Title
Essays in monetary policy

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Publication Date
2012

Peer reviewed|Thesis/dissertation

UNIVERSITY OF CALIFORNIA, SAN DIEGO

Essays in Monetary Policy

A dissertation submitted in partial satisfaction of the
requirements for the degree
Doctor of Philosophy

in

Economics

by

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2012

The dissertation of Aeimit Kirti Lakdawala is approved, and it is acceptable in quality and form for publication on microfilm and electronically:

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Chair

University of California, San Diego

2012

DEDICATION

To my parents, without whom I would not have embarked on this endeavor. And to my friends, without whom I would not have seen it through.

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ACKNOWLEDGEMENTS

I would like to thank Professor James Hamilton for his invaluable advice, guidance and most importantly his unwavering belief.

Additionally I would like to thank the members of my committee and Professor Valerie Ramey, Professor Marjorie Flavin and the participants at the macroeconomics seminars and lunch workshops for helpful comments and suggestions.

Finally I would like to thank my colleagues at University of California, San Diego, especially Leah Nelson and Kevin Novan.

Chapter 3, in part is currently being prepared for submission for publication of the material. Debortoli, Davide; Lakdawala, Aeimit. The dissertation author was the co-primary investigator and author of this material.

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ABSTRACT OF THE DISSERTATION

Essays in Monetary Policy

by

Aeimit Kirti Lakdawala

Doctor of Philosophy in Economics

University of California, San Diego, 2012

Professor James D. Hamilton, Chair

My thesis considers three issues related to monetary policy. The first chapter is an empirical investigation into the changes in the weight that the Federal Reserve has put on inflation relative to output. The second chapter considers the theoretical implications of globalization on inflation and monetary policy specifically focusing on the foreign competition channel. Finally, the third chapter estimates a level of credibility for the Federal Reserve.

Chapter 1

Changes in Federal Reserve Preferences

Abstract

This paper explores the dynamic behavior of Federal Reserve preferences to gain a deeper understanding of the motivations behind monetary policy decisions. I develop a model of optimizing central bank behavior where preferences are captured by the relative weight put on stabilizing inflation versus minimizing the output gap. Unlike previous work, I allow this parameter to vary continuously over time to reflect gradual changes in underlying preferences. I estimate the preference parameter series using a Bayesian Markov Chain Monte Carlo algorithm with non-linear filtering methods. There is a drastic but steady rise in the weight on inflation around the appointment of Paul Volcker which is sustained into the early 90s; however, I find variation in preferences throughout the sample period. These results suggest that preference changes have been complex and cannot be captured by the commonly used assumption of a one-time discrete shift. The estimated preference series is used in several applications, including the construction of a new measure of monetary shocks that is used to estimate the impact of monetary policy on the economy.

1.1 Introduction

The Federal Reserve has a dual mandate of full employment and price stability, but quite often there is a short-run tradeoff between these two objectives. For example, although the Federal Reserve has tried to combat the current high unemployment rate by using both traditional and unconventional measures, it has been cautious in implementing more aggressive policy actions. This is in part due to the fear of causing a future rise in inflation. Thus at each point in time, the Fed is forced to choose which it dislikes more: high unemployment or high inflation. The weight that the Federal Reserve places on inflation relative to unemployment can be thought of as a measure of Federal Reserve preferences and is a crucial input into monetary policy decisions. The primary goal of this paper is to estimate how these preferences have evolved over time in order to gain a deeper understanding of the motivations behind Federal Reserve actions.

While there have been many attempts to model the behavior of the Federal Reserve, virtually all of the existing work has used some version of a Taylor rule, where interest rates respond to output and inflation (see Clarida et al. (2000), Lubik and Schorfheide (1 March 2004) and Boivin and Giannoni (2006) for split-sample estimation; see Boivin (2006), Kim and Nelson (2006), Cogley and Sargent (2005) and Fernandez-Villaverde et al. (2010) for estimation allowing for more flexible time variation). However, while these parsimonious rules are reasonable approximations of observed monetary policy actions, they are only reduced form representations of monetary policy behavior. The estimated coefficients of the Taylor rule capture both the combined effect of underlying structural parameters of the economy and Fed preferences. Therefore, although previous work has established that Federal Reserve behavior has changed over time by estimating movements in Taylor rule coefficients, these changes cannot be used as direct evidence that preferences have changed.

There are two main reasons why central bank preferences can change over time. First, the composition of the Federal Open Market Committee (FOMC), the Fed's main monetary policy making arm, changes over time. Preferences can change with the election of a new chairman. One of the most famous examples of such a change is the appointment of Paul Volcker in 1979; Meltzer (2006) states that the biggest difference with the appointment of Paul Volcker was the changing of the weight the Fed put on inflation relative to unemployment. While the Fed chairman has changed only a handful of times in the last few decades, the composition of the FOMC changes more often with rotating voting rights for Presidents of four of the regional Federal Reserve Banks and changes in members of the Board of Governors. Second, Fed preferences can change due to political pressure on the Fed. There are accounts of Presidents Johnson and Nixon putting pressure on Fed chairmen Martin and Burns to refrain from monetary tightening (Meltzer (2011)). More recently with the financial crisis, Di Maggio (2010) provides evidence of monetary policy being influenced by Congress. The Fed has also been subject to public disapproval by politicians, for example the open letter sent by Republican congressmen (WSJ (September 20, 2011)). It is important to note that there has been varying degree of political pressure at different points in time which could affect the weight the Fed puts on inflation versus unemployment.

In this paper I use a simple model of optimizing central bank behavior and estimate a time-varying series of central bank preferences. The central bank minimizes a quadratic loss function which involves stabilizing inflation around an inflation target and minimizing the output gap. The weight on inflation relative to output gap is used as the measure of preferences. Minimization of this loss function subject to the constraints describing the economy gives an optimal interest rate rule. The coefficients of this optimal interest rate rule are functions of the time-varying preference parameter and can thus drift over time.

The literature on Fed preferences has typically estimated two values for the the preference parameter by splitting the sample at the appointment of Paul Volcker (Dennis (2006), Favero and Rovelli (2003), Ozlale (2003), Salemi (2006) and Best (2011)). These papers all find that the weight on inflation has been higher in the post-Volcker sample. The only paper to allow a more general form of time variation is Owyang and Ramey (2004), where the preference parameter is modeled as a Markov-switching process. They find multiple switches between hawk and dove regimes suggesting that preferences cannot be captured by the more common approach of having a single discrete shift. Additionally as discussed above there is reason to believe that preferences could have changed in a more gradual manner. Finally it is not clear why there would only be two regimes. It seems reasonable to expect that the Fed could be in a hawk regime but have differing intensities of hawkishness. Allowing for continuous variation in preferences is a flexible approach which would provide a decent approximation even in the case that there were truly only discrete changes in preferences.

Estimation is carried out using a Bayesion Markov Chain Monte Carlo (MCMC) algorithm, specifically a block-wise Metropolis Hastings algorithm. The time-varying preference parameter enters non-linearly in the optimal policy rule and is estimated using the Carter and Kohn (1994) simulation smoother augmented with the Extended Kalman Filter. Over the past few decades exogenous shocks have displayed a high degree of heteroskedasticity as shown by Sims and Zha (2006) and Primiceri (2005) among others. Ignoring this heteroskedasticity can lead to spurious time variation in the coefficients and inaccurate inference as pointed out by Hamilton (2010) and Sims and Zha (2006). To mitigate this concern, I explicitly take heteroskedasticity into account using the stochastic volatility specification.

I find that the Fed put lower weight on inflation in the 1970s. The weight starts rising gradually around the appointment of Paul Volcker in 1979 and the rise is sustained into the early 1990s. There is also some variation in the mid 70s under Arthur Burns and and a fall in the early 1990s under Alan Greenspan. The results suggest that it would be a mistake to treat Fed preferences as following a one-time discrete change. Furthermore, even if one insisted on modeling preferences as a one-time discrete change it is not clear when the break point should be. I then compare my results with two recent papers that estimate a Taylor rule with changing coefficients (Fernandez-Villaverde et al. (2010) and Bianchi (2009)). As an illustrative example I consider two time periods where the Taylor rule estimates from the two papers suggest a similar response of the Fed to inflation. However, my estimates show that Fed preferences were quite different in the two time periods. I then consider a shock to inflation in these two time periods. An impulse response analysis shows that the response of the economy is different in the two time periods.

This highlights the need to model optimal central bank behavior to rigorously understand the motivations behind the historical behavior of the Federal Reserve.

Changes in the estimated preference parameter are used to construct a novel measure of monetary policy shocks. In their seminal survey on monetary policy shocks Christiano et al. (1999) point to exactly these changes in preferences as an interpretation of monetary policy shocks estimated in VARs. I embed my measure of monetary policy shocks in a conventional VAR and evaluate its effects on the economy. The shocks constructed from the estimated preferences display more serial dependence than the conventional VAR shocks and the correlation between them is not high. Nevertheless the response of output and prices is remarkably similar to both measures of shocks. I interpret this as providing additional evidence that supplements the VAR literature that studies the effects of monetary policy.

Two counterfactual exercises are considered to shed light on the inflation episode of the 1970s and the Great Moderation that started in the early 1980s. First, I evaluate whether an early appointment of Paul Volcker (in the mid 1960s) would have avoided the inflation episode. The results suggest that a stronger preference for inflation relative to output gap would have led to lower inflation but "Volcker-style preferences" alone would not be enough to avoid the Great Inflation. A recent paper by Bianchi (2009) considers the effect of agents' learning about the preferences of the Fed and finds that inflation would be significantly lowered if agents thought that a more hawkish chairman was going to be appointed. This suggests that the counterfactual exercise in this paper may be capturing the lower bound of the effects of appointing Volcker earlier. Second, I consider the role of preferences and volatility of shocks in the Great Moderation. I construct counterfactual histories after fixing the standard deviation of the residuals and the preference parameters to their mean values in the pre-1984 sample. I find a limited role for the size of the shocks and preferences to affect the volatilities of aggregate variables.

An alternative way to model time variation in the preferences of the Federal Reserve would be to allow the inflation target to vary over time. In this model a change in the inflation target only affects the constant term in the optimal interest rate rule without changing the responses to inflation or output gap, whereas a change in the weight parameter affects both the constant term and the responses. Given the empirical evidence of changes in the monetary policy rule it seems more natural to consider a model where Fed preferences are allowed to affect the responses to inflation and output gap. Furthermore, I discuss how the inflation target in this model relates to other uses in the literature and show that the overall framework of this model is consistent with a wide variety of models that use a time-varying inflation target.

The rest of the paper is organized as follows. In the next Section I setup the model and explain the optimization problem. Section 3 discusses this paper's framework in relation to a time-varying inflation target. In Section 4 I outline the estimation strategy and discuss the Bayesian estimation algorithm. I discuss the main results in Section 5 and conduct counterfactual analyses in Section 6. In Section 7 I use the estimated preference parameter series to back out a new measure of monetary policy shocks and assess its impact on the economy. Section 8 offers some concluding remarks.

1.2 The Model

I use a simple model where the central bank minimizes a quadratic loss function subject to linear constraints that characterize the behavior of the economy.

1.2.1 Constraints

I use the backward-looking model outlined in Rudebusch and Svensson (1998). The main advantages of this setup are that it is parsimonious and fits the data well. Previous work has also used this model to study the preferences of the Fed (Dennis (2006), Favero and Rovelli (2003) and Ozlale (2003)). The backward looking equations can be thought of as representing adaptive expectations.[1] The model incorporates two basic equations describing the behavior of

[1]This backward looking model implies that agents form expectations based on past realizations of data. This is not a trivial assumption and incorporating forward looking behavior may have important implications. However there is disagreement about whether to model agents'

inflation and the output gap. The first equation is the aggregate supply curve (or the Phillips curve) which relates inflation to lagged inflation and the output gap.

$$\pi_t = b_0 + b_1\pi_{t-1} + b_2\pi_{t-2} + b_3\pi_{t-3} + (1 - b_1 - b_2 - b_3)\pi_{t-4} + b_4\tilde{y}_{t-1} + v_t \quad (1.1)$$

where π_t is annualized quarterly inflation and $\tilde{y}_t$ is the output gap. The coefficients on the lags of inflation are restricted to sum to one. This implies that there is no long run tradeoff between inflation and the output gap. This assumption is consistent with the natural rate hypothesis and means that the Fed cannot manipulate inflation to have a permanent effect on the output gap.[2] The error term (v_t) can be interpreted as a supply shock. The second equation is the IS curve which relates the output gap to lagged output gaps and the real interest rate as follows

$$\tilde{y}_t = a_0 + a_1\tilde{y}_{t-1} + a_2\tilde{y}_{t-2} + a_3\left[i^a_{t-1} - \pi^a_{t-1}\right] + g_t \quad (1.2)$$

where i_t is the annualized quarterly fed funds rate and $i^a_t = \frac{1}{4}\sum_{j=0}^{3} i_{t-j}$ and $\pi^a_t = \frac{1}{4}\sum_{j=0}^{3} \pi_{t-j}$ are the one year trailing averages of the fed funds rate and inflation respectively. Here the error term (g_t) represents a demand shock. In the estimation the variables are constructed in the following manner. $\pi_t \equiv 400 * [\ln(P_t) - \ln(P_{t-1})]$ is quarterly inflation of GDP chain-weighted price index at an annualized rate and $\tilde{y}_t \equiv 100 * [\ln(y_t) - \ln(y^*_t)]$ is the output gap. y_t is quarterly real GDP and y^*_t is the Congressional Budget Office's measure of potential output.

1.2.2 Loss Function

The loss function of the central bank is assumed to be quadratic.

$$L = \tilde{E}_t \sum_{j=0}^{\infty} \beta^j \left[\alpha_t \left(\pi^a_{t+j} - \pi^*\right)^2 + \tilde{y}^2_{t+j} + \nu(i_{t+j} - i_{t+j-1})^2\right] \quad (1.3)$$

The first two terms of the objective function are standard and represent

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expectations in a completely rational framework or as following some limited information form of learning. In the current paper any of these extensions would significantly increase the computational burden in the estimation and are thus left for future work.

[2] Note that the estimated coefficients will imply that there is a short-run tradeoff.

the Federal Reserve's dual mandate of price stability and full unemployment. The central bank wants to keep annual inflation close to an inflation target π^* and the output gap close to zero.[3] There are three main reasons to assume a quadratic form for the loss function. First, quadratic loss functions can be motivated from first principles by taking a second order approximation to the representative agent's utility function (Woodford (2003a)). Second, quadratic loss functions are widely used in the monetary policy rules literature (Taylor (1999), Rudebusch and Svensson (1998)). This makes it easy to compare my estimates to the literature. Third, a quadratic loss function with linear constraints keeps the model tractable which is especially important given the involved nature of the estimation procedure.

The inclusion of the third term $\nu(i_{t+j} - i_{t+j-1})^2$ is somewhat controversial. For a theoretical motivation for including this term see Woodford (2003a). This term can also be motivated by the central bank's desire to reduce volatility of asset prices by avoiding big changes in the interest rate. Rudebusch (2002), Rudebusch (2005), Castelnuovo and Surico (2004) have argued that the central bank does not value smoothing directly but rather the term arises as an artefact of other things like autocorrelated shocks hitting the economy or potential concern about model uncertainty. However, in recent empirical work Borger et al. (2011) and Coibion and Gorodnichenko (2011) find that the central bank does indeed care about smoothing interest rates. For the purpose of this paper, the debate about the true source of observed sluggishness in interest rates is not important. I include the interest rate smoothing term in the loss function to improve the fit of the empirical model but the primary focus is on the weight the central bank puts on inflation relative to output gap.

Here, the main departure from the standard loss function is that the weight on inflation relative to output gap (α_t) is time-varying. There are several reasons to model this parameter as time-varying. First, this weight can change with the changing composition of the FOMC committee where new committee members may be more hawkish or dovish. An extremely clear and uncontroversial example of this weight parameter increasing is the appointment of Chairman Volcker who

[3] Changing annual inflation to contemporaneous inflation does not change the results.

was a self-subscribed inflation hawk, Meltzer (2006) says the following when talking about the changes that Paul Volcker brought to the Federal Reserve: "... he changed the weights on inflation and unemployment" on page 186. Furthermore, other committee members of the FOMC change over time. Second, there is differing degree of political pressure on the Federal Reserve. There are accounts of Presidents Johnson and Nixon putting pressure on Fed chairmen Martin and Burns to refrain from monetary tightening, see Meltzer (2011). There is also evidence of political pressure on the Fed during the current crisis, see Di Maggio (2010). This changing political pressure can be captured by time variation in the weight the Fed puts on inflation relative to output gap, with lower values of α_t representing the case when the Fed receives more pressure from politicians to be dovish. The loss function specified here with the time-varying weight on inflation relative to output gap is a flexible and convenient way to capture time variation in central bank preferences.

1.2.3 Optimal Policy

In each period t, the central bank committee convenes to choose interest rates. The committee agrees on collective preferences within each period, as captured by α_t. I assume that the committee expects this preference parameter to remain constant at the current value in the future. Thus they do not account for the possibility of future updates and the associated uncertainty when formulating the optimal interest rate rule. This assumption is similar to the one made in the learning literature, see Sargent (1993), Sargent (2001) or Evans and Honkapohja (2001) for a detailed exposition and Primiceri (2006) and Sargent et al. (2006) for recent uses. Intuitively this means that the FOMC members do not try to compensate for the possibility that future committee members may be more hawkish or dovish than the current committee members.[4] With this assumption in place

[4]This assumption may not be innocuous. In a theory paper Debortoli and Nunes (2011) show that current central bankers change their behavior to account for the possibility that future committees may be more hawkish or dovish than they are. But the empirical quantitative relevance of this effect has not been explored. Here I take a pragmatic approach and ignore this effect to keep the model tractable.

the optimization problem can be handled by standard linear quadratic procedures (Sargent (1987)).

The central bank chooses the interest rate i_t to minimize the loss function (1.3) subject to the equations governing the economy (1.1) and (1.2). Appendix A gives the details of the setup of the model in state space form and derives the optimal policy rule. Given the loss function and constraints, the optimal policy rule takes the following form.

$$\begin{aligned} i_t &= f_t + F_{1,t}\pi_t + F_{2,t}\pi_{t-1} + F_{3,t}\pi_{t-2} + F_{4,t}\pi_{t-3} \\ &+ F_{5,t}\tilde{y}_t + F_{6,t}\tilde{y}_{t-1} + F_{7,t}i_{t-1} + F_{8,t}i_{t-2} + F_{9,t}i_{t-3} \end{aligned}$$

The coefficients of this rule, $F_{i,t}$, depend on the constant parameters of the constraints $(a_0, a_1, a_2, a_3,\ b_0, b_1, b_2, b_3, b_4)$, the constant policy preference parameters (β, π^*, ν) and the time-varying preference parameter (α_t). Note that the coefficients of this rule are non-linear functions of these parameters.

1.3 Why not a time-varying inflation target?

A potential critique of this paper's approach is that the Fed's inflation target rather than the preference parameter changes over time. I believe this criticism is misguided and discuss why below.

First, it is important to clarify what the inflation target means in this model's framework and its relation to the measure of inflation targets in other studies. In this paper (and in all others that use a loss function to model central bank behavior) the inflation target is the level of inflation that the central bank would want if the other variables in the loss functions were equal to their targets, i.e. it is π^* in the loss function function in (1.3). This implies that if the output gap is zero then the central bank would want inflation equal to the inflation target.[5] I refer to π^* as the unconditional inflation target. This is distinct from the level of inflation that the central bank actually chooses (either directly, as in Sargent et al.

[5]The interest rate smoothing term is ignored for ease of exposition.

(2006) and others, or indirectly by setting the interest rate, as in this paper). I will refer to this second concept as the conditional inflation target. Unfortunately these two concepts have been used interchangeably in the literature.[6] The important point is that the model in this paper allows for a time-varying conditional inflation target. The central bank may choose a level of inflation higher or lower than its unconditional target depending on the state of the economy.

Second, I argue that large changes in the unconditional inflation target (π^*) are unreasonable. For example, this would imply that the Federal Reserve would have wanted high inflation in the 1970s even if the output gap was zero. The following quote from Meltzer (2006) about the thoughts of then chairman Arthur Burns corroborates my view and the framework of time-varying preferences in general.

> During the Great Inflation, the Federal Reserve also held the view that more than a modest increase in unemployment, even if temporary, was unacceptable as a way of reducing inflation. As Burns said, in principle, the Federal Reserve could have slowed money growth to end inflation at any time. In practice, it reduced its independence by acceding to the fashion that interpreted the Employment Act as giving greater weight to unemployment and lesser weight to inflation.

I think the problem is that the literature using Taylor-type rules does not model optimal central bank behavior and thus it is not clear how to (and often not important to) differentiate between a central bank primitive (unconditional inflation target) and something the central bank can affect (conditional inflation target). But the difference is crucial when analyzing the motivation behind Federal Reserve actions. In the framework of this paper, even with a low unconditional inflation target the central bank can choose a high rate of inflation depending upon, among other things, where the variables in the loss function are relative to their targets and the preference parameters. Thus high inflation in the 1970s can be perfectly compatible with a low Federal Reserve unconditional inflation target.

[6] For example, in the abstract of Sargent et al. (2006), the authors refer to an "inflation target" which corresponds to the conditional inflation target as define here. While on page 1197 they refer to π^* as the "targeted level of inflation".

Finally, recall that in this framework a change in the unconditional inflation target would only change the intercept term in the optimal interest rate rule. The coefficients (response to inflation, output gap and lagged interest rates) are unaffected by the unconditional inflation target, while a change in the preference parameter affects both the intercept and the coefficients. A similar point is made by Nelson (2005).[7] Given the evidence supporting time variation in the coefficients of the Fed's reaction function it seems reasonable to have a model that allows changes in Fed preferences to affect these coefficients.

1.4 Estimation

The three equations (1.1),(1.2) and (1.4) can be written as a system in the following manner (detailed derivation is in Appendix B).

$$A_{0,t}y_t = A_{1,t} + A_{2,t}y_{t-1} + A_{3,t}y_{t-2} + A_{4,t}y_{t-3} + A_5 y_{t-4} + \Sigma_t \varepsilon_t \qquad (1.4)$$

where $y_t \equiv [\pi_t, \tilde{y}_t, i_t]'$. Note that I have added the error term e_t to the interest rate equation. For estimation purposes this shock is required to avoid the stochastic singularity problem. This is motivated by assuming that the econometrician does not have all the information available to the policymaker and thus the estimated decision rule omits certain variables which are represented by the error term (Hansen and Sargent (1980)). The coefficient matrices $A_{i,t}$ have a time subscript because they are functions of the time-varying preference parameter. The preference parameter α_t is assumed to follow a random walk.

$$\alpha_t = \alpha_{t-1} + v_t, \qquad \text{where } v_t \sim N(0, Q) \qquad (1.5)$$

The random walk process is a flexible and parsimonious way of modeling time-varying parameters. It can capture permanent shifts in the preference parameter

[7]This quote from page 9 suggests that a change in the inflation target should show up in the intercept of the monetary policy rule rather than the coefficients: "If the rise in inflation in the 1970s reflected a shift to a higher inflation target, it should imply an interest-rate rule with a sizable intercept term together with a greater than one-for-one response to deviations of inflation from target..."

and involves estimating fewer parameters than a general autoregressive process. This specification even provides a decent approximation in the case that the true data generating process displays a discrete shift. This specification is quite standard in the literature.

The variance matrix of the structural errors is $\Omega_t = \Sigma_t \Sigma_t'$. A triangular decomposition of Ω_t gives

$$\Omega_t = L \Psi_t \Psi_t' L'$$

where

$$\Psi_t = \begin{bmatrix} \sigma_{1,t} & 0 & 0 \\ 0 & \sigma_{2,t} & 0 \\ 0 & 0 & \sigma_{3,t} \end{bmatrix}, \; L = \begin{bmatrix} 1 & 0 & 0 \\ l_{2,1} & 1 & 0 \\ l_{3,1} & l_{3,2} & 1 \end{bmatrix}$$

The standard deviations $\sigma_{i,t}$ are modeled as geometric random walks following the stochastic volatility literature as follows.

$$log\ \sigma_t \;=\; log\ \sigma_{t-1} + \eta_t, \text{ where } \eta_t \sim N(0, W) \tag{1.6}$$

There is time variation in only the variance terms and not the covariances. This assumption is similar to the one made in Cogley and Sargent (2005) and is reasonable here because there is time variation in the covariance of the reduced form variance matrix which is introduced by the presence of the time-varying preference parameter in the optimal policy rule. The reduced form variance matrix is given by

$$A(\delta, \alpha_t, \nu)^{-1} \Omega_t \left[A(\delta, \alpha_t, \nu)^{-1} \right]'$$

The innovations in the model are assumed to be jointly normal with the following variance matrix

$$Var \left(\begin{bmatrix} \varepsilon_t \\ v_t \\ \eta_t \end{bmatrix} \right) = \begin{bmatrix} I & 0 & 0 \\ 0 & Q & 0 \\ 0 & 0 & W \end{bmatrix}$$

The model characterized by the constraints ((1.1) and (1.2)), the optimal interest rate rule (1.4) and the random walk processes for the time-varying parameters and stochastic volatility ((1.5) and (1.6)) can now be written in state space form. It is effectively a three equation VAR with drifting parameters in the interest rate equation and stochastic volatility. The only source of drift in the coefficients of the interest rate rule is the time variation in the preference parameter α_t. Sims and Zha (2006) estimate unrestricted reduced form VARs and when they allow the coefficients to drift they find the specification that fits the data the best is one where only the coefficients of the monetary policy rule change, consistent with the model here.

Appendix B shows how these above equations are transformed to the following nonlinear state system

$$y_t = W_t\delta + Z_t\tilde{\beta}(\delta, \alpha_t, \nu) + A(\delta, \alpha_t, \nu)^{-1}\Sigma_t\varepsilon_t \tag{1.7}$$

$$\alpha_{t+1} = \alpha_t + v_t \tag{1.8}$$

$$log\ \sigma_t = log\ \sigma_{t-1} + \eta_t \tag{1.9}$$

I estimate the following set of parameters: α_t: time-varying weight on inflation, δ: coefficients of the constraints in (1.1) and (1.2), ν: weight on interest rate smoothing, Ψ_t: time-varying variance terms, L: covariance terms, and the hyperparameters W and Q which represent the variances of the shocks to the time-varying volatilities and preference parameter respectively. I outline the estimation algorithm in the next section.

1.4.1 Bayesian MCMC Estimation

I divide the parameters into 7 blocks: $\theta = [\alpha_t, \delta, \nu, \Psi_t, L, Q, W]$. Bayesian estimation treats the parameters to be estimated as random variables. Then a prior distribution about these parameters is combined with the data to form the posterior distribution which can be used for inference. The MCMC algorithm involves breaking down the high dimensional joint posterior into smaller dimensional conditional posteriors. A block-wise Metropolis-Hastings algorithm is used to provide numerical samples from these conditional posterior distributions of the parameters.

The full details of the estimation procedure are provided in Appendix B and

C. Here I give a brief overview of the estimation algorithm and prior selection. The innovation of this paper is the estimation of the time-varying preference parameter and accordingly I discuss its estimation approach in more detail than the rest of the parameters. For drawing time-varying parameters, the standard simulation smoothers used in MCMC algorithms like those in Carter and Kohn (1994) or Durbin and Koopman (2002) assume a linear state space model. Here the time-varying preference parameter enters non-linearly in the observation equation (1.7). I use the Extended Kalman Filter (EKF) to tackle the non-linearities. The EKF linearizes the observation equation at each point in time using a first order Taylor expansion and then the standard filtering techniques of the Kalman Filter can be applied. The performance of the EKF depends crucially on the the linearization errors being "small." I show in Appendix E that the non-linearity in this model is not extreme and thus the EKF performs reasonably well. In the same appendix, I also discuss alternative non-linear filtering methods used in the literature and show that for the given model, there are no significant improvements made by using the more involved filtering techniques. I use the simulation smoother of Carter and Kohn (1994) where the filter forward part of the algorithm is done using the EKF. The sample backward step is identical to the standard case as the measurement equation (1.8) is linear. In the sample backward step I use the rejection sampling technique outlined in Cogley and Sargent (2005).

The rest of the parameter block is estimated using procedures that are standard in the literature. The parameters of the constraint (δ) and the weight on interest rate smoothing term (ν) enter non-linearly and thus the conditional posterior distributions are not known. I use a Metropolis-Hastings step to sample these parameters. The Metropolis-Hastings involves sampling from a candidate distribution and then accepting the draws with a probability that depends on the ratio involving the prior and the likelihood. The stochastic volatility terms of Ψ_t are drawn using the mixture of normals approach of Kim et al. (1998). The conditional posteriors for the hyperparameters Q, W and the covariance terms L are known and therefore a Gibbs sampling step can be used.

