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The risk management approach
to monetary policy,
nonlinearity and aggressiveness:
the case of the US Fed

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ABSTRACT

We estimate regime switching models where the strength of the response of monetary policy to macroeconomic conditions depends on the level of risk associated with the inflation outlook and risk in financial markets. Using quarterly data for the Greenspan period we find that: *i*) risk in the inflation outlook and volatility in financial markets are a powerful driver of monetary policy regime changes in the U.S.; *ii*) the response of the US Fed to the inflation outlook is invariant across policy regimes; *iii*) however, in periods of high economic risk, monetary policy tends to respond more aggressively to the output gap and the degree of inertia tends to be lower than in normal circumstances; and *iv*) the US Fed is estimated to have responded aggressively to the output gap in the late 1980s and beginning of the 1990s, and in the late 1990s and early 2000s.

JEL classification numbers: C24, C51, E52

Keywords: US Fed, monetary policy, risk management, smooth-transition regression model, aggressiveness.

NON-TECHNICAL SUMMARY

Starting with Taylor (1993), a large body of literature has focused on the derivation and estimation of linear monetary policy reaction functions in the United States and abroad. Despite their simplicity, these policy rules have fit the data relatively well. More recently, economists started to focus on the possibility that monetary policy may react in a nonlinear manner to economic activity and inflation. This nonlinear behaviour may arise as a result of deviations from the conventional minimisation of quadratic loss functions subject to linear Phillips curves and aggregate demand schedules. However, another factor that can lead to potential nonlinearity in monetary policy is an uncertain economic environment. Several sources of uncertainty affect the implementation of monetary policy in real time.

First, policymakers are uncertain about the state of the economy because they have only an imperfect knowledge about the data used in monetary policymaking (*data uncertainty*). Indeed, measures of economic activity and inflation (such as real GDP and the GDP deflator) are subject to substantial revisions following the quarter of their release; and useful concepts, such as potential output and the NAIRU are usually measured with a substantial margin of error. There seems to be agreement in the literature that policymakers should be less aggressive with respect to poorly measured targets.

Second, policymakers are uncertain regarding the impact of policy on the economy and about the structure of the economy (*parameter uncertainty*). So far, the literature has been divided as to whether or not monetary policy in the presence of parameter uncertainty should be more or less aggressive than absent uncertainty. Starting with Brainard (1967), a large body of theoretical literature postulated that uncertainty about the quantitative impact of policy on the economy should lead to less aggressiveness in monetary policy (Svensson, 1999). However, Estrella and Mishkin (1999), Peersman and Smets (1999) and Rudebusch (2001) found that parameter uncertainty has only negligible quantitative effects on the feedback parameters. Yet another strand of literature shows that uncertainty regarding the structure of the economy and/or the impact of policy should lead to a more responsive approach to monetary policy (Söderström, 2002; Giannoni, 2007; Flamini and Milas, 2011).

Finally, policymakers are uncertain about the distribution of shocks hitting the economy (*shock uncertainty*). As is well known, optimal policy in a linear-quadratic framework with only shock uncertainty exhibits certainty equivalence. Consequently, the degree of uncertainty does not affect the optimal policy rule, which depends only on the expected value of the target variables. The central bank acts as it would in a non-stochastic economy. This is the hypothesis underlying the derivation and estimation of linear Taylor rules. This literature has been criticised on the grounds that it implies that the costs of being wrong do not depend on whether the future value of inflation is over or underestimated. In the “robust control” approach to monetary policy, the authorities do care about the worst case scenario. Indeed, they choose the policy that minimizes the loss over all possible values for a given parameter within a given range. In this case, aggressive interest rate movements might be called for in order to avoid very bad outcomes (Giannoni 2002; Onatski and Stock, 2002).

The results of the “robust control” approach are in line with the views expressed by several US Fed Governors. Indeed, US Fed Governors have stressed on several occasions the importance of an uncertain outlook for the conduct of monetary policy (“risk management approach” to monetary policy). Former Chairman Greenspan (2004) describes this approach by stating that “Given our inevitably incomplete knowledge. . . a central bank needs to consider not only the most likely future path for the economy but also the distribution of possible outcomes about that path”. The risk-management approach may also lead to a more aggressive response of monetary policy to macroeconomic conditions, depending on the level of risk facing the economy. Former Governor Mishkin discusses the case of financial market disruptions, which

pose significant risks to the macroeconomic outlook. He maintains that when financial markets are strained, risk management is crucial in formulating the appropriate response of monetary policy. In particular, he claims that “policy in this setting tends to respond aggressively when a large shock becomes evident; for this reason, the degree of inertia in such cases may be markedly lower than in more routine circumstances”. In that light, he maintains that “the Federal Reserve’s policy strategy is aimed at providing insurance to help avoid more severe macroeconomic outcomes”.

We contribute to the empirical literature on monetary policy under uncertainty by estimating regime switching models where the strength of the response of monetary policy to macroeconomic conditions depends on the level of risk facing the economy. This monetary policy rule follows Mishkin’s idea that the strength of the monetary policy response to economic shocks should depend on the variances of shocks hitting the economy. In doing so, we do not attempt to distinguish between the various theories mentioned before. Instead, we want to document empirically whether or not monetary policy implemented by the US Fed has depended on the level of risk facing the economy. Our measures of risk are based on the previously mentioned statements by former Fed officials. First, following Greenspan’s emphasis on the distribution of outcomes around central paths, we use measures of dispersion associated with the outlook of inflation derived from surveys among professional forecasters. Second, because former Governor Mishkin focused on the importance of stress in financial markets in formulating an appropriate monetary policy response, we use a measure of risk in financial markets derived from stock options. Moreover, we use real time data from the Greenbook to estimate the regime switching models because there is wide recognition that using *ex-post* data has a series of drawbacks. The focus is on the Greenspan period because of his emphasis on the risk management approach in monetary policy making in the United States.

Our starting point is the estimation of linear monetary policy feedback rules that have been widely estimated in the literature. These feedback rules have been tested for neglected nonlinearity arising from the level of inflation, the output gap and the stance of monetary policy, as suggested by the empirical literature on nonlinear Taylor rules. They have also been tested for non-linearity arising from the level or risk facing the economy, as suggested by the risk management approach and the other theories mentioned before. When linearity is rejected, nonlinear Taylor rules are estimated using nonlinear least squares techniques. The main findings of the paper are as follows: *i*) risk in the inflation outlook and volatility in financial markets are a more powerful driver of monetary policy regime changes than variables typically suggested in the literature, such as the level of inflation, the output gap and the Fed Funds rate; *ii*) estimation of regime switching models shows that the response of the US Fed to the inflation outlook is invariant across policy regimes; *iii*) however, in periods of high economic risk monetary policy tends to respond more aggressively to the output gap and the degree of inertia tends to be lower than in normal circumstances; and *iv*) the US Fed is estimated to have responded aggressively to the output gap in the late 1980s and beginning of the 1990s, and in the second half of the 1990s and early 2000s. These findings are by and large consistent with the views expressed by former Governor Mishkin who suggested that in periods of high economic risk monetary authorities tend to respond aggressively while the degree of inertia is markedly lower than in normal circumstances.

1 INTRODUCTION

Starting with Taylor (1993), a large body of literature has focused on the derivation and estimation of linear monetary policy reaction functions in the United States and abroad. Despite their simplicity, these policy rules have fit the data relatively well. More recently, economists started to focus on the possibility that monetary policy may react in a nonlinear manner to economic activity and inflation. This nonlinear behaviour may arise as a result of deviations from the conventional minimisation of quadratic loss functions subject to linear Phillips curves and aggregate demand schedules (Svensson, 1997; Ball, 1999; Clarida *et al.*, 1999). The loss function of the central bank may not be quadratic because of asymmetries in the response of monetary policy to inflation in different points of the business cycle and/or the size of deviations of actual inflation from explicit or implicit targets (Bec *et al.*, 2002; Martin and Milas, 2004; Rabanal, 2004; Dolado *et al.*, 2005; Kim *et al.*, 2005; Taylor and Davradakis, 2006; Cukierman and Muscatelli, 2008). It is also possible that the Phillips curve may reflect more complex price-setting mechanisms than those subsumed in a linear specification (Schaling, 2004; Dolado *et al.*, 2004 and 2005).

Another factor that can lead to potential nonlinearity in monetary policy is an uncertain economic environment. Former Chairman Greenspan stated that “Uncertainty is not just an important feature of the monetary policy landscape; it is the defining characteristic of that landscape” (Greenspan, 2003). Several sources of uncertainty affect the implementation of monetary policy in real time. First, policymakers are uncertain about the state of the economy because they have only an imperfect knowledge about the data used in monetary policymaking (*data uncertainty*). Indeed, measures of economic activity and inflation (such as real GDP and the GDP deflator) are subject to substantial revisions following the quarter of their release; and useful concepts, such as potential output and the NAIRU are usually measured with a substantial margin of error. There seems to be agreement in the literature that policymakers should be less aggressive with respect to poorly measured targets (Staiger *et al.*, 1997; Estrella and Mishkin, 1999; Peersman and Smets, 1999; Orphanides *et al.*, 2000; Rudebusch, 2001; Aoki, 2003; Ehrmann and Smets, 2003).

