Has Monetary Policy Become More Aggressive, But Less Effective Over Time?

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Abstract

This paper examines the changes in monetary policy and monetary transmission over time in four developed countries (the United States, the United Kingdom, Canada, and Australia) using time-varying vector autoregression (TVP-VAR) models. The results suggest some comovements in the monetary policy reactions to unemployment across countries before the recent Global Financial Crisis (GFC). The policy rate seems to react more aggressively against unemployment in more recent years. However, the effects of monetary policy shocks on unemployment and inflation appear to have weakened over time.

JEL classification: *C54, E52, F44*

Keywords: *monetary policy, monetary transmission, Time-Varying VAR*

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* The author is hugely benefited from discussions with Ippei Fujiwara, Paul Burke and Jouchi Nakajima. This is an extended analysis from Fujiwara, Nakajima and Phan (2013) with more focus on the time variations of monetary policy transmission mechanism. Any errors remain my own responsibility.

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1. Introduction

Thanks to Keynesian economics, the importance of monetary policy has been acknowledged widely, at least in the short run. Over time, central banks in many developed countries have increasingly adopted inflation targeting as the main regime. However, since the start of the Global Financial Crisis (GFC) in late 2007, it seems that monetary policy all around the world became more aggressive against unemployment and GDP growth, yet the main monetary policy tool (the policy interest rate) appears to be less and less effective over time.

This paper explores mainly a long period before the GFC and provides evidence of a "more aggressive but less effective over time" monetary policy across some developed countries. Technically, this paper is motivated by the empirical topic of whether monetary policy and transmission have changed over time. More precisely, the paper addresses two questions: (1) Have monetary policy reactions to unemployment and inflation changed over time?; and (2) Have the effects of monetary policy shocks on unemployment and inflation changed over time?

On the first question, Primiceri (2005) uses a tri-variate time-varying parameter VAR (TVP-VAR) model to suggest that US monetary policy became more reactive to inflation and unemployment during the 1980s to 2001 compared to the 1960s and 1970s. Some earlier research including by Judd and Rudebusch (1998), Clarida *et al.* (2000), Cogley and Sargent (2001, 2003), and Lubik and Schorfheide (2004) also suggests that US monetary policy was more aggressive against inflation under the FED chairmanship of Paul Volcker (August 1979 to August 1987) and Alan Greenspan (August 1987 to January 2006) than under Arthur Burns (January 1970 to March 1978). Meanwhile others find little evidence of changes over time in the way US monetary policy reacts to inflation and unemployment (see, for example, Bernanke and Mihov, 1998; Leeper and Zha, 2002; Sims, 1999, 2001).

The second question is about the monetary transmission mechanism to unemployment and inflation. Primiceri (2005) finds that monetary transmission to unemployment and inflation did not change much across the different Federal Reserve (FED) chairmanships of Burns, Volcker, and Greenspan. Boivin and Giannoni (2006) use a simple VAR model to argue that the effects of monetary policy on inflation and output declined in the post-Volcker

period (after 1979Q4). Gali and Gambetti (2009) use TVP-VAR models to suggest that the effects of demand-type shocks (which might include the effect of the policy shocks) on output and inflation have declined over time. Meanwhile Canova and Gambetti (2009) use a sign restriction strategy with TVP-VAR models and find that output has become more responsive to monetary shocks in the US since the 1990s.

The literature of comparing monetary policy and monetary transmission between different countries comprises either studies among countries within the Euro area, or among G-7 countries. On monetary policy reaction functions, Romer (2005) argues that policy makers in different countries share some perceptions and form similar beliefs about the role of monetary policy, therefore monetary policy reactions could be similar in different countries. Nelson (2005a, 2005b) suggests a unified framework of beliefs prevailing among various developed countries. Recently, Chatterjee (2014) uses a Bayesian dynamic latent factor model to show that a common `G-7 factor' plays an important role in the comovement of monetary reactions to inflation among G-7 countries during the period 1988-2003. Suda and Zervou (2014) argue that there might be a long-run relationship in the responses of monetary policy to inflation in G-7 countries.

Gerlach and Smets (1995) are among the first to compare the monetary transmission mechanisms of different countries. They use a structural vector autoregression (SVAR) model and report that the effects of monetary policy actions on inflation and output are similar across G-7 countries. Mojon and Peersman (2001) use SVAR models for individual countries of the Euro area before 1999 and conclude that the effects of monetary policy on GDP and prices are broadly similar among the countries. Peersman (2004) also finds similar output responses to monetary policy shocks in seven Euro countries. Ciccarelli and Rebucci (2006) use a time-varying coefficient VAR to suggest that the long-run cumulative impact of monetary policy shocks on output has decreased since 1991 in four European countries (Germany, France, Italy, and Spain). Cecioni and Neri (2011) use SVAR and dynamic stochastic general equilibrium (DSGE) models to conclude that the effects of monetary policy shocks on output and prices in the Euro area have not changed much before and after the commencement of the Euro area in 1999.