1.4.2 Priors

I use 10 years of data from 1955:Q2 to 1965:Q1 as a training sample to set up the priors. The priors for δ, $log(\sigma_0)$ and L are assumed to be normal which is a standard assumption. For the training sample I estimate an unrestricted time invariant VAR with OLS which is similar in setup to the full model to compute the prior parameters. The prior variance for these three is set high enough so that the prior is effectively non-informative. The prior for the interest rate smoothing term is also normal but with an even larger prior variance such that the prior mean has no effect on the results. The prior distribution of W is assumed to be inverse-Wishart which is a common way of modeling variance matrices. The parameters of this prior distribution are set to the same values used in Primiceri (2005). I discuss the selection of the prior for Q in detail below. My assumptions over the priors can be summarized as the following:

$$\begin{aligned}
\delta &\sim N(\delta_{OLS}, 10.V_{\delta,OLS}) \\
log(\sigma_0) &\sim N(log(\sigma_{0,OLS}, I_n) \\
L &\sim N(L_{OLS}, 10.V_{L_{OLS}}) \\
W &\sim IW((.01^2).4.I_n, 4) \\
Q &\sim IG(Q_{prior}, \nu_Q) \\
\nu &\sim N(\nu_0, 100.V_{\nu,0})
\end{aligned}$$

The starting value for the preference parameter (α_0) cannot be estimated using OLS and is set in the following manner. Using Maximum Likelihood, I estimate the three equations of the model ((1.1),(1.2) and (1.4) on the training sample period without allowing for any time variation, i.e. the preference parameter is constant and there is no stochastic volatility. I use the parameter estimate from this estimation as the starting value (α_0). I specify the associated variance to be quite large and it turns out that using different starting values for α_0 does not affect the results. The prior for Q is inverse-Gamma, which is standard for modeling the variance of a normal distribution. Since the estimation of α_t is a new specification there is no precedent in the literature regarding the parameters of the inverse-Gamma prior. The inverse-Gamma specification involves choosing two parameters: the degrees of freedom (or shape) ν_Q and the scale parameter Q_{prior}. The prior distribution can be thought of as representing the equivalent of ν_Q "observations" with sum of squared residuals Q_{prior}. I use $\nu_Q = 2$ which is the minimum required for a proper prior but is quite small relative to the sample size of 168. For some guidance about the value of Q_{prior}, I look at Primiceri (2005), where an unrestricted time-varying structural VAR is estimated. I choose Q_{prior} such that the prior mean implies a 30% average cumulative change in the coefficients of the interest rate equation with a 95% probability. This implies less than half the time variation as chosen in Primiceri (2005), who sets the parameters such that for the given sample "...the prior mean for Q implies a 95% probability of a 78% average cumulative change in the coefficients". This seems reasonable as the time variation in the interest rate coefficients is of a restricted form in this paper and comes only from preferences, as opposed to the unrestricted model in Primiceri (2005) which allows time variation to come from any source. Changing the value of Q_{prior} does affect the scale of the estimates of the preference parameter but the implied estimates of the response parameters in the interest rate rule are similar across different specifications. The correlation of the estimated preference parameter α_t for different prior specifications is very close to 1, indicating that the choice of the prior has no effect on the dynamics of the estimated preference parameter.

1.5 Results

Two parameters of the loss function (β and π^*) are fixed and the remaining parameters of the model are estimated. I fix the discount factor (β) at 0.99 and the unconditional inflation target (π^*) at 2. The value for β is standard in the literature; decreasing it to 0.95 does not change the results much. The value of 2 for the unconditional inflation target has been used by several others in the literature (Primiceri (2006) and Sargent et al. (2006)). Additionally this number is often reported in the news media as reflecting the Federal Reserve's unofficial target. The concern that the inflation target may actually be varying with time has been addressed in Section 3. In the literature it is more typical to normalize the weight on inflation to 1 and estimate the relative weight on output gap. Here, the weight on output gap in the loss function is normalized to 1 so that the estimated weight is the relative weight on inflation. As I discuss below, the estimates imply that inflation was more important to the Fed than output gap and thus the weight on output gap relative to inflation is lower than one. A non-negativity constraint on the preference parameter needs to be imposed in the non-linear filtering estimation. Computationally, this is more cumbersome for small values (less than 1) and thus the normalization used here is more convenient.

The parameter estimates of the constraints (δ) are listed in Table 1.1. 95^{th} and 5^{th} percentiles are also listed. The point estimates of the constraints are similar to the other papers that have used this model (for example, Dennis (2006) and Favero and Rovelli (2003)). But the estimate of the weight on interest rate smoothing term, ν seems quite high. However, to compare this value to the existing literature we need to divide by the weight on inflation.[8] This implies that the parameter comparable to the existing literature averages around 50. Even this value seems a bit high, though there are several reasons for this. "First, the magnitude of this parameter is very sensitive to the specified model. For example, estimates of this weight range from 0.0051 in Favero and Rovelli (2003) to 37.168 in Dennis (2006) to 2131 in Primiceri (2006). Second, the large estimated magnitude is partly due to the sample period here which includes the first half of the 2000s when interest rates were adjusted far more gradually. Third, Castelnuovo (2006) finds that specifying a forward looking model reduces the estimated weight on interest rate smoothing. Finally, adding an additional term in the loss function involving the squared deviation of the interest rate (interest rate variability) reduces this estimated value even further. As mentioned earlier there is a debate in the literature regarding the true source of the observed sluggishness in the policy instrument. Here the interest rate smoothing term is not important as we are primarily concerned with the dynamic behavior of the weight on inflation versus

[8]This is because of the different normalization employed in this paper.

output gap.

Figure 1.9.5 plots the posterior mean of the smoothed time-varying weight on inflation with 16th and 84th percentile bands. A few things stand out. First, the weight on inflation is lower in the mid 1960s and 1970s as compared to post 1980s. Second, as expected, there is a rise in the weight on inflation around the appointment of Paul Volcker. Interestingly the weight keeps rising throughout Volcker's term and into the first few years of Alan Greenspan's term. Third, there is variation in the 1970s with the lowest point reached around 1975, but also a gradual decline towards the end of Greenspan's regime. This suggests that it would be misguided to treat the preference change as a one-time discrete change. Even if a discrete change were imposed it is not clear when the discrete change should be modeled as there is a steady increase in the weight starting from around 1977, two years before Volcker's appointment. Figure 1.9.5 shows the weight parameter set against the NBER recessions and divided up by the chairmen of the Federal Reserve. Chairman Arthur Burns (1970-1978) presides a over a drop in the weight on inflation with the lowest point being reached towards the end of his tenure. Under chairmen William Miller (1978-1979) and Paul Volcker (1979-1987) the Fed consistently becomes more hawkish. With the appointment of Alan Greenspan (1987-2006) this trend continues for a few years but then there is a gradual decline in the weight on inflation for the next 10 years. The magnitude of the estimated weight on inflation means that the relative weight on output gap versus inflation varied from 0.25 in the mid 1970s down to 0.0833 in the early 1990s. This is in line with the general consensus in the literature that inflation has been more important to the Federal Reserve than the output gap.

To highlight the importance of the dynamics of the estimated preference parameter I compare my results to two new papers that estimate Taylor rules with changing coefficients; Fernandez-Villaverde et al. (2010) use a time-varying parameter Taylor rule in a Dynamic Stochastic General Equilibrium (DSGE) model while Bianchi (2009) uses a Taylor rule whose coefficients follow a regime-switching process. For illustrative purposes I consider two time periods, one in the mid 1970s and the other at the end of 1990s. Fernandez-Villaverde et al. (2010) find that the response to inflation is low in the mid 1970s, rises with the appointment of Paul Volcker and falls in Alan Greenspan's tenure to the same level observed in the mid-1970s. Similarly Bianchi (2009) finds that the probability of a dove regime is high in the mid 1970s and also again in the late 1990s. Figure 1.9.5 shows that the weight on inflation has fallen leading up to both those time periods suggesting a more dovish Fed relative to the last few years. But notice that the level of the weight on inflation is drastically higher in the late 1990s implying quite different behavior on part of the central bank. To evaluate the quantitative importance of this difference I calculate impulse responses after a one unit shock to inflation in both time periods. A unit shock is used instead of a one standard deviation shock to make the proper comparison as the standard deviations are different in the two time periods. Figure 1.9.5 shows the response of inflation, output gap and interest rates for 1975:Q1 and 1998:Q2. Given the 1998:Q2 preferences, the Fed initially responds more strongly by increasing the fed funds rate more and maintains a higher rate for about 5 years. This results in inflation staying lower on average and reaching the steady state faster, but at the cost of a bigger fall in output. Due to the bigger fall in inflation under the 1998:Q2 preferences the Fed can actually bring interest rates back to steady state values quicker in the long run. However, in the models estimated by Fernandez-Villaverde et al. (2010) and Bianchi (2009) the response to inflation would not show such a differential response in the two time periods.[9] Thus even though the estimated Taylor rule coefficients from the two papers imply similar Fed behavior, the underlying preferences estimated in this model are quite different in the two time periods.

When interpreting these results a potential concern is that the Fed may not have used the short term interest rate as the policy instrument for the full sample, thus invalidating the estimates for that sample. Bernanke and Mihov (1998) conclude that the fed funds rate is a good indicator of monetary policy except for the short period between 1979 and 1982, representing the well known episode of non-borrowed reserves targeting. This concern is mitigated by allowing the variance of the residuals (especially for the fed funds rate) to vary over time with stochas-

[9]The differences between the results here and the estimated Taylor rules in the two papers could be due to changes in the structure of the economy among other things.

tic volatility. The stochastic volatility framework also addresses the more general concern that ignoring heteroskedasticity can lead to spurious movements in the coefficients and inaccurate inference (Hamilton (2010) and Sims and Zha (2006)). Figure 1.9.5 plots the standard deviation of the residuals of the inflation, output gap and interest rate equations. Across the board the standard deviation is higher before the 1980s. This confirms the results of earlier studies that use VARs with stochastic volatility. Not surprisingly the variance of the residual in the interest rate equation is estimated to be quite high during the reserves targeting period. The important point is that even after allowing the variances of the shocks to drift, time variation is found in the preference parameter.

A cursory glance at Figure 1.9.5 suggests that the weight on inflation tends to rise before recessions. To investigate this relationship between the preference parameter and NBER defined recessions more formally I conduct Granger causality tests similar to the ones performed in Owyang and Ramey (2004). First I construct a recession dummy r_t which is equal to 1 for the first quarter of every recession and 0 otherwise. Two series h_t and d_t are constructed to represent hawkish moves and dovish moves in the following manner.

$$
\begin{aligned}
h_t &= \max[\alpha_t - \alpha_{t-1}, 0] \\
d_t &= \max[\alpha_{t-1} - \alpha_t, 0]
\end{aligned}
$$

The Granger causality tests are performed by running the restricted and unrestricted regressions using two years of lags. The F-statistics of the exclusion restrictions and the corresponding p-values are reported in Table 1.3. An interesting pattern emerges from the Granger causality tests. Hawk moves help predict recessions but the converse is not true. Dove moves do not have predictive power for recessions but rather recessions can help predict dove moves. This analysis suggests that when the Fed gets more hawkish policy it is typically followed by a recession. Once a recession has started the Fed is more likely to switch to a dovish stance, perhaps due to more political pressure.

1.6 Counterfactual Analysis

In this section I conduct two counterfactual analyses to gain insight into two of the most important phenomena of the post war period; the Great Inflation episode of the 1970s and the ensuing Great Moderation.

1.6.1 The Great Inflation

Here I pose the following hypothetical question: Would the early appointment of Paul Volcker have avoided the inflation episode of the 1970s? To answer this question I simulate the path of inflation by freezing the Fed preferences at the average value estimated for the first term of the Volcker regime.[10] First I compute the residuals for the inflation equation. Next the counterfactual inflation is initialized to the actual level of inflation in the first year of the sample. I then simulate a path of inflation using "Volcker-style" preferences but fix shocks hitting the economy at the estimated residuals from the original results. This gives the simulated path of inflation from 1967 to 1983 with Paul Volcker hypothetically heading the Fed, but with the same true observed shocks hitting the economy; thus the only difference between the paths is the change in preferences.

Figure 1.9.5 shows this simulated path of inflation along with the actual inflation path. The results suggest that inflation would have been lower under Volcker in the 1970s but not low enough to avoid the high inflation episode. Since the economy is described by a backward looking model, agents adapt their expectations of Volcker's "appointment" with a lag. If agents were instead forward-looking they would lower their inflation expectations sooner. For example, Bianchi (2009) performs a counterfactual where he imposes beliefs on the agents such that they expect that an extremely hawkish chairman is going to be appointed in the future. He finds this change in expectations dramatically lowers the simulated path of inflation. Thus I interpret the fall in inflation found here to be the lower bound of the effects that different Fed preferences would have had on the inflation episode of the 1970s.

[10]Using the preferences averaged over the full Volcker regime produces a slightly bigger fall in the simulated path of inflation.

1.6.2 The Great Moderation

The causes of the fall in the volatilities of macroeconomic variables since the early 1980s have been widely debated in the literature. Three main explanations have emerged: good luck, good policy and structural change. The good luck hypothesis states that the economy has been subject to more fortuitous shocks since the 1980s (Stock and Watson (2003)). The good policy explanation mainly focuses on the improved policy of the Federal Reserve (Clarida et al. (2000), Boivin and Giannoni (2006)). The structural change explanation attributes the lower volatility to other shifts in the structure of the economy such as better inventory management (Ramey (2006), McConnell and Perez-Quiros (2000)). The model here allows me to test the importance of the first two channels.

The first row of Table 1.2 documents the decline in volatility in the data. The standard deviations of inflation, output gap and fed funds rate have each fallen by at least 30%. The next row lists the model implied values and shows that the model does a good job of capturing the fall seen in the data. In the first counterfactual I assess the effect of removing the observed fall in the standard deviation of the residuals. The three macro variables are simulated using the estimated residuals and parameters but fixing the standard deviation of the residuals to their average value in the pre 1984:Q1 period.[11] The thought experiment is the following: How would the aggregate variables have behaved if there had not been the observed decline in the standard deviations of the shocks hitting the economy? If the volatilities of the counterfactual values do not display a similar fall between the pre-1984:Q1 and post-1984:Q1 samples, then we can conclude that the size of the shocks played a big role in the Great Moderation. What we observe in the third row is that the fall in the volatilities of counterfactual values is smaller than in the second row, but the difference is not large. This suggests a limited role for the size of the shocks to affect the volatilities of aggregate variables. The second counterfactual is similarly performed but here the value of the preference parameter is fixed to its pre-1984:Q1 mean. The results in the fourth row sug-

[11] 1984:Q1 is typically used as the break date when considering the Great Moderation (McConnell and Perez-Quiros (2000),Stock and Watson (2003)).

gest that change in preferences also did not play an important part in the Great Moderation. For both the counterfactual analyses, the biggest differences show up in the standard deviations of the fed funds rate. This is not so surprising as the stochastic volatility results find the biggest fall in the standard deviations of the fed funds rate equation.

It is important to keep in mind the details of this specific model when interpreting the counterfactual results regarding the Great Moderation. First, this model uses the output gap while most of the literature has documented the Great Moderation using real output. Second, even though the change in preferences does not appear crucial, it does not necessarily imply that monetary policy did not play a role. For example, it is possible that the monetary authority became better at evaluating and forecasting economic conditions, which improved the overall conduct of policy. This could have helped lower the volatility of aggregate variables but this channel is not captured here.

1.7 A New Measure of Monetary Policy Shocks

There is a large literature that tries to evaluate the effects of monetary policy. But systematic monetary policy decisions are endogenous with respect to developments in the economy and cannot help identify the effects of monetary policy on the economy. Thus there has been much interest in identifying exogenous measures of monetary policy shocks to help us understand how monetary policy decisions affect the economy. Vector Autoregressions (VAR) are quite often used in identifying monetary policy shocks. Typically the monetary policy shock is specified as the residual in an interest rate equation after some identifying assumptions about the contemporaneous relationships between the variables have been made.

For illustrative purposes I consider a simple quarterly VAR with the following variables: 1) Y_t: Log of Real GDP, 2) P_t : Log of GDP Deflator and 3) FFR_t: fed funds rate, matching the sample size used in the main estimation. I use the most common recursive identification assumption and order the variables $[Y_t, P_t, FFR_t]$. Thus monetary policy cannot contemporaneously affect output or prices but does respond to their current values. This is a simplified version of the benchmark VAR used in Christiano et al. (1999) and many other papers. I will refer to it as the CEE VAR. Figure 1.9.5 shows the response of output, prices and the fed funds rate to a one standard deviation monetary policy shock, with 90% bootstrapped confidence intervals. The hump shaped response of output is very similar to the one shown in Christiano et al. (1999). The rise in the price level after a contractionary monetary policy shock seems unusual but is actually common in the literature and is known as the price puzzle.[12] While there is disagreement about the identifying assumptions and the specific variables to use in the VAR, there is reasonable consensus regarding the use of the residual of the interest rate equation as the measure of monetary policy shock. However, it is not clear how one should interpret these shocks. These shocks are plotted in the top panel of Figure 1.9.5.

I propose using the exogenous change in the preference parameter as a new measure of monetary policy shocks. This has intuitive appeal because this represents changes in the fundamental behavior of monetary policy decision making that are not endogenous to economic developments. Additionally Christiano et al. (1999) suggest this measure as one of their interpretations for the monetary policy shock in VARs. They say that one interpretation of monetary policy shocks is ...

> ... exogenous shocks to the preferences of the monetary authority, perhaps due to stochastic shifts in the relative weight given to unemployment and inflation.

The bottom panel of Figure 1.9.5 plots estimated residuals of the preference parameter, $\hat{v}_t = \alpha_t - \alpha_{t-1}$. A positive value for the shock implies a more hawkish stance of monetary policy, similar in concept to a contractionary monetary policy shock. There are large negative shocks in the mid 70s followed by large positive shocks in the early 80s after which the shocks are smaller in magnitude. These shocks exhibit a stronger autocorrelation than the shocks estimated from the CEE VAR.

[12]Typically commodity prices are added to the VAR to mitigate this problem. In this analysis I will focus on the effect of monetary policy on output and the decision to add commodity prices or not is not important.

Next I embed my measure of monetary policy shocks in a VAR to consider its effect on the economy. I follow Romer and Romer (2004) where they cumulate their measure of monetary policy shocks to represent the stance of monetary policy. This means I enter the cumulated shock series $\lambda_t = (\sum_{j=1}^{t} \hat{v}_j)$ instead of the fed funds rate. Thus the impulse response of output to a shock to the preference series will give us the effects of this new measure of monetary policy on output. Figure 1.9.5 plots the response of output and price level to a one standard deviation shock to preferences. The response of output to this new shock is very similar to the one using the CEE VAR shocks (Figure 1.9.5), although there is a larger fall and the trough is reached later with my measure of monetary policy shocks. The response of prices is also similar qualitatively but again with a bigger drop. This similarity is striking considering the fact that the correlation between the monetary policy shocks is only 0.25.[13] I interpret this as providing supporting evidence for the view expressed in Christiano et al. (1999) that the estimated monetary policy shock from recursive VARs captures exogenous shocks to the Fed's preference on inflation versus output stabilization.

1.7.1 Preference Shocks and Long Term Interest Rates

In a theory paper Ellingsen and Soderstrom (2001) investigate the effects of unanticipated monetary policy actions on interest rates. They categorize monetary policy shocks as either endogenous or exogenous. An endogenous shock occurs when the Fed reveals new information about the economy and moves short term and long term interest rates in the same direction. An exogenous shock occurs when there is a preference change and this moves short term and long term interest rates in opposite directions. Interestingly their theory model is very similar to the model here and they define preferences in precisely the same way.[14] As in this model, an exogenous shock is a change in the loss function weight on inflation versus output

[13]While this may seem surprising, Christiano et al. (1999) find that the effects of monetary policy shocks are robust to using different specifications. Sims (1998) provides a good explanation of why it can be consistent to have disagreeing measures of monetary policy shocks which agree on their effects.

[14]They normalize the weight on inflation to 1.

gap. Ideally I would regress interest rates on the estimated change in preferences to test this theory. But this is not straightforward as the timing is different in the two models. I use quarterly data whereas their model makes predictions for the changes in interest rates after every FOMC meeting which happens roughly every month and a half.

However in a follow-up paper, Ellingsen and Soderstrom (2005) construct a series of exogenous policy changes by reading interviews with traders and analysts in the Wall Street Journal. They classify FOMC decisions into exogenous and endogenous based on the text of these articles and interviews, starting with the October 20th 1998 meeting and ending with the June 25th 2003 meeting. They use this series and confirm the theoretical prediction that exogenous preference changes move short and long term interest rates in different directions. I calculate the correlation between their subjective measure of preference changes and changes in my estimated preference series. I construct a dummy variable that takes the value of 1 if there is any FOMC meeting within that quarter that they classify as including an exogenous change and 0 otherwise. In their classification they do not distinguish between positive or negative exogenous changes (i.e. hawkish or dovish). Thus to be consistent with their measure I take the absolute value of the first differenced preference parameter, $|\alpha_t - \alpha_{t-1}|$.[15] The correlation between $|\alpha_t - \alpha_{t-1}|$ and the dummy variable is 0.24 with a t-statistic of 1.9. While the correlation is not extremely high it does suggest that when there are big changes in this paper's estimated preference parameter, Ellingsen and Soderstrom (2005) are more likely to categorize that period as an exogenous preference change. This result is obtained even though the timing of the two series is not quite consistent. Estimating a modified version of my model which correctly aligns the timing with FOMC meeting can help uncover the effects of monetary policy decisions on long term interest rates in a rigorous objective manner and is left for future work.

[15] In constructing this series I use the filtered value of the preference parameter. This is desirable as the bond markets are reacting to their beliefs about monetary policy preferences using only contemporaneously available data, while the smoothed estimates are based on data from the full sample.

1.8 Conclusion

This paper starts with the observation that the ubiquitous Taylor rule cannot identify deeper central bank preferences and thus does not paint the complete picture of the motivations behind monetary policy actions. Using a simple model of optimizing central bank behavior, I estimate a continuously time-varying series of the weight on inflation relative to output gap. This parameter enters non-linearly in the model and is estimated by developing a Bayesian Markov Chain Monte Carlo algorithm that uses non-linear filtering techniques.

Consistent with the anecdotal evidence, the results show that there is a large rise in the weight on inflation with the appointment of Paul Volcker. However, this rise is both gradual and steady and lasts until the early years of Alan Greenspan's regime. The weight parameter displays instability even in the pre- and post-Volcker periods which invalidates the common assumption made in the literature of a one time discrete change. The estimation of the time-varying preference parameter also provides a novel measure of monetary policy shocks. I embed this measure of monetary policy shocks in a standard VAR to evaluate its effects on the economy. The response of output and prices to this new measure of monetary policy shocks is surprisingly similar to the responses to conventional measures constructed from the residuals of the interest rate equation. This provides supporting evidence for the way in which the VAR literature has evaluated the impact of monetary policy shocks.

One way to think about changes in the behavior of monetary policy is to broadly categorize it into two fields: 1) changes coming from policy mistakes and 2) changes coming from policy preferences. The existing literature has mostly focused on the former (Primiceri (2006), Sargent et al. (2006) and Orphanides(2003)). The basic idea is that the Federal Reserve made mistakes in evaluating the state of the economy or the dynamics governing the economy. While existing literature has given ample evidence in support of this line of thinking, the main motivation for this paper is that not enough attention has been paid to the role of policy preferences and its implied consequences. The findings in this paper motivate a unifying framework that takes into account both policy preferences and policy mistakes as a promising area of future research.

1.9 Appendix

1.9.1 Appendix A: Derivation of the optimal policy rule

To apply the linear quadratic regulator of Sargent (1987) I start by putting the constraints (1.1) and (1.2) in the following state space form where z_t is the state vector and x_t is the control variable.

$$z_{t+1} = C + Az_t + Bx_t + u_{t+1}$$

where $z_t \equiv [\pi_t, \pi_{t-1}, \pi_{t-2}, \pi_{t-3,}\tilde{y}_t, \tilde{y}_{t-1}, i_{t-1}, i_{t-2}, i_{t-3}]'$, $x_t \equiv [i_t]$ and $u_{t+1} \equiv [v_t, g_t, 0]'$,

$$C = [b_0, 0, 0, 0, a_0, 0, 0, 0, 0]'$$
$$B = [0, 0, 0, 0, \frac{a_3}{4}, 0, 1, 0, 0]'$$
$$A = \begin{bmatrix} b_1 & b_2 & b_3 & 1-b_1-b_2-b_3 & b_4 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ -\frac{a_3}{4} & -\frac{a_3}{4} & -\frac{a_3}{4} & -\frac{a_3}{4} & a_1 & a_2 & \frac{a_3}{4} & \frac{a_3}{4} & \frac{a_3}{4} \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \end{bmatrix}$$

Following Dennis (2006) I rewrite the loss function (1.3) in the following way, see Sargent (1987) for more details.

$$
\begin{aligned}
L &= \tilde{E}_t \sum_{j=0}^{\infty} \beta^j [(z_{t+j} - \bar{z})' W_t (z_{t+j} - \bar{z}) + (x_{t+j} - \bar{x})' Q (x_{t+j} - \bar{x}) \\
&\quad +2(z_{t+j} - \bar{z})' H (x_{t+j} - \bar{x}) + 2(x_{t+j} - \bar{x})' G (z_{t+j} - \bar{z})]
\end{aligned}
$$

where

$$
\begin{aligned}
W_t &= P' R_t P \\
P &= \begin{bmatrix} \frac{1}{4} & \frac{1}{4} & \frac{1}{4} & \frac{1}{4} & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \end{bmatrix} \\
R_t &= \begin{bmatrix} \alpha_t & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & \nu \end{bmatrix} \\
H' &= G = \left[0_{1\text{x}6} \, , -\frac{\nu}{2}, 0_{1\text{x}2} \right] \\
Q &= \nu
\end{aligned}
$$

The optimal rule for x_t is then given by

$$
\begin{aligned}
x_t &= \bar{x} - F_t \bar{z} \\
F_t &= -\left(Q + \beta B' M_t B\right)^{-1} \left(H' + G + \beta B' M_t A\right) \\
M_t &= W_t + F_t' Q F_t + 2 H F_t + 2 F_t' G + \beta \left(A + B F_t\right)' M_t \left(A + B F_t\right)
\end{aligned}
$$

The coefficients of the optimal rule are found by iterating on the above matrix Riccatti equations. To speed up the computation a modified version of Matlab's "dare.m" command is used which implements the QZ algorithm, see Arnold and Laub (1984) for more details.

