Real Time Changes in Monetary Policy – A Nonparametric VAR Approach

by

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Abstract

This paper investigates changes in monetary policy and the possibility of linkages with recent changes in the US economy towards increased stability. We propose a nonparametric tool to investigate local parameters and dynamic impulse response functions in a monetary VAR system. The advantage of this tool is that it allows recursive real time analysis of the local average effects of a shock to any given variable in the VAR system. In addition, the framework is very flexible as all model parameters are time varying at any point in time. This allows examination of complex dynamics such as nonlinearities, nonstationarities, and asymmetric behavior over time and across business cycle phases without a need to specify a functional form for the density function. The method is applied to real time unrevised data on inflation, nominal interest rates, and output in the U.S. The results suggest that there have been abrupt as well as gradual changes in the systematic part of the VAR, in the variances of the shocks, and in the monetary transmission mechanism. We find that the Fed's response to inflation and real activity, and the economy's response to monetary policy are highly nonlinear before 1980 and much more stable afterwards. In addition, we find that although changes in monetary policy are important to explain the smaller impact of shocks to output and inflation, changes in the propagation and transmission mechanisms may have been the source of increased stability.

KEY WORDS: Monetary Transmission, Local Estimation, Nonstationarities, Business Cycle, Stability, Nonparametric.

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1. Introduction

A large body of research has focused on the examination of the increased stability in output and inflation since the mid 1980s. Some authors attribute it to changes in the real side of the economy, such as technological and financial innovations that may affect firms and consumers' behavior and make the economy less susceptible to shocks. Others reckon that the culprit is a reduction in the size of shocks rather than in its propagation through the economy. In particular, the increased stability might be associated with changes in the impact of monetary shocks on the economy or with changes in the monetary transmission mechanism. However, there is no consensus on whether there have been changes and on their nature.

The investigation of these potential changes is important as it has implications on the temporary or permanent nature of this stability. If the main source is a reduction in the occurrence or size of shocks, economic stability will subside when confronted with larger ones, whereas it will be more lasting if associated with changes in the propagation of shocks. There has been recent evidence indicating the role of changes in monetary policy on real economic activity. Several papers find that the impact of monetary policy on inflation and output has reduced in the last decades.[1] For example, Boivin and Gianonni (2002, 2007) using a structural vector autoregression and a general equilibrium model, respectively, show a smaller impact of monetary policy shocks on the economy since the early 1980s. This finding has led to investigation on whether monetary policy has become less powerful, perhaps because changes in financial innovations or other structural changes may have enabled the private sector to insulate themselves from the impact of fluctuations in interest rate. On the other hand, the evidence might reflect the opposite, that is, a more transparent and effective monetary policy conduct may have counteracted the impact of shocks to inflation and output (see e.g. Clarida, Galí, and Gertler 2000 and Boivin and Giannoni 2002).

This paper proposes a nonparametric vector autoregression to investigate potential changes in the dynamics of interest rates, output, and inflation. We use a recursive framework in which all model parameters are time varying at any point in time. This allows examination of potential nonlinearities and nonstationarities in the dynamics of the VAR system, and the nature of changes in the monetary policy shocks, in the Fed's reaction function, and in the monetary transmission mechanism to the economy. In particular, we can examine important questions such as whether there have been changes in the effectiveness of monetary policy or a reduction in the impact of monetary policy shocks on output and inflation, among others.

[1] See the special issue of the Federal Reserve Bank of New York's Economic Policy Review associated with the Conference Financial Innovation and Monetary Transmission, 2001. This is the overall conclusion of the Conference as compiled in Kuttner and Mosser (2002).

Several recent papers have investigated potential changes in the monetary policy conduct over time. An influential paper is Clarida, Gali and Gertler (2000), which studies the Fed's reaction function in the last decades. They provide evidence that the Taylor's rule was not met in the pre-Volcker period – that is, an increase in inflation was associated with a smaller raise in interest rate. However, they find evidence of abrupt changes related to Volcker's monetary policy in 1979, from which point on the Fed's reaction function has been consistent with the Taylor's rule.

This finding has been contested regarding the nature of changes – whether they were abrupt or more gradual. In addition, some authors find that taking into account heteroskedasticity or the use of revised versus real time data might change the conclusions. Cogley and Sargent (2001) using a reduced VAR with drifting parameters find that changes in monetary policy have been more gradual. Sims (1999, 2001), Stock (2001), and Sims and Zha (2004) provide evidence that Cogley and Sargent's (2001) conclusions might be related to changes in the variance of shocks pre and post Volcker. However, Cogley and Sargent (2005), extending their previous work to include heteroskedasticity in the VAR shocks, find that there have been significant changes in the policy parameters separated from changes in variance. Orphanides (2001) points to problems in estimating the Fed's reaction function with revised data since this conceals how policymakers might have historically reacted to the information available to them at each point in time. Orphanides (2002, 2004) reestimate Clarida, Gali and Gertler's (2000) model using real time data and find that the Fed's reaction function is not very different pre and post Volcker.

Boivin (2005) proposes a model that combines the main issues discussed in the literature. In particular, a forward looking Taylor's rule with time varying parameters that takes into account heteroskedasticity in the policy shock is estimated using real time data. Boivin (2005) finds evidence of important changes in monetary conduct over time, albeit these changes are modeled as being gradual. In particular, the monetary policy response to inflation was strong until 1974, but decreased substantially from this date until 1980. On the other hand, the Fed's response to real activity reduced throughout the 1970s. In addition, the transition under Volcker was more gradual with most changes taking place between 1980 and 1982. From the mid-1980s on the evidence is of an increased Fed's response to inflation and a reduction in its response to real activity.

The monetary VAR model proposed in this paper is recursively estimated and yields time series for each of the model parameters. Since all parameters are time varying at any point in time, the variances of the shocks can display heteroskedasticity. In addition, the framework allows for abrupt or gradual changes in the parameters as well as asymmetries across business cycle phases. Notice that the timing of the change can be different for each parameter. The analysis is carried out using real time unrevised data. The impulse response functions as well as the time series of all estimated parameters of the model are used as tools to investigate changes in monetary policy and in real activity over time.

The VAR model enables us to separate out systematic responses to changes in interest rates from exogenous monetary policy shocks. The errors from the interest rate equation are generally interpreted as monetary policy shocks and taken as a measure of policy changes. Cochrane (1994) and Rudebusch (1998), among others, have criticized exogenous policy shocks for the implication that the Fed randomizes its policy decisions, or because of a low correlation between these shocks and some standard measures of past policy actions. As argued by Bernanke and Mihov (1998) and Christiano, Eichenbaum, and Evans (1999) there are some random elements affecting policy decisions such as changes in preferences of policymakers regarding the relative importance of inflation stabilization versus recession. Furthermore, when VARs are estimated using ex-post revised data, the shocks could also reflect measurement error due to data revisions. As discussed in Bernanke and Mihov (1998) and Orphanides (2001), the presence of data revisions in the errors may bias the response of some variables in addition to compromising their interpretation as monetary policy shocks. The use of unrevised real time data, on the other hand, unveils how policymakers have historically reacted to the information available to them at each point in time for implementing policy. The reaction functions reflect uncertainties regarding the state of the economy and inflation, as they rely on preliminary and incomplete information about the variables. As a result, the residuals obtained from the policy reaction function reflect monetary policy shocks as taken place in real time.

The model is estimated using a nonparametric tool to investigate local parameters and local dynamic impulse response functions in a VAR system. In general, nonparametric estimation requires aggregation of coefficients for the purpose of statistical inference. This paper, in contrast, proposes a method to construct nonparametric local parameters based on Local Linear Least Squares that do not involve aggregation. The advantage of this tool is that it allows real time analysis of the local average effects of a shock to any given variable in the VAR system for each observation. In addition, potential nonlinearities, nonstationarities, and asymmetric behavior can be examined without the need for specifying a functional form for the density function, and information in the tail regions can be incorporated in the model.

Our results suggest that there have been abrupt as well as gradual changes in the systematic part of the estimated VAR, in the variances of the shocks, and in the monetary transmission mechanism. We find that the Fed's response to inflation and real activity, and the economy's response to monetary policy are highly nonlinear before 1980-1982 and much more stable afterwards. This result is probably the reason behind the conflicting findings obtained in the literature. In particular, the volatility and large swings in the relationships between these series pre-1982 may compromise sub-samples analysis – as it is commonly done in the literature – depending on the dates chosen to split the sample. In addition, not taking into account nonstationarities in the form of abrupt breaks can affect the results.

We find that the Fed's reaction to real activity was increasingly stronger from 1971 to 1981, where it reached a peak, and has been gradually decreasing since. However, the current values are still stronger in the 2000s than they were in the 1960s and 1970s. On the other hand, the economy's response to monetary policy was weaker in the first period but increasing over time until a peak in 1980. In fact, the contractionary impact of higher rates on real activity was strongest between 1967-1970 and 1976-1982, and has been getting steadily weaker from 1982 on. However, the relationship in the 2000s is still strong than the average values prevailing between 1970 and 1975.

With respect to the Fed's reaction to inflation, it was historically strongest around the 1970 recession. During most of the 1970s, however, the Fed's reaction was the weakest compared to the rest of the sample even though it showed an upward movement with a peak in 1981. This is in accord with the findings in Clarida, Galí, and Gertler (2000) and Boivin (2005). From this date on, it reduced gradually until the end of the sample, but once again the current values are still above the average in the 1970s. Finally, we find that until 1972 increases in interest rate led to a fall in subsequent inflation. However, from 1972 on this relationship became positive, and this association – known as the price puzzle in the literature – is strongest between 1976 and 1986. The price puzzle has being steadily decreasing since 1986.

Using the resulting time series of estimated parameters, impulse responses, and variances we also investigate whether the increased stability in the economy since the early 1980s is due mainly to a reduced important of shocks or to changes in their propagation mechanism. We find that although both play a role, the timing of the breaks and the turning points in which the gradual changes have occurred suggest that changes in the transmission mechanism may be a causal factor in the decreased response of output and inflation to monetary policy. We also find that the recent dynamics of interest rate may have been playing an important role, reflecting a more proactive monetary policy aimed at stabilizing output and inflation.

The structure of this paper is as follows: Section 2 presents the monetary VAR model. Section 3 discusses the nonparametric estimation. The empirical results are presented in Section 4. Section 5 summarizes the main findings and Section 6 concludes.

2. Monetary Vector Autoregression Model

Following Bernanke and Blinder (1992), let's assume that the "true" model of the economy is represented by the structural vector autoregression:

$$\mathbf{Y}_t = \sum_{i=0}^{p} E_i \mathbf{Y}_{t-i} + \sum_{i=0}^{p} C_i R_{t-i} + \mathbf{v}_t^y \qquad (1)$$

$$R_t = \sum_{i=0}^{p} D_i \mathbf{Y}_{t-i} + \sum_{i=0}^{p} G_i R_{t-i} + v_t^R \qquad (2)$$

The system (1) and (2) allows both contemporaneous and p lagged values of each variable in any equation. Let $\mathbf{Y}_t$ be a vector of nonpolicy macroeconomic variables, and R_t a scalar representing the policy instrument. Equation (2) describes the reaction function of the policy instrument to changes in the system while equation (1) represents the response of the nonpolicy variables. The vector of structural disturbances $\mathbf{v}_t^y$ is orthogonal and also mutually uncorrelated with the scalar exogenous policy shock v_t^R. The latter assumption implies that v_t^R is independent from contemporaneous macroeconomic conditions, which is part of the definition of an exogenous policy shock.

