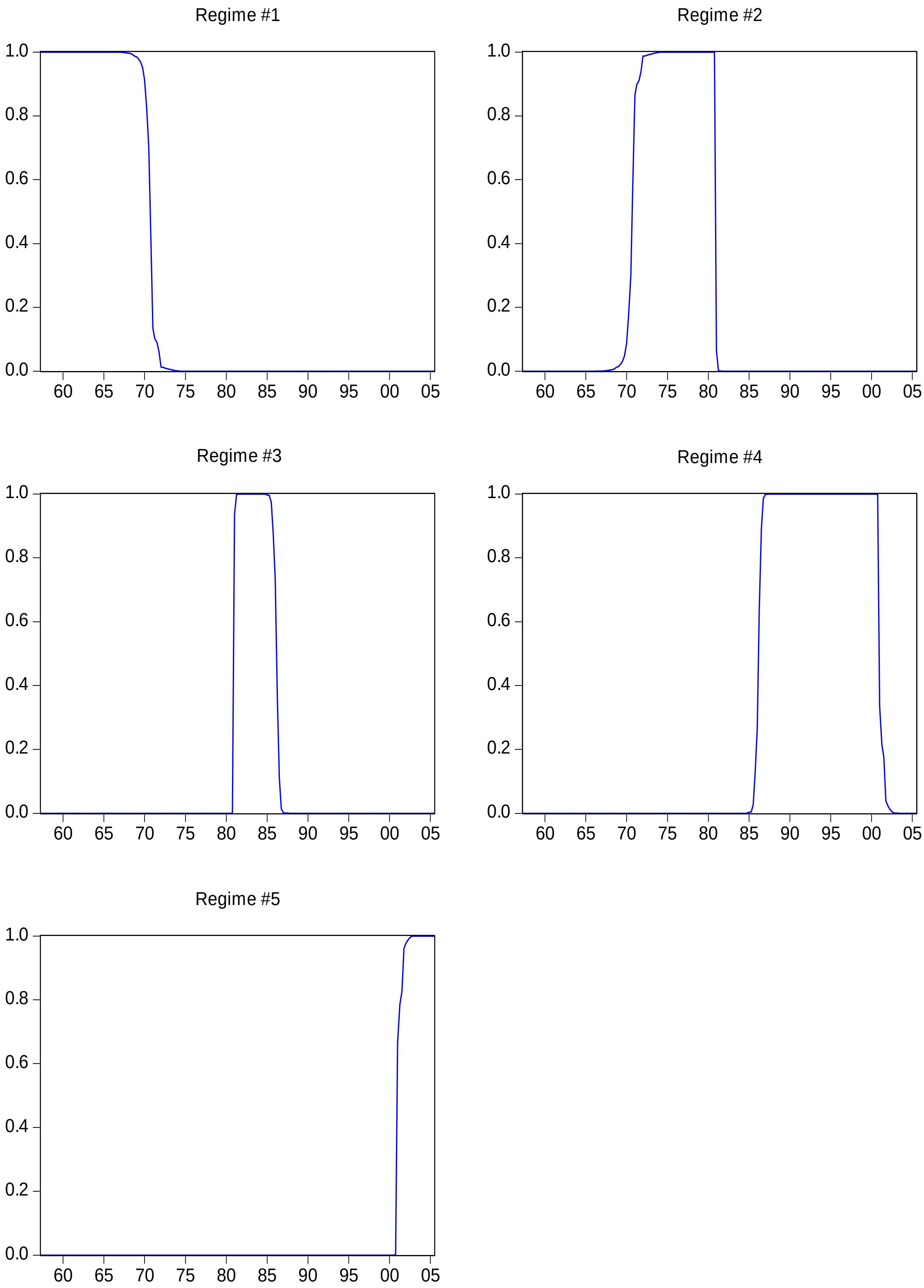


Figure 7a. Regime-switching mean of real interest rate and 90% confidence bands

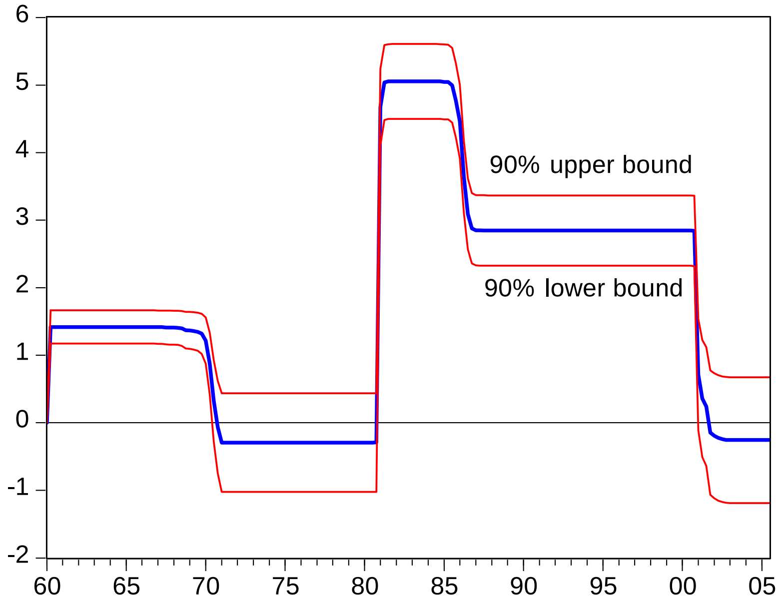


Figure 7b. Regime-switching persistence of real interest rate and 90% confidence bands