Second, policymakers are uncertain regarding the impact of policy on the economy and about the structure of the economy (*parameter uncertainty*). Milton Friedman described the first aspect of this uncertainty in terms of the “long and variable” lags between a change in policy and the time at which it finally influences the economy. Moreover, monetary authorities cannot be sure that the models they use to guide their policies are a good description of the environment they operate in. So far, the literature has been divided as to whether or not monetary policy in the presence of parameter uncertainty should be more or less aggressive than absent uncertainty. Starting with Brainard (1967), a large body of theoretical literature postulated that uncertainty about the quantitative impact of policy on the economy should lead to less aggressiveness in monetary policy (Svensson, 1999). However, Estrella and Mishkin (1999), Peersman and Smets (1999) and Rudebusch (2001) found that parameter uncertainty has only negligible quantitative effects on the feedback parameters. Yet another strand of literature shows that uncertainty regarding the structure of the economy and/or the impact of policy should lead to a more responsive approach to monetary policy. Flamini and Milas (2011) show that when the exogenous volatility surrounding a specific state variable increases, the optimal policy response to that variable should increase too. Such preemptive behaviour reduces the risk of large deviations of the economy from the steady state that would deteriorate the distribution forecasts of the output gap and inflation. The author also finds that higher uncertainty about the output gap makes monetary policy less inertial. In the same vein, Söderström (2002) shows that when there is uncertainty about persistence of inflation, it may be optimal for the central bank to respond to shocks more aggressively in order to prevent them from having a lasting impact on inflation. This is because the variance of inflation increases with the distance from target. Consequently, to reduce the amount of uncertainty about the future path of inflation, optimal policy becomes more aggressive, pushing inflation closer to target. Finally, Giannoni (2007) shows

that when policymakers face uncertainty about the parameters in the model and about the shock process, the robust optimal policy rule requires the interest rate to respond more strongly to fluctuations in inflation and in changes in the output gap.

Finally, policymakers are uncertain about the distribution of shocks hitting the economy (*shock uncertainty*). As is well known, optimal policy in a linear-quadratic framework with only shock uncertainty exhibits certainty equivalence. Consequently, the degree of uncertainty does not affect the optimal policy rule, which depends only on the expected value of the target variables. The central bank acts as it would in a non-stochastic economy. This is the hypothesis underlying the derivation and estimation of linear Taylor rules. This literature has been criticised on the grounds that it implies that the costs of being wrong do not depend on whether the future value of inflation is over or underestimated. In the “robust control” approach to monetary policy, the authorities do care about the worst case scenario. Indeed, they choose the policy that minimizes the loss over all possible values for a given parameter within a given range. In this case, aggressive interest rate movements might be called for in order to avoid very bad outcomes (Giannoni 2002; Onatski and Stock, 2002).

The results of the “robust control” approach are in line with the views expressed by several US Fed Governors. Indeed, former Governor Mishkin criticises the linear-quadratic approach to monetary policy because it implies “a linear response to shocks and the strength of these responses does not depend on the variances or any other aspect of the probability distribution of the shocks” (Mishkin, 2008). He concludes that, “while the linear-quadratic framework may provide a reasonable approximation to how monetary policy should operate under fairly normal circumstances, this approach is less likely to be adequate for thinking about monetary policy when the risk of poor economic performance is unusually high”. Indeed, US Fed Governors and presidents of regional Feds have stressed on several occasions the importance of an uncertain outlook for the conduct of monetary policy (“risk management approach” to monetary policy).¹ Former Chairman Greenspan (2004) describes this approach by stating that “Given our inevitably incomplete knowledge. . . a central bank needs to consider not only the most likely future path for the economy but also the distribution of possible outcomes about that path”. In turn, Bernanke (2004) proposes that when setting monetary policy, the authorities should take into account both their baseline forecast and the various risks to that forecast. Finally, Evans (2011) also supports a risk management approach to monetary policy. In particular, in a context of subdued economic activity and inflation and high economic uncertainty in the aftermath of the peak of the international financial crisis, he proposes to “formulate a monetary policy strategy that carefully balances the risks associated with the reasonable alternative economic scenarios that we face and is as robust as possible to miscalculations as to which of these scenarios is predominantly true”.

As suggested by the “robust control” literature, the risk-management approach may also lead to a more aggressive response of monetary policy to macroeconomic conditions, depending on the level of risk facing the economy. Former Governor Mishkin discusses the case of financial market disruptions, which pose significant risks to the macroeconomic outlook. He maintains that when financial markets are strained, risk management is crucial in formulating the appropriate response of monetary policy. In particular, he claims that “policy in this setting tends to respond aggressively when a large shock becomes evident; for this reason, the degree of inertia in such cases may be markedly lower than in more routine circumstances”. In that light, he maintains that “the Federal Reserve’s policy strategy is aimed at providing insurance to help avoid more severe macroeconomic outcomes”. In the same vein, when discussing the effective implementation of monetary policy at very low interest rates and facing the threat of deflation, Bernanke and Reinhart (2004)

¹ It is important to note that the risk management referred to in this paper is different from the risk management of financial risks in central banks’ balance sheets. In particular, the latter refers to risk policies, procedures and limits that protect the capital position of a central bank and its profitability, which are crucial elements of central bank credibility.

state that “...policymakers are well advised to act preemptively and aggressively to avoid facing the complications raised by the zero lower bound”. Risk management therefore appears as critical for both academics and central bankers, as emphasized by Greenspan (2004) “...the conduct of monetary policy in the United States has come to involve, at its core, crucial elements of risk management”.

In this paper, we contribute to the empirical literature on monetary policy under uncertainty by estimating regime switching models where the strength of the response of monetary policy to macroeconomic conditions depends on the level of risk facing the economy. This monetary policy rule follows Mishkin’s idea that the strength of the monetary policy response to economic shocks should depend on the variances of shocks hitting the economy.² In doing so, we do not attempt to distinguish between the various theories mentioned before. Instead, we want to document empirically whether or not monetary policy implemented by the US Fed has depended on the level of risk facing the economy. Our measures of risk are based on the previously mentioned statements by former Fed officials. First, following Greenspan’s emphasis on the distribution of outcomes around central paths, we use measures of dispersion associated with the outlook of inflation derived from surveys among professional forecasters. Second, because former Governor Mishkin focused on the importance of stress in financial markets in formulating an appropriate monetary policy response, we use a measure of risk in financial markets derived from stock options. Moreover, we use real time data from the Greenbook to estimate the regime switching models because there is wide recognition that using *ex-post* data has a series of drawbacks. To our knowledge, this is the first time that real time data are used in the estimation of nonlinear Taylor rules for the United States. The focus is on the Greenspan period because of his emphasis on the risk management approach in monetary policy making in the United States.

Our starting point is the estimation of linear monetary policy feedback rules that have been widely estimated in the literature. These feedback rules have been tested for neglected nonlinearity arising from the level of inflation, the output gap and the stance of monetary policy, as suggested by the empirical literature on nonlinear Taylor rules surveyed later on in this paper. They have also been tested for non-linearities arising from the level or risk facing the economy, as suggested by the risk management approach and the other theories mentioned before. When linearity is rejected, nonlinear Taylor rules are estimated using nonlinear least squares techniques. The main findings of the paper are as follows: *i*) risk in the inflation outlook and volatility in financial markets are a more powerful driver of monetary policy regime changes than the variables typically suggested in the literature, such as the level of inflation, the output gap and the Fed Funds rate; *ii*) estimation of regime switching models shows that the response of the US Fed to the inflation outlook is invariant across policy regimes; *iii*) however, in periods of high economic risk monetary policy tends to respond more aggressively to the output gap and the degree of inertia tends to be lower than in normal circumstances; and *iv*) the US Fed is estimated to have responded aggressively to the output gap in the late 1980s and beginning of the 1990s, and in the second half of the 1990s and early 2000s. These findings are by and large consistent with the views of former Governor Mishkin who suggested that in periods of high economic risk monetary authorities tend to respond aggressively while the degree of inertia is markedly lower than in normal circumstances.

The remainder of the paper is organised as follows. Section 2 describes the data used in the empirical analysis. Section 3 reports the results of the estimation of linear Taylor rules that have been widely used in the empirical literature. In Section 4, we test for neglected nonlinearity in these linear rules using a large set of potential transition variables. We then estimate nonlinear monetary policy reaction functions where the

2 Another strand of literature has estimated monetary policy rules that include a measure of macroeconomic risk along with the more traditional drivers of monetary policy, such as inflation and the output gap. See Dolado *et al.* (2004), Bekaert *et al.* (2013), Alcidi *et al.* (2011), Baxa *et al.* (2011) and Andrade *et al.* (2011).

strength of the response of monetary policy to macroeconomic conditions depends on the level of risk facing the economy. Section 5 concludes.

2 DATA

Simple monetary policy reaction functions in the United States specify that the US Fed sets the Federal Funds rate as a function of inflation and the output gap. Very often, the analysis underlying these feedback rules has been based on unrealistic assumptions regarding data availability, ignoring difficulties associated with the accuracy of initial data and subsequent revisions (Orphanides, 2001). Indeed, there is wide recognition that using *ex-post*, revised data has a series of drawbacks. First, policy rules that are based on unrealistic assumptions about the timeliness of data availability do not describe a policy that central banks could have actually followed in real time. Monetary policy reaction functions that set the Federal Funds rate using the current-quarter output gap and inflation based on the output deflator are simply not operational, because this information is only available much later. Second, Taylor rules based on *ex-post*, revised data can mislead efforts to identify the historical pattern of monetary policy because new renditions of the data would imply a different monetary policy stance.³ And third, estimation of monetary policy feedback rules with revised data yields biased parameter estimates, in as much as revisions to real-time data tend to represent measurement error rather than news.⁴

In this paper we follow Orphanides (2001, 2003 and 2004) and Fernandez *et al.* (2010) and use real time data to estimate monetary policy reaction functions for the United States.⁵ In particular, we rely on data from the Greenbook, a report by the Federal Reserve staff analysing current economic conditions and forecasting a large set of macroeconomic variables before each meeting of the Federal Open Market Committee (FOMC). The Greenbook, available from the Federal Reserve Bank of Philadelphia, allows us to reflect as closely as possible the information set as used by policymakers in real time.⁶

Monetary policy reaction functions are estimated using the quarterly average of daily effective Federal Funds Rates as the dependent variable, available from the Federal Reserve Bank of Saint Louis. As in Taylor (1993), inflation is measured as the four quarter rate of change in the implicit output deflator. Expected values for annual inflation are computed based on forecasts of the quarterly rate of change in the GDP deflator reported in the Greenbook.⁷ In particular, we follow Orphanides (2003) and compute the expected four quarter percentage change in the GDP deflator from the quarter of last available actual data (*i.e.*, we compute the percentage change in the GDP deflator between quarters $t-1$ and $t+3$). Past, current and future values of the output gap are measured as the percent deviation of real GDP from potential output, also available from the Greenbook.⁸

The theoretical literature reviewed before and the risk-management approach to monetary policy suggest considering not only the most likely future path for the economy but also the distribution of possible

3 Orphanides (2001) finds that US monetary policy is less accommodative to inflation when Taylor rules are estimated using real-time rather than revised data.