Equations (1) and (2) are not identified if further assumptions are not imposed. Following Bernanke and Blinder (1992), Rotemberg and Woodford (1997), Bernanke and Mihov (1998), Boivin and Gianonni (2002), among several others, a minimum set of restriction that allows identification of the impact of policy shocks is to assume that they affect the macroeconomic variables with one lag, $C_o = 0$. That is, the nonpolicy variables depend on contemporaneous and lagged values of $\mathbf{Y}_t$, but only on lagged values of R_t. This assumption implies a delayed response of the economy to policy shocks due to lags in the transmission mechanism. The policy variable, on the other hand, is assumed to respond to all contemporaneous and lagged variables in the system. That is, policymakers are assumed to have contemporaneous information about the nonpolicy variables. This is a plausible assumption with the use of unrevised real time data, which is the first information available to the Fed to implement policy on a current basis.[2]

The structural VAR can be written as:

$$\mathbf{Y}_t = (I - E_0)^{-1} \sum_{i=1}^{p} E_i \mathbf{Y}_{t-i} + (I - E_0)^{-1} \sum_{i=1}^{p} C_i R_{t-i} + (I - E_0)^{-1} \mathbf{v}_t^y \qquad (3)$$

$$R_t = \sum_{i=1}^{p} [D_i + D_0 (I - E_0)^{-1} E_i] \mathbf{Y}_{t-i} + \sum_{i=1}^{p} [G_i + D_0 (I - E_0)^{-1} C_i] R_{t-i} + G_0 R_t + D_0 (I - E_0)^{-1} \mathbf{v}_t^y + v_t^R, \qquad (4)$$

which shows the relationship between the reduced-form and structural coefficients. Given the assumptions proposed, the estimation of this dynamic system can be implemented using OLS in each equation. The Cholesky decomposition of the covariance matrix is applied assuming that v_t^R is

[2] We have alternatively estimated the models assuming that policymakers know only lagged values of the nonpolicy variable, which is motivated by lags in the collection of data. This assumption is more appropriate when using revised data. However, given the low correlation between the disturbances in the system, we find the results to be very similar and qualitatively equivalent in both cases.

uncorrelated with $\mathbf{Y}_t$ (the policy variable ordered last), which allows estimation of the exogenous policy shock v_t^R and calculation of the impulse response functions.

The propagation of the shocks to the economy is measured by:

$$(I-E_0)^{-1}\sum_{i=1}^{p} E_i \mathbf{Y}_{t-i} + (I-E_0)^{-1}\sum_{i=1}^{p} C_i R_{t-i} \text{ and}$$

$$\sum_{i=1}^{p}[D_i + D_0(I-E_0)^{-1}E_i]\mathbf{Y}_{t-i} + \sum_{i=1}^{p}[G_i + D_0(I-E_0)^{-1}C_i]R_{t-i} + G_0 R_t$$

In particular, the reaction function of the Fed to output and inflation can be examined through the coefficients associated with their lagged values in the interest rate equation. On the other hand, the response of output and inflation to changes in interest rate can be analyzed through the coefficients associated with lagged values of interest rate in their equations. Finally, potential changes in the transmission mechanism are studied though the impulse response functions.

3. Parametric and Nonparametric Estimation

Parametric Estimation

Let equations (3) and (4) be represented by the $(n \text{ x } 1)$ vector $\mathbf{Z}_t$ containing the values that n variables take at date t, which follows a *pth*-order vector autoregression:

$$\mathbf{Z}_t = \mathbf{c} + \boldsymbol{\beta}_1 \mathbf{Z}_{t-1} + \boldsymbol{\beta}_2 \mathbf{Z}_{t-2} + \ldots + \boldsymbol{\beta}_p \mathbf{Z}_{t-p} + \mathbf{v}_t \qquad \mathbf{v}_t \sim i.i.d.N(0,\boldsymbol{\Omega}), \tag{5}$$

and let $\mathbf{x}_t$ be a vector containing a constant and the p lags of each of the elements of $\mathbf{Z}_t$:

$$\mathbf{x}_t \equiv \begin{bmatrix} 1 \\ \mathbf{Z}_{t-1} \\ \mathbf{Z}_{t-2} \\ \vdots \\ \mathbf{Z}_{t-p} \end{bmatrix} \quad and \quad \mathbf{B}' \equiv [\mathbf{c}\ \boldsymbol{\beta}_1\ \boldsymbol{\beta}_2 \ldots \boldsymbol{\beta}_p].$$

Thus, $\mathbf{x}_t$ is a $[(np+1) \text{ x } 1]$ vector and $\mathbf{B'}$ is a $[n \text{ x } (np+1)]$ matrix. The system can then be written as:

$$\mathbf{Z}_t = \mathbf{x}_t'\mathbf{B} + \mathbf{v}_t \tag{6}$$

OLS parametric estimation of equation (6) would yield:

$$\underset{[nx(np+1)]}{\hat{\mathbf{B}}'} = [\sum_{t=1}^{T} \mathbf{Z}_t \mathbf{x}_t'][\sum_{t=1}^{T} \mathbf{x}_t \mathbf{x}_t']^{-1}.$$

The r*th* row of $\hat{\mathbf{B}}'$ is:

$$\underset{[1x(np+1)]}{\hat{\boldsymbol{\beta}}_r'} = [\sum_{t=1}^{T} \mathbf{Z}_{rt} \mathbf{x}_t'][\sum_{t=1}^{T} \mathbf{x}_t \mathbf{x}_t']^{-1}.$$

For our specific monetary VAR, $\mathbf{Z}_t = (Y_{1t}, Y_{2t}, R_t)$ is the vector containing the nonpolicy variables, Y_{1t}, Y_{2t}, and the policy instrument R_t, $\mathbf{v}_t = (v_t^{y_1}, v_t^{y_2}, v_t^R)$, and $\hat{\boldsymbol{\beta}}'_r$ is the *[1×(12+1)]* vector of regression coefficients for the *rth* equation, with *p=4* lags and *n=3*.[3]

In general, the impact of transitory shocks to the VAR system is studied through impulse response functions (IRFs) – the dynamic multipliers are obtained from the MA(∞) representation of the VAR and orthogonalized using Choleski's decomposition.

Nonparametric Estimation

We propose a nonparametric method to estimate the density function that involves local estimation of the model parameters. More specifically, the VAR is estimated using the nonparametric local linear least squares method (LLLS). This method fits a local least squares line within an interval as specified by the window width of a kernel density function. The empirical kernel density function places more weight on the observations closest to the conditioning observation and increasingly less weight as the distance between the measuring and conditioning observations increases. This conditioning process is implemented for *each and every* observation of each regressor, which enables analysis of information in the tail regions. Thus, for *T* observations, this estimation procedure yields *T* sets of each of the estimated parameters and impulse response functions, as explained below. Given the assumptions proposed in the last section, the nonparametric VAR can be estimated equation-by-equation as in the parametric case.

Let ***W****= (**Z**, **x**)* be a *[(np + n)* x *1]* vector, *f = f(w)* be the continuous density function of ***W*** at a point *w*, and $w_1, \cdots, w_T$ be the observations drawn from *f*. The nonparametric method allows direct estimation of *f(w)* without assuming its form. The weighting process is implemented using a multivariate Gaussian kernel density (estimator of $\hat{f}$) based on Rosenblatt-Parzen's criterion (Rosenblatt 1956, Parzen 1962). Let $j = 1, \ldots, T$ be the j^{th} estimation of the Gaussian kernel density function, $\boldsymbol{K}_j$, which measures the distance between the i^{th} observation of the regressor set, for $i = 1, \ldots, T$, and the j^{th} conditioning observation of the regressor set:

$$\mathbf{K}_j = \sum_{i=1}^{T} \mathbf{K}(\boldsymbol{\Psi}_j) \tag{7}$$

[3] In the empirical estimation we find that four is the optimal lag length of the VAR using AIC and SBC.

where $\mathbf{K}(\boldsymbol{\Psi}_j) = \frac{1}{(2\pi)^{\frac{k}{2}}} exp\left\{-\frac{1}{2}\left[\left(\frac{x_{1i}-x_{1j}}{h_1}\right)^2 + \cdots + \left(\frac{x_{mi}-x_{mj}}{h_m}\right)^2 + \cdots + \left(\frac{x_{ki}-x_{kj}}{h_k}\right)^2\right]\right\}$,

$\boldsymbol{\Psi}_j = \left[\frac{x_{1i}-x_{1j}}{h_1} \cdots \frac{x_{mi}-x_{mj}}{h_m} \cdots \frac{x_{ki}-x_{kj}}{h_k}\right]$, and h_m is the window width or the interval in which the LLLS is fitted for the m^{th} regressor, for $m = 1, \ldots, k$. The closer the i^{th} observation of each of the regressors is to the corresponding j^{th} conditioning observation, the larger is the weight the kernel $\mathbf{K}_j$ assigns to it. This weighting process is implemented for all T observations of the VAR based on each j^{th} conditioning observation. From the j^{th} VAR estimation, the j^{th} conditional local slope coefficients are obtained, which is discussed in more detail further below. Since the kernel assigns a weight to each observation of the dataset that sums to unity, the local nonparametric regression resembles the Weighted Least Squares (see e.g. Cleveland 1979 and Stone 1977).

The choice of the window width is important in non-parametric estimation. Over-smoothing of the data causes an increase in bias and a decrease in variance, whereas under-smoothing leads to a smaller bias but a larger variance. The window width is chosen based on the minimization of the sum of the squared errors of the local nonparametric regressions (Stone 1977 and Cai 2007). This yields a window width, h_r, for each r^{th} equation of the VAR with $r = 1, \ldots, n$.[4] The window width h_r is obtained through the use of an extensive grid search and a plug-in method for each equation of the VAR. The resulting optimal window width not only minimizes the sum of the squared errors of the local nonparametric regressions, it also takes into account the possibility of saddle-points.