1.9.2 Appendix B: Setup of model for Bayesian estimation

I first start by stacking equations 1.1,1.2 and 1.4 to get the following form

$$A_{0,t}y_t = A_{1,t} + A_{2,t}y_{t-1} + A_{3,t}y_{t-2} + A_{4,t}y_{t-3} + A_{5,t}y_{t-4} + \Sigma_t\varepsilon_t$$

$$\text{where} \;\; y_t \equiv [\pi_t, \tilde{y}_t, i_t]' \;,\;\; \varepsilon_t \equiv [v_t, g_t, e_t]'$$

$$A_{0,t} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ -F_{1,t} & -F_{5,t} & 1 \end{bmatrix} \qquad A_{1,t} = \begin{bmatrix} b_0 \\ a_0 \\ f_t \end{bmatrix} \qquad A_{2,t} = \begin{bmatrix} b_1 & b_4 & 0 \\ -\frac{a_3}{4} & a_1 & \frac{a_3}{4} \\ F_{2,t} & F_{6,t} & F_{7,t} \end{bmatrix}$$

$$A_{3,t} = \begin{bmatrix} b_2 & 0 & 0 \\ -\frac{a_3}{4} & a_2 & \frac{a_3}{4} \\ F_{3,t} & 0 & F_{8,t} \end{bmatrix} \quad A_{4,t} = \begin{bmatrix} b_3 & 0 & 0 \\ -\frac{a_3}{4} & 0 & \frac{a_3}{4} \\ F_{4,t} & 0 & F_{9,t} \end{bmatrix}$$

$$A_5 = \begin{bmatrix} 1 - b_1 - b_2 - b_3 & 0 & 0 \\ -\frac{a_3}{4} & 0 & \frac{a_3}{4} \\ 0 & 0 & 0 \end{bmatrix}$$

Now pre-multiply both sides by $A_{0,t}^{-1}$

$$\begin{aligned} y_t &= A_{0,t}^{-1}A_{1,t} + A_{0,t}^{-1}A_{2,t}y_{t-1} + A_{0,t}^{-1}A_{3,t}y_{t-2} \\ &+ A_{0,t}^{-1}A_{4,t}y_{t-3} + A_{0,t}^{-1}A_{5,t}y_{t-4} + A_{0,t}^{-1}\Sigma_t\varepsilon_t \\ &= B_{1,t} + B_{2,t}y_{t-1} + B_{3,t}y_{t-2} + B_{4,t}y_{t-3} + B_{5,t}y_{t-4} + A_{0,t}^{-1}\Sigma_t\varepsilon_t \end{aligned}$$

$$
\begin{aligned}
B_{1,t} &= \begin{bmatrix} b_0 \\ a_0 \\ f_t + F_{5,t}a_0 + F_{1,t}b_0 \end{bmatrix} \\
B_{2,t} &= \begin{bmatrix} b_1 & b_4 & 0 \\ -\frac{a_3}{4} & a_1 & \frac{a_3}{4} \\ F_{2,t} - \frac{F_{5,t}a_3}{4} + F_{1,t}b_1 & F_{6,t} + F_{5,t}a_1 + F_{1,t}b_4 & F_{7,t} + \frac{F_{5,t}a_3}{4} \end{bmatrix} \\
B_{3,t} &= \begin{bmatrix} b_2 & 0 & 0 \\ -\frac{a_3}{4} & a_2 & \frac{a_3}{4} \\ F_{3,t} - \frac{F_{5,t}a_3}{4} + F_{1,t}b_2 & F_{5,t}a_1 & F_8 + \frac{F_5 a_3}{4} \end{bmatrix} \\
B_{4,t} &= \begin{bmatrix} b_3 & 0 & 0 \\ -\frac{a_3}{4} & 0 & \frac{a_3}{4} \\ F_{4,t} - \frac{F_{5,t}a_3}{4} + F_{1,t}b_3 & 0 & F_{9,t} + \frac{F_{5,t}a_3}{4} \end{bmatrix} \\
B_{5,t} &= \begin{bmatrix} 1 - b_1 - b_2 - b_3 & 0 & 0 \\ -\frac{a_3}{4} & 0 & \frac{a_3}{4} \\ -\frac{F_{5,t}a_3}{4} - F_{1,t}(b_1 + b_2 + b_3 - 1) & 0 & \frac{F_{5,t}a_3}{4} \end{bmatrix}
\end{aligned}
$$

Now finally we rewrite the above equation in the following form for Bayesian estimation

$$
y_t = W_t\delta + Z_t\tilde{\beta}(\delta, \alpha_t, \nu) + A(\delta, \alpha_t, \nu)^{-1}\Sigma_t\varepsilon_t \tag{1.10}
$$

$$
\alpha_{t+1} = \alpha_t + v_t \tag{1.11}
$$

where $\varepsilon_t \sim N(0, I_n)$ and $v_t \sim N(0, Q)$

$$\begin{aligned}
y_t &= [y_{1,t}, y_{2,t} y_{3,t}]' \text{ with } y_{1t} = \pi_t - \pi_{t-4} \ \ , y_{2,t} = \tilde{y}_t \ , y_{3,t} = i_t \\
W_t &= \begin{bmatrix} w'_{1,t} & 0_{1\text{x}4} \\ 0_{1\text{x}5} & w'_{2,t} \\ 0_{1\text{x}5} & 0_{1\text{x}4} \end{bmatrix} \\
w_{1,t} &= [1, \pi_{t-1} - \pi_{t-4}, \pi_{t-2} - \pi_{t-4}, \pi_{t-3} - \pi_{t-4}, \tilde{y}_{t-1}]' \\
w_{2,t} &= [1, \tilde{y}_{t-1}, \tilde{y}_{t-2}, \frac{1}{4}\left(i_{t-1} - \pi_{t-1} + i_{t-2} - \pi_{t-2} + i_{t-3} - \pi_{t-3} + i_{t-4} - \pi_{t-4}\right)]'
\end{aligned}$$

$$\begin{aligned}
\delta &= \begin{bmatrix} \delta_1 \\ \delta_2 \end{bmatrix}, \quad \begin{matrix} \delta_1 = [b_0, b_1, b_2, b_3, b_4]' \\ \delta_2 = [a_0, a_1, a_2, a_3]' \end{matrix} \\
Z_t &= \begin{bmatrix} 0_{1\text{x}11} \\ 0_{1\text{x}11} \\ z'_{3,t} \end{bmatrix}, z_{3,t} = [1, \pi_{t-1}, \pi_{t-2}, \pi_{t-3}, \pi_{t-4}, \tilde{y}_{t-1}, \tilde{y}_{t-2}, i_{t-1}, i_{t-2}, i_{t-3}, i_{t-4}]'
\end{aligned}$$

$$\tilde{\beta}(\alpha_t,\delta,\nu) = \begin{bmatrix} f_t + F_{5,t}a_0 + F_{1,t}b_0 \\ F_{2,t} - \frac{F_{5,t}a_3}{4} \\ F_{3,t} - \frac{F_{5,t}a_3}{4} + F_{1,t}b_1 \\ F_{4,t} - \frac{F_{5,t}a_3}{4} + F_{1,t}b_3 \\ -\frac{F_{5,t}a_3}{4} + F_{1,t}(1-b_1-b_2-b_3) \\ F_{6,t} + (F_{5,t}a_1 + F_{1,t}b_4 \\ F_{5,t}a_2 \\ F_{7,t} + \frac{F_{5,t}a_3}{4} \\ F_{8,t} + \frac{F_{5,t}a_3}{4} \\ F_{9,t} + \frac{F_{5,t}a_3}{4} \\ \frac{F_{5,t}a_3}{4} \end{bmatrix}, A(\delta,\alpha_t,\nu)^{-1} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ F_{1,t} & F_{5,t} & 1 \end{bmatrix}$$

$$Ł \equiv \begin{bmatrix} 1 & 0 & 0 \\ l_{21} & 1 & 0 \\ l_{31} & l_{32} & 1 \end{bmatrix} \text{ and } \Psi_t \equiv \begin{bmatrix} \sigma_{1,t} & 0 & 0 \\ 0 & \sigma_{2,t} & 0 \\ 0 & 0 & \sigma_{3,t} \end{bmatrix}, \Sigma_t = L\Psi_t\Psi_t'L'$$

The $F_{i,t}$ are functions of α_t, δ, ν as governed by the optimal policy restrictions. We will divide the parameters into the following 7 blocks: [$\alpha_t, \delta, \nu, Q, W, \Sigma_t, L$].

1.9.3 Appendix C: Bayesian MCMC: Block-wise Metropolis Hastings

Here we outline the algorithm for estimating the model presented in the previous section. The MCMC algorithm gives a draw from the joint posterior of the parameters θ which is divided into 7 blocks, $\theta = [\alpha_t, \delta, \nu, Q, W, \Psi_t, L]$. This is done by drawing from the distribution of each block conditional on all the other blocks. When this full conditional distribution is known (as is the case for Q, W and L) a Gibbs step is used. When this full conditional distribution is not known (as is the case for ν and δ) a Metropolis-Hastings step is used. The stochastic volatilities Ψ_t are drawn using the Kim et al. (1998) mixture of normals approach. Finally for the time-varying preference parameter α_t is drawn by using the Carter and Kohn (1994) simulation smoother that is augmented with the Extended Kalman Filter to handle the non-linearity. Each step is discussed in detail below. In Appendix D, I discuss the convergence properties of the estimation procedure.

Likelihood Function

Consider the model as written in equations (1.10) and (1.11). We can rewrite that in the following manner.

$$\begin{aligned} A(\delta, \alpha_t, \nu)\left(y_t - W_t\delta - Z_t\tilde{\beta}(\delta, \alpha_t, \nu)\right) &= \Sigma_t\varepsilon_t \\ \alpha_{t+1} &= \alpha_t + v_t \end{aligned}$$

If we define $u_t \equiv A(\delta, \alpha_t, \nu)\left(y_t - W_t\delta - Z_t\tilde{\beta}(\delta, \alpha_t, \nu)\right)$ then we write down the likelihood function in the following manner.

$$p(Y|\theta) = \prod_{t=1}^{T} (2\pi)^{-\frac{n}{2}} \left|\Sigma_t^{-1}\right|^{1/2} exp\left\{-\frac{1}{2}u_t'\Sigma_t^{-1}u_t\right\}$$

Y denotes the full set of data from time $t = 1, 2, ...T$.

Drawing δ: Coefficients of the Constraints

Conditional on the variance parameters Ψ_t,L and preference parameters α_t and ν drawing δ is a problem of sampling the coefficients of a nonlinear regression.

The prior for δ is multivariate normal.

$$p(\delta) = (2\pi)^{-(k+1)/2} |V_0^{-1}|^{\frac{1}{2}} exp\left\{-\frac{1}{2}(\delta - \delta_0)'V_0^{-1}(\delta - \delta_0)\right\}$$

The posterior is given by

$$\begin{aligned} p(\delta|Y, \theta\backslash\delta) &\propto p(\delta)p(Y|\theta) \\ &\propto exp\left\{-\frac{1}{2}(\delta - \delta_0)'V_0^{-1}(\delta - \delta_0)\right\} exp\left\{-\frac{1}{2}\sum_{t=1}^{T} u_t'\Sigma_t^{-1}u_t\right\} \end{aligned}$$

The notation $\theta\backslash\delta$ represents all the parameters in θ except δ. For a given draw of $\delta^{(g)}$ the Metropolis-Hastings algorithm involves generating a draw from a candidate generating density, $q(.)$. Let this candidate draw be called $\delta^{(g+1)}$. Then this new draw is accepted with the following probability.

$$\alpha(\delta^{(g+1)}, \delta^{(g)}) = min\left(\frac{p(\delta^{(g+1)}|Y, \theta\backslash\delta).q(\delta^{(g)})}{p(\delta^{(g)}|Y, \theta\backslash\delta).q(\delta^{(g+1)})}, 1\right)$$

Here I use a multivariate normal candidate generating density which is centered around the current draw $\delta^{(g)}$.

$$\delta^{(g+1)} = \delta^{(g)} + N(0, c_\delta V_\delta)$$

This is known as a random walk Metropolis-Hastings step. The algorithm is run initially for 1000 iterations. V_δ is set to the posterior covariance of the δ draws from this initial run. I then tune the parameter c_δ to get an acceptance rate of between 25% and 35% as recommended by Gamerman and Lopes (2006). The random-walk algorithm performed better than the independence chain that is sometimes used as an alternative.

Drawing ν: Weight on Interest Rate Smoothing

The algorithm for drawing ν is identical to the one for drawing δ. I initially tried to block both δ and ν in the same Metropolis-Hastings step, but separating them into two blocks increased the convergence efficiency. Assuming a normal prior for ν, I pick the variance of the normal candidate generating density V_ν in the same way as δ but now tune c_ν to get acceptance rates around 45% as there is only one parameter to draw here.

Drawing α_t: Time-varying Weight on Inflation

This step of the MCMC algorithm is the most involved. I use the Carter and Kohn (1994) simulation smoother and add the Extended Kalman Filter (EKF) to perform the forward filter portion of the algorithm. As will become clear the sampling backwards step remains unchanged as the transition equation in the state space model is still linear. There are various options for performing non-linear filtering but there is no general rule regarding which non-linear filter is the most efficient. Unscented Kalman Filter and Particle Filter are two alternative methods that are commonly used. I chose the EKF over these two methods and explain in detail in Appendix E the reasons for doing so.

The model can be written in state space form in the following manner

$$y_t = h(\alpha_t, X_t, \Gamma, \varepsilon_t) \quad \text{where } \varepsilon_t \sim N(0, \Sigma_t)$$
$$\alpha_{t+1} = \alpha_t + v_{t+1} \qquad \text{where } v_t \sim N(0, Q)$$

X_t is lagged data, Γ includes the parameters of the constraints (δ) and loss function (ν). The first step of the simulation smoother involves filtering forward using the EKF, which is done with the following two equations. Let $\alpha_{t|t} = E(\alpha_t|Y^t, \theta)$ and $P_{t|t} = Var(\alpha_t|Y^t, \theta)$.

$$\begin{aligned} \alpha_{t|t} &= \alpha_{t-1|t-1} + K_t \left[y_t - h(\alpha_{t|t-1}, X_t, \Gamma, 0) \right] \\ P_{t|t} &= \left[I - K_t H_t \right] \left(P_{t-1|t-1} + Q \right) \end{aligned}$$

where

$$\begin{aligned} K_t &= P_{t|t-1} H_t \left[H_t P_{t|t-1} H_t' + M_t \Sigma_t M_t' \right]^{-1} \\ H_t &= \left. \frac{\partial h()}{\partial \alpha} \right|_{\alpha_{t|t-1}} \\ M_t &= \left. \frac{\partial h()}{\partial \varepsilon} \right|_{\varepsilon_{t|t-1}} \end{aligned}$$

The second step involves sampling backwards in time. For the final period T sample from a normal with mean $\alpha_{T|T}$ and variance$P_{T|T}$ which are just the filtered values. For each preceding t sample with the mean $\tilde{\alpha_t}$ and variance $\tilde{P_t}$ given by

$$\begin{aligned} \tilde{\alpha_t} &= \alpha_{t|t} + J_t \left(\alpha_{t+1} - \alpha_{t|t} \right) \\ \tilde{P_t} &= P_{t|t} - J_t P_{t|t} \end{aligned}$$

where $J_t = P_{t|t}P^{-1}_{t+1|t}$. Note that since the transition equation is linear this step is the same as in the standard simulation smoother. There is a technical issue that arises in this modified simulation smoother. The weight on inflation α_t cannot take on negative values because that implies explosive behavior. To impose stability I follow the rejection sampling approach that is outlined in Cogley and Sargent (2005). This means that if at any t a negative draw of α_t is encountered then the entire series of draws from $T, T-1, ...t$ is discarded and sampling starts again at T. This imposes the non-negativity constraint in the backward sampling but here I need to strictly impose this constraint even in the forward filtering. This is because optimal policy is undefined with a negative weight on inflation and we can not continue with the Extended Kalman Filter recursions if any filtered value is negative. To deal with this issue I apply the Estimate Projection approach outlined in Simon (2010). This method projects the unconstrained filtered estimate onto the constraint surface.

Drawing Ψ_t: Volatility States

Start with the model in the following form (as derived in Appendix B)

$$y_t \quad = \quad W_t\delta + Z_t\tilde{\beta}(\delta, \alpha_t, \nu) + A(\delta, \alpha_t, \nu)^{-1}\Sigma_t\varepsilon_t$$

Additionally using the triangular decomposition we can write $\Sigma_t = L\Psi_t$ where

$$Ł \equiv \begin{bmatrix} 1 & 0 & 0 \\ l_{21} & 1 & 0 \\ l_{31} & l_{32} & 1 \end{bmatrix} \text{ and } \Psi_t \equiv \begin{bmatrix} \sigma_{1,t} & 0 & 0 \\ 0 & \sigma_{2,t} & 0 \\ 0 & 0 & \sigma_{3,t} \end{bmatrix},$$

Using these rewrite the model in the following form

$$y^*_t = \Psi_t\varepsilon_t$$

where $y_t^* = L^{-1}\left[A(\delta,\alpha_t,\nu)\left(y_t - W_t\delta - Z_t\tilde{\beta}(\delta,\alpha_t,\nu)\right)\right]$. Now square both sides and take logs.

$$y_t^{**} = 2h_t + e_t$$
$$h_t = h_{t-1} + \eta_t$$

where $y_{i,t}^{**} = log(y_{i,t}^2 + \bar{c})$, where $\bar{c}$ is an offset constant set to .001,$h_{i,t} = log(\sigma_{i,t})$ and $e_{i,t} = log(\varepsilon_{i,t}^2)$. Now we have a linear model but the errors are no longer normal but instead $log(\chi^2(1))$. I use the approach outlined in Kim et al. (1998) which involves approximating the $log(\chi^2(1))$ with a mixture of 7 normal distributions. See Kim et al. (1998) and Primiceri (2005) for more details of the algorithm.

Drawing L: Covariance terms

Again start with the model in the following form (as derived in Appendix B)

$$y_t = W_t\delta + Z_t\tilde{\beta}(\delta,\alpha_t,\nu) + A(\delta,\alpha_t,\nu)^{-1}\Sigma_t\varepsilon_t$$

Now rewrite it in the following form

$$A(\delta,\alpha_t,\nu)\left(y_t - W_t\delta - Z_t\tilde{\beta}(\delta,\alpha_t,\nu)\right) = L\Psi_t\varepsilon_t$$

Now defining $\hat{y}_t = A(\delta,\alpha_t,\nu)\left(y_t - W_t\delta - Z_t\tilde{\beta}(\delta,\alpha_t,\nu)\right)$ and $\hat{\varepsilon}_t = \Psi_t\varepsilon_t$ we can write

$$L^{-1}\hat{y}_t = \hat{\varepsilon}_t$$

Finally we get

$$\hat{y}_t = C_t l + \hat{\varepsilon}_t$$

$$
\begin{aligned}
C_t &= \begin{bmatrix} 0 & 0 & 0 \\ -\hat{y}_{1,t} & 0 & 0 \\ 0 & -\hat{y}_{1,t} & -\hat{y}_{2,t} \end{bmatrix} \\
l &= [l_{21}, l_{31}, l_{32}]'
\end{aligned}
$$

Now conditional on the rest of the parameters drawing l_{21}, l_{31}, l_{32} is a problem of sampling from a linear regression. The prior for l is normal with mean L_{prior} and variance $V_{L,prior}$. This results in a normal posterior

$$
\begin{aligned}
l &\sim N(\bar{L}, \bar{V_L}) \\
\bar{V_L} &= \left(V_{L,prior}^{-1} + \sum_{t=1}^{T} C_t' \left(\Psi_t \Psi_t'\right)^{-1} C_t \right)^{-1} \\
\bar{L} &= \bar{V_L} \left(V_{L,prior}^{-1} L_{prior} + \sum_{t=1}^{T} C_t' \left(\Psi_t \Psi_t'\right)^{-1} \hat{y}_t \right)
\end{aligned}
$$

Drawing W and Q: Hyperparameters

The full conditional distributions of W and Q are known and can be sampled using a Gibbs step. Q is specified as having a inverse-Gamma prior with shape parameter ν_Q and scale parameter Q_{prior}. Conditional on observing α_t we can construct $u_t = \alpha_t - \alpha_{t-1}$ and draw from the posterior, which is also inverse-Gamma. Note here I will draw Q^{-1} from a Gamma distribution.

$$
\begin{aligned}
& Q^{-1} \sim \; Gamma\left(\bar{Q}^{-1}, \bar{\nu}_Q\right) \\
\bar{\nu}_Q &= T + \nu_Q \\
\bar{Q} &= Q_{prior} + \sum_{t=1}^{T} u_t u_t'
\end{aligned}
$$

The prior for W is inverse-Wishart with degrees of freedom ν_W and scale matrix W_{prior}. Conditional on observing logσ_t we can construct $\eta_t = log\sigma_t - log\sigma_{i,t-1}$ and draw from the inverse-Wishart posterior of W. Again, I will draw

W^{-1} from a Wishart distribution.

$$W^{-1} \sim W\left(\bar{W}^{-1}, \bar{\nu}_W\right)$$
$$\bar{\nu}_W = T + \nu_W$$
$$\bar{W} = W_{prior} + \sum_{t=1}^{T} \eta_t \eta_t'$$

1.9.4 Appendix D: Convergence Diagnostics

The Markov chain should mix well, i.e. it should converge to the invariant distribution which is the posterior distribution in this case. Here I report several different checks of convergence that are commonly used in the literature. I use a total of 75,000 draws with a burn-in sample of 10,000 (this means that the first 10,000 draws are discarded). Then I use a thinning factor of 2 (thinning factor of i means that only the i^{th} draws are stored). This gives an effective number of draws equal to 32,500. In preliminary runs I found that the parameter blocks drawn using the Metropolis-Hastings step δ, ν were slower to mix and thus these two blocks were drawn twice in every iteration. From the total 150,000 draws for these blocks the first 10,000 are discarded and then a thinning factor of 8 is used, this gives an effective sample of 14,000.

A simple tool to analyze convergence is to look at the autocorrelations across the draws. I compute the 20^{th} order autocorrelations and report them in Table 1.9.5. A good rule of thumb is that convergence is satisfactory if the autocorrelations are less than 0.2 in absolute value. As seen in the table these values are low for all the parameters except δ. Another tool is to use the Raftery and Lewis (1992) method to determine the total number of draws required. This number gives the total number of draws required to estimate the quantile q up to an accuracy of r with probability p. I report the total number of runs setting q = .025, r = .025 and s = .95. The table shows that the required number of runs is much lower than the total number of actual runs for all the parameters. Finally I calculate the inefficiency factors, this is the inverse of the relative numerical efficiency of Geweke (1992). This is the inverse of $1 + 2\sum_{k=1}^{\infty} \rho_k$ where ρ_k is the k^{th} order autocorrelation. Here a value of 20 or lower is considered satisfactory. Again this number is quite low for all the parameters.

Additionally, runs with randomly selected starting values all converged to the same estimates. Overall, the diagnostics give satisfactory results regarding the convergence of the Markov Chain.

1.9.5 Appendix E: Justification for Extended Kalman Filter

The simulation smoother algorithm is based on the optimality results derived from a linear state space model with normal errors. The model in this paper can be written in state space form in the following manner.

$$\begin{aligned} y_t &= h(\alpha_t, X_t, \Gamma, \varepsilon_t) \quad \text{where } \varepsilon_t \sim N(0, \Sigma_t) \\ \alpha_{t+1} &= \alpha_t + v_{t+1} \qquad \text{where } v_t \sim N(0, Q) \end{aligned}$$

α_t is the time-varying preference parameter, X_t is lagged data, Γ contain the constant parameters and ε_t and v_t are the shocks. Here the errors are normal but the observation equation is not linear. Specifically since the unobservable variable α_t enters non-linearly we cannot use the standard Kalman Filter. The EKF deals with the non-linearity by taking a first order Taylor expansion around the current filtered estimate and then uses the regular Kalman Filter recursions. As long as the non-linearity is not severe the EKF gives a good approximation to the optimal estimate. Thus if the function $h(.)$ is not too nonlinear in α_t then the EKF will be fine.

Remember in this model α_t only appears in the interest rate equation. Fixing the constant parameters Γ at their posterior means, Figure 1.9.5 plots the coefficients of the interest rate equation as functions of α_t, these are the $F_{i,t}$ from equation (1.4). The range of α_t on the x-axis includes the maximum and the minimum of the estimated values of α_t . It is apparent that the non-linearities are indeed not very severe and thus the EKF should be a good approximation.

To further confirm this result I have computed filtered and smoothed values using two other popular non-linear filters, the Unscented Kalman Filter (UKF) and the Particle Filter (PF). Again in this exercise I fix the values of the rest of the parameters at their posterior means. The filtered and smoothed values from these alternative filters are very similar to the Extended Kalman Filter. This is not surprising as these two filters tend to perform better in more extreme nonlinear and non-normal situations. Thus the EKF, UKF and PF give very similar results in this situation.

The particle filter is a Sequential Monte Carlo method, see Doucet et al. (2001) for more details. The PF is not chosen because of the high computational costs. To get a rough idea of the computational time we can look at Fernandez-Villaverde and Rubio-Ramirez (2005) who use the particle filter to estimate a larger non-linear DSGE model. With 60,000 particles it takes them 6.1 seconds to get one draw from the posterior distribution. Then 50,000 draws from the posterior results in about 88 hours of total computational time. For the model in this paper it takes more than 10 minutes for each draw from the posterior distribution with 60,000 particles. This makes clear the prohibitive computational time involved in using the particle filter for our model. The reason is that for every particle I need to use the optimal linear regulator to compute optimal policy which requires solving the matrix Riccatti equations. Thus even though each call of the optimal linear regulator takes a fraction of a second the overall computational time is too large.

The Unscented Kalman Filter is a filter based on the unscented transformation, see Julier and Uhlmann (1997) for more details. Typically the advantage of he UKF is that it does not require computing derivatives but in this model it takes about the same time computationally as the EKF. UKF was not chosen because it was harder to impose the non-negativity constraint on the filtered series, this is discussed in more detail in Appendix C.

Table 1.1: Parameter Estimates

IS Curve				Phillips Curve			
Parameter	Posterior Mean	95th percentile	5th percentile	Parameter	Posterior Mean	95th percentile	5th percentile
a0	0.1148	0.2229	0.0062	b0	-0.0883	0.0021	-0.1717
a1	1.124	1.2432	1.0055	b1	0.4427	0.546	0.348
a2	-0.2055	-0.0921	-0.324	b2	0.2046	0.3223	0.0976
a3	-0.0403	-0.014	-0.076	b3	0.1256	0.2405	0.011
				b4	0.1321	0.1776	0.0881

	Weight on interest rate smoothing		
Parameter	Posterior Mean	95th percentile	5th percentile
ν	440.9358	770.8697	196.8245

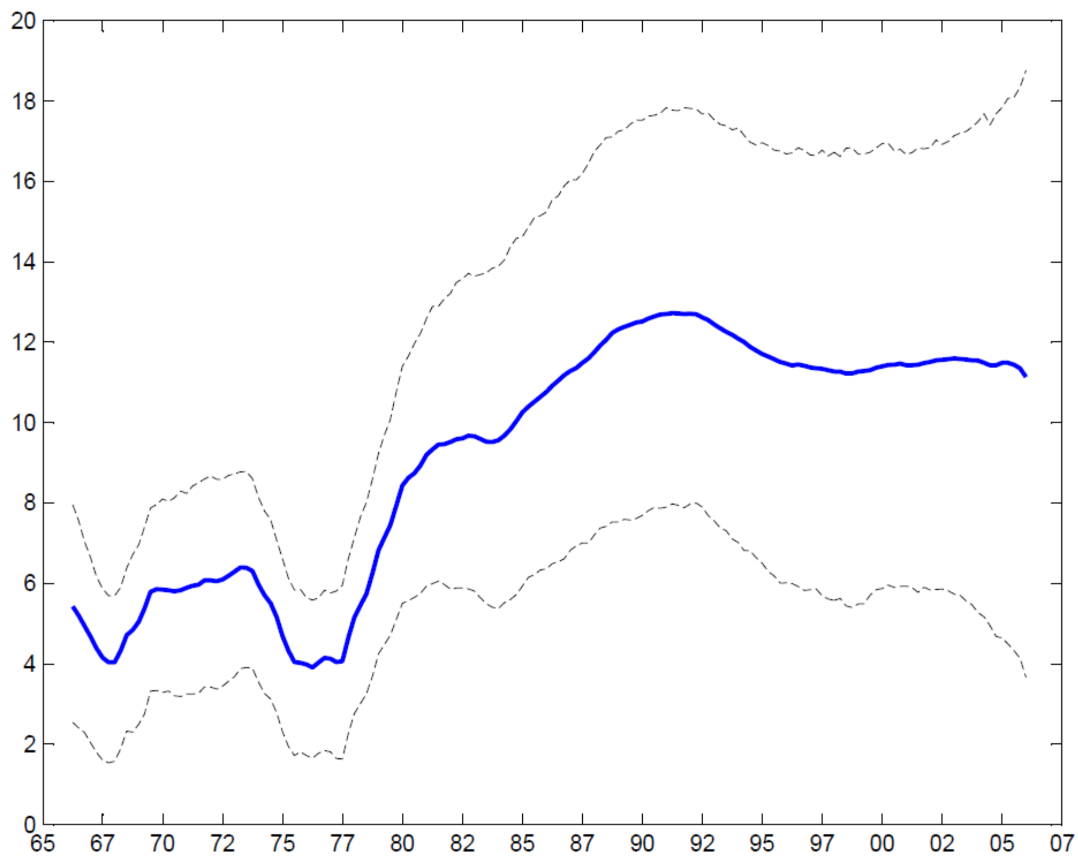

Figure 1.1: Time-varying weight on inflation

Table 1.2: Counterfactual Analysis: Great Moderation

	Standard Deviations		
	Inflation	Output Gap	Fed Funds Rate
Data			
pre 1984:Q1	2.377	3.366	3.597
post 1984:Q1	0.926	1.846	2.379
% fall: pre to post	0.610	0.452	0.339
Model			
pre 1984:Q1	1.952	3.159	3.746
post 1984:Q1	0.741	1.691	2.407
% fall: pre to post	0.620	0.465	0.358
Counterfactual (No SV)			
pre 1984:Q1	2.393	3.376	3.668
post 1984:Q1	1.123	2.064	3.068
% fall: pre to post	0.531	0.389	0.164
Counterfactual (No Preference Change)			
pre 1984:Q1	2.330	3.290	3.096
post 1984:Q1	0.983	1.837	2.518
% fall: pre to post	0.578	0.442	0.187

Table 1.3: Granger Causality Tests

	Hawk → Recession	Recession → Hawk	Dove → Recession	Recession → Dove
F-statistic	3.556	1.045	0.072	2.069
p-value	(0.0009)	(0.4061)	(0.9998)	(0.0431)

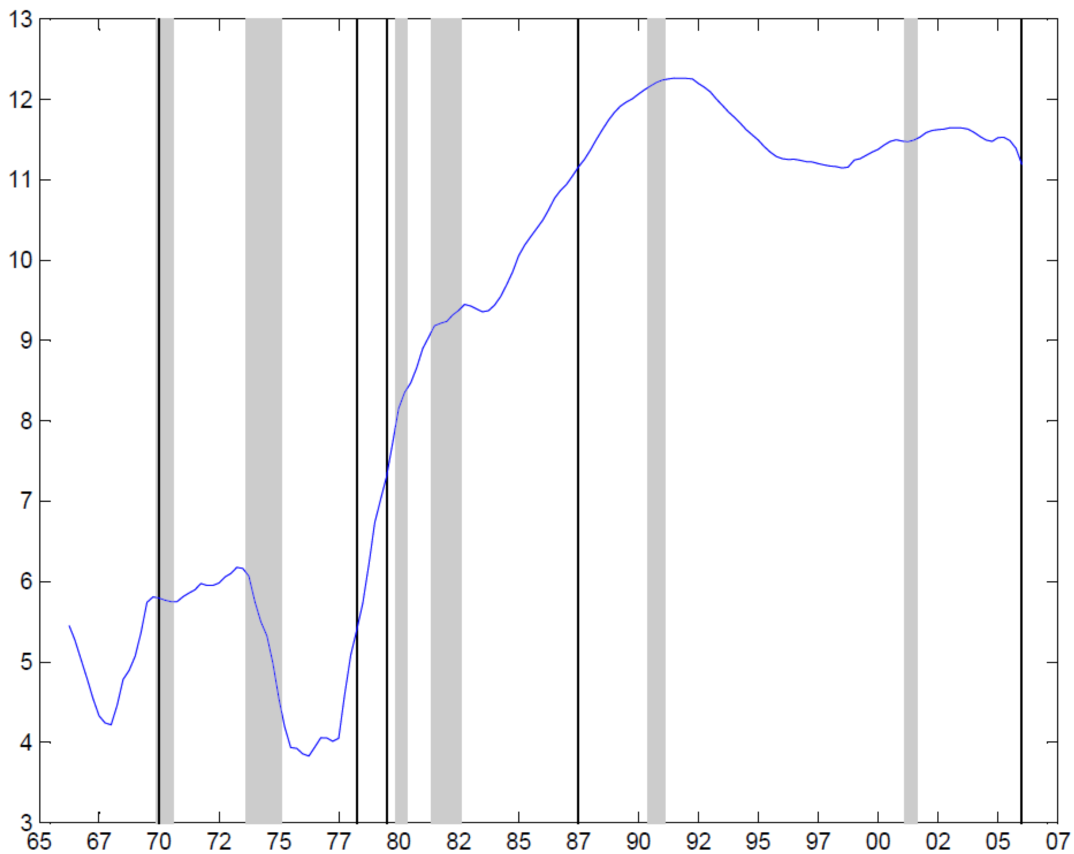

Figure 1.2: Time-varying weight on inflation with recession bars

Table 1.4: Convergence Diagnostics for Markov Chain Monte Carlo

	20th order autocorrelations			Raftery & Lewis runs in thousands			Inefficiency Factors		
Parameter Block	Mean	Max	Min	Mean	Max	Min	Mean	Max	Min
δ	0.217	0.405	0.091	5.55	8.76	2.93	30.51	56.80	15.14
ν	0.024	0.024	0.024	4.40	4.40	4.40	8.77	8.77	8.77
α_t	0.032	0.055	0.013	1.37	4.12	0.94	7.30	9.51	4.71
Q	0.056	0.056	0.056	4.41	4.41	4.41	12.15	12.15	12.15
W	0.020	0.021	0.016	1.98	2.04	1.94	2.39	2.42	2.34
Ψ_t	0.029	0.117	-0.011	1.59	9.66	0.93	4.39	13.33	0.46
L	0.054	0.088	0.020	1.09	1.11	1.07	9.41	16.09	2.72