4 Orphanides (2001) corroborates this hypothesis using data for the Taylor period (1987Q1-1992Q4). Rudebusch (2001) and Molodtsova *et al.* (2008) considered a longer sample period, running from the first quarter of 1979 to the fourth quarter of 1998 and found similar results.

5 Blattner and Margaritov (2010) estimate a monetary policy reaction function using real time data for the euro area.

6 As correctly pointed out by Orphanides (2004), members of the FOMC may have a different view about the economic outlook than that presented in the Greenbook. Because a consistent record of the Committee's quantitative assessment of the outlook is not available, the literature has used the Greenbook as a proxy for the Committee's assessment of economic prospects.

7 The Greenbook provides forecasts for the GNP price index until 1991, and for the GDP price index from 1992 onwards.

8 Some studies have used *ex-post* inflation data together with real time data for the output gap on the grounds that revisions to inflation tend to be much smaller (Qin and Enders, 2008; Molodtsova *et al.*, 2008). We prefer to use real time data for inflation because this variable enters the monetary policy reaction function with a coefficient that is normally two-to-three times as large as that for the output gap, making small revisions to inflation to have a sizable impact on prescribed policy (Orphanides, 2001).

outcomes around that path. The distribution of outcomes is proxied here by a cross-sectional dispersion measure associated with the quarterly forecasts of the GDP deflator in the Survey of Professional Forecasters (SPF) by the Federal Reserve Bank of Philadelphia.⁹ In particular, based on data from the SPF we first construct individual forecasts for the quarter-on-quarter inflation rate up to three quarters in the future. Then, using the 25th, 50th and 75th quartiles of the forecasts for each quarter we compute forecasts for the inflation rate between quarters $t-1$ and $t+3$ corresponding to each quartile. Finally, the dispersion measure is computed as the difference between the expected inflation rate three quarters ahead corresponding to the 75th and the 25th quartiles, divided by that of the 50th quartile, as follows:¹⁰

$$\sigma_{\pi,t}^2 = \frac{\pi_{t-1,t+3}^{75} - \pi_{t-1,t+3}^{25}}{\pi_{t-1,t+3}^{50}}$$

Where $\pi_{t-1,t+3}^P$ is the Pth percentile of the distribution of individual inflation forecasts three quarters ahead.

Our second measure of risk captures stress in financial markets because the US Fed has mentioned on several occasions the importance of financial market stress for the conduct of monetary policy (Mishkin, 2008). This measure of risk in financial markets is the VXO index by the Chicago Board Options Exchange (CBOE), a measure of market expectations of near-term volatility conveyed by S&P 500 stock index option prices.¹¹ **Figure 1** plots the measure of dispersion associated with the inflation outlook derived from the SPF and the VXO volatility index. It can be seen that both measures suggest that macroeconomic risk was high at the end of the 1980s and beginning of the 1990s, late in the 1990s, and in the early 2000s.

Our sample starts with the appointment of Alan Greenspan as the Chairman of the US Federal Reserve in the fourth quarter of 1987 because of his emphasis on risk management as the underlying framework for monetary policy making.¹² The estimation period ends in the fourth quarter of 2005. For the purpose of using quarterly data, and because the Federal Open Market Committee meets eight times per year, we follow Orphanides (2001, 2003 and 2004) and use data from Greenbook corresponding to the meeting closest to the middle of the quarter.

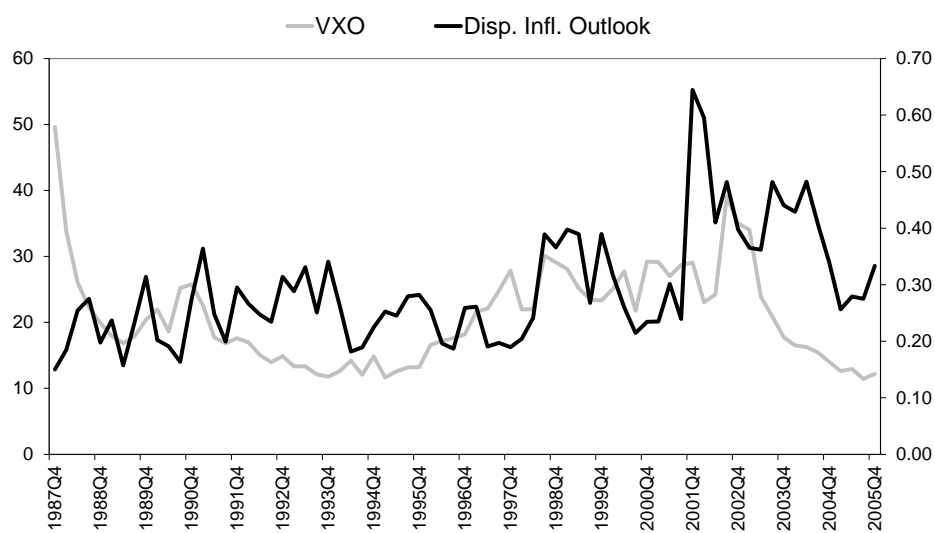
9 Fan charts attached to Greenbook forecasts are only available since 2002 and are not numerically reported.

10 Controlling by the median of the forecast is important because a given level of the interquartile range implies a different degree of uncertainty depending on the level of inflation.

11 It is important to note that we use the VXO rather than the VIX volatility index because of the longer time span covered by the former.

12 Other changes in the conduct of monetary policy under Greenspan include: *i*) a more dovish monetary policy stance (*i.e.*, a stronger response to unemployment) than under his predecessor; *ii*) smaller policy interest rate changes of exactly 25 basis points (attributable to the switch from targeting borrowing reserves to focusing on the Fed Funds rate), and requiring numerous adjustments to achieve the same cumulative tightening or easing; and *iii*) greater Fed communication transparency since the mid 1990s, which can be expected to enhance the power of monetary policy. See Blinder and Reis (2005).

Figure 1. Measures of macroeconomic risk



Source: Chicago Board Options Exchange (CBOE) and Federal Reserve Bank of Philadelphia.

3 SIMPLE MONETARY POLICY REACTION FUNCTIONS FOR THE UNITED STATES

3.1 Specification

Starting with Taylor (1993), the literature has estimated a large variety of monetary policy feedback rules where the policy instrument is assumed to depend on a small number of macroeconomic variables. In particular, in Taylor's original specification the policy interest rate was assumed to respond to current levels of inflation and the output gap.¹³ Despite its simplicity, this policy rule was found relatively successful in tracking the evolution of the effective Federal Funds rate over the period 1987-1992. One limitation of this rule pointed out by Orphanides (2003) is that estimation of a policy reaction function with a misspecified horizon can yield extremely misleading information regarding the responsiveness of policy to the outlook of inflation and economic activity. A forecast-based approach to monetary policy, where the US Fed reacts preemptively to changes in the economic environment became dominant in the literature. In Greenspan's view, "early action works best both because monetary policy works with a lag and because developing problems (such as rising inflation) may often be defused at lower cost in their early stages" (Greenspan, 2004). Another potential pitfall of the original rule is that it relies on concepts such as potential output, which may be unreliable as a policy indicator in real time. Hence, Orphanides (2003) proposed to extend the original Taylor rule with the growth rate of both actual and potential output, a rule that he calls "natural-growth targeting rule". Another limitation of the original Taylor rule has to do with the speed by which the policy interest rate is adjusted in response to new information on inflation and economic activity. Empirical evidence shows that the Fed tends to move policy rates in a series of small or moderate steps. This process (called inertia, interest-rate smoothing or gradualism) is modelled by including lagged values of the Federal Funds rate as an additional explanatory variable in the monetary policy feedback rule.¹⁴

In this section, we focus on a set of simple monetary policy feedback rules that have been widely estimated in the literature and that address the abovementioned limitations in the specification of the original Taylor rule. In particular, we consider specifications estimated by Clarida *et al.* (1998 and 1999) and Orphanides (2003).¹⁵ The general specification of the simple rule adopted here is as follows:

$$r_t = (1 - \rho_1 - \rho_2) \left(\alpha + \beta \pi_{t|t+3}^e + \phi x_{t/t}^e + \phi x_{t-1} + \theta (x_{t|t+3}^e - x_{t-1}) \right) + \rho_1 r_{t-1} + \rho_2 r_{t-2} + \eta_t \quad (1)$$

where r_t is the Federal Funds rate at time t , $\pi_{t|t+3}^e$ and $x_{t|t+3}^e$ are expected inflation and the output gap for period $t+3$ using information available until period t , and $x_{t/t}^e$ is expected output gap for period t , also using information available until time t . Expected values for the current quarter output gap reflect the fact that this variable is only available with a lag and hence needs to be forecast by the monetary authorities. As mentioned before, we rely on forecasts of inflation and the output gap over a four-quarter horizon starting from the quarter of latest available actual data (Orphanides, 2003). Hence, the year-ahead forecast is computed using information for periods $t-1$ and $t+3$. The choice of this forecast horizon is because monetary

13 Baxa *et al.* (2011) estimate Taylor rules for major OECD economies where the monetary authorities are assumed to respond as well to a large set of financial variables.