The regressor coefficients for the *jth* estimation obtained with the local nonparametric method are:

$$\underset{[nx(np+1)]}{\hat{\mathbf{B}}_j{}'} = [\textstyle\sum_{t=1}^{T}\mathbf{Z}_t\mathbf{K}_j\mathbf{x}_t'][\sum_{t=1}^{T}\mathbf{x}_t\mathbf{K}_j\mathbf{x}_t']^{-1}$$

The *rth* row of $\hat{\mathbf{B}}'$ for the *jth* estimation is:

$$\underset{[1x(np+1)]}{\hat{\boldsymbol{\beta}}_{rj}'} = [\textstyle\sum_{t=1}^{T}\mathbf{Z}_{rt}\mathbf{K}_j\mathbf{x}_t'][\sum_{t=1}^{T}\mathbf{x}_t\mathbf{K}_j\mathbf{x}_t']^{-1}$$

Thus, estimation of all T conditional sets of local nonparametric estimators yield T x *[n* x *(np+1)],* regressor coefficients. In our particular monetary VAR, the number of regressor coefficients estimated for each *jth* run is *39*. Thus, the nonparametric estimation yields a total of (*Tx39)* of those local

[4] In our empirical application, the window widths are nearly identical for all three equations of the monetary VAR.

parameters when applied to one dataset. Notice that the real time recursive analysis involves estimation of hundreds of datasets as explained in the next section.

In order to orthogonalize the MA coefficients through the use of the Choleski decomposition, the error terms from each *rth* equation are obtained from the LLLS regressions to form the variance-covariance matrix. The formation of the IRFs is then obtained in the same manner as for the parametric VAR.[5] For our particular monetary VAR, *(n x n)* impulse response functions are estimated for each *jth* run. Thus, a total of *(Tx9)* irfs are obtained with the local nonparametric estimation.

4. Empirical Results

The Data

We use real-time data for the analysis. These are the original and unrevised data available to economic agents at any given date in the past as opposed to the commonly used revised data currently available from government statistical agencies. The real time series were painstakingly compiled by the Federal Reserve Bank of Philadelphia. Details on how they were constructed can be found in Croushore and Stark (2001).

The series used in the VAR are changes in the Federal Funds rate, and the annualized log of the first difference of real GDP and of the GDP deflator.[6] The last two variables have been substantially revised over the period considered, including major definitional changes as well as correction of discrepancies caused by lags in the availability of primary data. We use the collected real time realizations, or *vintages*, of these time series as they would have appeared at the end of each month from the fourth quarter of 1965 to the first quarter of 2007. For each vintage the sample collected begins in the second quarter of 1959 and ends with the most recent data available for that vintage. Since the federal funds rate is not revised we use the currently available series.[7] We do not include the index of commodity prices, as it is commonly done in the literature to avoid the price puzzle, that is, that monetary tightening tends to lead to an increase rather than a fall in the price level. The reason for not including commodity prices is that we want to investigate potential changes in the price puzzle over time.

[5] We can also obtain global coefficients from the nonparametric estimation of the VAR through the use of aggregation. In this method the nonparametric slope coefficients for each equation and each regressor are aggregated by taking their average or their sum. The resulting global set of AR coefficients is then used to form the MA coefficients needed to form the IRFs. We have also estimated the model using these methods as well. The results are available upon request.
[6] See Orphanides and Van Norden (2005) for a discussion of the reliability of real time estimates of alternative ways to detrend output in real time.
[7] The Federal Funds rate is obtained from the St. Louis F.R.E.D.

Results

We report the results for the nonparametric VARs, which is recursively estimated for each point in the sample using vintage data from 1965:4 to 2007:1. As discussed in the previous section, from a dataset with T' observations, T sets of localized nonparametric conditional orthogonalized impulse response functions can be obtained, where T refers to the number of observations used to estimate the VAR(p) once the $p=4$ lags are taken into account.

In contrast to the parametric VAR, the nonparametric VAR yields local as well as global estimators. The local nonparametric estimation applied recursively to the increasing real time samples yields *23* sets of parameters for the 1965:4 vintage, based on the observations from 1959:1 to 1965:3 after taking account the lags; *24* sets for the 1966:1 vintage and so on until the 2007:1 vintage, which yields *188* sets of parameters. Thus, adding up, the local estimation results in *17,513* sets for each of the estimated parameters (variances, regressor coefficients, and irfs). This permits the study of localized effects of a shock to the system at any given point in time.

On the other hand, the aggregate nonparametric estimation applied recursively to the real time data results in only *1* set of global parameters for the 1965:4 vintage, since the average of the local parameters is considered; *2* sets for the 1966:1 vintage and so on until the 2007:1 vintage, which results in *166* sets of parameters. These are also the sets that would have been obtained in the recursive parametric estimation.

The aggregated parameters do not have well specified properties. Thus, we only report the results of the local parameters. However, given the vast number of parameters obtained and the rich dynamics that the estimation provides, the choice of the parameter sets to report must be based on the goal at hand. For example, for the 1965:4 vintage there are *23* sets of parameters equivalent to observations from 1959:1 to 1965:3, obtained from $\boldsymbol{\Psi}_j = \left[\frac{x_{1i} - x_{1j}}{h_1} \cdots \frac{x_{mi} - x_{mj}}{h_m} \cdots \frac{x_{ki} - x_{kj}}{h_k} \right]$, for j = 1965:3 and for i = 1959:1, …, 1965:2 (the kernel is unity for $i = j$). Recall that the window width determines how many of the x_is around x_j are to be used in forming the estimation of the parameters. The observations are weighted by the kernel $\mathbf{K}(\boldsymbol{\Psi}_j)$ for each j. For values of x_i that lie far from x_j, and with any given window width h, $\boldsymbol{\Psi}_j$ will be large and so the kernel will be small. Hence, these observations get low weight in the determination of the parameters.

Notice that for the 1966:1 vintage there are *24* sets of parameters, which include two sets of estimated parameters for x_i = 1965:4, one based only on current and past information, and another that is based on information one step ahead. Equivalently, there are *25* sets of parameters for the 1966:2 vintage, which include three sets for x_i= 1965:4, which are based on past and current information as well as data one and two-step ahead. Finally, for the 2007:1 vintage, there are *188* sets of parameters for x_i = 1965:4 (and

17,513 for each x_i for $i = 1,\ldots, T$) – the last set includes full information of the whole sample and is equivalent to estimating the model using revised data as of 2007:1.

Given the goals of this paper, we choose to report the local nonparametric parameters that are estimated using only current and past information of the unrevised real time data.[8] Thus, the real time recursive nonparametric estimation results in *(166* x *3)* variances, *(166* x *3)* covariances, (*166* x *39*) time varying coefficients, and *(166* x *9)* impulse response functions.[9]

4.1 Stability

Characteristic Roots

Several recent papers have examined parameter stability in monetary VAR models. While some find evidence of stability, such as Bernanke and Mihov (1998) and Christiano, Eichenbaum, and Evans (1999), others find that the parameters of monetary VAR are unstable as in Bernanke, Gertler, and Watson (1997), Boivin (1999), and Boivin and Gianonni (2002a, b), among several others. Boivin (1999) argues that the difference in results might be related to the power and small sample properties of the stability tests. Boivin and Gianonni (2002) apply Andrews (1993) sup-Wald test on each equation of the VAR in order to test jointly for the stability of all coefficients on the lags of a given variable. The evidence of instability is found to be strong. Although this test also allows estimation of break dates as a by-product, Boivin and Gianonni (2002) find that the estimated timing of the breaks is not consistent for each combination of the dependent variable and lags of a regressor.

In this section we investigate the stability of the monetary VAR model by estimating recursively, based on real time data, the characteristic roots of the system. The evolution of the roots allows identification of the location of breakpoints in the system. In addition, these dates are based on information as it actually took place at each point in time. The general stability condition for the vector autoregressive system is that the inverse of all characteristic roots must lie within the unit circle. We use numerical methods to obtain the characteristic roots of the VAR and to verify Schur theorem, which gives the necessary and sufficient conditions for stability.

We obtain a time series of the real time modulus of the largest inverse root of the characteristic of the autoregressive system, which is plotted in Figure 1. Each point in the graph corresponds to the results obtained from the estimation of a VAR in real time. The modulus increases above one indicating instability of the monetary VAR in several periods in the first half of the sample. In particular,

[8] We are exploring, in an on-going project, the results obtained using future information as a proxy for the Fed's expectations on inflation and economic activity and comparing the findings with the ones obtained when real time forecasts of the Greenbook are used instead.

[9] We have also estimated recursively the parametric counterpart of the VAR applied to the real time data. The results are very similar to the local nonparametric ones that use current and past information only.

nonstationarities occur between 1969:1-1971:3, 1974:3-1975:4, 1978:2-1979:3, in 1981:1, and in 1982:1. Some of these periods coincide with abrupt changes in the economy previously documented in the literature, such as a joint break in output, consumption, and investment in 1969:1 (see e.g. Bai, Lumsdaine, and Stock 1998), the oil shock in 1973-1975, and the shift in Fed operating procedures from 1979 to 1982.

While the first half of the sample is characterized by several instances of nonstationarities, there is no other time in which the real time monetary VAR became unstable since 1982:1. In fact, the dynamics of the moduli of the inverse characteristic roots across the two sub samples before and after this date are very distinct, with smaller and much less volatile values in the more recent period.

The inverse characteristic roots not only give important information regarding stability of the VAR, it also reveals more gradual variations in the autoregressive system, which could capture evolutionary changes in the monetary transmission mechanism. Notice that there was a permanent decrease in the modulus in 1983:1 with only a mild rise in 1985:1, from which point on the real time moduli of the inverse root stabilized around the values of 0.94-0.95.

Time-Varying Autoregressive Coefficients

Although the roots indicate the timing of nonstationarities in the VAR system, they do not uncover whether they arise from the dynamics of output, interest rates, inflation or from their joint relationship. There are some useful rules to check stability conditions in higher-order systems based on the values of the autoregressive coefficients in the VAR. For each VAR equation, a necessary condition for all inverse characteristic roots to lie inside the unit circle is $\sum_{i=1}^{p} \beta_i < 1$, and a sufficient condition is $\sum_{i=1}^{p} |\beta_i| < 1$. Thus, we can also use the real time recursively estimated parameters of the VAR to investigate nonstationarities.

Figure 2a plots the sum of the autoregressive parameters of inflation in the inflation equation, Figure 2b of interest rate in the interest rate equation, and Figure 2c of output in the output equation. Notice that the major changes in the inverse roots (Figure 1) and in the autoregressive parameters of the VAR model are not related to the phases of the business cycles but to structural changes in the economy and monetary policy regimes. The dynamics of inflation indicate nonstationarities at about the same time as the inverse of the characteristic roots of the VAR. On the other hand, the autoregressive coefficients for interest rates and output do not display instability, as their sum is always within the unit circle. Thus, nonstationarities in inflation seem to be the main driving force behind instability of the VAR system.

The sums of the autoregressive coefficients for both inflation and interest rate show an abrupt fall in the early 1980s and a more stable behavior after 1982 (Figures 2a and 2b). In addition, the dynamics across the two sub-samples are very distinct. These features are also found in the inverse of the roots of the VAR model, indicating that this is a result of the combined dynamics of interest rate and inflation.