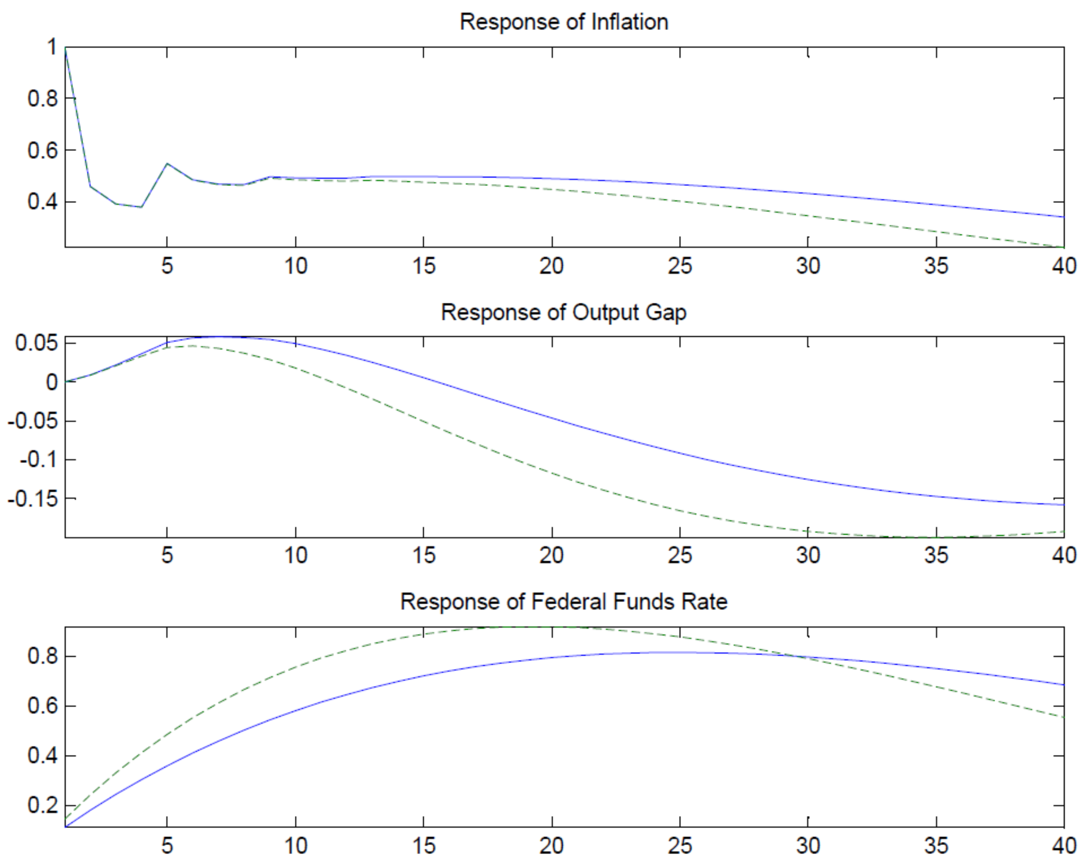

Figure 1.3: Impulse responses to a one unit shock in inflation.

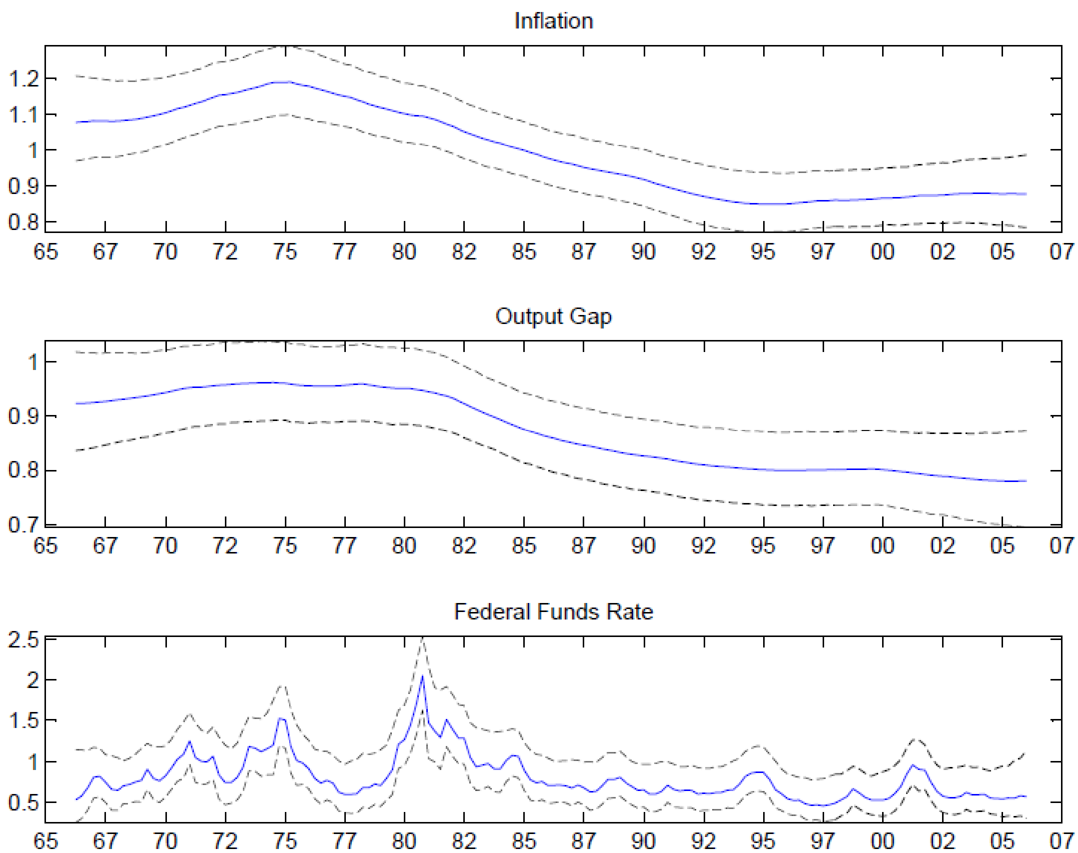

Figure 1.4: Stochastic Volatility

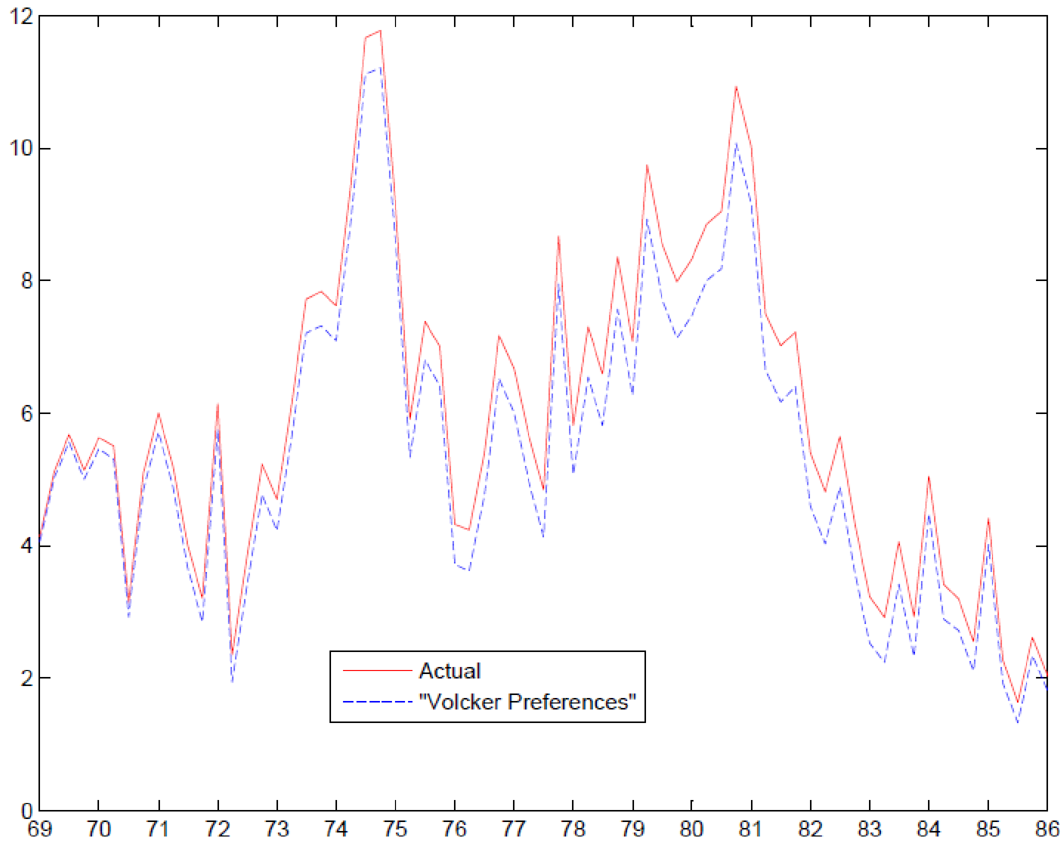

Figure 1.5: Counterfactual Analysis: Inflation

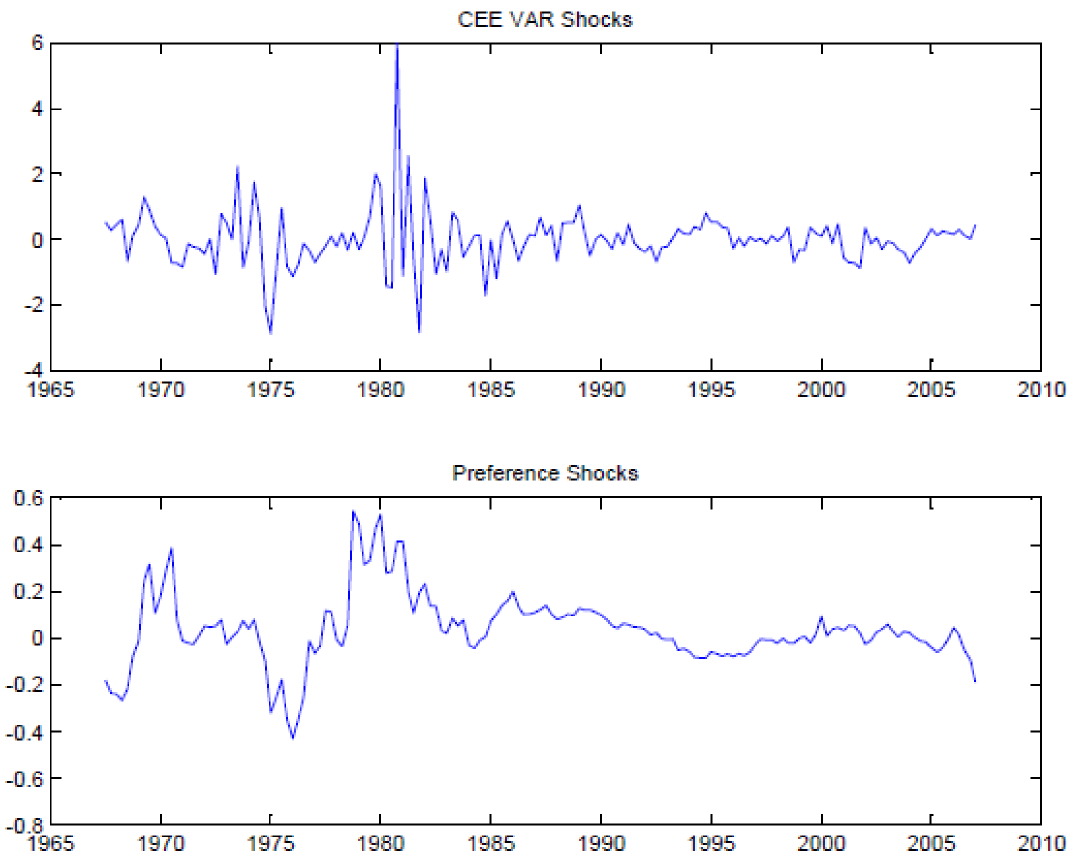

Figure 1.6: Monetary policy shocks

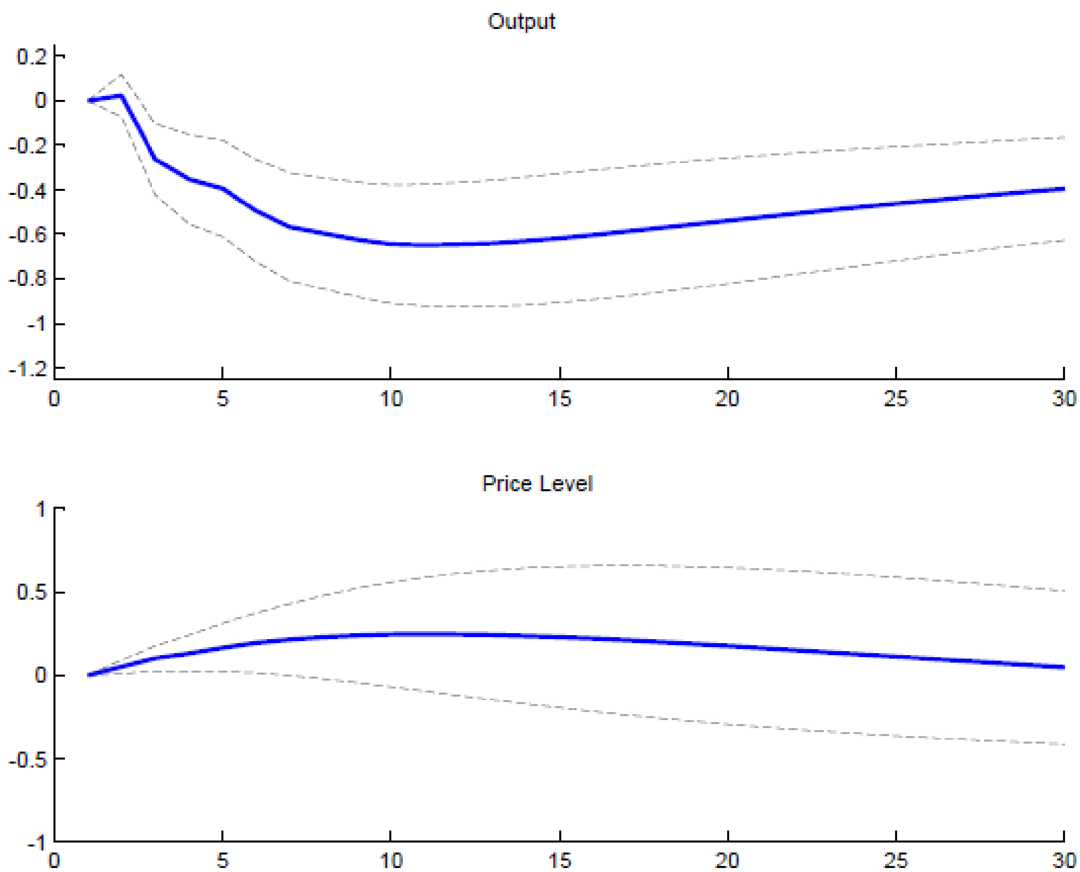

Figure 1.7: Response to monetary policy shock (fed funds Rate shock)

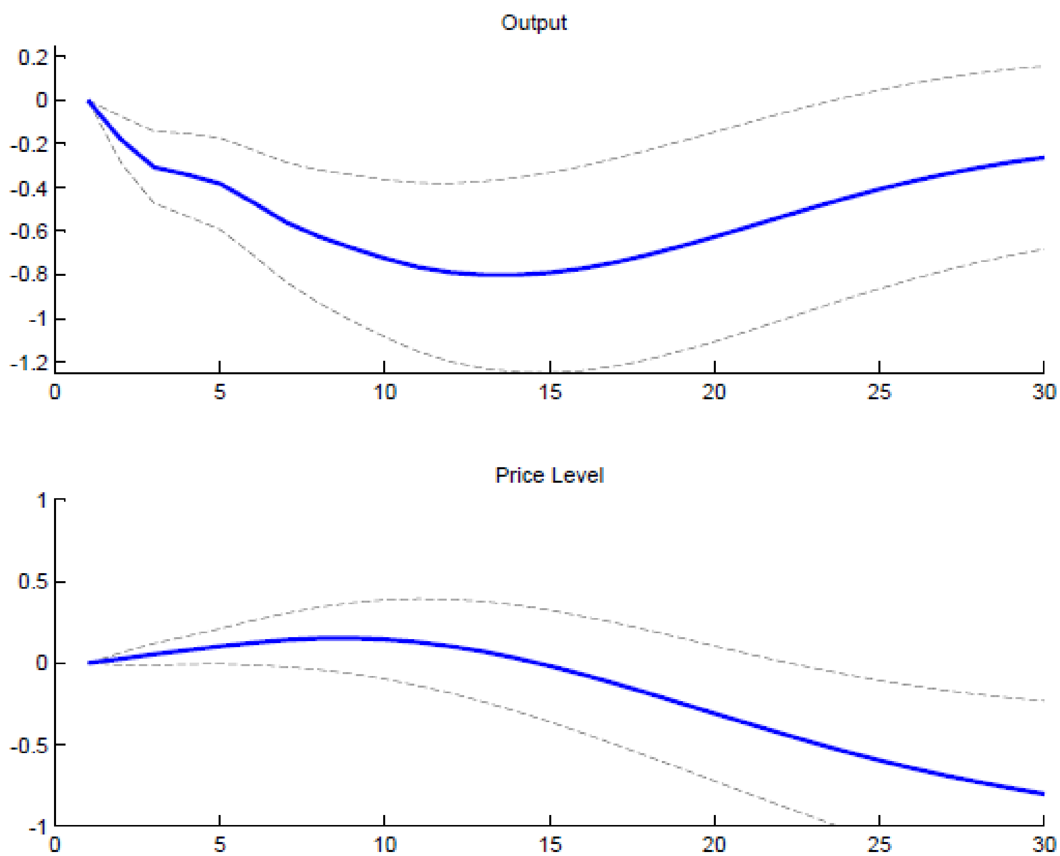

Figure 1.8: Response to monetary policy shock (Preference Shock)

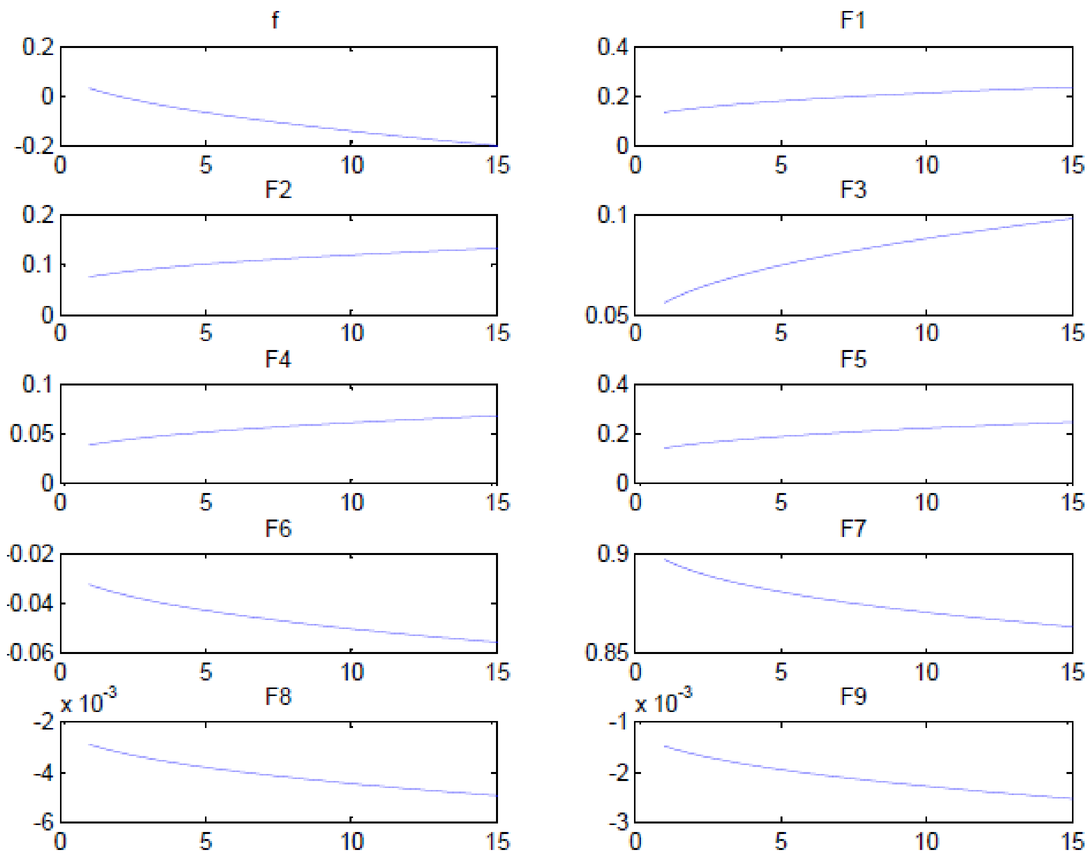

Figure 1.9: Coefficients of the optimal interest rate equation

Chapter 2

Globalization and Foreign Competition: Implications for Inflation and Monetary Policy

Abstract

The effects of globalization on macroeconomic dynamics and monetary policy have been widely discussed and debated, yet most studies fail to account for the possibility that domestic firms' markups may respond to changes in the prices of foreign competitors. This paper uses a non-constant elasticity demand function that explicitly models this competitive effect and analyzes the impact of globalization on the economy. The most significant impact arises in the response to technology shocks. When the foreign country experiences a positive technology shock, domestic firms lower their markups to prevent losing market share to cheaper imported goods. Thus inflation in the home country falls more and stays lower for longer when the home country is more open. This prompts the central bank in the home country to keep interest rates lower. Increased openness also changes the volatility of inflation and output gap under standard Taylor rules. Interestingly, the central bank can decrease this volatility by responding more strongly to either inflation or output gap. Finally, this paper corroborates earlier findings that globalization has a modest impact on the sensitivity of inflation to output gaps and

the monetary policy transmission mechanism.

2.1 Introduction

Globalization, loosely defined by economists as economic and financial integration, has exhibited a large sustained growth in the last few decades. A statistic commonly used to illustrate the rapid expansion of globalization is the share of imports in Gross Domestic Product (GDP). Figure 2.1 shows the ratio of nominal imports to nominal GDP for the US over time. There is a clear upward trend; the share of imports has risen from less than 10% of GDP in the 1980s to nearly 20% by the the mid-2000s. Imports are used for consumption and thus import prices feed through directly into consumer prices. However, an additional strategic effect may arise if imports exert competitive pressure on domestic firms.[1] In this scenario domestic firms may find it optimal to change their markups in response to the change in the foreign competitors' prices. Thus import prices could play a role in determining domestic inflation over and above their direct effect on consumer price inflation. There is an active ongoing debate concerning the role of globalization in inflation dynamics and monetary policy in the US; some studies find a large impact while others do not.[2] Until recently, most of the literature has ignored the competitive effect. However, failing to account for this competitive effect may lead to underestimates of the true impact of globalization. For example, Guerrieri et al. (2010) find a big effect of import prices on US inflation after explicitly accounting for this competitive effect.

This paper explores the role of globalization in light of the foreign competition effect. I use a two-country open economy New Keynesian model with sticky prices. The model builds on the canonical model of Clarida et al. (2002) by explicitly introducing the competitive effect through a non-constant elasticity of

[1]Admittedly, imports are also used as intermediate inputs and thus affect marginal costs but I will abstract from this channel in this paper. Nonetheless, Lipinska and Millard (2011) show that the effect of imports on consumption goods prices dominates the effect on production costs.

[2]For papers arguing for a big role of globalization, see Borio and Filardo (2007), IMF (2006), Auer and Fischer (2010) and references therein and for the opposing view see Ball (2006) and Ihrig et al. (2010) among others.

substitution demand function. In this framework, the price elasticity of demand of a domestic firm depends on the domestic firm's price relative to its competitors which includes foreign firms. If a foreign firm decreases its price, the domestic firm has an incentive to reduce its own price in order to avoid losing market share. I then solve for world general equilibrium and study the implications of increased globalization for macroeconomic dynamics and the conduct of monetary policy within this framework. Globalization is measured as the share of imports in GDP. I consider two cases: one with a low level of globalization where imports are 10% of GDP and another with a high level of globalization with imports being 20% of GDP to match the transition shown in Figure 2.1.

The main contribution of this paper is twofold. First, I consider the effects of globalization on the transmission of foreign technology shocks in an environment with the competitive effect. Second, I study the interaction between increased openness and changes in the systematic component of monetary policy and its implications for the volatility of inflation and output. Additionally, I consider the effects of globalization for the slope of the Phillips curve and transmission of domestic technology shocks and monetary policy shocks, to compare my results to the literature. Earlier work has modeled the non-constant elasticity demand function in the open economy framework, but mainly to study exchange rate related issues like pass-through (Gust et al. (2010) and Gopinath and Itskhoki (2010) among others). Others have used this setup to investigate the effects of globalization on transmission of domestic shocks. In Erceg et al. (2007) the focus is only on the transmission of domestic technology shocks and they do not consider the implications for monetary policy. Cwik et al. (2011) consider a larger DSGE model but they only focus on the transmission mechanism of monetary policy. Guerrieri et al. (2010) use the same non-constant elasticity demand function to estimate the role of imported price inflation on domestic inflation. But they do not solve for general equilibrium and only estimate the Phillips curve.

It has been hypothesized that globalization can affect the sensitivity of inflation to output gaps (known as the slope of the Phillips curve). Empirical studies have shown that the slope of the Phillips curve has fallen in the last couple of decades (Roberts (2006), Williams (2006) and Pain and Sollie (2006)). Nonetheless there is conflicting evidence about whether this decline is due to globalization. The IMF (2006) finds that this is true for industrialized countries while Ihrig et al. (2010) find contradicting evidence for the US. Here I show that qualitatively, increased openness makes the Phillips curve flatter but the quantitative effects are modest. This confirms the earlier result in Zaniboni (2008) who uses a similar setup.

In addition to affecting the slope, the non-constant elasticity framework adds an extra "shock" term to the level of domestic inflation Phillips curve. This extra term is a function of the terms of trade and the weight on it increases with the level of openness. Thus it is possible for globalization to affect the dynamics of output and inflation even though it has a modest impact on the sensitivity of inflation to the output gap. To explore this, I analyze the response of inflation and output to technology shocks. After a positive technology shock in the home country, the fall in domestic inflation and CPI inflation are tempered in the more open economy. But these effects are modest and I conclude that globalization does not have big effects on the transmission of domestic technology shocks. In contrast, in response to a positive technology shock in the foreign country, domestic inflation falls more and stays lower in the more open economy. This is because the competitive effect has a bigger impact in the more open economy. With imports comprising a bigger share of the consumption basket, domestic firms will feel more pressure to reduce their prices in order to avoid losing market share. This means that the central bank can keep interest rates lower in the more open economy.

From a monetary policy perspective, it is important to understand whether globalization has altered the monetary policy transmission mechanism. The transmission mechanism refers to the response of macroeconomic variables to monetary policy actions. The general consensus is that globalization has not altered the monetary policy transmission mechanism (Bernanke (2007), Woodford (2007) and Boivin and Giannoni (2008)).[3] Analyzing impulse responses of output and inflation to a monetary policy shock I find that increased openness has small effects on

[3] However, in a recent empirical paper, Cwik et al. (2011) find a relatively bigger effect of trade integration on the monetary policy transmission mechanism.

the monetary policy transmission mechanism, in agreement with previous work. Even if globalization is not changing how the economy reacts to monetary policy shocks, the systematic part of monetary policy could interact with globalization to have important effects. I analyze the model with different specifications of the monetary policy rule to explore this issue; one where the central bank responds to domestic inflation and another where they use CPI inflation. In the canonical open-economy model Clarida et al. (2002) find that optimal monetary policy can be implemented by a Taylor-type rule with domestic inflation. Engel (2009) extends their model to allow for local currency pricing and finds that CPI inflation should replace domestic inflation. While the impulse responses of inflation and output under the two rules are similar the volatilities are not. Under the domestic inflation Taylor rule, output gap and CPI inflation are more volatile while domestic inflation is less volatile. The central bank can get closer to the optimal policy by reacting more strongly to either inflation, output gap or both. This result arises due to the more enhanced interconnectedness between inflation, output gap and terms of trade in an open economy.