14 See Blinder and Reis (2005) for a literature review on potential reasons for inertia in monetary policy.

15 Similar Taylor rules have been estimated in Clarida *et al.* (2000), Orphanides (2001 and 2004), Qin and Enders (2008), Molodtsova *et al.* (2008) and Fernandez *et al.* (2010), among others.

policy-makers are mainly concerned about medium-term developments in the economic outlook. Finally, η_t is an error term.¹⁶

Coefficients ρ_i capture the degree of inertia in monetary policy, whereas coefficient β captures the response to inflation. If the latter are greater than unity the US Fed is said to act in a pro-active manner and the real interest rate adjusts in order to stabilise inflation. On the contrary, if it is smaller than unity, monetary policy is said to be accommodative. The goal of short-term demand management by the US Fed is captured by coefficients φ , ϕ and θ . When these coefficients are positive, monetary policy is said to be conducted in a counter-cyclical manner. Each specification of the Taylor rule mentioned before imposes a different set of restrictions on the parameters of Equation (1). These restrictions are summarised in Table 1.

There is a large body of literature providing explicit theoretical motivation for monetary policy reaction functions such as Equation (1). This literature has proved that these feedback rules are optimal under certain central bank preferences and a given structure for the economy. Moreover, because coefficients in Equation (1) are a combination of the weight the central bank places on inflation versus output and the economic structure, restrictions underlying Equation (1) are in principle testable. However, because these restrictions depend on the assumed underlying macroeconomic structure and central bank preferences, we follow Clarida et al. (1998) and estimate unrestricted versions of such feedback rules. An advantage of this agnostic approach is that it can accommodate a wide variety of macroeconomic frameworks. Moreover, it has been argued that parametric restrictions imposed on the functional specification of the reaction functions on the basis of structural models of central bank behaviour may generate misspecification biases (Kim et al., 2005).

Table 1. Summary of simple Taylor rules

Specification	Restrictions
Clarida <i>et al.</i> (1999)	In Clarida <i>et al.</i> (1999)'s specification the Federal Funds rate is assumed to respond to inflation in a pre-emptive fashion and to current values of the output gap. They also allow the interest rate to adjust smoothly to its target rate following an autoregressive process of order one. Hence, the restrictions are: $\rho_2 = \theta = \phi = 0$.
Clarida <i>et al.</i> (1998)	The authors extend Clarida <i>et al.</i> (1999) by adding an extra component of interest rate smoothing ($\rho_2 \neq 0$). In this case, we impose the following restrictions: $\theta = \phi = 0$.
Orphanides (2003)	In Orphanides (2003)'s specification, the Federal Funds rate is assumed to respond pre-emptively to inflation, to the "year-ahead" growth forecast relative to potential and to lagged values of the output gap. The restrictions are: $\rho_2 = \varphi = 0$. Note that the case where $\theta = -\phi > 0$ corresponds to the rule that targets forecasts of both inflation and the output gap. Such model has been estimated as well by Orphanides (2001).

3.2 Results

Table 2 reports the results of the estimation of Equation (1) over the Greenspan period using least squares methods.¹⁷ Empirical evidence shows that the US Fed fought inflation aggressively during the

16. The shock to the interest rate can reflect a pure random component to policy, or it can reflect interest rate jumps unrelated to movements in inflation and output due to unexpected reserve demand shocks (see Clarida *et al.*, 1998).

17. Because Clarida *et al.* (1998 and 1999) use realised values of inflation and the output gap, their forward looking Taylor rule was estimated by the General Method of Moments (GMM).

Greenspan era: the coefficient on inflation is greater than unity and statistically significant at conventional levels (Taylor principle) in all of the specifications. The estimated coefficient of the output gap is also positive and significant at conventional levels in all specifications and it ranges between 0.63 and 1.04. Hence, the empirical findings presented here suggest that monetary policy was conducted in a counter-cyclical manner in the United States during the Greenspan period. This is somewhat in contrast to estimates of the US Fed monetary policy reaction function over the joint Volker-Greenspan era, that tend to post an insignificant output gap both based on revised and real time data (Molodtsova *et al.*, 2008). In particular, Clarida *et al.* (2000) found that the coefficient measuring the sensitivity of policy rates to the economic cycle is only marginally significant or even insignificant (depending on the measure of potential output) during the Volcker-Greenspan era. Clarida *et al.* (1998 and 1999) found that the Fed reacted only to the output gap to the extent that it affected inflation expectations, because the output gap entered the set of instruments used in the econometric estimations but had no predictive power in the feedback rule. Hence, evidence of a counter-cyclical monetary policy is stronger when excluding from the sample the initial period of sharp disinflation.

Our monetary feedback rules also display a fair amount of inertia. The sum of the coefficients of the lagged policy interest rate ranges between 0.63 and 0.77, depending on the model. The size of these coefficients implies that between 37% and 23% of a change in the interest rate target is reflected in the Funds rate within one quarter, depending on the model. Such finding has been usually interpreted as evidence for the hypothesis that central banks adjust the interest rate gradually towards its target rate.¹⁸

18 This interpretation of the parameters of the lagged dependent variable has been questioned by some authors because it implies an implausibly slow adjustment speed. See Lansing (2002), Söderlind *et al.* (2004), Kim *et al.* (2005) and Rudebusch (2006), among others.

Table 2. Simple Taylor rules for the United States over the Greenspan period¹

Dep. Variable: Federal Funds rate

Variable	Clarida <i>et al.</i> (1999)		Clarida <i>et al.</i> (1998)		Orphanides (2003)	
	Estimate	Std. Err.	Estimate	Std. Err.	Estimate	Std. Err.
Constant	0.40	0.28	0.87	0.37**	-0.07	0.43
$\pi_{t t+3}^e$	1.92	0.12***	1.73	0.16***	2.16	0.19***
x_{t-1}					1.04	0.13***
$x_{t t}^e$	0.74	0.05***	0.63	0.06***		
$x_{t t+3}^e - x_{t-1}$					1.41	0.37***
r_{t-1}	0.63	0.04***	1.29	0.09***	0.74	0.04***
r_{t-2}			-0.52	0.08***		
Diagnostic tests						
Adjusted R-squared	0.98		0.99		0.98	
RMSE	0.32		0.26		0.31	
AIC	-2.20		-2.63		-2.26	
Autocorr. 1	37.31***		0.39		21.59***	
Autocorr. 4	9.91***		0.44		5.96***	

Notes: (1) $\pi_{t|t+3}^e$ = expected inflation between periods $t-1$ and $t+3$, x_{t-1} = output gap for period $t-1$, $x_{t|t}^e$ = expected output gap for period t , $x_{t|t+3}^e$ = expected output gap for period $t+3$, r_{t-i} = the federal funds rate at time $t-i$, $i = 1, 2$. The models are estimated by least-square methods over the period 1987:4-2005:4. The standard errors are based on the Newey-West heteroskedasticity and serial correlation robust estimator. Autocorr. 1 and 4 denote the Breusch-Godfrey Serial Correlation LM Test for first and fourth order autocorrelation, F statistics. ***, ** and * denote statistical significance at the 1%, 5% and 10% level, respectively.

4 NONLINEARITY IN MONETARY POLICY REACTION FUNCTIONS

4.1 Specification

Several nonlinear monetary policy reaction functions have been estimated for the United States and other developed countries and their performance has been found to be superior to their linear counterparts. For example, Martin and Milas (2004) and Taylor and Davradakis (2006) find that the Bank of England follows a nonlinear monetary policy rule, responding more strongly to changes in inflation when inflation is significantly above target. Bec *et al.* (2002) and Rabanal (2004) test the presence of asymmetries in US monetary policy and find that the US Fed was more concerned with inflationary pressures during economic booms, whereas contractions were essentially devoted to demand management. Dolado *et al.* (2005) tested the hypothesis that various central banks tighten monetary policy more aggressively when both inflation and output overshoot their targets. They provide empirical evidence supporting this hypothesis for central banks in Europe, but not for the United States. Petersen (2007) tests whether the US Fed sets its policy-rule according to the level of inflation and/or the output gap over the period 1985-2005. He shows that the Fed responded more forcefully to inflation, once inflation approached a certain threshold. Kim *et al.* (2005) and Cukierman and Muscatelli (2008) find that the US Fed reacted more aggressively to expected inflation above than below the inflation target and more strongly to expected output below than above potential. In the same vein, Qin and Enders (2008) find that the US Fed responded more aggressively to changes in inflation expectations when the monetary policy stance was either too tight or too loose. Kesriyeli *et al.* (2006) also estimate a nonlinear response in the United States according to the stance of monetary policy and find that when monetary policy is loosening, the authorities focus on demand rather than inflation management. Finally, Kilian and Manganelli (2008) found strong evidence against policy rules based on the assumption of quadratic symmetric preferences over the Greenspan period. In particular, they find that the Federal Reserve under Greenspan was highly risk averse with respect to deflationary developments, and somewhat less risk averse regarding inflationary developments.