In the case of inflation, the sum became more stable in the second half of the sample around the value of 0.90, with a slight increase in persistence to around 0.95 from 1995 on. The sum of the autoregressive coefficients for interest rate is also more volatile in the first period, oscillating from negative before and during recessions to positive during expansions. However, it shows a sudden decrease with a change in sign to negative from 1982 on. Mostly important, the autoregressive dynamics of interest rates have been slowly converging to zero, especially after 1995 and after 2004 (Figure 2b). This decrease in the persistence of interest rate in the VAR system is an important reason behind the findings regarding changes in the relationship between interest rates and the economy, as discussed in the next sections. Finally, the sum of the autoregressive coefficients for output displays less sudden changes and has been increasingly more stable, with a value between 0.5 and 0.6 (Figure 2c).

Summing up, there have been both abrupt changes in the dynamics of the VAR system – such as the ones around 1979-1982 – as well as more gradual and persistent changes – as it has been taking place since then. This is the scenario in which Lucas' critique (1976) becomes important. In general, economic agents form their expectations about future economic environment taking into account changes in the policy reaction function. A VAR with fixed coefficients would be consistent with firms and consumers that are backward looking or who do not discount changes in policy. This behavior is less plausible when the changes are dramatic and persistent as found here. The estimation proposed allows all recursive parameters of the model to be time-varying, which is more likely to address the Lucas' critique since it implies an evolution of the system of equations *conditional* on changes in policy.

4.2 The Relationship Between Output and Interest Rates

4.2.1 Reaction Functions: The Propagation Mechanism

Some of the structural changes in the monetary transmission mechanism have been gradual and, therefore, are not generally captured by formal break tests applied on revised data, which only identify abrupt changes in the economy. Since the VARs are estimated recursively for each date, it yields time series of the coefficients, which not only indicates potential nonstationarities, but it can also give insights on the evolution of the monetary VAR in real time. In this section we examine the bivariate relationship of the variables composing the VAR and find strong evidence that the link between monetary policy and the economy has changed over time.

Figures 3a and 3b show the sum of lagged coefficients of interest rate in the output equation, and the sum of lagged coefficients of output in the interest rate equation, respectively. A negative correlation between GDP growth and funds rate changes can take place due to the contractionary effect of higher rates on future output (economy's reaction to monetary policy). This is reflected in the negative sum of lagged interest rate coefficients in the output equation, as shown in Figure 3a. The real time evolution of these recursive coefficients also depicts large differences before and after 1980. A striking feature observed is the stability of the relationship between lagged interest rate and output in the second part of the sample compared to the earlier period. In addition, the relationship in the first period was weaker in absolute terms but increasing over time until a peak in 1980. In fact, the contractionary impact of higher rates on future output was strongest between 1967 and 1970 and, to a lesser degree, between 1976 and 1982. From 1980 on the strength of the relationship steadily decreases, although the sum of the coefficients is still large – around -2 – in 2007. In fact, this value is still higher in absolute terms than the average values prevailing between 1970 and 1975. This evidence casts doubt on discussions regarding a recent reduced impact of monetary policy on output compared to historical values.

At the business cycle frequency we observe that the strength of the relationship increased before recessions and decreased towards their end before 1980, implying that the contractionary effect of interest rate on output was stronger right before recessions and weaker when the economy was already in a recovery path. Interestingly, there are no significant changes in the strength of the link between funds rate and output around recessions after 1982. This supports the hypothesis that monetary policy may have played a small or no role as a causal factor in the last two recessions that took place since this date.

Generally, the Federal Reserve reduces interest rate when the economy weakens and raises it when output growth increases. This relationship is reflected in the positive sign of the sum of the lagged output coefficients in the interest rate equation (Figure 3b). As can be observed, this relationship got increasingly stronger from 1971 to a peak in 1981, and has been gradually decreasing since. Notice, however, that the reaction function of the Fed to changes in output is still stronger in the 2000s than it was in the 1960s and 1970s. Another difference before and after 1981 is that the link displays strong swings around economic recessions in the prior period and no substantial changes in the later one.

It is common in the literature to compare the relationship between output and interest rates over time by splitting the sample around the early 1980s. As demonstrated in Figures 3a and 3b, the volatility and large swings in the relationship between these series pre-1982 may compromise this analysis and yield misleading conclusions, depending on the dates chosen to split the sample.[10] Examination of the evolution of the bivariate relationship between output and funds rate, as opposed to changes cross sample, can shed a new light into this discussion. For example, a conclusion that may emerge from this analysis is that monetary policy has been more effective in not causing or contributing to contractions in output

[10] For example, Kuttner and Mosser (2002) compare the periods pre and post 1984 (using data up to 2000) and find that the correlation between funds rate changes and subsequent real GDP growth is weaker in the later period. However, this conclusion does not hold when this analysis is extended to 2007 or when compared with the period prior to 1975.

since 1982, whereas in the previous period there is a stronger association between tight monetary policy and subsequent recessions.

4.2.2 Transmission Mechanism – Evolution of Impulse Response Functions

We study potential changes in the impulse response functions of the monetary VAR over time by examining the evolution of each quarter's real time response in the last 40 years. Figure 4a displays the impulse response function of output to an unexpected unit increase in the Fed funds rate, while Figure 4b shows the impulse response of interest rate to a shock in output. Each graphic shows the response for up to nine periods.[11] The first three or four periods allow analysis of changes in strength of the response over time, while the subsequent ones indicate its persistence. For comparison, we plot the impulse response function estimated using vintage data from 2007:1 as the last graph in the bottom – each period in this graph corresponds to the last point in each one of the nine panels.[12]

The top tree panels in Figure 4a show the time series response of output to the Fed rates in the first three periods – the monetary transmission mechanism.[13] The response of output is strongest in period 3 (top middle panel) compared to other subsequent periods. It can be observed that in period 3 the response of output increases (in absolute value) gradually but substantially from the beginning of the sample until it reaches a peak in 1981. From then on the response decreases slightly but to values a lot larger than the ones prior to 1975. The panels showing the evolution of the response in periods five to nine indicate that the response slowly converges to zero. However, convergence is already attained in period nine in the first part of the sample but this is not case in the later period.

Several papers find that the response of output to monetary policy is much less accentuated and persistent since the early 1980s compared to the previous period. Although it is the case that on average the response may be stronger in the first sub sample, this result is mainly driven by the response of output to interest rates during the very small period between 1975 and 1983. This is also what we find from examining the economy's reaction function to monetary policy, as described in the previous section. The evidence from the evolution of the IRFs above also indicates that the effect of monetary policy shocks in real time is smaller for recent data compared to the period between 1975 and 1983 – when inflation was increasing substantially and the Fed was pursuing an aggressive contractionary policy – but larger compared to the previous period.

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[11] The response of output to shocks in interest rate in period one is zero due to the identification restriction.

[12] Confidence intervals for the irfs for the 2007 vintage can be obtained using nonparametric residual booststrap. For each run of the VAR the local nonparametric error terms are randomly shuffled with replacement. Based on this reshuffling, the LLLS VAR estimates and the bootstrapped irfs are estimated. The standard error for each dynamic multiplier is computed with 1.96 as the critical value.

[13] There is a small but insignificant positive increase in output in the second period, which is also found by several authors (see Boivin and Gianonni 2002).

Figure 4b shows the impulse response of interest rate to a shock in output. The response is positive in the first five periods and slowly converges to zero subsequently. This illustrates the Fed's tendency to increase rates when the economy is robust, and to decrease otherwise. The strongest response occurs in the second period (top middle panel), and it confirms the findings from the Fed's reaction function as described in the previous section (Figure 3a). In particular, the impact of output shocks on interest rate decreased from 1968 to 1973 and from 1978 to 1981. On the other hand, it increased substantially from 1973 to around 1978, rising again very gradually from 1981 on. A similar pattern is observed in period 3. Finally, the response converges faster after 1981 than during the period prior, as can be seen in periods four and on. Thus, the impulse response function shows evidence that the impact of shocks to output on interest rates has not reduced compared to the period pre 1980. In addition, we find evidence that the persistence of response to shocks is much smaller in the second period.

4.2.3 Evolution of Shocks

It has been documented in the literature that the variances of innovations in monetary VARs have decreased substantially across sub samples. Figures 5a and 5b show the recursively estimated real time variance of monetary policy and output shocks, respectively. The evidence confirms that there is a large difference in these variances before and after 1979. In particular, the variance of interest rate shocks increases threefold between 1979 and 1982 – reaching a peak this year – and decreases slowly but steadily from 1986 until the end of the sample (Figure 5a). Although the recent values are a lot smaller than the ones in the early 1980s, they are higher than the ones prevailing in the 1960s and 1970s. A similar pattern is observed in the variance of output shock. It grows smoothly and gradually in the first part of the sample until it reaches a peak in 1983. From this date on it decreases slowly until the end of the sample (Figure 5b).

The evolution of the variance of interest rate and output shocks over time also suggests that caution should be applied when analyzing changes through comparison of sub-samples. This is especially the case for interest rates shocks due to the oscillations between 1979 and 1985.

4.3 The Relationship Between Inflation and Interest Rates

4.3.1 Reaction Functions: The Propagation Mechanism

Figure 6a shows the sum of lagged coefficients of inflation in the interest rate equation. The positive relationship reflects the Fed's reaction to changes in inflation, tending to tighten monetary policy when inflation increases and to loose otherwise. The Fed's reaction was historically strongest around the 1970 recession. During most of the 1970s, however, the Fed's reaction was the weakest compared to the rest of the sample even though it showed an upward movement with a peak in 1981. From this date on, it reduced gradually until the end of the sample, but the current values are still above the average in the 1970s. As found for the relationship between output and interest rate, the Fed's reaction to inflation is also increasing before recessions and decreasing towards their end in the first part of the sample, but these dynamics are much less discernible after 1982.

Figure 6b plots the sum of lagged coefficients of interest rate in the inflation equation. Until 1972 there was a negative relationship between these series, implying that increases in interest rate led to a fall in subsequent inflation. However, from 1972 on this relationship became positive (with the exception of some quarters in 1974). This positive response of inflation to increases in interest rate in the U.S. is known as the price puzzle in the literature (see e.g. Bernanke and Blinder 1992; Christiano, Eichenbaum, and Evans and Kuttner 1998, Sims 1992, Balke and Emery 1994). Sims (1992) also shows that the price puzzle is found in several other countries such as France, Germany, Japan, and the U.K.

Some authors have shown that the price puzzle is sensitive to the sample used. In particular, Balke and Emery (1994) find that it is stronger for the period pre-1980 than for post-1982. We find instead that the price puzzle is not even found before 1972 and that the positive association between interest rates and future inflation is strongest between 1976 and 1986. During this period inflation and interest rate increased substantially and persistently until the early 1980s and fell together subsequently until 1986. In addition, the strength of the price puzzle has being decreasing since 1986 (Figure 6b).