This paper uses TVP-VAR models similar to the ones used by Primiceri (2005) and Nakajima (2011) to examine the two above-mentioned questions for four developed

countries: the United States (US), the United Kingdom (UK), Canada, and Australia. As pointed out by Suda and Zervou (2014), because of the operation of the European Central Bank (ECB) from 1999Q1, data for the three European G-7 members (Germany, France, Italy) are divisional and cannot be used smoothly pre- and post-ECB. Japan – the other G-7 member – has experienced a long period of zero interest rates since the late 1990s, which might lead to misleading and theoretically-inconsistent impulse responses (see, for example, Iwata and Wu, 2006; Fujiwara, 2006). Australia, meanwhile, is a non-G-7, developed economy with data available for the period of interest.

The results of this paper suggest that (i) there were comovements in the monetary policy reactions against unemployment across countries before the recent GFC and the policy rate seems to have become more aggressive against unemployment since the 1990s; (ii) monetary policy reactions to inflation/deflation are observed to be divided into two groups, with the responses in the US and UK showing a different pattern to the responses in Canada and Australia; and (iii) there are comovements in the effects of monetary policy on unemployment and inflation across countries, with these effects appearing to have become weaker over time.

The remainder of this paper is structured as follows. Section 2 provides a background description of inflation, unemployment, and monetary policy in the four countries of interest. Section 3 describes the TVP-VAR models that are used in this paper. Section 4 introduces the data. The empirical results are presented in Section 5. Section 6 concludes.

2. Background

In this section, a brief descriptive summary of macroeconomic developments and monetary policy in the four countries during the period 1971Q2–2011Q4 is provided. The key indicators used in this section are inflation, unemployment, and economic growth (real GDP growth).[1] The policy interest rate is employed to represent monetary policy (details on the data are provided in Section 4).

[1] In this paper, the annual growth rate of the GDP deflator is used for inflation, as in Primiceri (2005), Boivin and Giannoni (2006), and Baumeister and Benati (2013), among others.

2.1. US

Figure 1 shows the key macroeconomic indicators for the whole period in the US. As observed in Figure 1, in the US, the 1970s and early 1980s (until around 1982Q4) was a period of macroeconomic instability, featuring high inflation and fluctuating GDP growth. Inflation peaked at 11.1% in 1975Q1 and 10.2% in 1981Q1, with an average of 7.1% throughout this period. The peaks of inflation corresponded to the oil price shocks. During this period, three recessions were recorded (1974Q3–1975Q1, 1980Q2–1980Q3, and 1981Q4–1982Q1).[2] Unemployment also varied with high frequency and peaked at 10.7% in 1982Q4. In response, the policy rate was raised and lowered frequently, being 3.5% per annum in 1972Q1, increasing to 12.1% per annum in 1974Q3, decreasing again to 4.7% per annum in 1977Q1, and peaking at 17.8% per annum in 1981Q2.

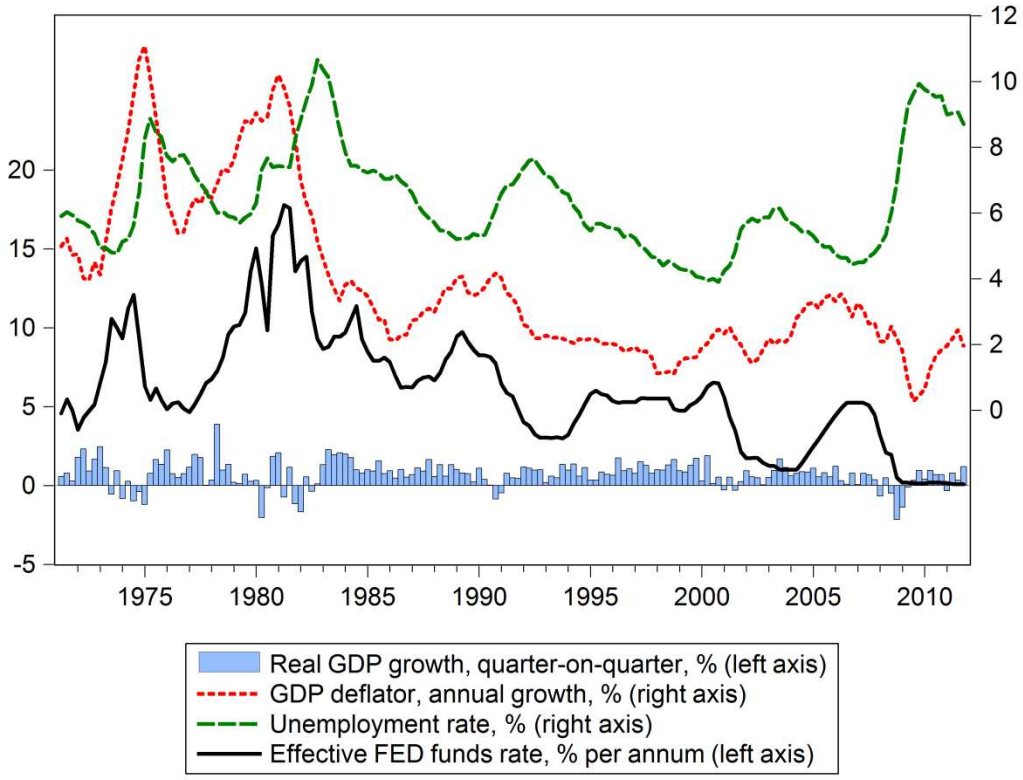
For the next 24 years, from 1983Q1 to 2007Q2, the Federal Reserve (FED) was successful in keeping inflation below 4.5% per annum. The policy interest rate followed inflation developments closely. The unemployment rate peaked at 7.6% in 1992Q3 and 6.1% in 2003Q2 but usually was within a range of 4–6%. During this period, the US economy experienced only one short recession (1990Q4–1991Q1) and two mild negative growth quarters in 2001 (not two consecutive quarters, but still classified as a recession by the NBER's Business Cycle Dating Committee – see NBER, 2014) at the time of the bursting of the `dot-com' bubble. Following this short downturn, unemployment kept rising until 2003Q2. The FED then decided to keep the policy rate at a low level of 1–2% per annum, being fearful of a recession comeback. After the expansion measures gained momentum, unemployment declined and prices increased, the federal funds rate increased to 5.2% per annum in 2006Q3 and stayed there until 2007Q2 (for more details, see Labonte, 2014).