Non-linear behaviour in monetary policy has been modelled based on discontinuous regime switching models, like in the case of threshold or Markov-switching models (Bec *et al.*, 2002; Rabanal, 2004; Assenmacher-Wesche, 2006; Taylor and Davradakis, 2006, Creel and Hubert, 2012), or continuous, as in smooth transition regression models (Martin and Milas, 2004; Kesriyeli *et al.*, 2006; Qin and Enders, 2008; Cukierman and Muscatelli, 2008; Baxa *et al.*, 2011). In this paper we follow the second strand of literature and use a smooth transition regression (STR) model to test the hypothesis that the strength of the response of monetary policy to macroeconomic conditions depends on the level of risk facing the economy. Smooth transition regression models have a series of advantages. First, they encompass discontinuous regime switching models. Indeed, if the true model is discontinuous, this feature will be captured in the econometric estimation of a smooth transition regression model. Second, smooth-transition regression models are locally linear, which facilitates interpretation. Third, from a theoretical point of view, the assumption of just a few discrete states can be too restrictive compared with the continuum of states implied by STR models. Finally, a smooth-transition regression model provides a more straightforward economic interpretation as the transition mechanism relies on an observable transition variable while Markov-switching specifications assumes that the transition variable is unobserved.

Nonlinearity in monetary policy can be estimated and tested in the following framework (Teräsvirta, 1998 and 2004):

$$r_t = z_t' \Psi_0 + z_t' \Psi_1 G(\gamma, c, s_t) + \mu_t \quad (2)$$

Where we have expanded Equation (1) and rewritten it using vector notation with

$z_t' = [1 \ \pi_{t|t+3}^e \ x_{t|t}^e \ x_{t-1} \ (x_{t|t+3}^e - x_{t-1}) \ r_{t-1} \ r_{t-2}]$ and $\Psi_i = [\alpha_i^* \ \beta_i^* \ \phi_i^* \ \phi_i^* \ \theta_i^* \ \rho_{1,i} \ \rho_{2,i}]'$, for $i = 0,1$. The variables are defined as in section 3.1, $G(\gamma, c, s_t)$ is a continuous transition function bounded between zero and one, s_t is the variable leading the transition across policy regimes, and μ_t is a sequence of independent, identically distributed errors.¹⁹

The form of the transition function defines the response of monetary policy to macroeconomic conditions. Two standard functions have been widely adopted in the literature:

$$G(\gamma, c, s_t) = (1 + \exp(-\gamma(s_t - c)))^{-1} \quad (3)$$

And:

$$G(\gamma, c, s_t) = 1 - \exp(-\gamma(s_t - c)^2) \quad (4)$$

The transition function defined in Equation (3) is a logistic function which increases monotonically in s_t . This function implies a response of monetary policy to macroeconomic conditions that switches monotonically from low to high values of the transition variable.²⁰ For example, if economic risk leads the transition across policy regimes, and assuming a positive response of monetary policy to economic activity and inflation in both the linear and non-linear parts of the model, then Equation (3) implies that the Fed will react more aggressively to macroeconomic conditions when risk is high than when it is low. By contrast, when the transition function is given by (4), the strength of the response switches when moving from intermediate to both high and low values of the transition variable.²¹ Equations (3) and (4) allow quite a lot of flexibility in modelling changes across monetary policy regimes. In both equations, the slope parameter $\gamma > 0$ captures the speed of the transition across regimes. For very small values of γ the transition across regimes is very slow. By contrast, if $\gamma \rightarrow +\infty$ the model becomes a two-regime threshold regression model. As suggested by Granger and Teräsvirta (1993), this parameter should be normalised by the variance of the transition variable because it is not scale-free. The location parameter c captures the threshold for regime change.

As mentioned in Section 3.1, estimation of Taylor rules in this paper is conducted in a reduced-form set up. Accordingly, the coefficients of the Taylor rule embody preference parameters as well as parameters

19 This model can be interpreted as a two-regime model where the transition between regimes is smooth. In particular, we can rewrite Equation (2) as $r_t = z_t'(\Psi_0 + \Psi_1 G) + \mu_t$. As G is bounded between zero and one, it can easily be seen that the coefficients fluctuate between Ψ_0 and $\Psi_0 + \Psi_1$.

20 From Equation (3) it can be seen that the transition function tends to 0 for low values of s_t and the strength of monetary policy is given by Ψ_0 . By contrast, for large values of s_t the function tends to 1 and the response of monetary policy to macroeconomic conditions is given by $\Psi_0 + \Psi_1$.

21 From Equation (4) it can be seen that this transition function is symmetric around the threshold parameter c . In particular, monetary policy responds to macroeconomic conditions with parameters Ψ_0 when the transition variable is close to c . By contrast, when the transition variable takes extreme values (either low or high), the response of monetary policy switches to $\Psi_0 + \Psi_1$.

characterizing the structure of the economy. Dolado *et al.* (2004 and 2005) disentangle nonlinearity in the Fed Funds rate related to either central bank preferences and nonlinearities in the aggregate supply schedule. The authors find that the aggregate supply schedule is well approximated by a linear relation in the United States. They conclude that nonlinearity in the response of the US Fed to macroeconomic conditions arises from asymmetries in central bank preferences, rather than in the structure of the economy. Moreover, as mentioned before for the case of the linear Taylor rules, we do not impose any restriction on the parameters of the reaction functions. Hence, the functional specification of the reaction function does not depend on the specific parameterization of the theoretical model describing central bank behaviour and the structure of the economy.

To test whether or not the parameters of the Taylor rule switch with the degree of risk facing the economy, we follow the four steps suggested in Teräsvirta (1998). First, a formal test is implemented to decide whether or not the data can be adequately characterized by the linear Taylor rules estimated before. This means testing linearity against regime switching in monetary policy using a smooth transition regression model under a set of potential transition variables. Second, if linearity is rejected, a variable is selected as the transition variable leading the change across monetary policy regimes. In particular, if linearity is rejected for more than one transition variable, the one with the strongest rejection probability is selected as the variable leading the transition across regimes. Third, a transition function, such as the logistic or exponential, is selected to model the Fed Funds rate using a sequence of nested, conditional statistical tests. Finally, the non-linear Taylor rules are estimated using non-linear least squares techniques.

The next section tests for neglected nonlinearity in the linear specifications estimated before and selects both the transition variable and the function that fits the data better. The subsequent section presents the results of the estimation of the non-linear monetary policy rules.

4.2 Testing for neglected nonlinearity in linear Taylor rules

The results of the estimation of linear monetary policy reaction functions presented in Section 3.2 amounts to assuming that the second term in Equation (2) is equal to zero. However, this assumption would entail a misspecification error in linear models if monetary policy was effectively non-linear. Ultimately, whether or not monetary policy reacts in a non-linear manner to macroeconomic conditions is an empirical question. Testing the hypothesis that the second term in Equation (2) is equal to zero using a Likelihood ratio test entails an identification problem, because Equation (2) is defined under the alternative hypothesis but not under the null.²² A way of solving the identification problem is by circumventing it by taking a Taylor expansion of the transition function with the null hypothesis $\gamma = 0$ as the expansion point (Teräsvirta, 1998 and 2004). The null hypothesis of linearity can then be tested in a straightforward manner using an approximate F test.²³ This F test is conditional on the selection of a transition variable, because Equation (2) requires the choice of such transition variable to lead the change across monetary policy regimes.

Empirical evidence surveyed before for the United States suggests inflation, the output gap and past values of the Fed Funds rate as potential candidates to lead the transition across monetary policy regimes. Dolado *et al.* (2005), Kim *et al.* (2005) and Cukierman and Muscatelli (2008) estimated non-linear reaction functions

²² Other tests, like the Lagrange Multiplier (LM) and the Wald test suffer from the same problem.

²³ The number of degrees of freedom depends on whether or not the transition variable belongs to the set of regressors and on the order of the expansion. This F test has been found to have good power even in small samples, while the empirical size of the test remains close to the nominal size (Teräsvirta, 1998).

where the response of monetary policy to inflation and output depends on the level of the respective gaps. Bec *et al.* (2002) and Rabanal (2004) test the presence of asymmetries in monetary policy depending on the state of the business cycle, rather than deviations of inflation from its targeted value. Finally, Kesriyeli *et al.* (2006) and Qin and Enders (2008) estimate a non-linear monetary policy reaction function in the United States according to the stance of monetary policy.

However, as mentioned in the introduction, the literature has greatly overlooked the potential nonlinearity arising from an uncertain economic environment. In Mishkin (2008)'s view, and based on the theories reviewed before, the strength of the response of monetary policy to macroeconomic conditions should depend on the level of risk facing the economy. Hence, this approach calls for a measure of economic risk to lead the transition across monetary policy regimes, rather than inflation, the output gap or past values of the Fed Funds rate. As mentioned before, we focus on measures of risk associated with the inflation outlook and risk in financial markets. Hence, $s_t \in \{\sigma_{\pi,t}^2, VXO_t\}$, where $\sigma_{\pi,t}^2$ is the inflation dispersion measure and VXO_t is volatility in financial markets, defined before.

Because the presence of nonlinearities in otherwise linear monetary policy reaction functions is an empirical question, we tested for neglected nonlinearity in the linear Taylor rules estimated before using two sets of transition variables: those suggested in the traditional empirical literature (inflation, output gap and Fed Funds rate), and the two measures of economic risk mentioned in the previous paragraph. After all, if nonlinearities arising from an uncertain economic environment offer a more accurate representation of the behaviour of monetary authorities in the United States, rejection of the linear hypothesis should be stronger for the two measures of economic risk.

Table 3 presents the results regarding nonlinearity tests for each transition variable (first column) and the set of models estimated before (subsequent columns). For each model we test the null hypothesis of linearity (F-test) and when it is rejected, we report the transition function selected by sequential statistical tests (Trans. Funct. column). Empirical evidence reported in this Table shows overwhelming support in favour of the hypothesis of non-linear behaviour in the conduct of monetary policy over the Greenspan period, with economic risk leading the transition across policy regimes. Only for risk in financial markets in the model estimated by Orphanides (2003) we cannot reject the null hypothesis of linearity at conventional statistical levels. For the remaining models and measures of risk, we can reject at the 10% level or less the null hypothesis of linearity in monetary policy in favour of economic risk leading the transition across policy regimes. By contrast, there is less evidence of non-linear behaviour in the conduct of monetary policy for the US Fed when considering traditional transition variables (inflation, interest rate and output gap). All in all, our findings show that risk in the inflation outlook and risk in financial markets are a more powerful driver of changes in monetary policy regimes than the variables typically considered in the literature. In these cases, the statistical tests consistently suggest a logistic transition function for the risk measures, implying a different response by the monetary authorities when economic risk is high than in normal times.