4.3.2 Transmission Mechanism – Evolution of Impulse Response Functions

The dynamics of the impulse response function of interest rate to shocks to inflation is shown in Figure 7a. Notice that the Fed's response is strongest in period 2 compared to other periods. However, the evolution of the response in period 2 displays some strong swings, especially before 1985. In particular, the Fed's response to inflation increased substantially from the late 1960s to 1973. Interestingly, there is a sudden decrease in the strength of the response from 1973 to 1979, and an abrupt increase again from 1979 to 1985. The evidence from the impulse response function combined with findings from the relationship between the lagged coefficients of inflation in the interest rate equation indicate that the Fed's reaction to the increase in inflation in the mid 1975 was not as timely or as strong as compared to the rest of the sample. The impulse response functions in the subsequent periods show that the impact of unexpected increases inflation on interest rate is short-lived converging to zero already in period 3, although following an oscillatory path.

The dynamics of the impulse response function of inflation to one unit unexpected increase in interest rate is shown in Figure 7b. Notice that the response is mostly positive in periods two and three, reflecting the price puzzle.[14] The evolution of the impulse response in period 3 (middle top panel in Figure 7b) is the most similar to the dynamics of the response function of inflation to interest rate (Figure 6b). The relationship was negative until 1972 and strongly positive between 1974 and 1981. From this point on, it has been positive but decreasing over time. Regarding persistence of the response of inflation to shocks to interest rate, there is no observable large difference over time.

4.3.3 Evolution of Shocks

Figure 8a shows the evolution over time of the variance of inflation innovations. As the variance of interest rates and output shocks, there are large differences in the variance of inflation innovations before and after the 1980s. In particular, it increases substantially from the beginning of the sample until it reaches a peak in 1985, and decreases steadily until the end of the sample. An interesting feature that emerges is that the variance tends to increase a couple of quarters before or at a recession. This was the case for all but the 1980 recession. The only time in which the variance rose and a recession did not follow was in 1985, which is related to a definitional change as explained in the section below.

Looking back at Figure 5a, the variance of nominal interest rate innovations displays a similar pattern, but it tends to slightly lag the variance of inflation shocks when the trend is upward and lead when the trend is downward. Both variances show some clustering, especially between 1960 and 1970, and between 1995 and 2000.

4.4 Comparison of Results with 2007 Vintage

In this section we report the results of recursively estimating the proposed monetary VAR using only data available in the 2007:1 vintage. This comparison can shed light on differences in findings due to use of real time versus revised data. In addition, this analysis illustrates in more detail the effect that definitional changes may have had in some of the model parameters. Recall that the real time analysis involves recursive estimation for each vintage. Each point in Figures 1 to 8 corresponds to the result of estimating the VAR for a particular vintage. On the other hand, each point in Figure 9 corresponds to the result of estimating the VAR for increasing samples from 1959:1 to 2006:4 using the same dataset as of 2007:1. The graphs also show the dates of definitional changes in GDP and GDP deflator.[15]

Figure 9a shows the estimated autoregressive parameters for interest rates in the interest equation, for the output parameters in the output equation, and for the inflation parameters in the inflation equation, using revised data as of 2007:1 and real time data. The dynamics of the parameters estimated using

[14] The response in period one is zero due to the identification restriction assumed in the VAR.
[15] Recall that the interest rate series are not revised.

revised data are very similar to the ones using real time data. In particular, they show the same abrupt changes before the 1980s, and the subsequent stabilization of the parameters is also attained at about the same time. In addition, as can be observed, the major changes in the parameters are unrelated to definitional changes in the data as their timing does not coincide, and the parameters obtained using only the 2007:1 vintage show similar oscillations. The only exception is for a minor increase in 1986 in the autoregressive parameters of the inflation equation using real time data.

Figure 9b plots, respectively, the lagged coefficients of interest rate on output equation, output in the interest rate equation, inflation in the interest rate equation, and interest rate in the inflation equation. An important finding is that the timing of major changes and turning points in the autoregressive and lagged coefficient parameters are the same using real time or revised. In addition, definitional changes played no role in the abrupt changes of the real time parameters as found before 1982. There are some minor increases in the values of the real time parameters of lagged output in interest rate equation coinciding with definition changes in 1991 and 1999, but overall the parameters obtained using real time and revised data show very similar dynamics. The one exception is for the real time lagged parameters of interest rate in the inflation equation, which show some divergence with the revised ones in the 1970s, and some changes in value related to definitional changes in 1985, 1991, and 1995. Recall that, as discussed before, this particular relationship reflects the price puzzle, and the VAR using GDP deflator does not yield dynamics as predicted by economic theory.

Figure 9c shows the variance of the shocks obtained using real time and revised data. Changes over time in the variances of the shocks to output and inflation are not related to definitional changes before the 1980s, but display changes coinciding with definitional changes in 1986, 1991, and 1995, especially for inflation. The variance of interest rate shocks is not affected by definitional changes, as interest rates do not undertake any revisions. Overall, all the variances show the same upward movement in the 1960s to the early 1980s and a negative trend from then on, regardless on whether real time or revised data are used. In addition, the timing of the reversal in the trend of the variance of interest rate and inflation shocks is unchanged, using revised or real time data. In particular, for both revised and the real time recursive estimations, these variances show a reversal in trend in 1982 and 1985, respectively. In the case of the variance of output shocks, the definitional change in 1986:1 introduces a level change that masks the timing of the reversal of its trend. We run recursive nonparametric VARs with a level correction for the real time vintages from 1986:1 on for comparison, which is also shown in Figure 9c. The turning point in the trend of the real time variance of output shocks is found to be 1983, which coincides with the one obtained using revised data.

Finally, we observe that estimation using revised data sometimes overestimate or underestimate the coefficients and the variance of the shocks, unveiling the transmission mechanism and the impact of shocks that took place in real time. We are investigating in an on-going project the implications of using different sets that carry out current or forward looking information on the parameter of the models. In particular, counterfactual experiments are used to reflect the Fed's information set in real time but with a transmission mechanism based on full information.

5. Summary of Findings

- There are several instances of nonstationarities in the dynamics of the monetary VAR, but they all occur before 1982. We find that the Fed's response to inflation and real activity, and the economy's response to monetary policy are highly nonlinear before 1980-1982 and much more stable afterwards. In addition, we find that interest rate, output, and inflation in the VAR system have become increasingly less persistent over time. This is particularly the case for interest rate, whose sum of the autoregressive parameters has reverted to negative after 1982, and has tended to values very close to zero since. The remarkable recent low persistence of interest rate, associated with increased stability in output and inflation, is one of the reasons behind the recent findings of lower impact of monetary policy shocks in the economy.
- The relationship between lagged output in the interest rate equation – the Fed's reaction to changes in real activity – has been steadily decreasing since 1981. The link between lagged interest rate in the output equation – the economy's reaction to monetary policy – has also slightly weakened since 1982. However, both bivariate relationships are still stronger in the 2000s than they were in the 1970s. These findings are also confirmed by the impulse response functions.
- The relationship between lagged inflation in the interest rate equation – the Fed's response to changes in inflation – was historically weakest during most of the 1970s compared to the rest of the sample, even though it rose substantially in this period, reaching a peak in 1981. The strength of the relationship steadily decreases from then on, but also to values above the average of the 1970s. We also find that the positive association between interest rates and future inflation – the reaction of inflation to monetary policy – is strongest and positive between 1976 and 1986, reflecting the price puzzle. However, the price puzzle has being decreasing since 1986. These results are also found by examining the evolution of the impulse response functions over time.
- At the business cycle frequency, the Fed's reaction to economic activity and inflation is increasing before recessions and decreasing towards their end in the first part of the sample, but these dynamics are much less discernible after 1982. On the other hand, the economy's response to monetary policy also increased before recessions and decreased towards their end, before 1980. This implies that the contractionary effect of interest rate on output was stronger right before recessions and weaker when the economy was already in a recovery path. Interestingly, there are no significant changes in the relationship

around recessions after 1982. A conclusion that may emerge from this analysis is that monetary policy did not become more or less effective to stabilize output. Instead, monetary policy has been more effective in not causing contractions in output since 1982, whereas in the previous period their relationship indicates a stronger association between tight monetary policy and subsequent recessions.

- An interesting finding is the sequence of changes in the VAR system. First, the strength of the economy's response to monetary policy reaches a peak in 1980, followed by a peak in the Fed's reaction to real activity and to inflation in 1981. On the other hand, the variance of interest rates, output, and inflation shocks started decreasing since 1982, 1983, and 1985, respectively.
- The timing and sequence of these structural changes suggest that the reduction in the variances of the shocks is not a causal factor in the changes in the response of the economy to inflation and monetary policy, or in the Fed's response to inflation and real activity. Instead, a reduction of the strength of the transmission mechanisms took place before the gradual long run decrease in the size of the shocks observed in the results.
- The nonlinear dynamics of the coefficients, variances, and impulse responses over time indicate that comparisons across samples can be sensitive to the break date chosen. In particular, the investigation of changes in monetary policy should take into consideration the large in the relationship between output, interest rate, and inflation in the 1970s.
- Comparison of the irfs of interest rates reveals a trade-off between the response to shocks to output and to inflation. In particular, the strength of the Fed's response was increasing to inflation shocks and decreasing to output shocks between 1968-1974 and 1970-1981. This trend reverts between 1974-1979, when there was a fall in the response to shocks to inflation and a rise to shocks to output. Interestingly, from the mid-1980s on the Fed's response to these shocks is more balanced, showing no discernible trade off.

6. Conclusion

This paper proposes a local nonparametric VAR method to investigate nonlinearities, nonstationarities in the relationship between inflation, nominal interest rates, and output. The monetary VAR is estimated using a local nonparametric recursive framework in which all model parameters are time-varying. The method is applied to real time unrevised data on these series and takes into account the possibility of abrupt or gradual changes in the parameters as well as changes across business cycle phases. The nonparametric impulse response functions as well as the time-varying recursive parameters of the model are used as tools to investigate the impact of monetary policy in the economy over time as well as changes in the reaction function of the Federal Reserve.

We find substantial evidence of nonlinearities and nonstationarities in the bivariate relationship between the variables that can shed light on potential changes in monetary policy and the monetary transmission mechanism over time. In particular, there have been abrupt as well as gradual changes in the systematic part of the estimated VAR, in the variances of the shocks, and in the transmission mechanism. The timing of these changes suggests that the reduction in the variances of the shocks is not a causal factor in changes in the transmission mechanism.