The remainder of the paper is organized as follows. Section 2 briefly outlines the important features of the model and describes the non-constant elasticity of substitution function. The detailed derivation of the model is relegated to the appendix. Section 3 discusses the calibration of the parameters. Section 4 presents the main results of this paper. Section 5 offers some concluding remarks.

2.2 The Model

The model is an extension of the standard New-Keynesian model used in Woodford (2003a) and Gali (2008) and uses the basic open-economy setup of Clarida et al. (2002). There are 2 countries, home and foreign, with representative consumers and identical technologies and preferences but not necessarily the same shocks. The consumer in each country consumes domestic and imported goods and has access to complete contingent claim securities. There is a continuum of intermediate goods firms in both countries. They operate in a monopolistically competitive market and set prices in a Calvo framework. They follow producer currency pricing (i.e. they price their goods in the currency of the country where they are produced). Money exists in the model only as a unit of account.[4]

The critical departure from the standard model is the demand function, which is characterized by non-constant elasticity of substitution. This stands in contrast to a Dixit-Stiglitz style constant elasticity of substitution aggregator that is ubiquitous in the literature. The constant elasticity of substitution results in a constant markup for intermediate goods firms which eliminates any direct channel through which a change in the price of imports leads to a change in the price of domestic goods. In contrast I explicitly model this channel by using a Kimball (1995) style non-constant elasticity of substitution aggregator. Under this framework, a change in the price of the imported good relative to the domestic good changes the optimal markup a domestic firm will charge. A New-Keynesian Phillips curve (NKPC) for domestic inflation is derived from the optimal behavior of the firms where the specific effects of the competitive channel are highlighted. First, foreign competition affects the sensitivity of domestic inflation to output gap and second, it results in an additional "shock" term that depends on the terms of trade. Increased openness leads to a higher weight on the terms of trade component.

The rest of the model is standard and a dynamic IS curve is derived from the first order conditions of the consumer's maximization problem. The model is closed by specifying a Taylor rule for central banks in both countries. Throughout the paper, only the home equations are shown as for the most part the foreign ones are similarly defined. Subscripts refers to the location of consumption (d for home and f for foreign) and superscripts refer to location of production ($*$ for foreign and none for home). The full details of the model and the derivations are in Appendix B.

Consumers

[4] See Woodford (2003a) Chapter 2 for a motivation for this approach

There is a representative consumer that chooses a composite consumption good C_t and labor supply N_t to maximize expected lifetime utility

$$E_0 \sum_{t=0}^{\infty} \beta^t U(C_t, N_t)$$

subject to a sequence of (nominal) budget constraints of the type

$$P_t C_t + E_t Q_{t,t+1} D_{t+1} = W_t N_t + D_t - T_t + \Pi_t$$

where P_t is the price of one unit of the composite consumption good C_t, N_t is labor supply, D_{t+1} is the payoff from a portfolio purchased in t, $Q_{t,t+1}$ is the stochastic discount factor, T_t are lump-sum taxes and Π_t are profits. The utility function is of CRRA form and separable in consumption and labor.

$$U(C,N) = \frac{C^{1-\sigma}}{1-\sigma} - \frac{N^{1+\varphi}}{1+\varphi}$$

Consumers aggregate domestic goods $C_{d,t}(i)$ and the imported goods $C_{f,t}(i)$ into the composite consumption good C_t. They minimize expenditure by choosing $C_{d,t}(i)$ and $C_{f,t}(i)$ taking as given the prices $P_{d,t}(i)$ (the price of the individual domestic intermediate good i) and $P_{f,t}(i)$ (the price of the individual intermediate imported good i). The particular aggregator I employ is based on Gust et al. (2010) and is also used by Guerrieri et al. (2010), who both build on one introduced by Dotsey and King (2005).

$$\min \int_0^1 P_{d,t}(i) C_{d,t}(i) di + \int_0^1 P_{f,t}(i) C_{f,t}(i) di$$

$$s.t. \begin{bmatrix} \left(\int_0^1 \frac{(1-\omega)^\rho}{(1-\nu)\gamma} \left[\frac{1-\nu}{1-\omega} \frac{C_{d,t}(i)}{C_t} + \nu \right]^\gamma di \right)^{\frac{1}{\rho}} \\ + \left(\int_0^1 \frac{\omega^\rho}{(1-\nu)\gamma} \left[\frac{1-\nu}{\omega} \frac{C_{f,t}(i)}{C_t} + \nu \right]^\gamma di \right)^{\frac{1}{\rho}} \end{bmatrix}^\rho - \frac{1}{(1-\nu)\gamma} = 0$$

The constraint implicitly defines the composite consumption good C_t as a function of the intermediate goods $C_{d,t}(i)$ and $C_{f,t}(i)$. ω is the share of imports in gdp and represents the index of openness. With $\omega < \frac{1}{2}$ there is home bias in preferences. I consider two values for $\omega = .1$ and $\omega = .2$ to represent low and high levels of globalization. Here I will not be concerned with trying to explain this increase in globalization but rather the focus will be on studying its effects. The remaining parameters ν, ρ, γ govern the elasticity. To better understand this aggregator first consider the special case of $\nu = 0$. In this scenario the aggregator collapses to the familiar CES case with the price elasticity of demand given by $\varepsilon = \frac{1}{1-\gamma}$ and the elasticity of substitution between home and foreign goods given by $\varepsilon_A = \frac{\rho}{\rho-\gamma}$ [5]. With $\nu \neq 0$ the elasticities are now functions of relative prices. Intuitively the consumer puts more weight on the price difference between goods the higher the value of ν is, Appendix A discusses this setup in more detail. The price elasticity of demand is now given by

$$\varepsilon_t(i) = \frac{1}{1-\gamma}\left[1 - \nu\left\{p_{d,t}(i)^{\frac{1}{1-\gamma}}\left((1-\omega) + \omega S_t^{\frac{\gamma}{\gamma-\rho}}\right)^{\frac{\rho}{\gamma}}\right\}\right]^{-1}$$

where $p_{d,t}(i) = \frac{P_{d,t}(i)}{P_{d,t}}$ and $S_t = \frac{P_{f,t}}{P_{d,t}}$(terms of trade). $P_{d,t}$ and $P_{f,t}$ are defined below.

Expenditure minimization yields the following demand curves for the domestic and imported intermediate goods.

$$\begin{aligned}
\frac{C_{d,t}(i)}{C_t} &= (1-\omega)\left[\frac{1}{1-\nu}\left(\frac{P_{d,t}(i)}{P_{d,t}}\right)^{\frac{1}{\gamma-1}}\left(1-\omega+\omega S_t^{\frac{\gamma}{\gamma-\rho}}\right)^{-\frac{\rho}{\gamma}} - \frac{\upsilon}{1-\nu}\right] \\
\frac{C_{f,t}(i)}{C_t} &= \omega\left[\frac{1}{1-\nu}\left(\frac{P_{f,t}(i)}{P_{f,t}}\right)^{\frac{1}{\gamma-1}}\left((1-\omega)S_t^{-\frac{\gamma}{\gamma-\rho}} + \omega\right)^{-\frac{\rho}{\gamma}} - \frac{\nu}{1-\nu}\right]
\end{aligned}$$

---

[5] In the CES case the aggregator is given by

$$C_t = \left[(1-\omega)^{\frac{\rho-\gamma}{\rho}} V_{d,t}^{\frac{\gamma}{\rho}} + \omega^{\frac{\rho-\gamma}{\rho}} V_{m,t}^{\frac{\gamma}{\rho}}\right]^{\frac{\rho}{\gamma}}$$

where

$$\begin{aligned}
V_{d,t} &= \left(\int_0^1 C_{d,t}(i)^{\gamma} di\right)^{\frac{1}{\gamma}} \\
V_{m,t} &= \left(\int_0^1 C_{f,t}(i)^{\gamma} di\right)^{\frac{1}{\gamma}}
\end{aligned}$$

where $S_t \equiv \frac{P_{f,t}}{P_{d,t}}$ is the terms of trade and $P_{d,t}$ and $P_{f,t}$ are indices of domestic and foreign prices given by

$$P_{d,t} = \left(\int_0^1 P_{d,t}(i)^{\frac{\gamma}{\gamma-1}} di \right)^{\frac{\gamma-1}{\gamma}} \ \ \& \ P_{f,t} = \left(\int_0^1 P_{f,t}(i)^{\frac{\gamma}{\gamma-1}} di \right)^{\frac{\gamma-1}{\gamma}}$$

The CPI, defined as the minimum cost of consuming on unit of the final composite consumption good, is then given by

$$\begin{aligned} P_t &= -\frac{\nu}{1-\nu} \left[(1-\omega) \int_0^1 P_{d,t}(i) di + \omega \int_0^1 P_{f,t}(i) di \right] \\ &+ \frac{1}{1-\nu} \left[(1-\omega) P_{d,t}^{\frac{\gamma}{\gamma-\rho}} + \omega P_{f,t}^{\frac{\gamma}{\gamma-\rho}} \right]^{\frac{\gamma-\rho}{\gamma}} \end{aligned}$$

Intermediate goods firms

There is a continuum of intermediate goods firms producing differentiated goods indexed by $i \in [0,1]$. They operate by hiring workers and face the following constant returns to scale technology

$$Y_t(i) = A_t N_t(i)$$

where A_t is the aggregate level of technology. Note that adding decreasing returns to $N_t(i)$ does not change the substantive results of the model.

Intermediate goods firms set price in a monopolistically competitive market. Price rigidity takes the form of Calvo pricing, in which $1-\theta$ fraction of firms are allowed to change prices in each period, independent of history. When reoptimizing they choose price $P_{d,t}^*$ to maximize expected future profit, taking into account the probability of not being able to alter their prices in the future. Profit maximization is characterized by

$$\max_{P_{d,t}^*} E_t \sum_{j=0}^{\infty} \theta^j Q_{t,t+j} [P_{d,t}^*(i) Y_{d,t+j}(i) - P_{t+j} MC_{t+j} Y_{d,t+j}(i)]$$

$$s.t. \ Y_{d,t+j}(i) = (1-\omega) \left[\frac{1}{1-\nu} \left(\frac{P_{d,t}^*(i)}{P_{d,t+j}} \right)^{\frac{1}{\gamma-1}} \left(1-\omega+\omega S_t^{\frac{\gamma}{\gamma-\rho}} \right)^{-\frac{\rho}{\gamma}} - \frac{\nu}{1-\nu} \right] Y_{t+j}$$

where MC_{t+j} is the real marginal cost. The optimization yields the following condition

$$E_t \sum_{j=0}^{\infty} \theta^j Q_{t,t+j} \left\{ \left(P_{d,t}(i) - \frac{\varepsilon_t(i)}{\varepsilon_t(i) - 1} MC_{t+j} \right) Y_{d,t+j}(i) \right\} = 0$$

The elasticity of substitution is given by

$$\varepsilon_t(i) = \frac{1}{1-\gamma} \left[1 - \nu \left\{ p_{d,t}(i)^{\frac{1}{1-\gamma}} \left((1-\omega) + \omega S_t^{\frac{\gamma}{\gamma-\rho}} \right)^{\frac{\rho}{\gamma}} \right\} \right]^{-1}$$

where $p_{d,t}(i) \equiv \frac{P_{d,t}(i)}{P_{d,t}}$. The elasticity is a function of the relative price of the domestic good i to the domestic price index and of the relative price of imports. The resulting markup under flexible prices is

$$\begin{aligned} \mu_t(i) &= \frac{\varepsilon_t(i)}{\varepsilon_t(i) - 1} \\ &= \left[\gamma + \nu(1-\gamma) p_{d,t}(i)^{\frac{1}{1-\gamma}} \left((1-\omega) + \omega S_t^{\frac{\gamma}{\gamma-\rho}} \right)^{\frac{\rho}{\gamma}} \right]^{-1} \end{aligned}$$

Consider a fall in S_t, which is an improvement in the terms of trade (foreign goods becoming cheaper relative to domestic goods). With the price of foreign goods decreasing relative to domestic goods, consumers will shift some consumption from the relatively expensive domestic goods to cheaper foreign goods. This basic mechanism is at work even if the elasticity is constant. But with $\nu \neq 0$ this price change increases the price elasticity of the consumers and thus they want to reduce their consumption of domestic goods even more. To combat this potential loss of market share domestic firms will reduce their markup. This result is conditional on the parameter values of the demand function being within a certain range, but as discussed in the calibration section empirically relevant values for the parameters do indeed fall in this range.

I will consider a steady state where all relative prices are equal to 1. In this steady state, even with $\nu \neq 0$ the elasticity and markup are constant as there are no price differences. Steady state price elasticity is $\varepsilon = \frac{1}{(1-\gamma)(1-\nu)}$ and steady state markup is given by $\mu = \frac{\varepsilon}{\varepsilon - 1}$.

The first order condition of the firm's optimal pricing problem is log linearized around a steady state where all relative prices are equal to 1. This gives the New Keynesian Phillips curve (NKPC) for $\pi_{d,t}$ which measures the inflation of the index of domestic prices (I will call it domestic inflation.)

$$\pi_{d,t} = \beta E_t \pi_{d,t+1} + \kappa \left[(1-\psi)\widehat{mc}_t + \psi \omega \frac{\varepsilon_A}{\varepsilon} s_t \right] \tag{2.1}$$

where

$$\begin{aligned}
\kappa &= \frac{(1-\beta\theta)(1-\theta)}{\theta} \text{ slope of NKPC in basic closed economy model} \\
\psi &= \frac{\nu\mu}{1+\nu\mu} \text{ where } \mu \text{ is steady-state markup} \\
\omega &= \text{share of imports in consumption} \\
\varepsilon_A &= \frac{\rho}{(\rho-\gamma)(1-\nu)} \text{elasticity of substitution between home and foreign goods} \\
\varepsilon &= \frac{1}{(1-\gamma)(1-\nu)} \text{price elasticity of demand in steady-state} \\
s_t &= \text{log terms of trade} \\
\widehat{mc}_t &= \text{ log deviation of marginal cost}
\end{aligned}$$

To understand this equation let's consider the special case of constant elasticity ($\nu = 0$). This implies $\psi = 0$ and the above equation reduces to $\pi_{d,t} = \beta E_t \pi_{d,t+1} + \kappa \widehat{mc}_t$ which is the standard NKPC, where inflation can increase due to a rise in expected inflation or a rise in marginal costs. In the non-constant case there are two main differences. First, the slope of the Phillips curve, i.e. the sensitivity of inflation to marginal costs, is affected. The slope of the Phillips curve is now $(1-\psi)\kappa$, which depends on the steady state value of the markup μ and the curvature of the demand function ν. Second, there is an extra additive term that involves the terms of trade and has an impact on domestic inflation. Intuitively the larger the deviation of the terms of trade from the steady state (i.e. a situation where domestic prices are quite different from foreign prices) the bigger impact it will have on domestic inflation. This effect operates through the variable markups channel discussed above and is bigger in a more open economy (higher ω).

Equilibrium

The intermediate goods market clears at home. Production of the domestic good is equal to home demand of the domestic good and foreign demand of the domestic good. Imposing equilibrium in the log linearized first order conditions of the consumer's utility maximization problem gives the IS curve, the relationship between the output gap, expected inflation and the natural real rate of interest.

$$\tilde{y}_t = E_t \tilde{y}_{t+1} - \frac{1}{\sigma_\alpha} \left[i_t - E_t \pi_{d,t+1} - r_t^n \right]$$

Here $\tilde{y}_t$ is the output gap defined as the difference between actual output y_t and the natural level of output y_t^n. As is common in these models the natural level of output is defined as the level of output that would prevail under flexible prices. In this two country model the natural level of output of the home country depends on the productivity of the home country but also the productivity of the foreign country. The real rate of interest is defined correspondingly.

Using the relation between marginal cost and output in the domestic NKPC equation (2.1) gives the following modified equation.

$$\pi_{d,t} = \beta E_t \pi_{d,t+1} + \kappa \left[(1-\psi)\kappa_o \tilde{y}_t + \psi\omega \frac{\varepsilon_A}{\varepsilon} s_t \right]$$

where $\kappa_o = \left[\sigma + \varphi + \tilde{\psi}^{-1} \left(\varphi\varepsilon_A + \omega - \phi\sigma \right) \right]$, $\tilde{\psi} = \frac{\sigma}{1+2\omega+2\sigma\phi}$ and $\phi = (2\omega(1-\omega)\varepsilon_A - \sigma^{-1}\omega(1-2\omega))$

This slope of the NKPC is now given by $\kappa(1-\psi)\kappa_o$ which represents the sensitivity of domestic inflation to domestic output gaps. This is of particular interest as there is an ongoing debate about the effect of globalization on this quantity. In this model, how increasing globalization affects this slope depends on the values of the rest of the parameters. This is discussed in detail in the Calibration and Results sections.

Overall CPI inflation in the home country depends on domestic inflation and the change in the terms of trade.

$$\pi_t = \pi_{d,t} + \omega \Delta s_t \tag{2.2}$$

Import prices can affect CPI inflation in two ways. First, this can happen directly through the effect of the terms of trade. The degree of dependence of CPI inflation on the terms of trade is governed by the openness parameter ω. Second, import prices can affect the desired markups of domestic firms and can thus have an impact on domestic inflation. The second effect disappears in the constant elasticity case as desired markups do not change. Keep in mind that these are direct effects and that there will be overall general equilibrium effects present as well. Finally I consider the monetary policy rule to close the model.

Monetary policy

Monetary policy is specified as a Taylor rule in both countries. Monetary authorities choose i_t (in home) and i_t^* (in foreign) by responding to CPI inflation and output gaps

$$\begin{aligned} i_t &= \tilde{\rho} + \phi_\pi \pi_t + \phi_y \tilde{y}_t + e_{m,t} \\ i_t^* &= \tilde{\rho}^* + \phi_\pi^* \pi_t^* + \phi_y^* \tilde{y}_t + e_{m,t}^* \end{aligned}$$

The shocks in both the equations follow AR(1) processes. Later I consider an alternative rule where domestic inflation is used in the Taylor rule.

2.3 Calibration

The discount factor is set to 0.99 implying an annualized steady state interest rate of 4%. The elasticity of labor supply is $\frac{1}{3}$ by setting the parameter in the utility function $\varphi = 3$. This is towards the higher end of estimates found in micro studies. But this is much lower than what is typically used in real business cycle literature. The risk aversion parameter σ is typically set somewhere in a range of 1 to 5, I use 2 which means the elasticity of intertemporal substitution is 0.5. The Calvo parameter is set to 0.75 implying that prices are changed on average once every 12 months. The parameters in the Taylor rule are set to $\phi_\pi = 1.5$ and $\phi_y = 0.5/4$. The parameters for the shock processes ρ_a and $\rho_{e,m}$ are set to match the first order autocorrelation of output and inflation following Zaniboni (2008).

Recall that the steady state relationship for the elasticity of substitution within home goods is $\varepsilon = \frac{1}{(1-\gamma)(1-\nu)}$ and the elasticity between home and foreign goods is $\varepsilon_A = \frac{\rho}{(\rho-\gamma)(1-\nu)}$. Thus there are 3 parameters of the demand function: γ, ρ and ν that need to be fixed. I set $\mu = 1.2$ which is a steady state markup of 20%, a standard number. This implies a steady state elasticity of substitution between home goods of $\varepsilon = 6$. The elasticity of substitution between home and foreign goods is set to $\varepsilon_A = 1.5$. These two calibrated values do not pin down the three parameters γ, ρ and ν. There is not much empirical work that estimates these demand function parameters in an open economy setting, especially ν. However there is one recent paper, Guerrieri et al. (2010) that has a similar setup to this model. They estimate a parameter $\psi = 0.73$. In my setting this means $\frac{\nu\mu}{1+\nu\mu} = 0.73$. Using this value I can pin down the value of ν and there is enough information to calibrate the demand function[6]. I will refer to this as the baseline calibration. The model is solved using the algorithm of Sims (2002).

2.4 Results

2.4.1 Slope of the New Keynesian Phillips Curve:

I start by considering the effect of increased openness on the slope of the Phillips curve. Recall the slope of the NKPC for domestic inflation is given by $\kappa(1-\psi)\kappa_o$. It is shown in Appendix B that the slope of the NKPC for CPI inflation is just the slope of domestic inflation scaled by the share of domestic goods in GDP ($(1-\omega)\kappa(1-\psi)\kappa_o$). Figure 2.2 plots these two slopes. Increasing openness makes both the Phillips curves flatter, i.e. it reduces the sensitivity of inflation to domestic output gaps. The slope of the CPI NKPC falls more but the effects for both are quantitatively modest. This corroborates the theoretical results of Zaniboni (2008) who uses a similar model but with a CES demand function. Note that the slope of the NKPC for domestic inflation would be unaffected by

[6]The calibrated values of μ and ε_A above are set to the same values used in Guerrieri et al. (2010) to ensure consistency.

globalization in the CES case.

This result holds for the chosen calibration but not for all parameter values. It can be shown that a sufficient condition for increased globalization to make the Phillips curve flatter is $\sigma\varepsilon_A > 1$. The main channels work through the relationship between output and marginal costs. When domestic output increases the terms of trade worsens and amplifies the effect of output on marginal cost. On the other hand because of international risk sharing domestic consumption rises less and thus the marginal rate of substitution affects wages to lower the impact of output on marginal costs. When $\sigma\varepsilon_A > 1$ the second effect dominates. While this condition is satisfied in the calibrated values here ($\sigma = 2$,$\varepsilon_A = 1.5$) there are certain empirical studies that find values for these two parameters that would not satisfy the above condition. For example many business cycle studies use log utility ($\sigma = 1$) and estimates for the trade elasticity are often found to be below one. This possibility combined with fact that the quantitative changes in the slope are small makes it hard to conclude that globalization has a large discernible effect on the slope. Nevertheless, globalization could affect inflation and monetary policy decisions through other channels. I explore these in the next section.

In an interesting paper Sbordone (2008) uses a similar non-constant elasticity demand function where the market share of domestic firms depends on the number of goods in the market. She finds that it is not clear whether globalization decreases the slope of the Phillips curve. Her analysis looks at the increase in competition (measured by higher number of traded goods) for a given level of openness across two different steady states: one with a low number of traded goods and one with many traded goods. Thus in the two steady states the elasticities are different. I use two different steady states where the elasticities are the same but levels of openness are different. Another difference is that her "slope" is the sensitivity of inflation to marginal costs and ignores the relationship between marginal costs and domestic output.

2.4.2 Monetary Policy Transmission

An integral part of conducting sound monetary policy involves understanding the effects of monetary policy decisions on the economy, known as the monetary policy transmission mechanism. As mentioned earlier, there is a concern that globalization has changed the monetary policy transmission mechanism. To contribute to the debate I analyze the response of the economy to monetary policy shocks. Figure 2.3 shows the response of domestic inflation, CPI inflation and output gap to a 25 basis point positive (i.e. contractionary) monetary policy shock in the home country. Two levels of openness, $\omega = .1$ and $\omega = .2$ are considered. The difference between the cases are small on impact and almost completely disappear after a few quarters. Thus openness does not seem to change the response of inflation and output to a monetary policy shock. This is in line with other studies (Woodford (2007) and Erceg et al. (2007). While the transmission mechanism is not affected by openness, the systematic component of monetary policy may interact with changes in globalization. In the next Section 4.4 shed some light on this issue by considering the volatilities of inflation and output gap under alternative monetary policy rules.

2.4.3 Technology Shock

I analyze the response of the home economy to technology shocks originating in both home and foreign countries. Figure 2.4 shows the impulse responses of domestic inflation, CPI inflation, output gap and the interest rate to a technology shock in a home country. Both CPI and domestic inflation fall and the output gap falls as well. Note that the technology shock does increase output but it increases the natural level of output even more and thus results in a fall in the output gap. The central bank responds by decreasing interest rates. Domestic inflation falls less in the more open economy. Since imported goods are more expensive relative to domestic goods, domestic firms will raise their markups. This moderates the fall of domestic inflation in a more open economy but the quantitative effect of this channel is small. Due to this smaller fall in domestic inflation and the fact that domestic goods make up a smaller share of consumption in the open economy, CPI inflation also falls less in the closed economy. Again the quantitative effects are modest. Thus these results suggest that globalization does not have a large effect on the transmission of domestic technology shocks.

Next I consider the impact of foreign technology shocks. Figure 2.5 shows the impulse responses of domestic inflation, CPI inflation, output gap and the interest rate to a technology shock originating in the foreign country. The most interesting difference shows up in the response of domestic inflation. As imported prices fall relative to domestic prices, domestic firms react by lowering their markup in order to avoid losing market share. This effect is bigger in the more open economy and domestic inflation falls a lot more. CPI inflation falls more in the open economy too; in part due to the effect on domestic inflation but also because imported goods make up a bigger share of consumption. In response, the central bank lowers the interest rate more aggressively in the open economy and keeps it lower for over a year.

2.4.4 Alternative Monetary Policy Rules and Volatility of Inflation and Output gap

Even if globalization does not affect how the economy reacts to monetary policy shocks, the systematic part of monetary policy could be affected by globalization. In the standard two country model Clarida et al. (2002) find that optimal monetary policy in an open economy is isomorphic to that in a closed economy. They derive a welfare-based loss function by taking a second order approximation to the representative agent's utility function following Rotemberg and Woodford (1998). The optimal policy is implemented with a Taylor-type rule that responds to domestic inflation. Engel (2009) extends the Clarida et al. (2002) framework and allows for local currency pricing.[7] In that framework he finds that the central bank can implement optimal policy with a Taylor-type rule that responds to CPI inflation. Here I analyze Taylor rules with both domestic inflation and CPI inflation and look at the consequences for the volatilities of inflation and output

[7] See Corsetti et al. (2010) for a detailed consideration of optimal monetary policy in open economies in various different settings.

gap. I calculate the volatilities of inflation and output gap under the two different Taylor rules; one that targets domestic inflation (DTR) and another that targets the CPI (CTR) to get a better understanding of the effects of globalization under the different monetary policy rules.[8]

Table 2.1 shows the unconditional standard deviations of domestic inflation, CPI inflation and the output gap. The first two columns show the standard deviations for the Taylor rule with CPI inflation (CTR), while the last two show the results for the Taylor rule with domestic inflation (DTR). A few observations stand out. First, with increasing openness domestic inflation becomes less volatile while CPI inflation becomes more volatile under both Taylor rules. For CPI inflation the intuition for this result can be gained by looking at equation (2.2). With higher values of ω, more weight is put on the terms of trade s_t which varies with both domestic and foreign shocks. For domestic inflation there are competing effects which can be seen in Figures 2.4 and 2.5. With a home technology shock the competitive effect acts to temper the change in domestic inflation while with a foreign technology shock the competitive effect acts to amplify it. The results suggest that the former effect dominates.

The second row shows the standard deviations under the scenario that the central bank reacts more strongly to inflation. Doubling the weight on inflation to 3 in the Taylor rule unambiguously reduces the volatilities of both measure of inflation and the output gap. This is similar to the result in Gali (2008) (Chapter 3) and is obtained because in these models the more hawkish the central bank gets, the closer it gets to optimal policy. However, here the same result is obtained by increasing the weight on output gap. The 3rd row in Table 2.1 shows the standard deviations with the weight on output gap doubled to 0.25. The standard deviations of inflation and output gap are lower compared to the benchmark Taylor rule parameters. In this open economy model the output gap is related to the terms of trade as shown in Appendix B. Additionally, note from equation 2.1 that the

[8] For the model with domestic inflation in the Taylor rule the impulse responses (not shown here) are very similar to those under the CPI inflation Taylor rule. Even the differences between $\omega = .1$ and $\omega = .2$ under the domestic inflation Taylor rule are similar to the CPI Inflation Taylor rule case.

terms of trade enters in the Phillips curve. Thus by reacting more strongly to the output gap the central bank can have a bigger impact on inflation and is a substitute of sorts to reacting more strongly to inflation. Finally, the last row shows that reacting more strongly to both inflation and output gap reduces the volatilities even more.

2.5 Conclusion

This paper begins with the observation that previous work that discusses the issue of globalization fails to account for the direct effect of foreign competition on domestic firm's markups. To contribute to this debate I develop a two country general equilibrium model with monopolistic competition, nominal rigidities and an explicit channel through which foreign competition can impact the setting of domestic prices and thus inflation. This channel operates through a non-constant elasticity which is a function of firm's prices relative to its competitors.

I find that globalization makes Phillips curve flatter but only under certain restrictions on the calibrated parameter values and additionally the quantitative effect is modest. The response of the economy to monetary policy shocks is not affected in a quantitatively important way by increased openness. Technology shocks have a bigger and longer lasting impact on inflation and output. The effect of increased openness on the reaction of inflation to foreign technology shocks may be of particular interest. From a positive perspective, the important question is whether globalization has contributed to the fall in inflation over the past two decades. Kamin et al. (2006) use a non-structural approach and find that Chinese exports have contributed very little to consumer price inflation in the US. Other authors have found similarly small effects. On the other hand, Guerrieri et al. (2010) explicitly model the strategic channel of foreign competition in a structural New-Keynesian open economy framework. They estimate a New-Keynesian Phillips curve and find that imports have helped lower domestic goods inflation by about 1/3 percentage point from 2000-2006. They also reject the constant elasticity of substitution assumption providing empirical support for the non-constant elasticity assumption. In this paper I find that in response to foreign technology shocks, domestic and CPI inflation fall more and stay lower for more than 10 quarters the more open the economy is. If foreign technology shocks have been an important factor driving domestic inflation then this provides a plausible theoretical explanation for their empirical findings.