Table 3. Testing linearity against nonlinearity in monetary policy reaction functions

Trans. Var.	Clarida <i>et al.</i> (1998)		Clarida <i>et al.</i> (1999)		Orphanides (2003)	
	F-test	Trans. Funct.	F-test	Trans. Funct.	F-test	Trans. Funct.
π_{t-1}	0.59		0.69		1.32	
	<i>0.84</i>		<i>0.71</i>		<i>0.24</i>	
r_{t-1}	1.56		2.19	Exp.**	2.16	Log.*
	<i>0.13</i>		<i>0.04</i>		<i>0.03</i>	
$\pi_{t t+3}^e$	1.42		1.63		0.81	
	<i>0.19</i>		<i>0.13</i>		<i>0.63</i>	
$x_{t t}^e$	1.46		1.02		1.26	
	<i>0.17</i>		<i>0.44</i>		<i>0.27</i>	
$\sigma_{\pi,t}^2$	1.68	Log.**	2.3	Log.***	1.72	Log.**
	<i>0.09</i>		<i>0.03</i>		<i>0.09</i>	
VXO_t	2.36	Log.***	3.49	Log.***	1.52	
	<i>0.02</i>		<i>0.00</i>		<i>0.14</i>	

Note: π_{t-1} = annual inflation based on the GDP deflator at time $t-1$, $\pi_{t|t+3}^e$ = expected annual inflation for period $t+3$ using information available until period t , r_{t-1} = federal funds rate at time $t-1$, $x_{t|t}^e$ = expected output gap for period t , $\sigma_{\pi,t}^2$ = dispersion in the inflation outlook at time t , VXO_t = VXO volatility index at time t . The entries under F-test for each transition variable in the first column show the F-statistics and the associated p-values (in italics) for the null hypothesis of linear monetary policy reaction functions against the alternative of smooth transition regression. When the null hypothesis is rejected, the following column (Trans. Funct.) reports the transition function selected by a sequential F-test procedure (Teräsvirta, 2004). *Exp.* stands for the exponential transition function defined in Equation (3), while *Log.* stands for the Logistic function in Equation (4). The estimation sample spans the period from 1987Q4 to 2005Q4. In the case of the VXO volatility index the test is performed over a shorter sample starting in 1988Q1 due to near singularity of the moment matrix related to the high volatility induced by the financial market crash of October 1987.

4.3 Non-linear monetary policy reaction functions and risk management

This section estimates regime switching models for the monetary policy rules under consideration, where the strength of the response of monetary policy to macroeconomic conditions depends on the level of risk facing the economy. For each rule, we estimate smooth transition regression models using the two measures of economic risk as the variable leading the transition across policy regimes. The exception is the case of risk in

financial markets in Orphanides (2003), where the null hypothesis of linearity was not rejected by the data. Models are estimated by non-linear least squares (NLLS) using the Marquardt- Levenberg algorithm.²⁴ One issue with the estimation of non-linear models is the existence of multiple minima as there is then no guarantee that the algorithm eventually returns values for the parameters that provide the best fit of the model. This is especially the case when the starting values are too far from the true value of the parameters and when the number of parameters to be estimated is large. Therefore, to facilitate estimation we proceed with a two-step identification strategy. Because the parameters of the transition function -the one capturing the speed of convergence and the threshold- are the most difficult to estimate, we first concentrate on the linear and non-linear parameters, fixing γ equal to 1 and c equal to the mean of the transition variable in order to obtain a set of initial values for the remaining parameters. In a second round of estimations, the restriction on the two parameters of the transition function is relaxed, and a grid search for their optimal value is implemented. We use an interval from 0.01 to 30 for γ , with increments of 0.1 units. The minimum and maximum values of the transition variable delimit the interval for the threshold parameter, in increments of 1 unit and 0.1 units for VXO and the dispersion of inflation, respectively. The advantage of using a grid algorithm is that it can provide a thorough sampling of the parameter space, mitigating the risk of picking a local minimum.

The results of the estimation of smooth transition regression models for the monetary policy rules under consideration are presented in **Table 4**. The upper part of the Table reports parameters in vector Ψ_0 , *i.e.*, the response coefficients of the US Fed in normal times, while the middle part presents the estimation of vector Ψ_1 and the parameters of the transition function. Finally, the lower part presents error diagnostic tests to assess the goodness of fit of the non-linear models.

Evidence presented in **Table 4** shows that in normal times the US Fed fights inflation and implements a counter-cyclical monetary policy, as suggested by the estimation of linear Taylor rules. The coefficients of inflation and the output gap are positive and statistically significant at conventional levels in vector Ψ_0 : they range between 0.44 and 0.61 for inflation, and between 0.14 and 0.25 for the output gap. These coefficients are not directly comparable with those from the linear Taylor rules in **Table 2** because we have expanded Equation (1) in order to facilitate convergence of the estimation algorithm. Comparable coefficients computed from **Table 4** range between 1.74 and 1.91 for inflation, and from 0.54 and 0.89 for the output gap. The magnitude of these coefficients suggests that the response to inflation is about the same as that one estimated in linear models, whereas the response to the output gap is somewhat weaker.

Our results also show that in periods of high economic risk the US Fed becomes more responsive to the business cycle, but not to the inflation outlook. The coefficients of the output gap now range between 0.3 and 0.45, depending on the model and the transition variable.²⁵ In other words, the US Fed reacts to a wider (narrower) output gap by tightening (loosening) monetary policy, and this policy response becomes more aggressive in periods of high economic risk. By contrast, the response of the US Fed to the inflation outlook appears to be invariant across policy regimes.

24 It can be argued that macroeconomic risk is endogenous to the monetary policy stance. This endogeneity would require a different estimation technique, such as General Methods of Moments (GMM). This might be particularly the case of risk in financial markets, which tends to react to monetary policy decisions. Bekaert et al. (2013) estimate a vector-autoregressive model to analyse the dynamic link between risk aversion in financial markets, economic uncertainty and monetary policy. They find that a lax monetary policy effectively decreases risk aversion, but only five months in the future. The response at a shorter-time interval is not significant. Hence, there seems to be no contemporaneous correlation between interest policy rates and measures of risk in financial markets.

25 These coefficients correspond to $\Psi_0 + \Psi_1$.

Results reported in **Table 4** also suggest that the degree of inertia in monetary policy tends to be lower in periods of high economic risk than in normal circumstances. The sum of the autoregressive coefficients switches from about 0.75 in normal times, to between 0.47 and 0.57 in periods of high economic risk, depending on the model specification. A lower value for the autoregressive coefficients implies a faster adjustment of the policy interest rate towards its fundamental determinants: whereas in normal times only about 25% of the adjustment to the new desired interest rate level takes place in one quarter, the speed raises to between 43% and 53% in periods of high economic risk, depending on the model. Overall, these results are by and large consistent with Mishkin’s hypothesis that in periods of high economic risk monetary policy tends to respond aggressively to macroeconomic conditions and the degree of inertia tends to be lower than in normal circumstances.²⁶

Figures 2 and 3 report the response coefficients of the US Fed to the output gap and the degree of inertia, as a function of economic risk over time. From equation (2) it can easily be seen that the response coefficients in the case of the output gap are given by:

$$\varphi_t^* = \varphi_0^* + \varphi_1^* G(\gamma, c, s_t)$$

In the case of inertia, these coefficients are given by:

$$\rho_t = \sum_{j=1}^J \rho_{0j} + \sum_{j=1}^J \rho_{1j} G(\gamma, c, s_t)$$

Starting with the output gap, when risk in financial markets is assumed to lead the transition across policy regimes (**Figure 2, Panel A**), the US Fed is estimated to have responded aggressively to the output gap at the beginning of 1988 and during 1990. The strong response reflects the attempt at a soft-landing following the stock market crash in 1987 and high volatility related to the Iraq invasion of Kuwait in the fall of 1990. During the tranquil period between the end of 1991 and 1996 the response is estimated accordingly to have been weaker. The US Fed turned aggressive again as risk in financial markets increased following a sequence of adverse events from the middle of 1997 to the end of 2003. These events include the Asian crisis in mid-1997, the Russian debt default in August 1998, the collapse of the hedge fund Long Term Capital Management (LTCM) in early 2000, the stock market crash of 2000–2002 associated with the collapse of the dot-com bubble, and the terrorist attacks of September 2001 and the ensuing fears of recession. When dispersion around the inflation outlook is assumed to lead the transition across policy regimes, the US Fed is estimated to have been aggressive at the beginning of 1991 and again in the late 1990s and the beginning of the 2000s, reflecting the previously mentioned events (**Figure 2, Panel B**). At the same time that the US Fed became more aggressive in periods of high economic risk, it also became less inertial in setting policy interest rates, implying a faster adjustment towards its fundamental determinants (**Figure 3**). In particular, monetary authorities in the United States smoothed interest rates particularly in the first half of the 1990s and at the end of the sample period, when economic risk was low. The estimated transition functions (**Figure 4**) show that the transition across monetary policy regimes is relatively fast.

26 Estimations were also performed over a sample ending in the fourth quarter of 2007, beyond the end of Greenspan as the chairman of the US Federal Reserve. Empirical evidence based on the new estimation sample also supports the hypothesis of non-linear behaviour in the conduct of monetary policy in the U.S., with economic risk leading the transition across policy regimes. At the same time, estimates of regime switching models for the new monetary policy rules appear to be less robust than those estimated based on the previous sample. In particular, the estimation algorithm failed to converge in one of the five models that were estimated, for three models the results were very similar to those presented in Table 4 and for one model the variables in the non-linear part of the model were not significant. These results are available from authors upon request.