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Figure 1 – Real Time Modulus of the Largest Inverse Root of Characteristic Autoregressive Polynomial, Nonstationarities (Shaded Area), and Abrupt Changes (Dotted Line)

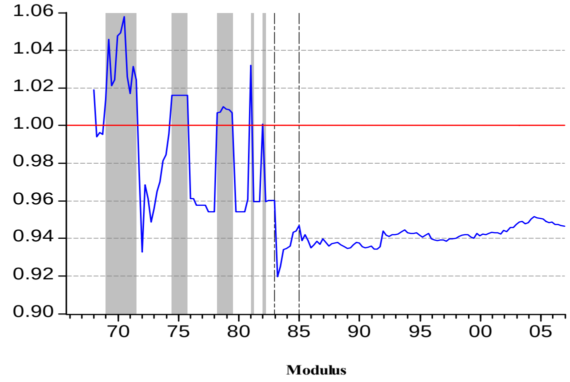


Figure 2a – Real Time Sum of Autoregressive Coefficients from Interest Rate Equation

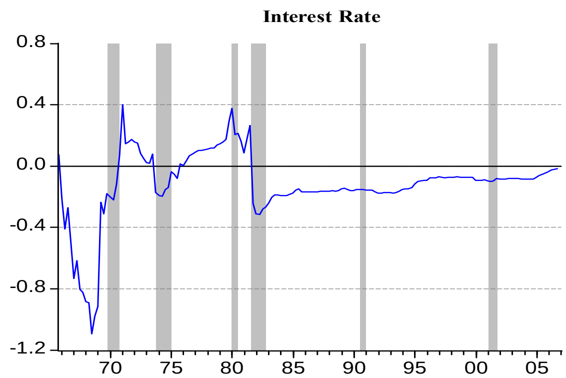


Figure 2b – Autoregressive Coefficients from Inflation Equation

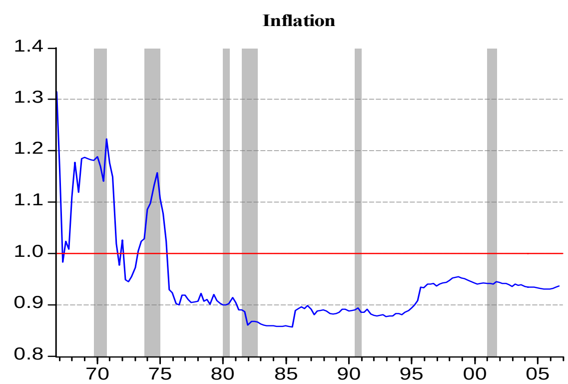


Figure 2c – Autoregressive Coefficients from Real GDP Equation

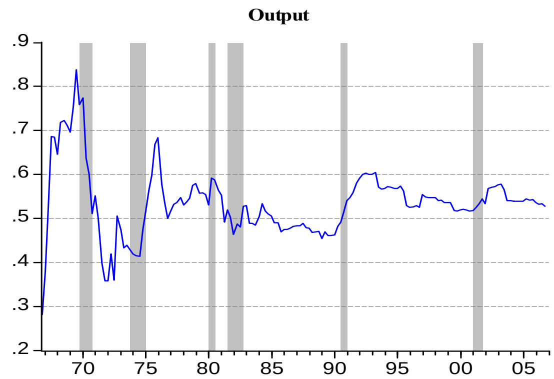


Figure 3a – Real Time Series of Sum of Lagged Interest Rate Coefficients in Output Equation and NBER Recessions (Shaded Area)

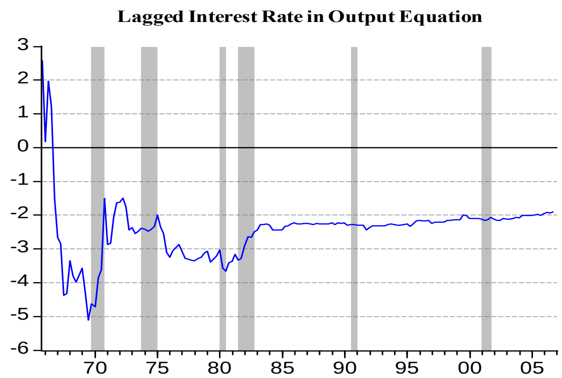


Figure 3b – Real Time Series of Sum of Lagged Output Coefficients in Interest Rate Equation and NBER Recessions (Shaded Area)

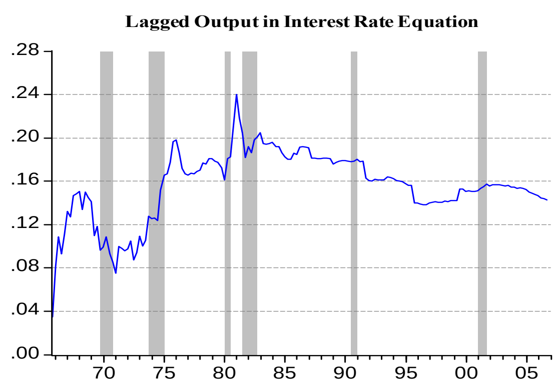
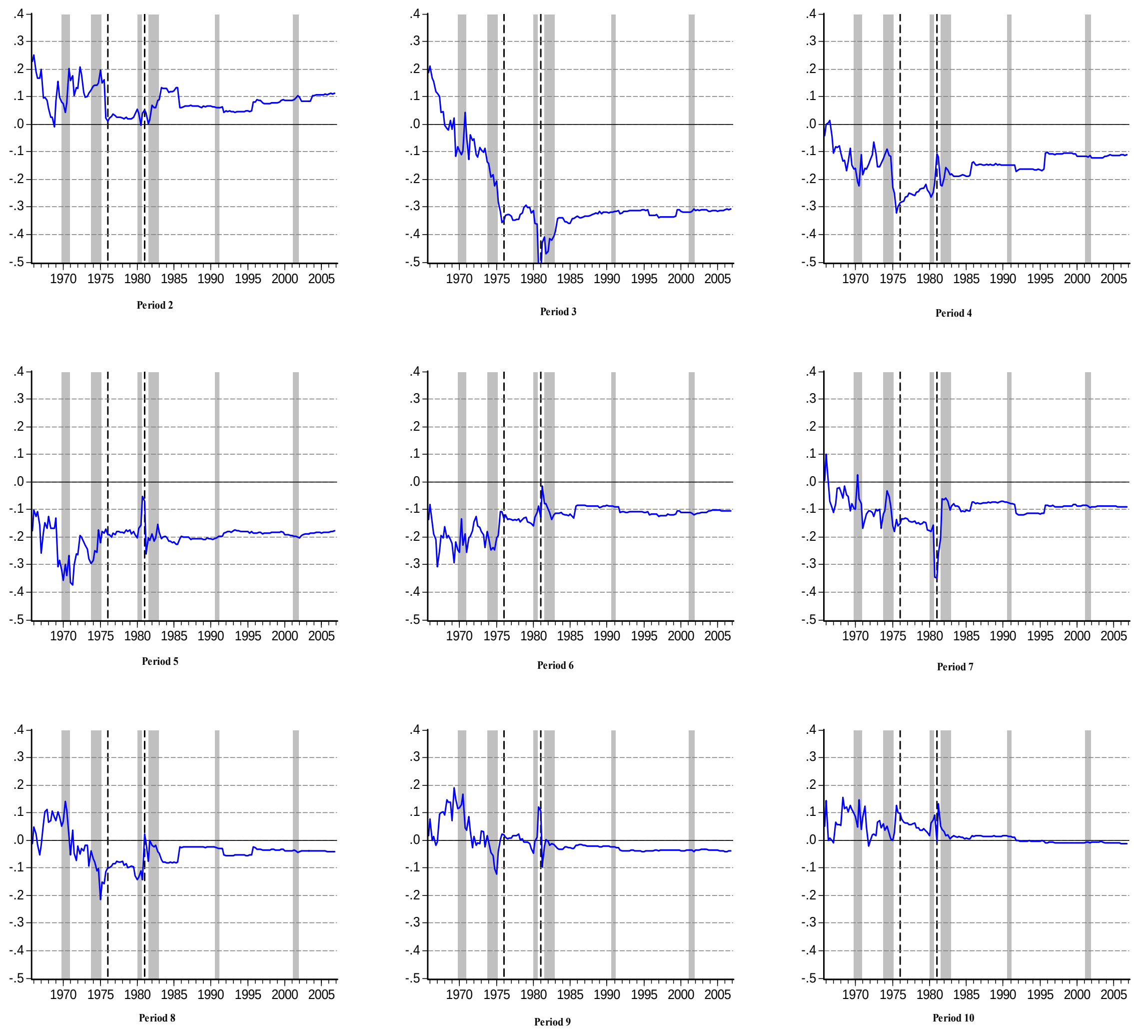


Figure 4a – Dynamics of Real Time Impulse Response of Output to Shocks to Interest Rate, NBER Recessions (Shaded Area) and Breakpoints (Dotted Line)

Real Time Response of Real GDP to Shocks to Interest Rates



IRF of Output to Shocks to Interest Rate

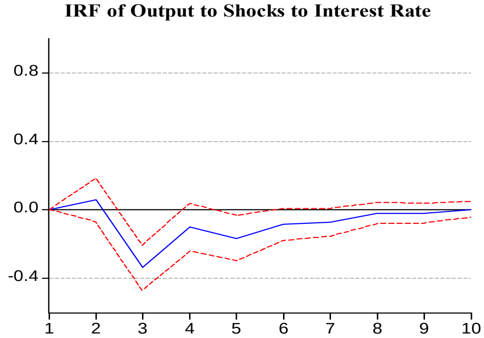
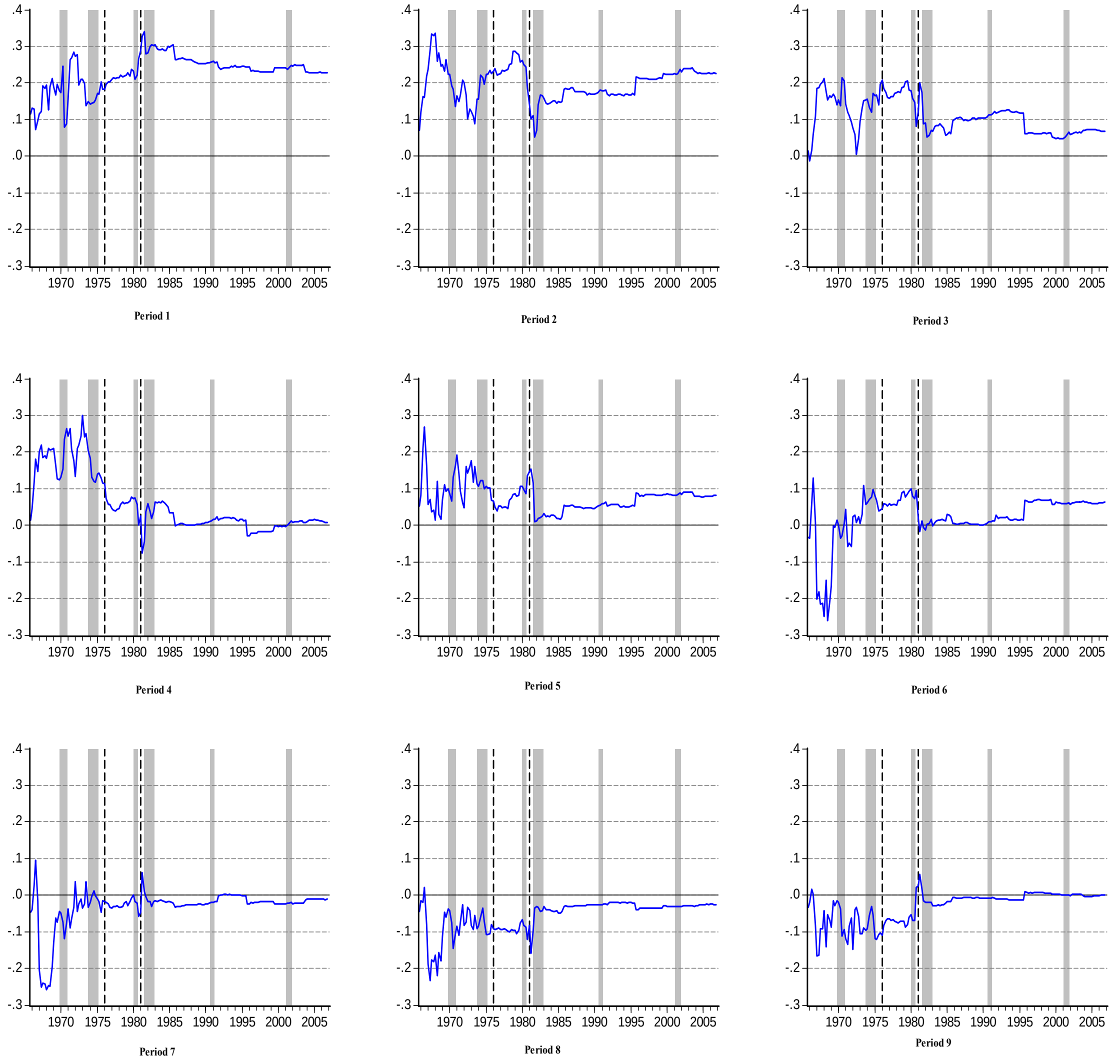