Finally, I find that increased openness increases the volatility of CPI inflation but reduces the volatility of domestic inflation. This is true whether the central bank targets domestic inflation or CPI inflation in the Taylor rule. In contrast to standard closed economy New Keynesian models, the central bank can reduce volatilities of inflation and output gap by reacting more strongly to either inflation, output gap or both. The natural extension of this line of research is to formulate optimal monetary policy within this framework. This will make clear how much increased openness should change optimal policy and is a promising area for future research.

Appendix A: The NCES Aggregator

Consumers minimize expenditure by choosing $C_{d,t}(i)$ and $C_{f,t}(i)$ taking as given the prices $P_{d,t}(i)$ (the price of the individual domestic intermediate good i) and $P_{f,t}(i)$ (the price of the individual intermediate imported good i).

$$\min \int_0^1 P_{d,t}(i)C_{d,t}(i)di + \int_0^1 P_{f,t}(i)C_{f,t}(i)di$$

$$s.t. \left[\begin{array}{l} \left(\int_0^1 \frac{(1-\omega)^\rho}{(1-\nu)\gamma} \left[\frac{1-\nu}{1-\omega} \frac{C_{d,t}(i)}{C_t} + \nu \right]^\gamma di \right)^{\frac{1}{\rho}} \\ + \left(\int_0^1 \frac{\omega^\rho}{(1-\nu)\gamma} \left[\frac{1-\nu}{\omega} \frac{C_{f,t}(i)}{C_t} + \nu \right]^\gamma di \right)^{\frac{1}{\rho}} \end{array} \right]^\rho - \frac{1}{(1-\nu)\gamma} = 0$$

The first thing to point out about this aggregator is that it implicitly defines the composite good C_t in terms of $C_{d,t}(i)$ and $C_{f,t}(i)$; that is there is no analytical form for it. Nonetheless this aggregator retains desirable properties of demand functions, most notably homotheticity. The non-constant elasticity arises in the case that $\nu \neq 0$. The elasticity is a function of relative prices. Since I consider a steady state where all prices are equal, at the steady state the value of ν is irrelevant as $C_{d,t}$ and $C_{f,t}$ are tied down by ω. Outside of the steady state ω and ν determine the optimal allocation between $C_{d,t}$ and $C_{f,t}$. When $\frac{C_{d,t}}{C_t} > \omega$ (as would occur when the price of the imported goods was more than the domestic goods), the optimal allocation is more skewed towards the domestic good the higher ν is. Intuitively a lager value for ν indicates that the consumer puts more weight on the difference between domestic and foreign prices in choosing her allocation of $C_{d,t}$ and $C_{f,t}$. Next consider the relationship between firm's markup and υ.. Figure 2.6 demonstrates how the markup changes with the firm's price relative to a domestic price index while Figure 2.7 shows how the markup also depends on the ratio of the foreign price index to domestic price index. In both figures, it is clear that the markup in the CES case ($\nu = 0$) is constant at 20% and is unaffected by competitive forces. As ν rises, the markup becomes more responsive to changes in relative price with respect to both its domestic and foreign competitors. That is, the higher a firm's price is relative to either domestic competitors or foreign competitors, the lower the markup will be.

Appendix B: The Full Model

Consumers

There is a representative consumer that chooses a composite consumption good C_t and labor supply N_t to maximize expected lifetime utility

$$E_0 \sum_{t=0}^{\infty} \beta^t U(C_t, N_t)$$

subject to a sequence of (nominal) budget constraints of the type

$$P_t C_t + E_t Q_{t,t+1} D_{t+1} = W_t N_t + D_t - T_t + \Pi_t$$

where P_t is the price of one unit of the composite consumption good C_t, N_t is labor supply, D_{t+1} is the payoff from a portfolio purchased in t, $Q_{t,t+1}$ is the stochastic discount factor, T_t are lump-sum taxes and Π_t are profits. The utility function is of CRRA form and separable in consumption and labor.

$$U(C,N) = \frac{C^{1-\sigma}}{1-\sigma} - \frac{N^{1+\varphi}}{1+\varphi}$$

The first order-conditions are derived by substituting for C_t in the utility function and differentiating with respect to N_t and D_{t+1} are

$$\frac{W_t}{P_t} = C_t^{\sigma} N_t^{\varphi}$$

$$Q_{t,t+1} = \beta E_t \left[\left(\frac{C_{t+1}}{C_t} \right)^{-\sigma} \left(\frac{P_t}{P_{t+1}} \right) \right]$$

The first equation shows the trade-off between consumption and labor allocation and the second equation is a standard consumption Euler equation. Log-linearizing the first order conditions yields

$$\begin{aligned} w_t - p_t &= \sigma c_t + \varphi n_t \\ c_t &= E_t c_{t+1} - \frac{1}{\sigma}(i_t - E_t \pi_{t+1} - \rho) \end{aligned}$$

Consumers aggregate domestic goods $C_{d,t}(i)$ and the imported goods $C_{f,t}(i)$ into the composite consumption good C_t. They minimize cost by choosing $C_{d,t}(i)$ and $C_{f,t}(i)$ taking as given the prices $P_{d,t}(i)$ (the price of the individual domestic intermediate good i) and $P_{f,t}(i)$ (the price of the individual intermediate imported good i).

$$\min \int_0^1 P_{d,t}(i) C_{d,t}(i) di + \int_0^1 P_{f,t}(i) C_{f,t}(i) di \text{ s.t.}$$

$$\left[\begin{array}{l} \left(\int_0^1 \frac{(1-\omega)^{\rho}}{(1-\nu)\gamma} \left[\frac{1-\nu}{1-\omega} \frac{C_{d,t}(i)}{C_t} + \nu \right]^{\gamma} di \right)^{\frac{1}{\rho}} \\ + \left(\int_0^1 \frac{\omega^{\rho}}{(1-\nu)\gamma} \left[\frac{1-\nu}{\omega} \frac{C_{f,t}(i)}{C_t} + \nu \right]^{\gamma} di \right)^{\frac{1}{\rho}} \end{array} \right]^{\rho} - \frac{1}{(1-\nu)\gamma} = 0$$

Let $\left(\int_0^1 \frac{(1-\omega)^\rho}{(1-\nu)\gamma}\left[\frac{1-\nu}{1-\omega}\frac{C_{d,t}(i)}{C_t}+\nu\right]^\gamma\right) = V_{dt}$ & $\left(\frac{\omega^\rho}{(1-\nu)\gamma}\left[\frac{1-\nu}{\omega}\frac{C_{f,t}(i)}{C_t}+\nu\right]^\gamma\right) = V_{mt}$. Let Λ_t be the Lagrange multiplier. The FOCs are

$$\begin{aligned}
P_{d,t}(i) &= \frac{\Lambda_t}{C_t}\left[V_{dt}^{\frac{1}{\rho}}+V_{mt}^{\frac{1}{\rho}}\right]^{\rho-1} V_{dt}^{\frac{1-\rho}{\rho}}\left[\frac{1-\nu}{1-\omega}\frac{C_{d,t}(i)}{C_t}+\nu\right]^{\gamma-1}(1-\omega)^{\rho-1} \\
P_{f,t} &= \frac{\Lambda_t}{C_t}\left[V_{dt}^{\frac{1}{\rho}}+V_{mt}^{\frac{1}{\rho}}\right]^{\rho-1} V_{mt}^{\frac{1-\rho}{\rho}}\left[\frac{1-\nu}{\omega}\frac{C_{f,t}(i)}{C_t}+\nu\right]^{\gamma-1}\omega^{\rho-1}
\end{aligned}$$

Rewriting the FOCs and defining $\tilde{P}_t = \frac{\Lambda_t}{C_t}$

$$\begin{aligned}
\left[\frac{1-\nu}{1-\omega}\frac{C_{d,t}(i)}{C_t}+\nu\right]^\gamma &= \left(\frac{P_{d,t}(i)}{\tilde{P}_t}\right)^{\frac{\gamma}{\gamma-1}}\left[V_{dt}^{\frac{1}{\rho}}+V_{mt}^{\frac{1}{\rho}}\right]^{\frac{\gamma(1-\rho)}{\gamma-1}} V_{dt}^{\frac{\gamma(\rho-1)}{\rho(\gamma-1)}}(1-\omega)^{\frac{\gamma(1-\rho)}{\gamma-1}} \\
\left[\frac{1-\nu}{\omega}\frac{C_{f,t}(i)}{C_t}+\nu\right]^\gamma &= \left(\frac{P_{f,t}}{\tilde{P}_t}\right)^{\frac{\gamma}{\gamma-1}}\left[V_{dt}^{\frac{1}{\rho}}+V_{mt}^{\frac{1}{\rho}}\right]^{\frac{\gamma(1-\rho)}{\gamma-1}} V_{mt}^{\frac{\gamma(\rho-1)}{\rho(\gamma-1)}}\omega^{\frac{\gamma(1-\rho)}{\gamma-1}}
\end{aligned}$$

Plug into definitions of V_{mt} & V_{dt}

$$\begin{aligned}
V_{dt} &= \int_0^1 \frac{(1-\omega)^{\frac{\gamma-\rho}{\gamma-1}}}{(1-\nu)\gamma}\left(\frac{P_{d,t}(i)}{\tilde{P}_t}\right)^{\frac{\gamma}{\gamma-1}}\left[V_{dt}^{\frac{1}{\rho}}+V_{mt}^{\frac{1}{\rho}}\right]^{\frac{\gamma(\rho-1)}{\gamma-1}} V_{dt}^{\frac{\gamma(1-\rho)}{\rho(\gamma-1)}} \\
V_{dt}^{\frac{\gamma-\rho}{\rho(\gamma-1)}} &= \int_0^1 \frac{(1-\omega)^{\frac{\gamma-\rho}{\gamma-1}}}{(1-\nu)\gamma}\left(\frac{P_{d,t}(i)}{\tilde{P}_t}\right)^{\frac{\gamma}{\gamma-1}}\left[V_{dt}^{\frac{1}{\rho}}+V_{mt}^{\frac{1}{\rho}}\right]^{\frac{\gamma(\rho-1)}{\gamma-1}} \\
V_{dt}^{\frac{1}{\rho}} &= \left[V_{dt}^{\frac{1}{\rho}}+V_{mt}^{\frac{1}{\rho}}\right]^{\frac{\gamma(\rho-1)}{\gamma-\rho}}\left(\frac{1}{(1-\nu)\gamma}\right)^{\frac{\gamma-1}{\gamma-\rho}}(1-\omega)\left[\int_0^1\left(\frac{P_{d,t}(i)}{\tilde{P}_t}\right)^{\frac{\gamma}{\gamma-1}}\right]^{\frac{\gamma-1}{\gamma-\rho}}
\end{aligned}$$

Now define $P_{d,t} = \left(\int_0^1 P_{d,t}(i)^{\frac{\gamma}{\gamma-1}}\right)^{\frac{\gamma-1}{\gamma}}$

$$V_{dt}^{\frac{1}{\rho}} = \left[V_{dt}^{\frac{1}{\rho}}+V_{mt}^{\frac{1}{\rho}}\right]^{\frac{\gamma(\rho-1)}{\gamma-\rho}}\left(\frac{1}{(1-\nu)\gamma}\right)^{\frac{\gamma-1}{\gamma-\rho}}(1-\omega)\left(\frac{P_{d,t}}{\tilde{P}_t}\right)^{\frac{\gamma}{\gamma-\rho}}$$

$$V_{mt} = \frac{\omega^{\frac{\gamma-\rho}{\gamma-1}}}{(1-\nu)\gamma}\left(\frac{P_{f,t}}{\tilde{P}_t}\right)^{\frac{\gamma}{\gamma-1}}\left[V_{dt}^{\frac{1}{\rho}} + V_{mt}^{\frac{1}{\rho}}\right]^{\frac{\gamma(1-\rho)}{\gamma-1}} V_{mt}^{\frac{\gamma(\rho-1)}{\rho(\gamma-1)}}$$

$$V_{mt}^{\frac{\gamma-\rho}{\rho(\gamma-1)}} = \frac{\omega^{\frac{\gamma-\rho}{\gamma-1}}}{(1-\nu)\gamma}\left(\frac{P_{f,t}}{\tilde{P}_t}\right)^{\frac{\gamma}{\gamma-1}}\left[V_{dt}^{\frac{1}{\rho}} + V_{mt}^{\frac{1}{\rho}}\right]^{\frac{\gamma(1-\rho)}{\gamma-1}}$$

$$V_{mt}^{\frac{1}{\rho}} = \left[V_{dt}^{\frac{1}{\rho}} + V_{mt}^{\frac{1}{\rho}}\right]^{\frac{\gamma(\rho-1)}{\gamma-\rho}}\left(\frac{1}{(1-\nu)\gamma}\right)^{\frac{\gamma-1}{\gamma-\rho}} \omega \left[\left(\frac{P_{f,t}}{\tilde{P}_t}\right)^{\frac{\gamma}{\gamma-1}}\right]^{\frac{\gamma-1}{\gamma-\rho}}$$

$$V_{mt}^{\frac{1}{\rho}} = \left[V_{dt}^{\frac{1}{\rho}} + V_{mt}^{\frac{1}{\rho}}\right]^{\frac{\gamma(\rho-1)}{\gamma-\rho}}\left(\frac{1}{(1-\nu)\gamma}\right)^{\frac{\gamma-1}{\gamma-\rho}} \omega \left(\frac{P_{f,t}}{\tilde{P}_t}\right)^{\frac{\gamma}{\gamma-\rho}}$$

$$\left(\frac{V_{dt}}{V_{mt}}\right)^{\frac{1}{\rho}} = \frac{1-\omega}{\omega}\left(\frac{P_{d,t}}{P_{f,t}}\right)^{\frac{\gamma}{\gamma-\rho}}$$

Now from the constraint we get

$$\left[\left(\frac{V_{dt}}{V_{mt}}\right)^{\frac{1}{\rho}} + 1\right]^{\rho} V_{mt} = \frac{1}{(1-\nu)\gamma}$$

Note V_{mt} can be rewritten as

$$V_{mt} = \frac{\omega^{\frac{\gamma-\rho}{\gamma-1}}}{(1-\nu)\gamma}\left(\frac{P_{f,t}}{\tilde{P}_t}\right)^{\frac{\gamma}{\gamma-1}}\left[\left(\frac{V_{dt}}{V_{mt}}\right)^{\frac{1}{\rho}} + 1\right]^{\frac{\gamma(1-\rho)}{\gamma-1}}$$

$$V_{mt} = \frac{\omega^{\frac{\gamma-\rho}{\gamma-1}}}{(1-\nu)\gamma}\left(\frac{P_{f,t}}{\tilde{P}_t}\right)^{\frac{\gamma}{\gamma-1}}\left[\frac{1-\omega}{\omega}\left(\frac{P_{d,t}}{P_{f,t}}\right)^{\frac{\gamma}{\gamma-\rho}} + 1\right]^{\frac{\gamma(1-\rho)}{\gamma-1}}$$

Now derive the demand for domestic good i. From the FOC

$$\left[\frac{1-\nu}{1-\omega}\frac{C_{d,t}(i)}{C_t} + \nu\right] = \left(\frac{P_{d,t}(i)}{\tilde{P}_t}\right)^{\frac{1}{\gamma-1}}\left[1 + \left(\frac{V_{mt}}{V_{dt}}\right)^{\frac{1}{\rho}}\right]^{\frac{(1-\rho)}{\gamma-1}}(1-\omega)^{\frac{(1-\rho)}{\gamma-1}}$$

$$\left[\frac{1-\nu}{\omega}\frac{C_{f,t}(i)}{C_t} + \nu\right] = \left(\frac{P_{f,t}}{\tilde{P}_t}\right)^{\frac{1}{\gamma-1}}\left[\left(\frac{V_{dt}}{V_{mt}}\right)^{\frac{1}{\rho}} + 1\right]^{\frac{(1-\rho)}{\gamma-1}}\omega^{\frac{(1-\rho)}{\gamma-1}}$$

Note we have

$$\begin{aligned}
\left(\frac{V_{dt}}{V_{mt}}\right)^{\frac{1}{\rho}} &= \frac{1-\omega}{\omega}\left(\frac{P_{d,t}}{P_{f,t}}\right)^{\frac{\gamma}{\gamma-\rho}} \\
\left(\frac{V_{mt}}{V_{dt}}\right)^{\frac{1}{\rho}} &= \frac{\omega}{1-\omega}\left(\frac{P_{d,t}}{P_{f,t}}\right)^{\frac{\gamma}{\rho-\gamma}}
\end{aligned}$$

With some algebra we can show that

$$\begin{aligned}
1+\left(\frac{V_{mt}}{V_{dt}}\right)^{\frac{1}{\rho}} &= \frac{1}{1-\omega}\left(\frac{P_{d,t}}{\tilde{P}_t}\right)^{\frac{\gamma}{\rho-\gamma}} \\
1+\left(\frac{V_{dt}}{V_{mt}}\right)^{\frac{1}{\rho}} &= \frac{1}{\omega}\left(\frac{P_{f,t}}{\tilde{P}_t}\right)^{\frac{\gamma}{\rho-\gamma}}
\end{aligned}$$

Plugging into the above equations

$$\begin{aligned}
\left[\frac{1-\nu}{1-\omega}\frac{C_{d,t}(i)}{C_t}+\nu\right] &= \left(\frac{P_{d,t}(i)}{\tilde{P}_t}\right)^{\frac{1}{\gamma-1}}\left[\frac{1}{1-\omega}\left(\frac{P_{d,t}}{\tilde{P}_t}\right)^{\frac{\gamma}{\rho-\gamma}}\right]^{\frac{(1-\rho)}{\gamma-1}}(1-\omega)^{\frac{(1-\rho)}{\gamma-1}} \\
\left[\frac{1-\nu}{1-\omega}\frac{C_{d,t}(i)}{C_t}+\nu\right] &= \left(\frac{P_{d,t}(i)}{\tilde{P}_t}\right)^{\frac{1}{\gamma-1}}\left[\left(\frac{P_{d,t}}{\tilde{P}_t}\right)^{\frac{\gamma}{\rho-\gamma}}\right]^{\frac{(1-\rho)}{\gamma-1}} \\
\frac{C_{d,t}(i)}{C_t} &= \left\{\left(\frac{P_{d,t}(i)}{\tilde{P}_t}\right)^{\frac{1}{\gamma-1}}\left[\left(\frac{P_{d,t}}{\tilde{P}_t}\right)^{\frac{\gamma}{\rho-\gamma}}\right]^{\frac{(1-\rho)}{\gamma-1}}-\nu\right\}\frac{1-\omega}{1-\nu} \\
\frac{C_{d,t}(i)}{C_t} &= (1-\omega)\left[\frac{1}{1-\nu}\left(\frac{P_{d,t}(i)}{\tilde{P}_t}\right)^{\frac{1}{\gamma-1}}\left(\frac{P_{d,t}}{\tilde{P}_t}\right)^{\frac{\gamma(1-\rho)}{(\rho-\gamma)(\gamma-1)}}-\frac{\nu}{1-\nu}\right] \\
&= (1-\omega)\left[\frac{1}{1-\nu}P_{d,t}(i)^{\frac{1}{\gamma-1}}\tilde{P}_t^{\frac{\rho}{\rho-\gamma}}P_{d,t}^{\frac{\gamma(1-\rho)}{(\rho-\gamma)(\gamma-1)}}-\frac{\nu}{1-\nu}\right] \\
&= (1-\omega)\left[\frac{1}{1-\nu}P_{d,t}(i)^{\frac{1}{\gamma-1}}\tilde{P}_t^{\frac{\rho}{\rho-\gamma}}P_{d,t}^{\frac{\rho}{\gamma-\rho}}P_{d,t}^{\frac{1}{1-\gamma}}-\frac{\nu}{1-\nu}\right] \\
\frac{C_{d,t}(i)}{C_t} &= (1-\omega)\left[\frac{1}{1-\nu}\left(\frac{P_{d,t}(i)}{P_{d,t}}\right)^{\frac{1}{\gamma-1}}\left(\frac{P_{d,t}}{\tilde{P}_t}\right)^{\frac{\rho}{\gamma-\rho}}-\frac{v}{1-\nu}\right]
\end{aligned}$$

$$\begin{aligned}
\left[\frac{1-\nu}{\omega}\frac{C_{f,t}(i)}{C_t}+\nu\right] &= \left(\frac{P_{f,t}}{\tilde{P}_t}\right)^{\frac{1}{\gamma-1}}\left[\left(\frac{V_{dt}}{V_{mt}}\right)^{\frac{1}{\rho}}+1\right]^{\frac{(1-\rho)}{\gamma-1}}\omega^{\frac{(1-\rho)}{\gamma-1}} \\
&= \left(\frac{P_{f,t}}{\tilde{P}_t}\right)^{\frac{1}{\gamma-1}}\left[\frac{1}{\omega}\left(\frac{P_{f,t}}{\tilde{P}_t}\right)^{\frac{\gamma}{\rho-\gamma}}\right]^{\frac{(1-\rho)}{\gamma-1}}\omega^{\frac{(1-\rho)}{\gamma-1}} \\
\left[\frac{1-\nu}{\omega}\frac{C_{f,t}(i)}{C_t}+\nu\right] &= \left(\frac{P_{f,t}(i)}{\tilde{P}_t}\right)^{\frac{1}{\gamma-1}}\left(\frac{P_{f,t}}{\tilde{P}_t}\right)^{\frac{\gamma}{\rho-\gamma}} \\
\frac{C_{f,t}(i)}{C_t} &= \omega\left[\frac{1}{1-\nu}\left(\frac{P_{f,t}(i)}{P_{f,t}}\right)^{\frac{1}{\gamma-1}}\left(\frac{P_{f,t}}{\tilde{P}_t}\right)^{\frac{\rho}{\gamma-\rho}}-\frac{\nu}{1-\nu}\right]
\end{aligned}$$

CPI

Starting with $P_tC_t = \int_0^1 P_{d,t}(i)C_{d,t}(i)di + P_{f,t}(i)C_{f,t}(i)$, using definition of $P_{d,t}$ and with a little algebra we can derive the equation for the CPI

$$\begin{aligned}
P_t &= -\frac{\nu}{1-\nu}\left[(1-\omega)\int_0^1 P_{d,t}(i)di+\omega\int_0^1 P_{f,t}(i)di\right] \\
&+ \frac{1}{1-\nu}\left[(1-\omega)P_{d,t}^{\frac{\gamma}{\gamma-\rho}}+\omega P_{f,t}^{\frac{\gamma}{\gamma-\rho}}\right]^{\frac{\gamma-\rho}{\gamma}}
\end{aligned}$$

International risk sharing and terms of trade

Foreign has an Euler equation similar to home given by,

$$Q_{t,t+1}=\beta E_t\left[\left(\frac{C^*_{t+1}}{C^*_t}\right)^{-\sigma}\left(\frac{P^*_t}{P^*_{t+1}}\right)\left(\frac{\xi_t}{\xi_{t+1}}\right)\right]$$

where ξ_t is the nominal exchange rate (the value of home currency in terms of foreign currency). Define the real exchange rate as $Q_t \equiv \frac{\xi_t P^*_t}{P_t}$. Combining this with the Euler equation at home gives the following risk sharing condition.

$$C_t = C^*_t Q_t^{\frac{1}{\sigma}} \quad \text{or} \quad c_t = c^*_t + \frac{1}{\sigma}q_t \text{ in logs}$$

Note that the above equation results from a normalization of initial conditions. Defining the terms of trade S_t (home) and S^*_t (foreign) as $S_t \equiv \frac{P_{f,t}}{P_{d,t}}$ and $S^*_t \equiv \frac{P^*_{d,t}}{P^*_{f,t}}$

and log-linearizing the CPI in the two countries gives

$$p_t = p_{d,t} + \omega s_t \;\;\&\;\; p^*_t = p^*_{f,t} + \omega s^*_t$$

Since there are no barriers to trade, the law of one price holds for each intermediate good in both countries

$$P_{d,t}(i) = \xi_t P^*_{d,t}(i) \;\;\&\;\; P_{f,t}(i) = \xi_t P^*_{f,t}(i)$$

Substituting these into the definition of the domestic price indices at home and foreign gives.

$$P_{d,t} = \xi_t P^*_{d,t} \;\;\&\;\; P_{f,t} = \xi_t P^*_{f,t}$$

Taking logs and denoting e_t as the log of the nominal exchange rate.

$$p_{d,t} = e_t + p^*_{d,t} \;\;\&\;\; p_{f,t} = e_t + p^*_{f,t}$$

This means that the terms of trade in home and foreign are related by

$$\begin{aligned} s_t &= p_{f,t} - p_{d,t} \\ &= e_t + p^*_{f,t} - e_t - p^*_{d,t} \\ &= -(p^*_{d,t} - p^*_{f,t}) \\ &= -s^*_t \end{aligned}$$

Substituting the CPI equations in the real exchange rate equation gives

$$\begin{aligned} q_t &= p^*_t + e_t - p_t \\ &= p^*_{f,t} + \omega s^*_t + e_t - p_{d,t} - \omega s_t \\ q_t &= (1 - 2\omega) s_t \end{aligned}$$

The terms of trade is thus related to the real exchange rate in a simple intuitive manner. For the case that is empirically relevant for the United State $\omega = .2$ an improvement in the terms of trade (fall in s_t) leads to an appreciation of the real exchange rate (i.e. rise in q_t). Substituting this into the risk sharing equation gives a relation between home and foreign consumption

$$c_t = c_t^* + \frac{1-2\omega}{\sigma} s_t$$

Terms of Trade and Output

Note home (and foreign) output can be written as a function of consumption

$$y_t = c_t + \phi s_t \;\; \& \;\; y_t^* = c_t^* + \phi s_t^*$$

Consumption in the two countries are related to the terms of trade in the following way

$$c_t = c_t^* + \frac{1-2\omega}{\sigma} s_t$$

Using the above the two equations

$$s_t = \tilde{\psi}(y_t - y_t^*)$$

where $\tilde{\psi} \equiv \frac{\sigma}{1-2\omega+2\sigma\phi}$

Marginal Cost and Output Gap

In log-linear form

$$\begin{aligned}
mc_t &= w_t - p_{d.t} - a_t \\
&= w_t - p_t + \omega s_t - a_t \qquad \text{using cpi equation} \\
&= \varphi n_t + \sigma c_t + \omega s_t - a_t \quad \text{using consumers foc} \\
&= \varphi(y_t - a_t + \varepsilon_A s_t) + \sigma\left(y_t - \phi s_t\right) + \omega s_t - a_t - \varphi \ln(1-\omega) \quad \text{using A.} \\
&= y_t(\sigma + \varphi) + s_t(\varphi\varepsilon_A + \omega - \phi\sigma) - a_t(1+\varphi) - \varphi \ln(1-\omega) \\
&= y_t(\sigma + \varphi) + \tilde{\psi}\left[y_t - y_t^*\right](\varphi\varepsilon_A + \omega - \phi\sigma) - a_t(1+\varphi) - \varphi \ln(1-\omega)
\end{aligned}$$

The natural level of output is defined as the equilibrium level of output with flexible prices. In the flexible price equilibrium marginal cost is $mc = -\mu$. Thus natural rate of output is defined as

$$y_t^n = -\mu + y_t^* \tilde{\psi}(\varphi \varepsilon_A + \omega - \phi\sigma) - -a_t(1+\varphi) - \varphi \ln(1-\omega)$$

Note that the natural rate of output for the home country depends on the output in the foreign country. Then the log deviation of marginal cost can be expressed as a proportional to the output gap $\tilde{y}_t \equiv y_t - y_t^n$

$$\widehat{mc}_t = \kappa_o \tilde{y}_t$$

where $\kappa_o \equiv \left[\sigma + \varphi + \tilde{\psi}^{-1}(\varphi \varepsilon_A + \omega - \phi\sigma)\right]$

Equilibrium

The intermediate goods market clears at home. Production of the domestic good is equal to home demand of the domestic good and foreign demand of the domestic good.

$$Y_{d,t}(i) = C_{d,t}(i) + C_{d,t}^*(i)$$

Substituting the optimal demands from home $C_{d,t}(i)$ and foreign $C_{d,t}^*(i)$

$$\begin{aligned} Y_{d,t}(i) &= (1-\omega)\left[\frac{1}{1-\nu}\left(\frac{P_{d,t}(i)}{P_{d,t}}\right)^{\frac{1}{\gamma-1}}\left(1-\omega+\omega S_t^{\frac{\gamma}{\gamma-\rho}}\right)^{-\frac{\rho}{\gamma}} - \frac{\upsilon}{1-\nu}\right] C_t \\ &+\omega\left[\frac{1}{1-\nu}\left(\frac{P_{d,t}^*(i)}{P_{d,t}^*}\right)^{\frac{1}{\gamma-1}}\left((1-\omega)\, S_t^{\frac{\gamma}{\rho-\gamma}}+\omega\right)^{-\frac{\rho}{\gamma}} - \frac{\upsilon}{1-\nu}\right] C_t^* \end{aligned}$$

Log-linearizing around a steady state where relative prices are 1

$$y_{d,t}(i) = c_t + \phi s_t - \varepsilon(1-\omega)p_{d,t}(i) - \varepsilon\omega p_{d,t}^*(i)$$

where $\phi \equiv [2\omega(1-\omega)\varepsilon_A - \sigma^{-1}\omega(1-2\omega)]$, $\varepsilon \equiv \frac{1}{(1-\gamma)(1-v)}$ is the steady-state elasticity of substitution between domestic intermediate goods and $\varepsilon_A \equiv \frac{\rho}{(\rho-\gamma)(1-\nu)}$ is the steady-state elasticity of substitution between home and foreign goods. Aggregate output is defined implicitly by the following equation

$$\int_0^1 \frac{1}{(1-\nu)\gamma}\left[\frac{1-\nu}{1-\omega}\frac{Y_{d,t}(i)}{Y_t}+\nu\right]^\gamma di = \frac{1}{(1-\nu)\gamma}\left[\frac{1-\nu}{1-\omega}(1+v)\right]^\gamma$$

In log-linear form

$$y_t = \int_0^1 y_{d,t}(i)di$$

Substituting the equilibrium equation for $y_{d,t}(i)$ in the above equation gives

$$y_t = c_t + \phi s_t$$

Using a similar equation for foreign and the risk-sharing condition

$$\begin{aligned} y_t &= c_t^* + \frac{1-2\omega}{\sigma}s_t + \phi s_t \\ &= y_t^* - \phi s_t^* + \frac{1-2\omega}{\sigma}s_t + \phi s_t \\ y_t &= y_t^* + \tilde{\psi}^{-1}s_t \end{aligned}$$

where $\tilde{\psi} \equiv (2\phi + \frac{1-2\omega}{\sigma})^{-1}$. The above two equations can be combined with the consumption Euler equation $c_t = E_t c_{t+1} - \frac{1}{\sigma}(i_t - E_t\pi_{t+1} - \rho)$ to yield the dynamic IS curve

$$\tilde{y}_t = E_t\tilde{y}_{t+1} - \frac{1}{\sigma_\alpha}\left[i_t - E_t\pi_{d,t+1} - r_t^n\right]$$

where $r_t^n \equiv \tilde{\rho} + y_t^n + y_{t+1}^n + \frac{\sigma\phi-\omega}{\sigma\tilde{\psi}^{-1}}E_t\Delta y_{t+1}^*$ is the natural real rate of interest and $\sigma_\alpha \equiv \sigma\left(1 - \frac{\phi\sigma-\omega}{\sigma\tilde{\psi}}\right)$ The log deviation of marginal cost can be written in terms of output gap $\tilde{y}_t = y_t - y_t^n$

$$\widehat{mc}_t = \kappa_o\tilde{y}_t$$

where $\kappa_o \equiv \left[\sigma + \varphi + \tilde{\psi}(\varphi\varepsilon_A + \omega - \phi\sigma)\right]$, $\tilde{\psi} \equiv \frac{1}{1-2\omega+2\sigma\phi}$ and $\phi \equiv [\sigma 2\omega(1-\omega)\varepsilon_A - \sigma^{-1}\omega(1-2\omega)]$. The natural rate of output for home depends not only on the productivity process but also on foreign output. Plugging this marginal cost equation into the Phillips curve for domestic inflation gives

$$\pi_{d,t} = \beta E_t \pi_{d,t+1} + \kappa\left[(1-\psi)\kappa_o \tilde{y}_t + \psi\omega\frac{\varepsilon_A}{\varepsilon}s_t\right]$$

This equation shows the two main ways how foreign factors affect domestic inflation. Import prices influence domestic inflation directly, as reflected in the terms of trade s_t. Note the degree to which s_t affects domestic inflation depends on steady state values of the elasticities and the degree of openness. Increased openness (higher ω) means domestic inflation is more affected by changes in the terms of trade.