Our results are by and large consistent with anecdotal evidence from several Board members regarding the behaviour of the US Fed over this period. Chairman Greenspan himself stated that in episodes of high economic risk, like the stock market crash of 1987, the crises of 1997-98 and following the terrorist attacks in September 2001, simple rules are inadequate as either descriptions and prescriptions of policy, offering grounds for deviating from the linear-quadratic approach to monetary policy.²⁷ In particular, Governor Ferguson and Governor Blinder interpret Greenspan's policy rate cut during the crisis of 1998 in light of the risk management approach to monetary policy, where not only the most likely expected outcome matters for monetary policy but also the entire distribution of possible outcomes. They argue that at the time, the US economy was expanding and was not in any apparent need of monetary stimulus. Most of the contrary, they state that several FOMC members had been urging Greenspan to tighten since 1996. However, monetary policy was eased because the risks triggered by the Russian debt default and the near collapse of a large hedge fund threatened to snowball into a wide financial crisis, with negative consequences for inflation and economic activity.²⁸ In Ferguson's words: "Even though the unemployment rate was reaching new lows- which according to standard relationships would lead to higher inflation and which standard monetary policy rules would recommend addressing by tightening policy- the FOMC judged that the severity of the financial crises was likely to imperil future growth and lowered interest rates substantially." Governor Kohn (2007) also attributes to risk management the policy rate cuts that started at end-2002 and their maintenance at very low levels during most of 2003 and 2004. He states that the FOMC noted that a continued fall in inflation would be unwelcome, largely because such an eventuality might potentially lead to persistently weak real activity with interest rates stuck at zero. He states that "We had carefully analysed the Japanese experience of the early 1990s; our conclusion was that aggressively moving against the risk of deflation would pay dividends by reducing the odds on needing to deal with the zero bound on nominal interest rates should the economy be hit with another negative shock." When discussing the effective implementation of monetary policy when interest rates are close to the zero lower bound and deflationary risks are high, Bernanke and Reinhart (2004) state that "...policy-makers are well advised to act pre-emptively and aggressively to avoid facing the complications raised by the zero lower bound".

Overall, results presented in **Table 4** support the view that regime switching monetary policy rules fit the data better than their linear counterparts. Whereas the adjusted R^2 are broadly unchanged across linear and non-linear specifications, both the RMSE and the Akaike Information Criteria are lower in the non-linear equations. Moreover, all the specifications seem to capture well the non-linear dynamics of the data. All the tests of non-remaining non-linearity point to non-rejection of the null hypothesis of absence of remaining additive non-linearity.

27 See Greenspan (2004).

28 See Ferguson (2003) and Blinder and Reis (2005).

Table 4. Non-linear monetary policy reaction functions

	Clarida <i>et al.</i> (1999)				Clarida <i>et al.</i> (1998)				Orphanides (2003)	
	$\sigma_{\pi,t}^2$		VXO_t		$\sigma_{\pi,t}^2$		VXO_t		$\sigma_{\pi,t}^2$	
Vector Ψ_0	Estimate	Std.	Estimate	Std.	Estimate	Std.	Estimate	Std.	Estimate	Std.
Constant	0.32**	0.14	0.32**	0.15	0.24**	0.10	0.15	0.11	0.21	0.15
$\pi_{t t+3}^e$	0.61***	0.10	0.44***	0.14	0.46***	0.08	0.44***	0.10	0.53***	0.07
x_{t-1}									0.25***	0.02
$x_{t t}^e$	0.23***	0.02	0.21***	0.04	0.14***	0.03	0.15***	0.11		
$x_{t t+3}^e - x_{t-1}$									0.33***	0.07
r_{t-1}	0.65***	0.04	0.76***	0.05	1.22***	0.09	1.15***	0.11	0.72***	0.04
r_{t-2}					-0.48***	0.07	-0.38***	0.09		
Vector Ψ_1										
Constant	0.64	0.48	-0.19	0.23	0.88	0.70	0.14	0.17	0.70	0.69
$\pi_{t t+3}^e$	-0.38	0.45	0.30	0.19	-0.23	0.59	0.23	0.23	-0.31	0.46
x_{t-1}									0.20*	0.11
$x_{t t}^e$	0.16**	0.07	0.17**	0.07	0.31***	0.11	0.17***	0.04		
$x_{t t+3}^e - x_{t-1}$									-0.08	0.17
r_{t-1}	-0.18	0.13	-0.19**	0.09	-0.71***	0.24	-0.08	0.17	-0.22	0.20
r_{t-2}					0.44*	0.23	-0.09	0.14		
Transition function										
γ	2.47		3.01		2.9		6.35		3.25	
c	0.4		20.2		0.4		21		0.21	
Diagnostic tests										
Adj. R sqd.	0.98		0.98		0.99		0.99		0.98	
RMSE	0.29		0.29		0.29		0.23		0.29	
AIC	-2.28		-2.30		-2.68		-2.72		-2.29	
Autocorr. 1	26.3***		27.2***		1.22		1.26		14.8***	
Autocorr. 4	7.6***		7.3***		1.73		0.60		4.42***	
NRNL	0.62		1.67		0.62		0.86		1.06	

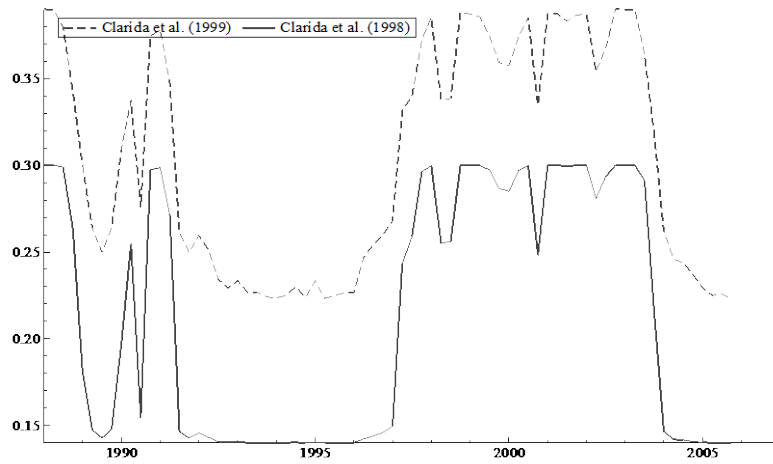
Note: $\pi_{t|t+3}^e$ = expected inflation between periods $t-1$ and $t+3$, x_{t-1} = output gap for period $t-1$, $x_{t|t}^e$ = expected output gap for period t ,

$x_{t|t+3}^e$ = expected output gap for period $t+3$, r_{t-i} = Federal Funds rate at time $t-i$, for $i=1,2$. The transition variables are: $\sigma_{\pi,t}^2$ =

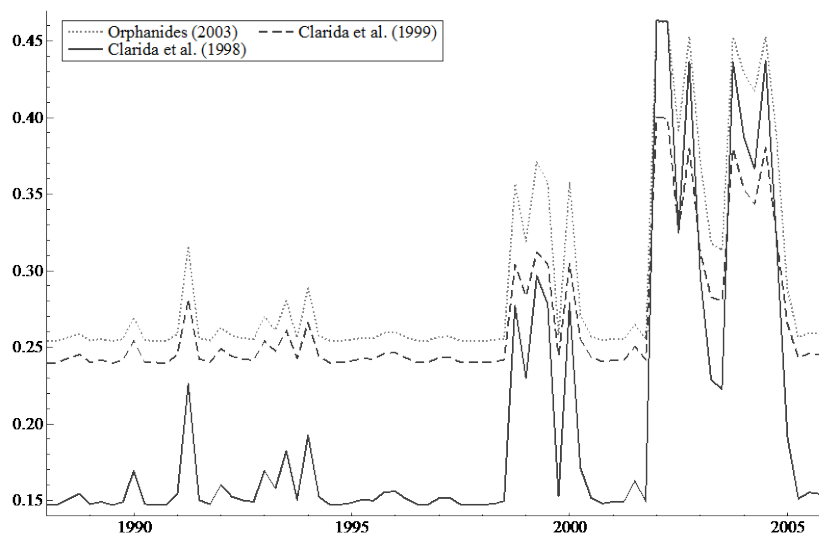
dispersion in the inflation outlook at time t , and VXO_t = VXO volatility index at time t . Orphanides (2003) is estimated with one transition variable because linearity was not rejected for the VXO index. Models are estimated by NLLS using the Marquardt-Levenberg optimisation algorithm. The sample spans the period 1987Q4 to 2005Q4. In the case of the VXO volatility index the estimations are performed over a shorter sample starting in 1988Q1 (see note to Table 3). Autocorr. 1 and 4 denote the LM test for first and fourth order autocorrelation. NRNL is the F tests of no additive nonlinearity against an additive STR model. See Teräsvirta (2004) for details regarding the autocorrelation and the NRNL test. (*), (**) and (***) denote significance at the 10, 5 and 1% levels, respectively.