Figure 4b – Dynamics of Real Time Impulse Response of Interest Rates to Shocks to Output, NBER Recessions (Shaded Area) and Breakpoints (Dotted Line)

Real Time Response of Interest Rates to Shocks to Real GDP



IRF of Interest Rate to Output

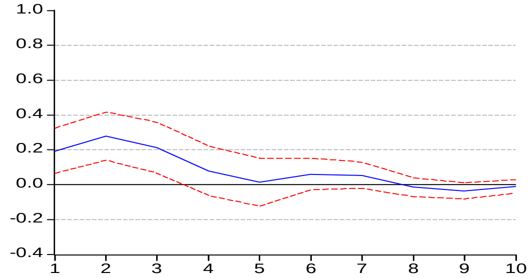


Figure 5a – Real Time Variance of Interest Rate Shocks

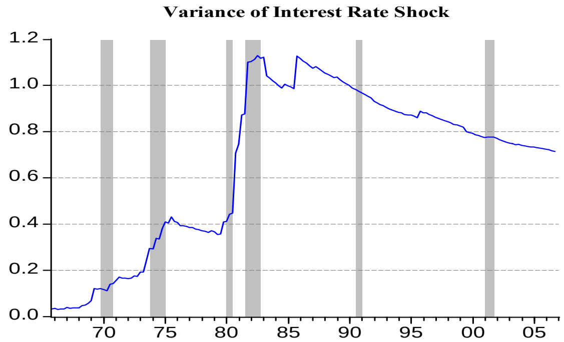


Figure 5b – Real Time Variance of Output Shocks

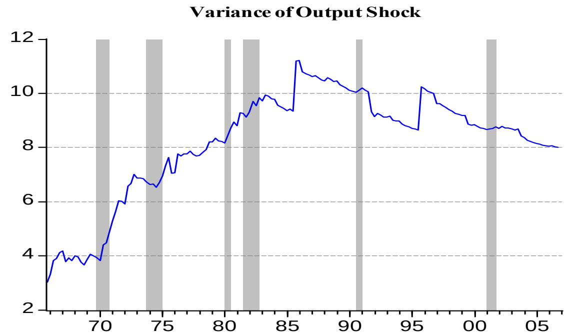


Figure 6a – Real Time Series of Sum of Lagged Inflation Coefficients on Interest Rate Equation and NBER Recessions (Shaded Area)

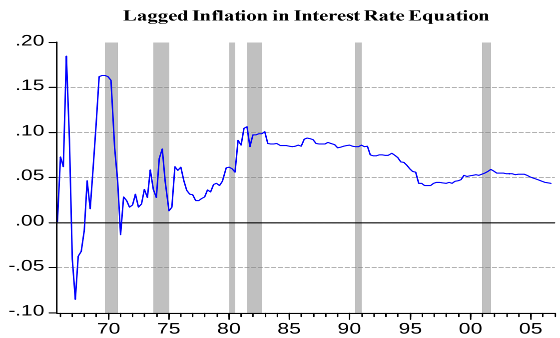


Figure 6b – Real Time Series of Sum of Lagged Interest Rate Coefficients on Inflation Equation and NBER Recessions (Shaded Area)

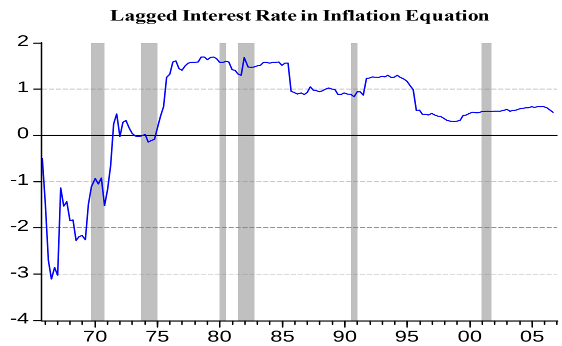
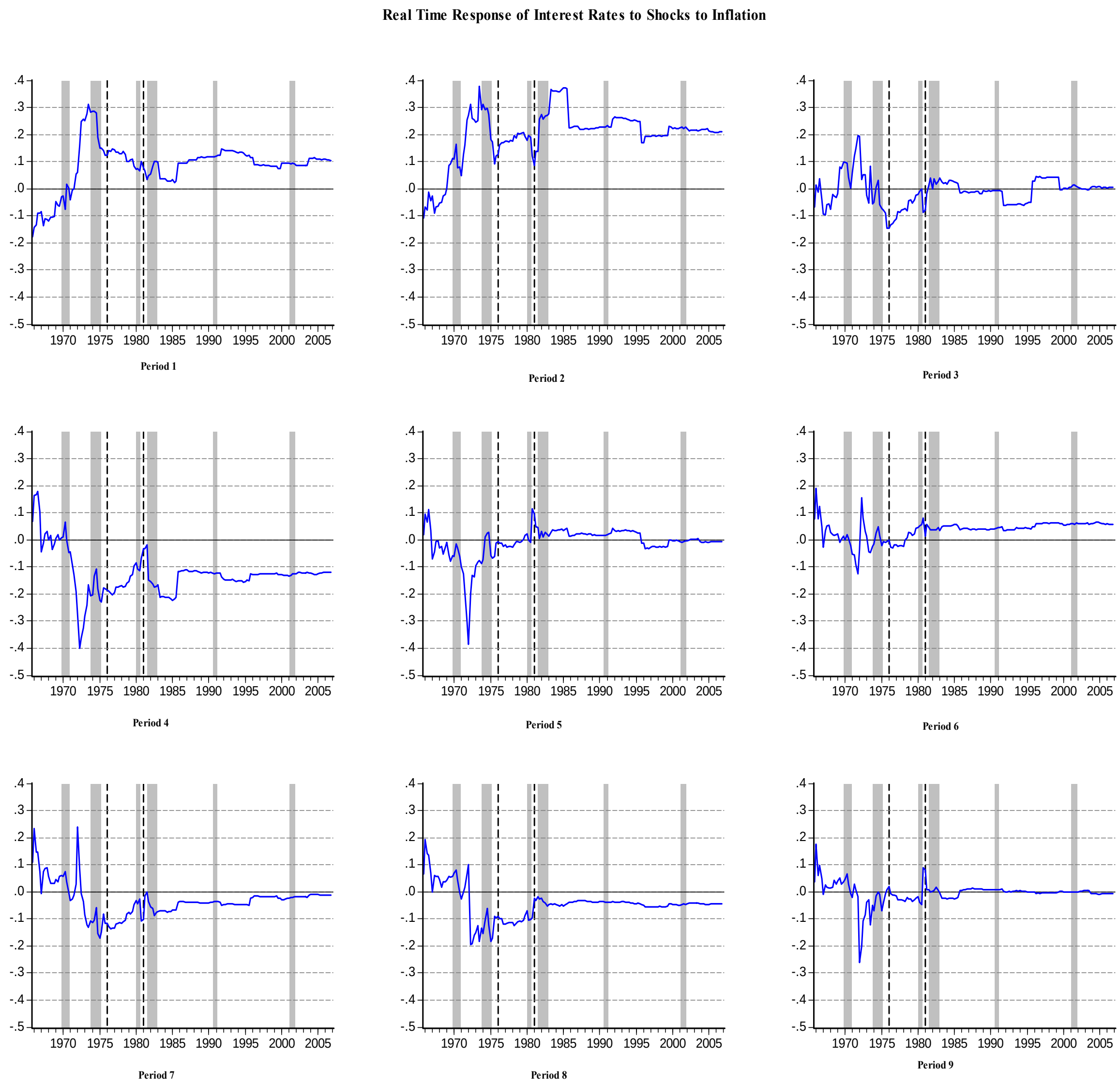


Figure 7a – Dynamics of Real Time Impulse Response of Interest Rates to Shocks to Inflation, NBER Recessions (Shaded Area) and Breakpoints (Dotted Line)