CPI inflation is related to domestic inflation in the following manner

$$\pi_t = \pi_{d,t} + \omega\Delta s_t$$

where $\Delta s_t = s_t - s_{t-1}$. Finally, to close the model we need to specify the monetary policy rule.

Equations used to solve model using Sims (2002) procedure

Home

$$\begin{aligned}
\pi_t &= \pi_{d,t} + \omega \Delta s_t \\
\pi_{d,t} &= \beta \pi_{d,t+1} + \kappa(1-\tilde{\psi})\kappa_0 \tilde{y}_t + \delta s_t + \eta^{\pi_d} \\
\tilde{y}_t &= y_t - y_t^n \\
y_t &= y_{t+1} - \frac{1}{\sigma}(i_t - \pi_{t+1} - \tilde{\rho}) - \phi \Delta s_{t+1} + \eta^y \\
s_t &= \frac{y_t - y_t^*}{\psi} \\
a_t &= \rho_a a_{t-1} + \varepsilon_a \\
e_{m,t} &= \rho_{e,m} e_{m,t-1} + \varepsilon_{e,m} \\
i_t &= \tilde{\rho} + \phi_\pi \pi_t + \phi_y \tilde{y}_t + e_{m,t}
\end{aligned}$$

Foreign

$$\begin{aligned}
\pi_t^* &= \pi_{f,t}^* + \omega \Delta s_t^* \\
\pi_{f,t}^* &= \beta \pi_{f,t+1}^* + \kappa(1-\tilde{\psi})\kappa_0 \tilde{y}_t + \delta s_t + \eta^{\pi_{f^*}} \\
\tilde{y}_t^* &= y_t^* - y_t^{n,*} \\
y_t^* &= y_{t+1}^* - \frac{1}{\sigma}(i_t^* - \pi_{t+1}^* - \tilde{\rho}) - \phi \Delta s_{t+1}^* + \eta^y \\
s_t^* &= \frac{y_t^* - y_t}{\psi} \\
a_t &= \rho_a a_{t-1} + \varepsilon_a \\
e_{m,t}^* &= \rho_{e,m}^* e_{m,t-1}^* + \varepsilon_{e,m}^* \\
i_t^* &= \tilde{\rho} + \phi_\pi^* \pi_t^* + \phi_y \tilde{y}_t + e_{m,t}
\end{aligned}$$

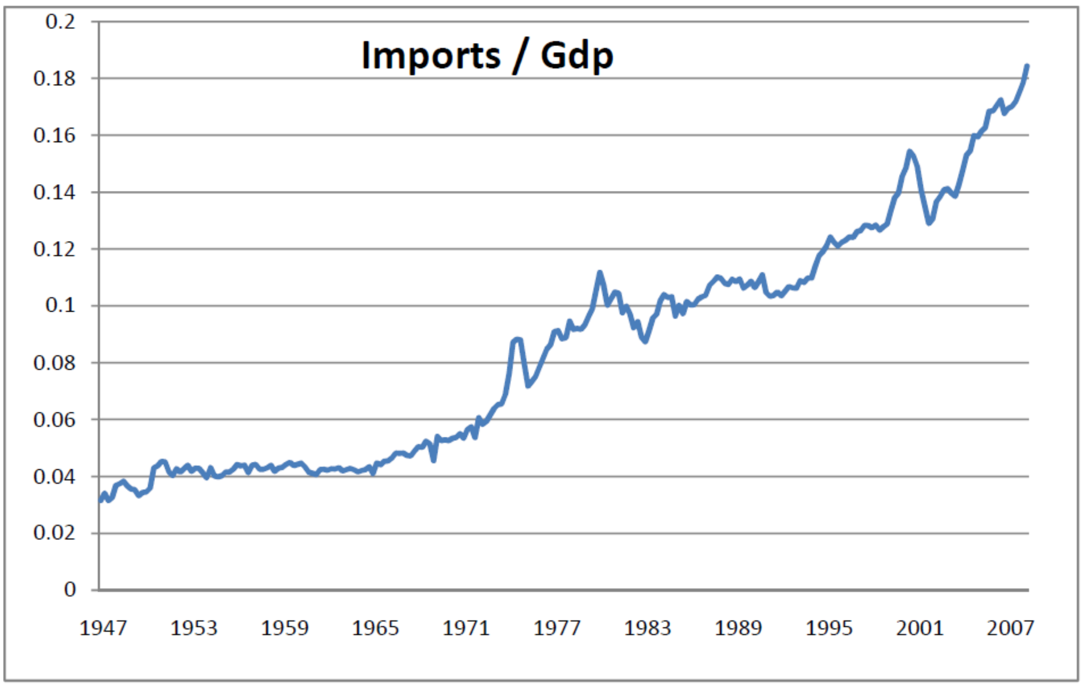

Figure 2.1: Ratio of nominal imports to nominal GDP

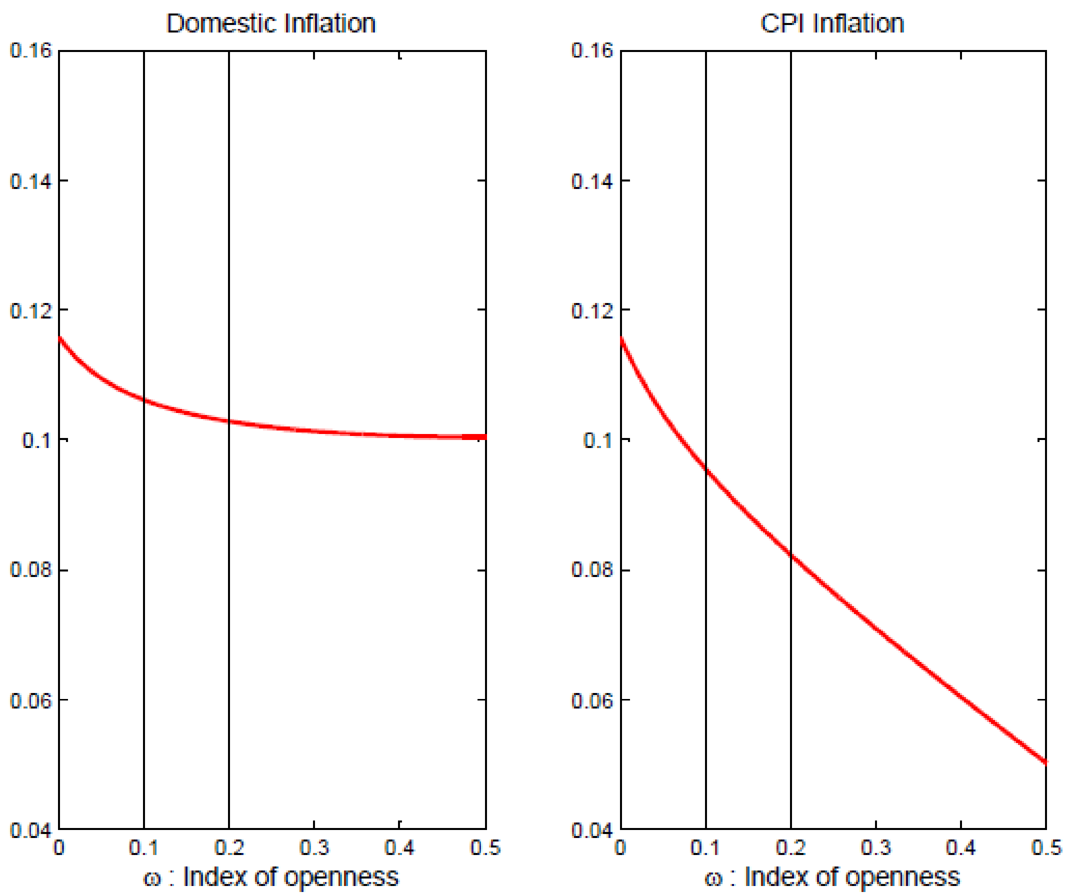

Figure 2.2: Slope of the New Keynesian Phillips Curve

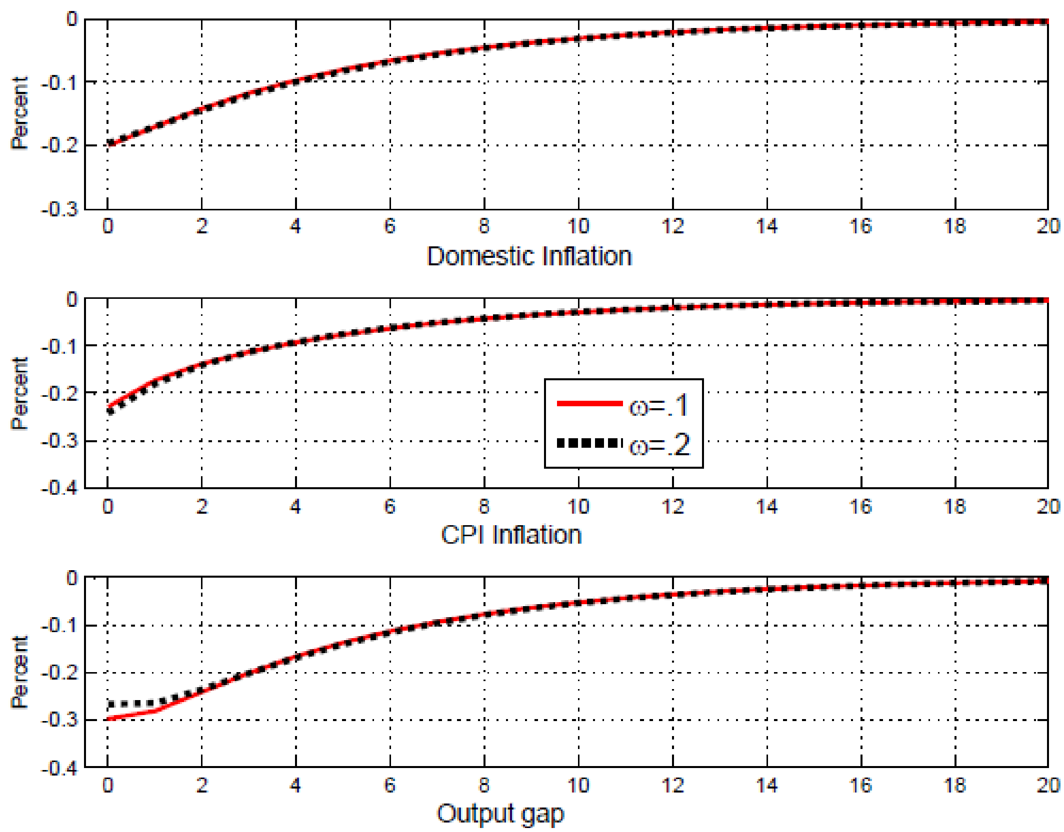

Figure 2.3: Response to a monetary policy shock

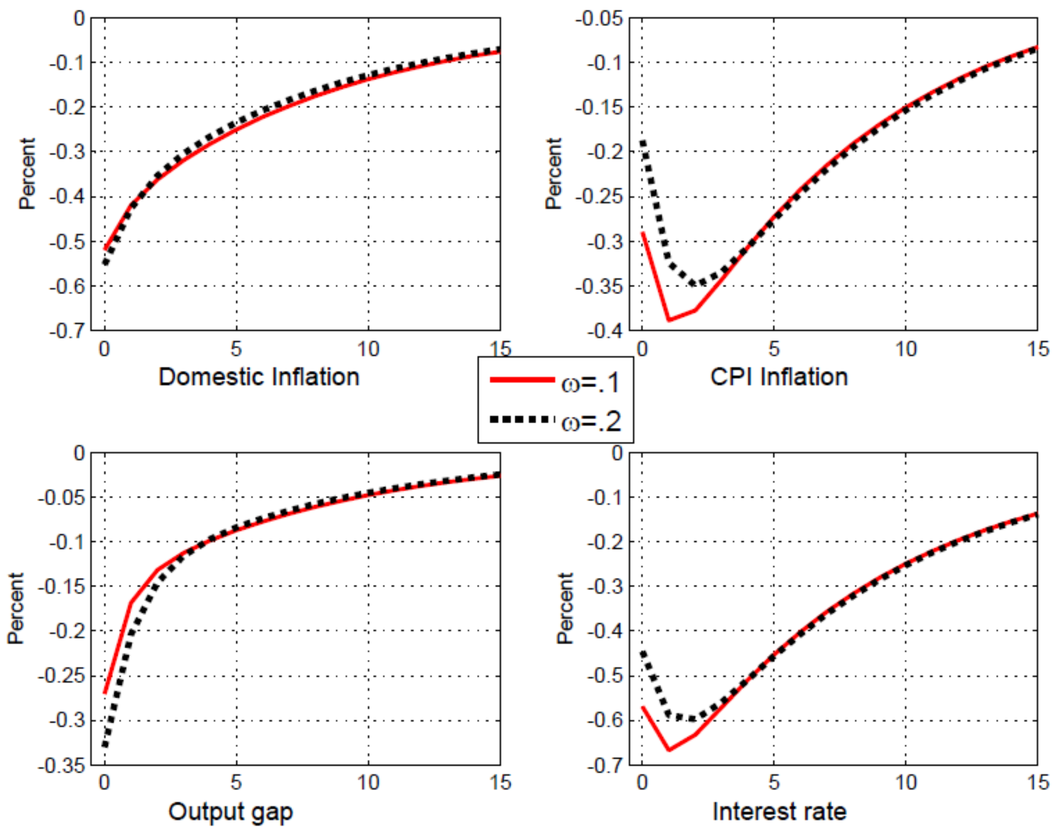

Figure 2.4: Response to a domestic technology shock

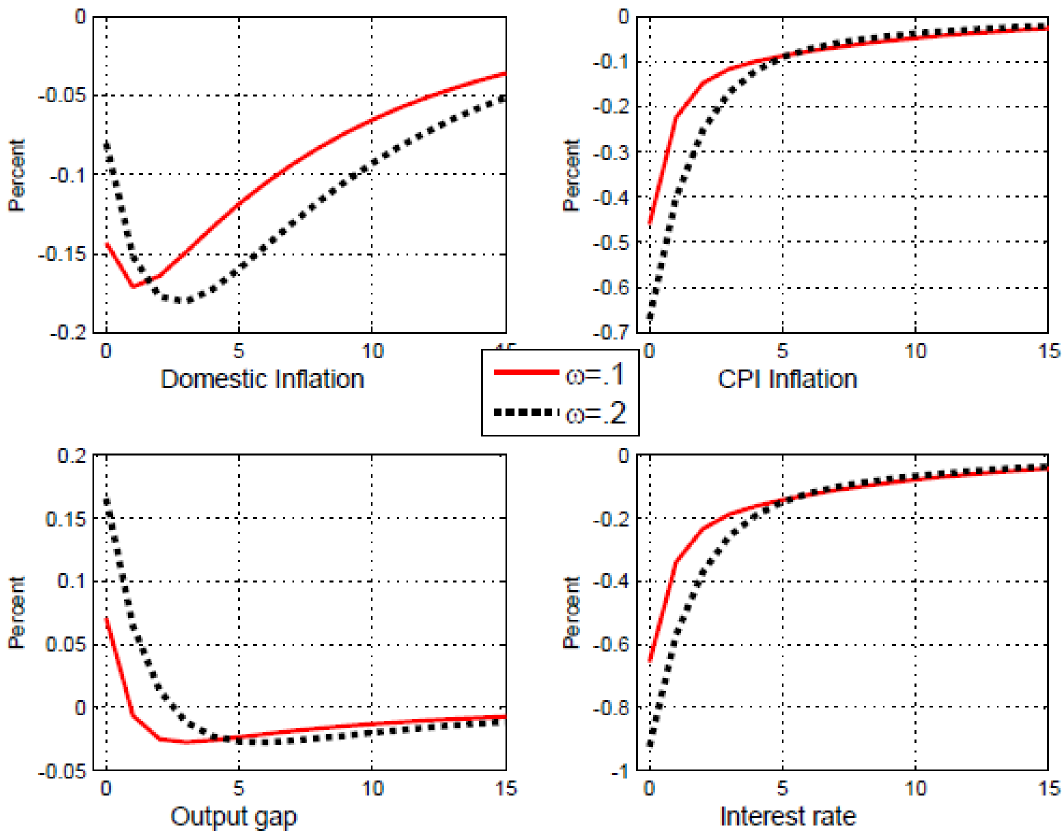

Figure 2.5: Response to a foreign technology shock

Table 2.1: Unconditional standard deviations

Standard deviations of inflation and output gap

	CTR		DTR	
	$\phi_\pi = 1.5$, $\phi_y = .125$		$\phi_\pi = 1.5$, $\phi_y = .125$	
	$\omega = .1$	$\omega = .2$	$\omega = .1$	$\omega = .2$
Domestic Inflation	3.28	3.24	3.23	3.14
CPI Inflation	3.84	4.12	4.04	4.87
Output Gap	1.25	1.18	1.38	1.34
	$\phi_\pi = 3$, $\phi_y = .125$		$\phi_\pi = 3$, $\phi_y = .125$	
	$\omega = .1$	$\omega = .2$	$\omega = .1$	$\omega = .2$
Domestic Inflation	1.46	1.43	1.47	1.45
CPI Inflation	1.72	1.80	2.06	2.86
Output Gap	0.66	0.74	0.63	0.62
	$\phi_\pi = 1.5$, $\phi_y = .25$		$\phi_\pi = 1.5$, $\phi_y = .25$	
	$\omega = .1$	$\omega = .2$	$\omega = .1$	$\omega = .2$
Domestic Inflation	2.80	2.75	2.76	2.69
CPI Inflation	3.31	3.59	3.50	4.31
Output Gap	1.08	1.03	1.18	1.15
	$\phi_\pi = 3$, $\phi_y = .25$		$\phi_\pi = 3$, $\phi_y = .25$	
	$\omega = .1$	$\omega = .2$	$\omega = .1$	$\omega = .2$
Domestic Inflation	1.35	1.33	1.37	1.35
CPI Inflation	1.63	1.73	1.96	2.76
Output Gap	0.62	0.70	0.59	0.58

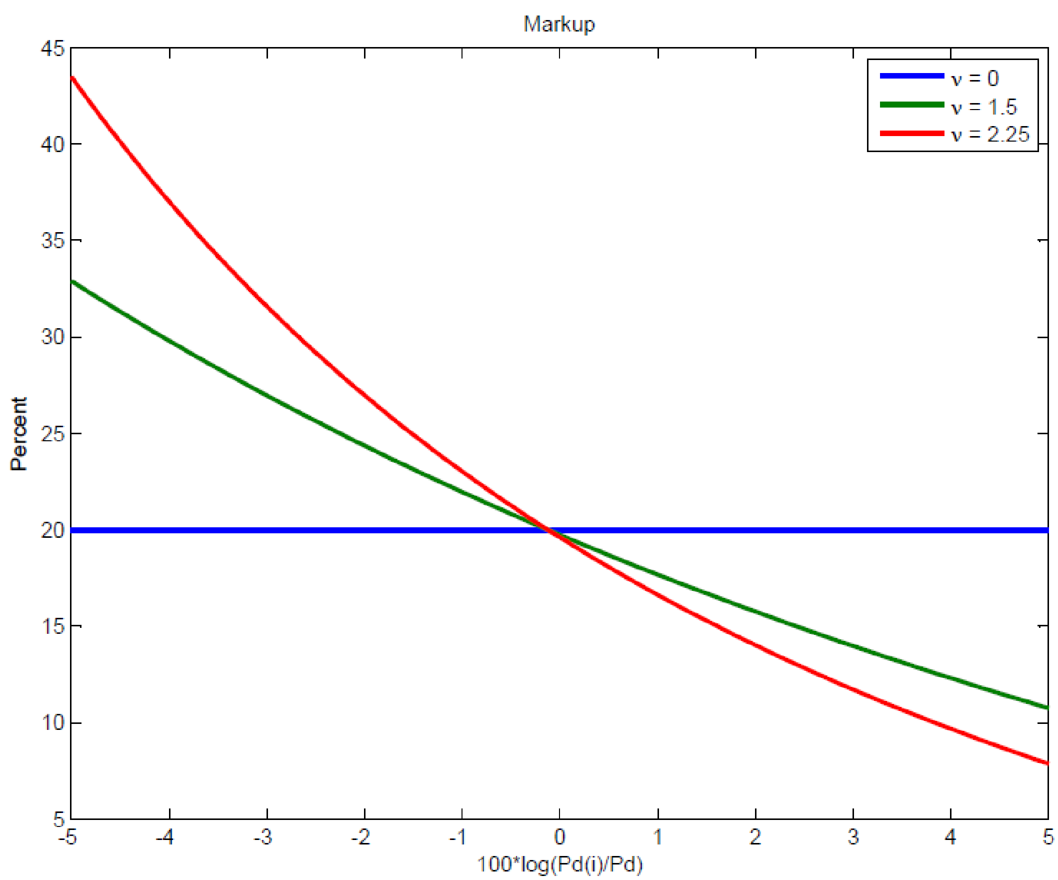

Figure 2.6: Markup (domestic firm's price relative to domestic competitors)

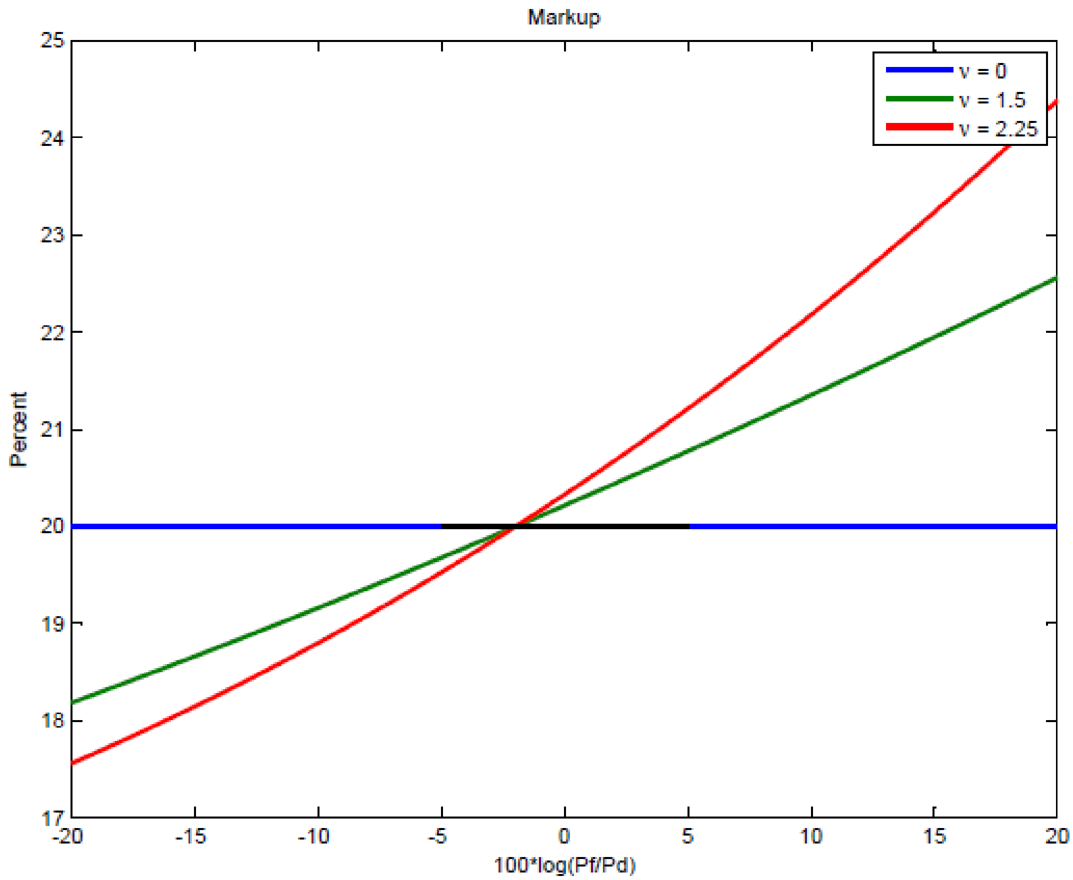

Figure 2.7: Markup (domestic firm's price relative to foreign competitors)

Chapter 3

How Credible is the Federal Reserve?

joint work with Davide Debortoli[1]

Abstract

This paper uses the loose commitment setup of Debortoli and Nunes (2010) to get an estimate of the Federal Reserve's credibility. This setting lets the central bank have a commitment technology at the same time allowing for the possibility of occasional reoptimizations. We model the Federal Reserve as following optimal policy within this loose commitment framework in the workhorse dynamic stochastic general equilibrium model of Smets and Wouters (2007). The estimated results suggest that the Federal Reserve has a reasonably high level of credibility. Although the Fed has reaped a large share of the potential welfare gains from being fully credible, there is still some room for improvement.

JEL *classification*: C32, E58, E61.
Keywords: Commitment, Discretion, Linear-Quadratic

[1]Preliminary work: Do not cite

3.1 Introduction

Since the seminal work of Kydland and Prescott (1977) and Barro and Gordon (1983), the issue of time-inconsistency has been an important factor in the analysis of optimal policy. The expectations of forward-looking agents are crucially affected by their assessment of the conduct of policy. Thus a policy maker can reap the benefits of shaping these expectations by announcing a plan and credibly committing to it. But in the future there is a temptation to renege on past promises. The literature has typically modeled optimal policy operating in two extreme versions of this environment. In the first called full commitment, the policy maker is fully credible. Full commitment assumes that the policy maker possesses a commitment technology where once the optimal plans have been formulated, these are implemented for all time periods and agents completely trust the policy maker. On the other extreme a setting of discretion assumes that the agents have zero trust and the policy maker reformulates new plans every period. But it's not entirely obvious that either of them reasonably represents the realistic setting of actual policy.