Figure 2. The response of monetary policy to the output gap and changes in regime

A. VXO as transition variable



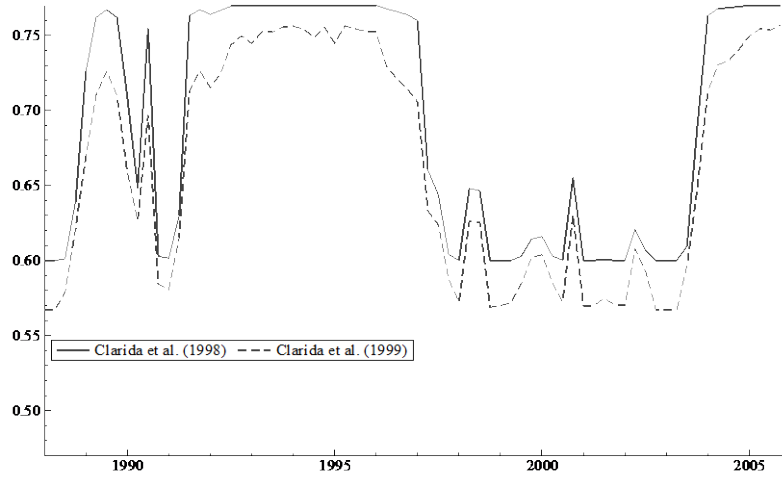
B. Dispersion in the inflation outlook as transition variable



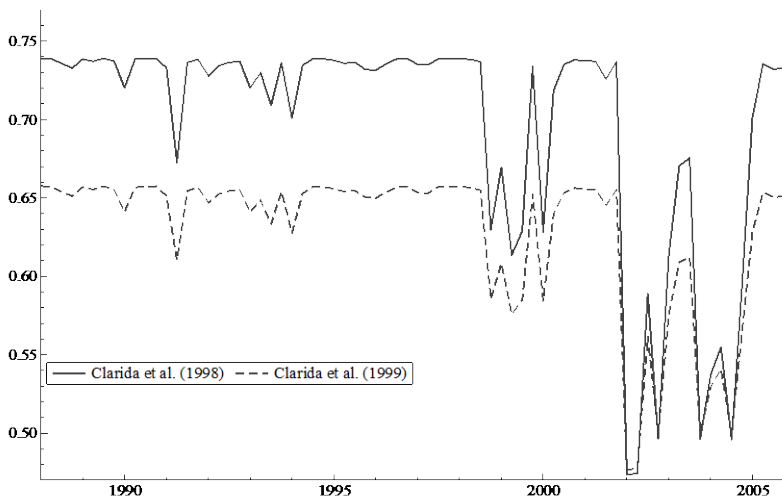
Note: The figures plot the response coefficients as a function of economic risk through time for different models and transition variables.

Figure 3. Inertia in monetary policy and changes in regime

A. VXO as transition variable



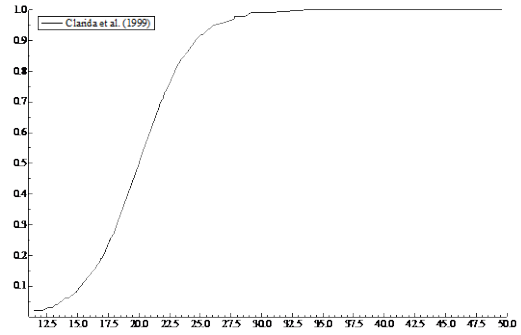
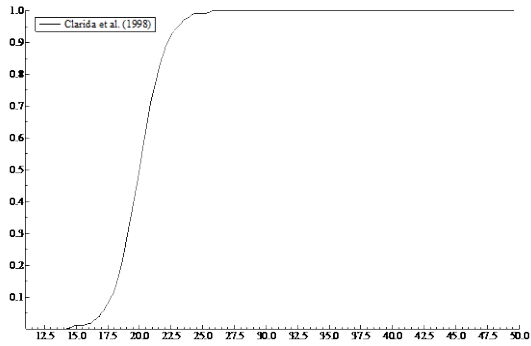
B. Dispersion in the inflation outlook as transition variable



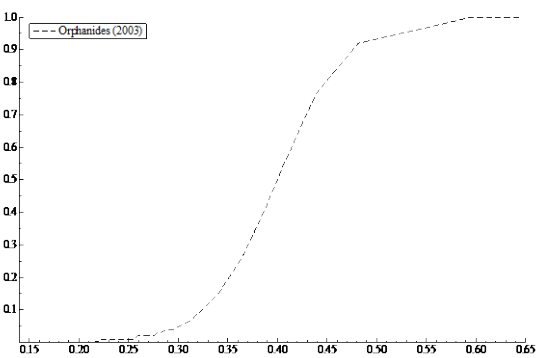
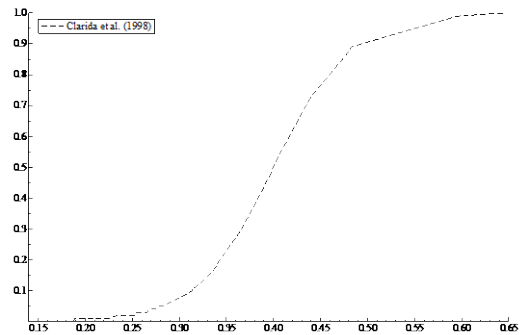
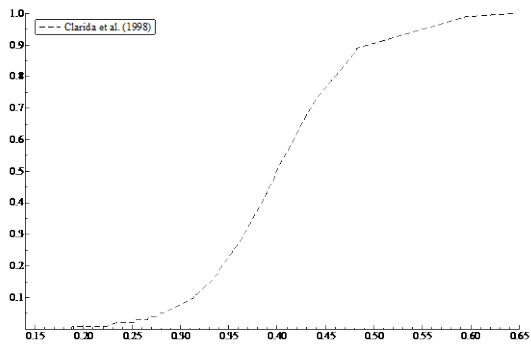
Note: The figure plots the coefficients for the lagged Federal Funds rate as a function of economic risk through time for different models and transition variables.

Figure 4. Estimated logistic transition functions

A. VXO as transition variable



B. Dispersion in the inflation outlook as transition variable



5 CONCLUSION

Most of the analysis regarding the estimation of non-linear monetary policy reaction functions has focused on the possibility that the central bank may respond in a non-linear manner to inflation in different points of the business cycle or depending on the size of the deviation of actual inflation from explicit or implicit targets. They have also focused on the implications of more complex price-setting mechanisms than those subsumed in linear Philips curves. Several non-linear monetary policy reaction functions have been estimated for the United States and other developed countries and their performance has been found to be superior to their linear counterparts.

Another source of potential nonlinearity that has been greatly overlooked by the literature stems from an uncertain economic environment. Several sources of uncertainty affect the implementation of monetary policy in real time: data uncertainty, parameter uncertainty and shock uncertainty. While there seems to be agreement in the literature that policy-makers should be less aggressive with respect to poorly measured targets, the literature has been divided as to whether or not monetary policy in the presence of parameter uncertainty should be more or less aggressive than absent uncertainty. While part of the literature suggests that monetary authorities should be cautious under parameter uncertainty, its quantitative impact has been found to be negligible in simulated models. Yet another strand of literature shows that uncertainty regarding the structure of the economy and/or the impact of policy should lead to a more responsive approach by the authorities. The literature also suggests that monetary policy should be more aggressive in the presence of shock uncertainty. In particular, the “robust control” approach suggests that monetary policy should be aggressive in order to avoid very bad outcomes. This prescription is in line with the views expressed by several US Fed Governors and the risk-management approach to monetary policy. Indeed, former US Fed Chairman Alan Greenspan proposed that under risk management monetary policy should consider not only the most likely future path for the economy but also the distribution of possible outcomes about that path. Moreover, former Governor Mishkin stated that when macroeconomic risk is high, monetary policy tends to respond aggressively, while the degree of inertia tends to be lower than in normal circumstances.

We contribute to the empirical literature on the risk-management approach by estimating regime switching models where the strength of the response of monetary policy to macroeconomic conditions depends on the level of risk associated with the inflation outlook and risk in financial markets. Our measures of risk are closely related to the wording used by former Governors of the US Federal Reserve. Moreover, we use real time data to estimate the regime switching models and focus on the Greenspan period because of his emphasis in the risk management approach. To our knowledge, this is the first time that real time data are used in the estimation of non-linear Taylor rules for the United States.

The main findings of the paper are as follows: *i*) risk in the inflation outlook and volatility in financial markets are a more powerful driver of monetary policy regime changes than the variables typically suggested in the literature, such as the level of inflation, the output gap and the Fed Funds rate; *ii*) estimation of regime switching models shows that the response of the US Fed to the inflation outlook is invariant across policy regimes; *iii*) however, in periods of high economic risk monetary policy tends to respond more aggressively to the output gap and the degree of inertia tends to be lower than in normal circumstances; and *iv*) the US Fed is estimated to have responded aggressively to the output gap in the late 1980s and begging of the 1990s, and in the second half of the 1990s and early 2000s. The more aggressive response is consistent with anecdotal evidence from several Board members regarding the behaviour of the US Fed over periods of high economic risk. These findings are also by and large consistent with former Governor Mishkin’s view that in periods of high economic risk monetary authorities tend to respond aggressively while the degree of inertia is markedly lower than in normal circumstances.

To a certain extent, our results are consistent with those in Rabanal (2004), Kesriyeli *et al.* (2006) and Cukierman and Muscatelli (2008). Rabanal (2004) found that the Federal Reserve targets inflation and conducts monetary policy in a highly inertial manner during economic booms, while during recessions it targets output growth and conducts monetary policy more aggressively. Kesriyeli *et al.* (2006) estimate a non-linear response in the United States over part of the Volcker and Greenspan period according to the stance of monetary policy and find that when monetary policy is loosening, monetary authorities focus on demand rather than inflation management. Finally, Cukierman and Muscatelli (2008) found evidence of a non-linear monetary policy rule over the Greenspan period, when the US Fed is estimated to have responded more aggressively to changes in the output gap when this gap was negative. These results are somewhat consistent with ours in as much as periods of weak economic activity, loosening monetary policy and periods of high economic risk are somewhat correlated. However, our findings show that the US Fed always targeted inflation, and that economic risk is a more powerful driver of regime changes than either economic activity or policy interest rates, in full agreement with the risk management approach to monetary policy.

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