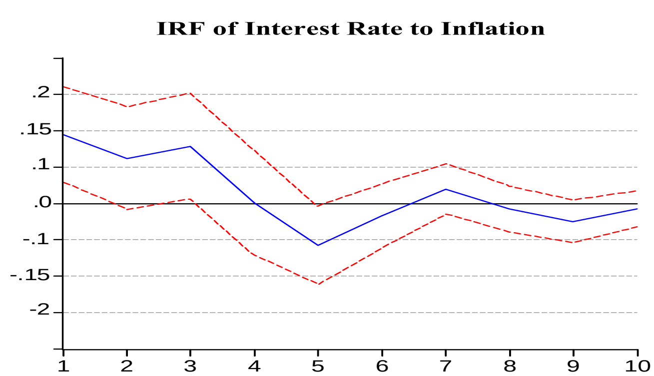
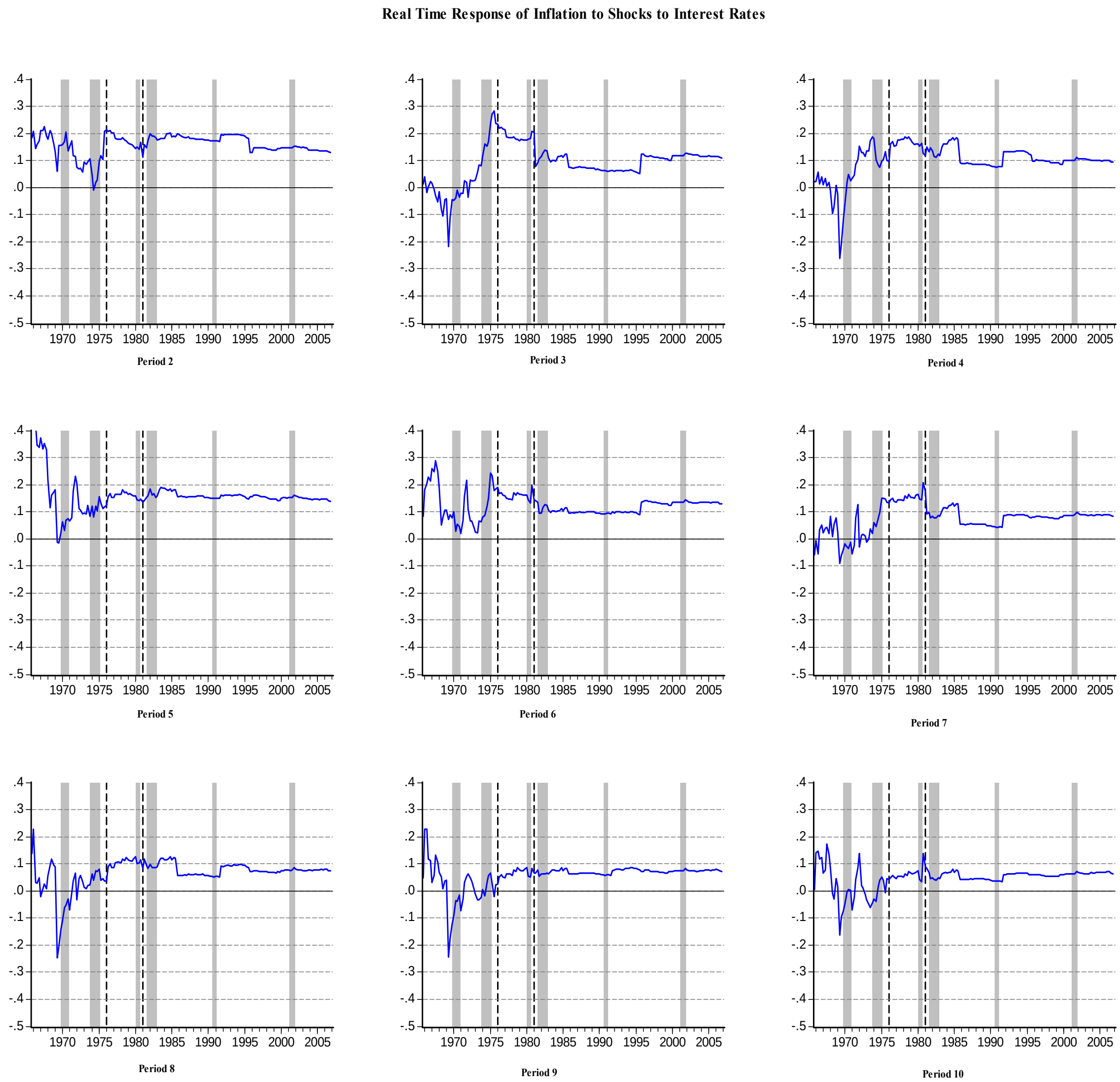


Figure 7b – Dynamics of Real Time Impulse Response of Inflation to Shocks to Interest Rate, NBER Recessions (Shaded Area) and Breakpoints (Dotted Line)



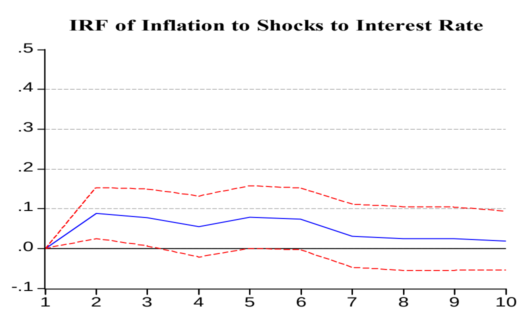


Figure 8 – Real Time Variance of Inflation Shocks

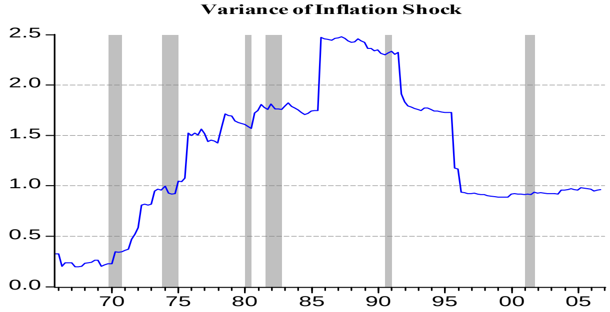


Figure 9a – Autoregressive Parameters for the Equations of the VAR for 2001:7 Vintage (—), for All Vintages in Real Time (—), Dates of Definitional Changes in the Series (Dotted Lines) and NBER Recessions (Shaded Areas)

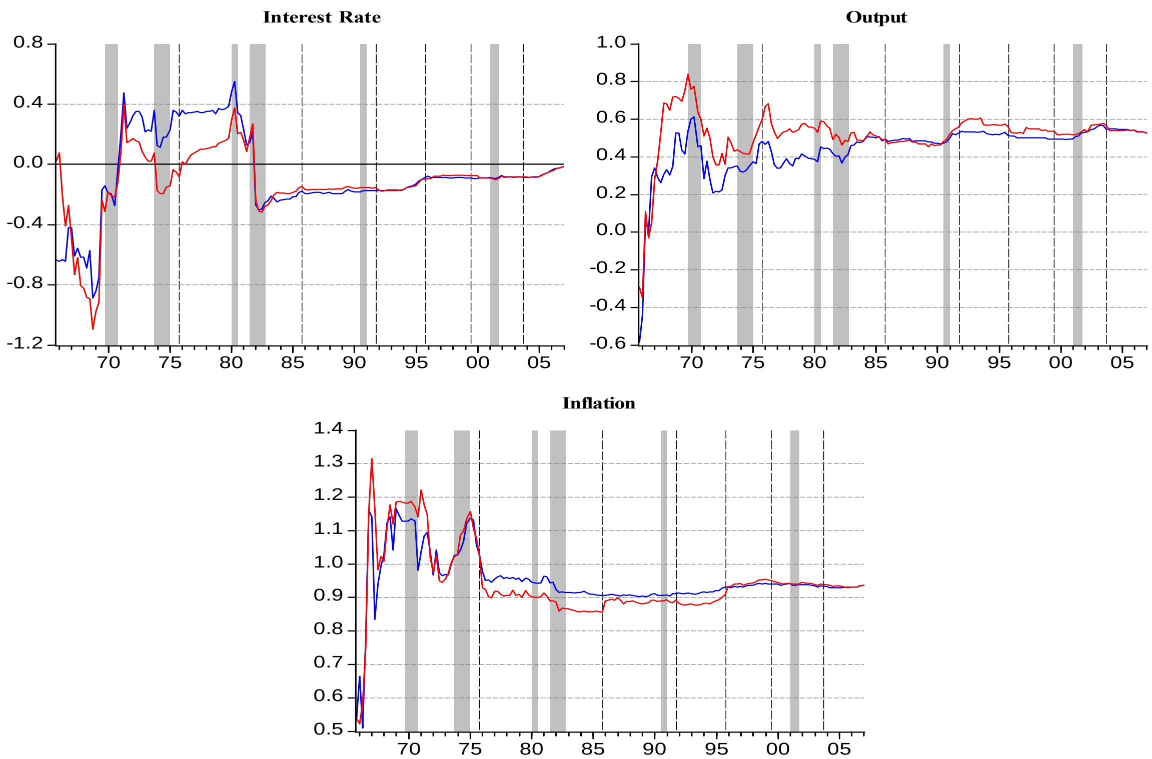


Figure 9b – Lagged Parameters in the Equations of the VAR for 2001:7 Vintage, (—), for All Vintages in Real Time (—), Dates of Definitional Changes in the Series (Dotted Lines) and NBER Recessions (Shaded Areas)

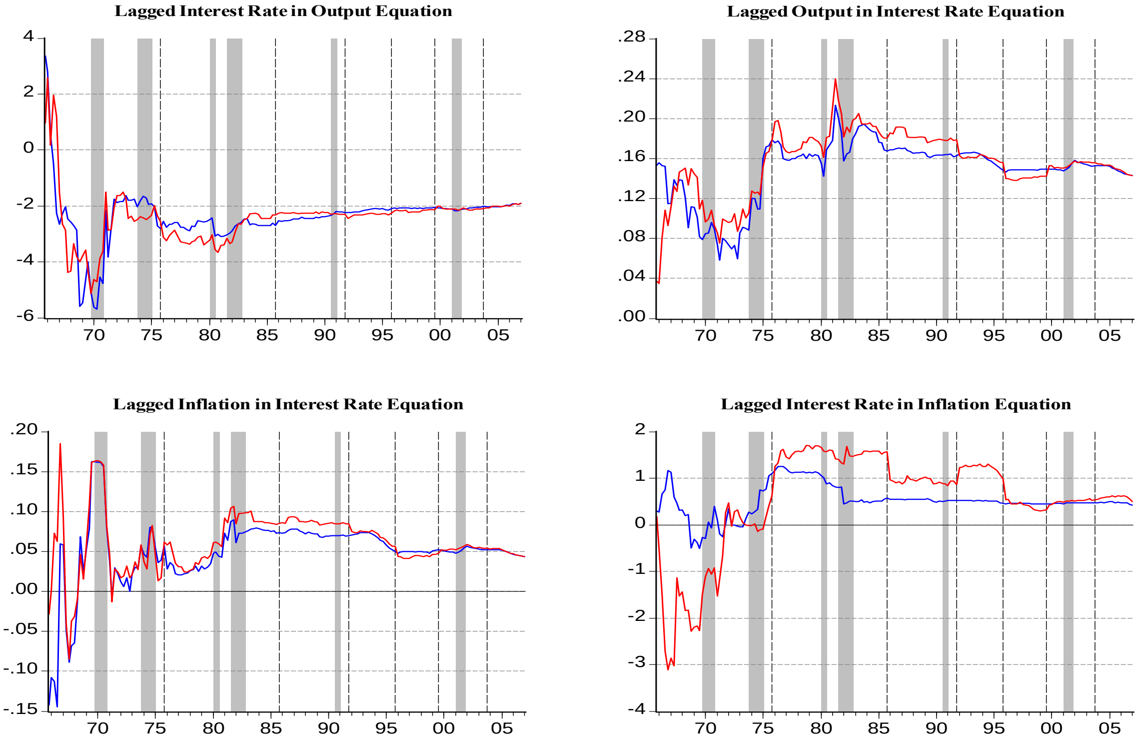


Figure 9c – Recursively Estimated Variances of the Shocks of the VAR for 2001:7 Vintage, (—), for All Vintages in Real Time (—), Real Time with Level Correction (—), Dates of Definitional Changes in the Series (Dotted Lines),and NBER Recessions (Shaded Areas)