To get around this dichotomy there has been some work that allows for flexibility in this setting. Starting with Roberds (1987) and followed by Schaumburg and Tambalotti (2007), Debortoli and Nunes (2010) and Debortoli et al. (2012) formulate an environment which we will refer to as loose commitment.[2] The policy maker is endowed with a commitment technology but occasionally gives in to the temptation to renege on past promises. Agents in the economy are aware of this and take it into account while forming their expectations. This framework nests the two extreme cases of full commitment and discretion while allowing for a continuum of possibilities in the middle. While the above mentioned papers explore the theoretical implications of this setting, there has not been any empirical work.[3]

The main goal of this paper is to use the loose commitment setting to estimate the Federal Reserve's level of credibility. We use the workhorse dynamic

[2]The loose commitment terminology was first suggested by Debortoli and Nunes (2010). Roberds (1987) used "stochastic replanning" while Schaumburg and Tambalotti (2007) used "quasi-commitment".

[3]To the best of our knowledge no work has estimated a model with loose commitment.

stochastic general equilibrium model of Smets and Wouters (2007) where the only difference is that central bank conducts optimal monetary policy in a loose commitment framework.[4] Consistent with the Fed's mandate, the central bank is modeled as trying to stabilize inflation and output gap. It has a commitment technology but faces stochastic reoptimization shocks that make it revise its plans. These shocks are governed by an exogenous Markov switching process. We estimate the unconditional probability of this Markov process being in a commitment regime and interpret it as the Federal Reserve's level of credibility. It can be thought of as a continuous variable measuring the durability of the Federal Reserve's promises, with higher numbers corresponding to higher levels of credibility. This is similar to the concept first stated in Blackburn and Christensen (1989) as "the extent to which beliefs about the current and future course of economic policy are consistent with the program originally announced by policymakers" and recently used by Schaumburg and Tambalotti (2007) and Debortoli and Nunes (2010).

Of course this is not the only way of measuring credibility. Faust and Svensson (2001) suggest looking at the difference between inflation expectations and the Fed's inflation target. On the other hand, Rogoff (1985) suggests using the relative weight on output in the loss function. We view our results as complementary to these views. Our definition is somewhat related to Cukierman (1992) who suggested using an empirical measure of independence as gauged by the turnover of central bank governors. Our results provide some supporting evidence for this. We find that the filtered probability of not fulfilling past promises rises a number of times in the 1970s when the Federal Reserve had four different governors (William Martin Jr., Arthur Burns, William Miller and Paul Volcker), whereas this probability stays fairly low throughout the 1980s and 1990s when the Fed is presided over by only two governors (Paul Volcker and Alan Greenspan).

The Smets and Wouters (2007) model is augmented with optimal policy under loose commitment and solved using the efficient technique of Debortoli et al. (2012). Estimation is carried out using Maximum Likelihood Estimation, following the Kim and Nelson (1999) extension of the Hamilton (1989) approach to state

[4] In the Smets and Wouters (2007) model monetary policy is specified using a simple Taylor rule.

space models.[5] The unconditional probability of commitment is estimated to be 0.82, which implies that the Federal Reserve is expected to reoptimize plans once every 6 quarters. We then consider the welfare implications of our estimated probability of commitment. Using a relative measure of conditional welfare we find that the Federal Reserve has captured most of the benefits that can be gained by increasing credibility even though the estimated probability is considerably less than one. This is a result of the nonlinearity in the welfare gains associated with increased credibility. Nonethless, the results suggest that there is still some room for improvement.

The rest of the paper is organized as follows. In the next section we briefly describe the loose commitment framework and explain how the probability of commitment can be used as a measure of credibility for the Federal Reserve. Section 3 outlines the dynamic stochastic general equilibrium model that forms the setting for this paper. Then we explain the formulation of optimal policy under loose commitment in section 4. Section 5 explains the estimation procedure and the next section outlines the results. Section 7 concludes.

3.2 Measuring Credibility through Loose Commitment

The loose commitment framework endows the central bank with a commitment technology. But occasionally the central bank is tempted and decides to renege on its promises. Agents in this economy are aware of this possibility and take this into account while forming expectations. Even though they expect a reoptimization once in a while, during a commitment regime (i.e. the period between two reoptimizations) agents' expectations are in line with the promised optimal policy by the central bank.

The reoptimizations occur exogenously and are governed by a two state Markov-switching process η_t. This assumption of stochastic reoptimization is made

[5] We are currently working on a Bayesian estimation technique using the Metropolis-Hastings algorithm. The details are provided in Section 5 and the appendix.

to keep the model and the estimation tractable. In the case of the Federal Reserve this can happen if there is outside pressure from the political or the financial system. Additionally this can happen as the composition of the Federal Open Market Committee (the Fed's main monetary policy making arm) changes over time. We just assume that these events are exogenous to the developments in the economy. When $\eta_t = 1$ past promises are honored, while $\eta_t = 0$ implies a reoptimization. The probability of staying in a commitment period is given by γ.

$$\eta_t = \begin{cases} 1 \text{ with prob } \gamma \\ 0 \text{ with prob } 1 - \gamma \end{cases}$$

One advantage of this setup is that it nests the full commitment ($\gamma = 1$) and discretion ($\gamma = 0$) cases while allowing for any intermediate value of γ. We will interpret the estimated value of γ as an indicator of the Federal Reserve's credibility.

3.3 The Model

The theoretical model underlying our analysis is based on Smets and Wouters (2007). The model includes nominal frictions in the form of sticky price and wage settings allowing for backward inflation indexation.[6] It also features real rigidities – habit formation in consumption, investment adjustment costs, variable capital utilization, and fixed costs in production. The dynamics are driven by six orthogonal shocks: total factor productivity, two shocks affecting the intertemporal margin (risk premium and investment-specific technology shocks), two shocks affecting the intratemporal margin (wage and price-markup shocks), and an exogenous government spending shock. Unlike Smets and Wouters (2007), we do not consider a specific interest rate rule nor the associated monetary policy shock. Instead, we assume that the central bank solves an optimal policy problem, and letting the

[6]Sticky nominal wages and prices follow the formulations of Erceg et al. (2000) and Yun (1996).

degree of commitment (γ) as a parameter to be estimated.[7]

The central bank is assumed to minimize the following quadratic period loss function.

$$\pi_t^2 + w_y \widetilde{y}_t^2 + w_r (i_t - i_{t-1})^2$$

where π_t is inflation, $\widetilde{y}_t$ is the output gap and i_t is the nominal interest rate. Without loss of generality, the weight on inflation is normalized to one so that w_y and w_r represent the weights on output gap and interest rate relative to inflation. Note that this loss function does not represent the utility-based welfare function corresponding to this specific model, however we use it for the following reasons. First, deriving the utility-based welfare function is challenging in the SW model and has not been done yet, to the best of our knowledge. Second, this type of loss function has been widely used in the monetary policy rules literature (Taylor (1999) and Rudebusch and Svensson (1998) and shown to reasonably describe central bank behavior (Dennis (2006)). Finally, the linear quadratic setting makes the model tractable and well suited for estimation. This period loss function can be written in terms of the endogenous variables as $y_t' W y_t$.

Additionally we are also considering the case where the central bank's objectives coincide with those of the underlying society. In doing so we will need to assume the presence of appropriate production subsidies so that the model steady-state is efficient. This will allow us to derive a purely-quadratic welfare criterion based on the household's utility, without imposing the so-called "timeless perspective" assumption, which would be inconsistent with the "loose-commitment" setting under consideration. The resulting criterion would then be appropriate for studying stabilization properties of monetary policies, or more generally cases when the steady-state inefficiencies are relatively small. As discussed e.g. in Debortoli and Nunes (2006), Levine et al. (2008) and Benigno and Woodford (2012) in models with large steady-state distortions the "timeless perspective" assumption is necessary to cast the problem into the convenient linear-quadratic framework.

[7]The detailed derivations of the model equations are omitted for brevity and available in an online appendix.

3.4 Optimal Policy under Loose Commitment

The linearized DSGE model of Smets and Wouters (2007) can be written in the following manner as a function of y_t, the endogenous variables and v_t, the exogenous disturbances.

$$A_{-1}y_{t-1} + A_0 y_t + A_1 E_t y_{t+1} + Bv_t = 0$$

Following Debortoli and Nunes (2010) we can write the optimization problem of the central bank in the following manner.

$$y'_{-1}Py_{-1} + d = \min_{\{y_t\}_{t=0}^{\infty}} E_{-1}\sum_{t=0}^{\infty}(\beta\gamma)^t[y'_t W y_t + \beta(1-\gamma)(y'_t P y_t + d)]$$

$$s.t. A_{-1}y_{t-1} + A_0 y_t + \gamma A_1 E_t y_{t+1} + (1-\gamma)A_1 E_t y^r_{t+1} + Bv_t = 0.\forall t$$

The central bank is assumed to start with a reoptimization. In the loss function the first part $y'_t W y_t$ is the period loss function while the second part $y'_t P y_t + d$ represents the value to the policy maker when a reoptimization occurs next period. The expectations in the constraints are a sum of two parts, equal to $E_t y_{t+1}$ (weighted by γ) which relate to the case when past promises are honored and $E_t y^r_{t+1}$ (weighted by $1-\gamma$) which relate to the case when there is a reoptimization. A Markov-perfect equilibrium is used so that the expectations under reoptimization are functions of the current state variables, $E_t y^r_{t+1} = \widetilde{H} y_t$ and the policy maker cannot affect $\widetilde{H} y_t$. Then the method of Marcet and Marimon (2011) is applied and the problem is rewritten in the Lagrangean framework. The solutions takes the following form

$$\begin{bmatrix} y_t \\ \lambda_t \end{bmatrix} = \begin{bmatrix} H_{yy} & H_{y\lambda} \\ H_{\lambda y} & H_{\lambda\lambda} \end{bmatrix} \begin{bmatrix} y_{t-1} \\ \lambda_{t-1} \end{bmatrix} + \begin{bmatrix} G_y \\ G_\lambda \end{bmatrix} v_t$$

where λ_t is the lagrange multiplier. There is an intuitive interpretation where λ_{t-1} is set to zero in a reoptimization representing the fact that past promises are ignored. The solution for the unknown matrices is reduced to finding a fixed point. The detailed derivation and proofs of this setup can be found in Debortoli and Nunes (2010) and Debortoli et al. (2012). The advantage of this approach is that it allows us to efficiently compute the model's state-space representation and facilitate the estimation of the medium-scale DSGE model with relative ease.

3.5 Estimation Procedure

The solved equations of the model can be written in the state space notation of Kim and Nelson (1999).

$$y_t = H\beta_t + Az_t$$
$$\beta_t = \tilde{\mu} + F_{s_t}\beta_{t-1} + Gv_t$$

The errors are assumed to be distributed normally, $v_t \sim N(0, Q)$. Compared to the general setup of Kim and Nelson (1999), only the values of the parameter matrix F_{s_t} are dependent on the Markov-switching process S_t (which can be either 1 or 0) and the transition probabilities of this Markov process which are given by the transition matrix P. Note this is different from the normal setting where the matrices of the state space system do not explicitly depend on the transition probabilities of the switching process. But it does here since the probability of commitment affects how agents form their expectations. This Markov-switching process corresponds to η_t process described in the previous section, and the transition matrix P is given by

$$P = \begin{bmatrix} \gamma & 1-\gamma \\ \gamma & 1-\gamma \end{bmatrix}$$

The rows of this transition matrix are the same, representing the fact that the switching happens independently. This means that next period's probability of a reoptimization (or honoring past promises) is the same regardless whether the central bank has reoptimized this period or not.[8]

Using this setup the model can be estimated either by Maximum Likelihood or using Bayesian techniques. In practice, the high dimensional likelihood function

[8] This setup is used to be consistent with the theory model.

is unwieldy. It typically takes longer for the estimation algorithm to converge and it is often difficult to distinguish between a global and local maximum. Additionally it is much harder to impose restrictions on the estimated parameter space using Maximum Likelihood as opposed to Bayesian methods. For example, if we want to rule out combinations of the parameters that imply explosive dynamics, it is straightforward to do with the Bayesian estimation algorithm but can be quite cumbersome with Maximum Likelihood. All these issues are manageable for a small number of parameters but get worse with the dimension of the estimated parameter space.

In the current draft we estimate only a subset of the parameters. As mentioned earlier, the main departure from the Smets and Wouters (2007) model is the modeling of monetary policy. Monetary policy setting in the loose commitment setup involves three new parameters; the loss function weight on output gap (w_y), the loss function weight on interest rate smoothing (w_r) and the probability of commitment (γ). We estimate these three parameters using Maximum Likelihood while fixing the rest of the parameters to the values estimated in Smets and Wouters (2007).[9] For consistency we use the same dataset as Smets and Wouters (2007) with the same data range. As mentioned above the Maximum Likelihood algorithm works well when the dimension of the estimated parameters is small.

The estimation is carried out using Kim and Nelson (1999)'s extension of the Hamilton (1989) filter to state space models to deal with unobservable variables. We can evaluate the likelihood function in the following manner. M is the number of states that the Markov-switching process can take, equal to two here. The parameter vector to be estimated is $\theta = [w_y, w_r, \gamma]$.

[9]We are currently working on a Bayesian estimation technique. This uses Metropolis-Hastings algorithm that will allow us to estimate all the parameters of the model jointly. The algorithm for this estimation is outlined in the appendix. The Metropolis-Hastings algorithm does require some fine tuning and we are currently in the process of doing this.

Step 1: Perform the Kalman Filter for $i = 1, ..M, j = 1, ..M$

$$\begin{aligned}
\beta^{i,j}_{t|t-1} &= \tilde{\mu} + F_j \beta^i_{t-1|t-1} \\
P^{i,j}_{t|t-1} &= F_j P^i_{t-1|t-1} F'_j + GQG' \\
\eta^{i,j}_{t|t-1} &= y_t - H\beta^{i,j}_{t|t-1} - Az_t \\
f^{i,j}_{t|t-1} &= HP^{i,j}_{t|t-1} H' \\
\beta^{i,j}_{t|t} &= \beta^{i,j}_{t|t-1} + P^{i,j}_{t|t-1} H' [f^{i,j}_{t|t-1}]^{-1} \eta^{i,j}_{t|t-1} \\
P^{i,j}_{t|t} &= (I - P^{i,j}_{t|t-1} H' [f^{i,j}_{t|t-1}]^{-1} H) P^{i,j}_{t|t-1}
\end{aligned}$$

Step 2: Perform the Hamilton Filter

$$\begin{aligned}
P(S_t, S_{t-1}) &= P(S_t | S_{t-1} P(S_{t-1} | \psi_{t-1}) \\
f(y_t | \psi_{t-1}) &= \sum_{S_t} \sum_{S_{t-1}} f(y_t | S_t, S_{t-1}, \psi_{t-1}) P(S_t, S_{t-1} | \psi_{t-1}) \\
P(S_t | \psi_t) &= \sum_{S_{t-1}} P(S_t, S_{t-1} | \psi_t)
\end{aligned}$$

Note that the conditional density is normal and given by

$$f(y_t | S_{t-1} = i, S_{t=j}, \psi_{t-1}) = (2\pi)^{-\frac{N}{2}} \, |f^{i,j}_{t|t-1}|^{-\frac{1}{2}} exp\{-\frac{1}{2} \eta^{i,j'}_{t|t-1} (f^{i,j}_{t|t-1})^{-1} \eta^{i,j}_{t|t-1}\}$$

Step 3: Perform the Kim & Nelson approximations to collapse the M^2 unobservable $\beta^{i,j}_{t|t}$ into M ones. For each j calculate the following

$$\begin{aligned}
\beta^j_{t|t} &= \frac{\sum_{i=1}^M P(S_t = i, S_t = j | \psi_t) \beta^{i,j}_{t|t}}{P(S_t = j | \psi_t)} \\
P^j_{t|t} &= \frac{\sum_{i=1}^M P(S_t = j, S_{t-1} = i | \psi_t) [P^{i,j}_{t|t} + (\beta^j_{t|t} - \beta^{i,j}_{t|t})(\beta^j_{t|t} - \beta^{i,j}_{t|t})']}{P(S_t = j | \psi_t)}
\end{aligned}$$

Step 4: After performing steps 1-3 $\forall t$ we can evaluate the log likelihood function

$$l(\theta) = \sum_{t=1}^T ln(f(y_t | \psi_{t-1}))$$

This likelihood function is then maximized with respect to θ.

3.6 Results

As mentioned earlier, the non monetary policy related parameters are fixed at the values estimated in Smets and Wouters (2007). The data range goes from 1966:Q1 to 2004:Q1, which is the same as in Smets and Wouters (2007) for consistency.[10] The MLE estimates of the 3 parameters relating to monetary policy setting under loose commitment are shown in Table 1, along with the standard errors. The standard errors are small, which is not surprising given that that only 3 parameters are estimated. The estimates of w_y and w_r indicate that stabilizing inflation is more important to the Federal Reserve as compared to output gap or smoothing interest rates. These values are also in the range of the numbers suggested in Woodford (2003b). The probability of commitment γ is 0.82 which means that the average duration of a commitment regime for the Federal Reserve is around 6 quarters. Or put another way, the Federal Reserve is expected to reoptimize once every 6 quarters.

Figure 3.1 shows the filtered probability of commitment, i.e. $P(\eta_t = 1|\psi_t)$, the probability that $\eta_t = 1$ conditional on all available information upto time t.[11] The grey bars indicate periods where the filtered probability is below 0.5.[12] It is interesting to note that several reoptimization episodes seemed to have occurred in the 1970s, when there was a lot of turnover at the Fed involving four different chairmen Starting in the late 70s (coinciding with the appointment of chairman Paul Volcker) there is a long period of commitment that lasts into the early 2000s. Then there are a couple of other reoptimization episodes. The timing of these last two episodes are interesting as Taylor (2009) has suggested that the Federal Reserve deviated from a simple Taylor rule in the early 2000s by keeping interest rates too low.

In the setting of this model, the agents' welfare is maximized when the

[10]We plan to extend the data range once we jointly estimate all the parameters using Bayesian methods. One advantage of the loose commitment setting is that the zero lower bound does not pose any issues and thus we can use data that goes through the financial crisis, which would be a challenge in the Smets and Wouters (2007) model with a simple Taylor rule.

[11]We can also look at the smoothed probability of commitment which would condition on all information upto time T. The resulting graph is very similar.

[12]This is just a simple rule meant as a visualization aid.

central bank is fully credible, i.e. when $\gamma = 1$. A natural question then is to see how much loss in welfare occurs when the central bank's credibility is less than perfect. In doing the welfare analysis we calculate conditional welfare gains that are standardized by the total gains of changing credibility from discretion to full-commitment.[13] This technique has the desirable property that the results are invariant to any affine transformation of the central bank's objective function. Specifically we calculate the welfare using the formula $\frac{V_{\gamma}-V_{\gamma=0}}{V_{\gamma=1}-V_{\gamma=0}}$ and plot it against different values of γ in figure 3.2.[14] The figure reveals that there are big welfare losses when the probability of commitment is low. For the estimated value of $\gamma = 0.82$ we notice that majority of the welfare gains from being committed have already been reaped. Although there is definitely room for improvement by increasing γ.

3.7 Conclusion

This paper starts with the argument that the conventional modeling of full commitment or discretion is too restrictive when considering optimal central bank policy. We use the loose commitment framework to model the Federal Reserve in the medium-scale DSGE model of Smets and Wouters (2007). A first pass is made at estimating the Federal Federal Reserve's level of credibility in this setting. The results suggest that the Federal Reserve has a reasonably high level of credibility as measured by the unconditional probability of commitment. The estimates point to more episodes of reoptimizations in the 1970s as compared to the 1980s and 1990s. Relative to the welfare maximizing case of full commitment, the estimates indicate that the Federal Reserve has performed fairly well.

Other than the obvious way of honoring its commitments there is another potential way for the Federal Reserve to increase its credibility. It can better communicate with the public about current and future policy actions. Indeed, under the helm of chairman Ben Bernanke, the Federal Reserve has taken several

[13] The results are similar if we do not condition on the realization of the shocks.

[14] Note that the current graph is from Debortoli et al. (2012), where the values of w_y and w_r are slightly different but there would be very little change in the results.

measures to achieve exactly this. In 2012 the Federal Reserve announced an official inflation target of 2%. Additionally they started releasing individual forecasts of the FOMC members' relating to economic activity. While increased transparency can undoubtedly help the public understand Federal Reserve policy, it is a double edged sword. If the public better understands what the Fed has promised it could become harder and/or more costly for the Fed to get away with not fulfilling those promises.

Chapter 3, in part is currently being prepared for submission for publication of the material. Debortoli, Davide; Lakdawala, Aeimit. The dissertation author was the co-primary investigator and author of this material.

3.8 Appendix

3.8.1 Metropolis-Hastings Algorithm

This section explains the details of the Bayesian estimation procedure that uses the Metropolis-Hastings algorithm and will be used to estimate all the parameters of the model jointly. As outlined in Section 5 we can rewrite the model as

$$y_t = H\beta_t + Az_t$$

$$\beta_t = \mu + F_{s_t}\beta_{t-1} + Gv_t$$

$$v_t \sim N(0, Q)$$

The values of the parameters in F_{s_t} are dependent on a Markov-switching process S_t (which can be either 1 or 0) and the transition probabilities of this Markov process which are given by the transition matrix P.

Define $\theta = [H, A, \mu, F_{s_t}, G, Q]$, $S^t = [S_1, S_2, ...S_t]$ and $y^t = y_1, y_2, ...y_t$.

Step I: Conditional on P and θ we generate S^T using the Gibbs sampling step in the following manner

1. Run Kim & Nelson's modified Hamilton Filter to get $p(S_t|y^t)$
2. For $t = T$, draw from a Uniform(0,1) if it is less than $p(S_T = 1|y^T)$ then assign $S_T = 1$ or 0 otherwise
3. For each $t = T-1, T-2, ...1$, generate $S_t|y^t, S_{t+1}$ by first calculating

$$Pr[S_t = 1|S_{t+1}, y^t] = \frac{p(S_{t+1}|S_t = 1)p(S_t = 1|y^t)}{\sum_{j\in M} p(S_{t+1}|S_t = j)p(S_t = j|y^t)}$$

   Next draw from a Uniform(0,1) and if it is less than $Pr[S_t = 1|S_{t+1}, y^t]$ then assign $S_t = 1$ or 0 otherwise.

Step II: Conditional on θ and S^T we generate P with Random-Walk Metropolis-Hastings using the following steps. For a given draw P^o

1. Generate $P^n = P^o + N(0, V_P)$

2. Accept P^n with probability $\alpha = min\{\frac{f(y_t|P^n,\theta,S^T)}{f(y_t|P^o,\theta,S^T)},1\}$

Note the assumed prior for P is $Uniform[0,1]$.

Step III: Conditional on P and S^T we generate θ using another Metropolis-Hastings step. For a given draw of θ^o,

1. Generate $\theta^n = \theta^o + N(0, V_\theta)$

2. Accept θ^n with probability $\alpha = min\{\frac{f(y_t|\theta^n,P,S^T)p(\theta^n)}{f(y_t|\theta^o,P,S^T)p(\theta^o)},1\}$

where $f(.)$ is the likelihood and $p(.)$ is the prior.

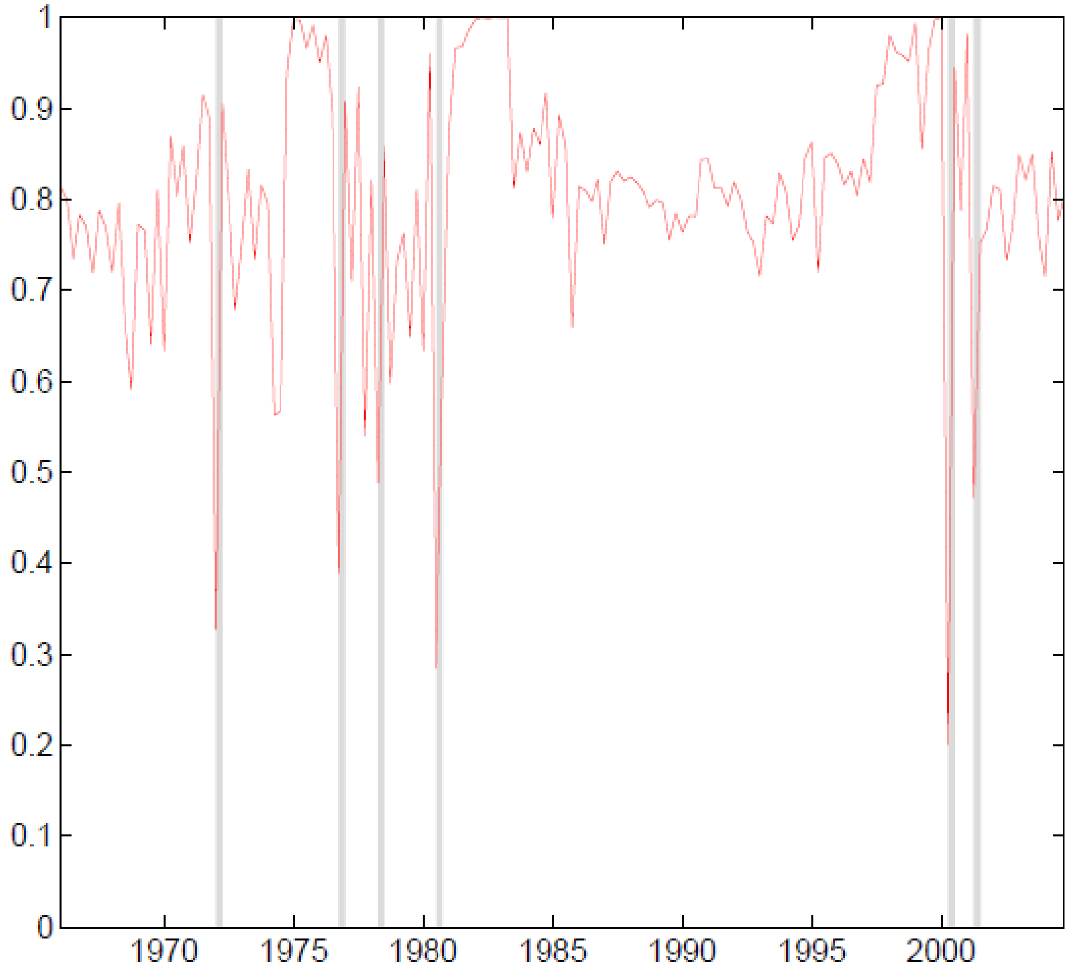

Figure 3.1: Filtered Probability of Commitment

Table 3.1: Parameter Estimates

	γ	w_y	w_r
	0.815	**0.019**	**0.011**
Std. Err.	(0.039)	(0.004)	(0.005)

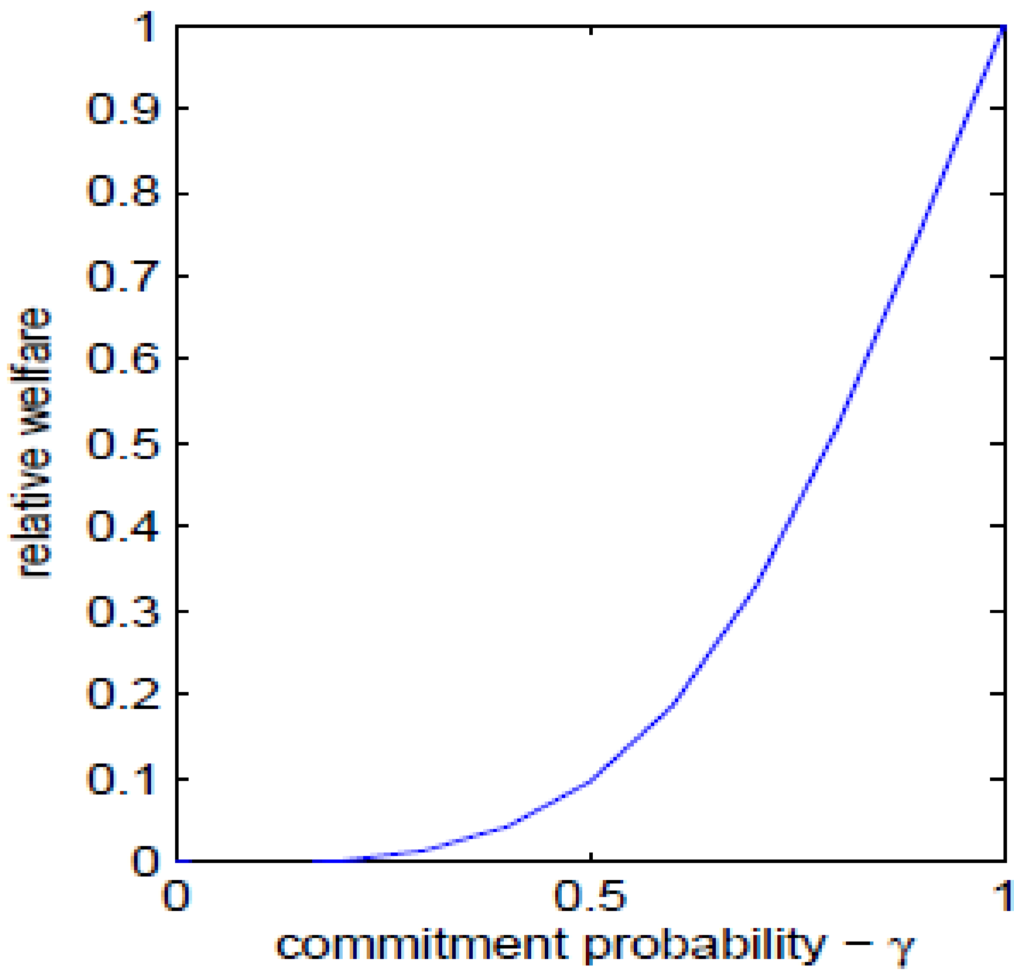

Figure 3.2: Welfare: $\frac{V_\gamma - V_{\gamma=0}}{V_{\gamma=1} - V_{\gamma=0}}$

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