Some dramatic changes happened since the financial crisis starting in 2007Q3. Initiating in the subprime housing market, the crisis spread to the financial sector and then to the macro economy. In spite of a short pick up in 2008Q2, the US economy entered a

[2] `Recession' is defined as two consecutive quarters of negative real GDP growth. The US National Bureau of Economic Research (NBER) has a different definition of recession (NBER, 2014).

severe recession until 2009Q2 and continued to have low growth. Although inflation was not an issue, unemployment rose to a peak of nearly 10% at 2009Q4. In response, the federal funds rate was pushed down to unprecedented levels. Starting in September 2007, in a series of ten moves, the FED decreased the target of its policy rate until it arrived at `between 0 and 0.25% per annum' and kept it there until the end of 2011 (even until now in 2014). Because of this technical zero lower bound (ZLB), since then the FED has had to use unconventional expansion packages (`quantitative easing' – QE) as the main tool of monetary policy rather than the federal funds rate target.[3]

Figure 1 Key economic indicators in the US, 1971Q2–2011Q4



Sources: see Appendix A.

[3] Other unconventional methods include direct credit facilities to banks and non-bank institutions; central bank liquidity swaps with the ECB, Bank of Japan, and others; and forward guidance to affect expectations (see Labonte, 2014).

As argued by Stevens (1999) and Mishkin and Schmidt-Hebbel (2001), being able to gain credibility in achieving and maintaining low and stable inflation for an extended period since 1983 might be one of the reasons why the FED has not switched to an inflation targeting regime, despite its adoption in other countries such as New Zealand, Canada, the UK, Australia. At the end of 2011, the statutory role of the FED was still the dual mandate of maximum employment and stable prices.[4]

2.2. UK

Figure 2 presents a similar pattern of key indicators for the UK's economy. Inflation was high in the 1970s until 1982Q4, with peaks of 28.2% in 1975Q2 and 22.5% in 1980Q2 due to the oil price shocks, more than double the respective inflation levels in the US. Three recessions happened in the UK in this period, with the longest lasting for more than a year (from 1980Q1 to 1981Q1). Unemployment was low during the 1970s, but increased to 10.5% in 1982Q4. The policy interest rate also fluctuated frequently in response to the developments of inflation and unemployment/economic growth, with the peak as high as 17% per annum in 1980Q2.

Unlike in the US, inflation in the UK did not maintain a decline throughout the 1980s. Inflation began to rise in 1986Q1 and stayed around 7–8% until the end of 1991. The policy rate was raised and kept as high as nearly 15% per annum. The UK then experienced a long recession from 1990Q3 to 1991Q3.[5]

After the British Sterling left the European Exchange Rate Mechanism (ERM), the Bank of England took up inflation targeting from October 1992. The UK then experienced a long period of low and stable inflation, steady economic growth, and solid employment (the Great Moderation). Inflation was kept within the band 1.5–3.5%, GDP growth remained continuously positive until 2008Q1, while the unemployment rate gradually decreased and stayed around 4.5–5.5%. The policy interest rate was kept within 3.5–7.3% per annum.

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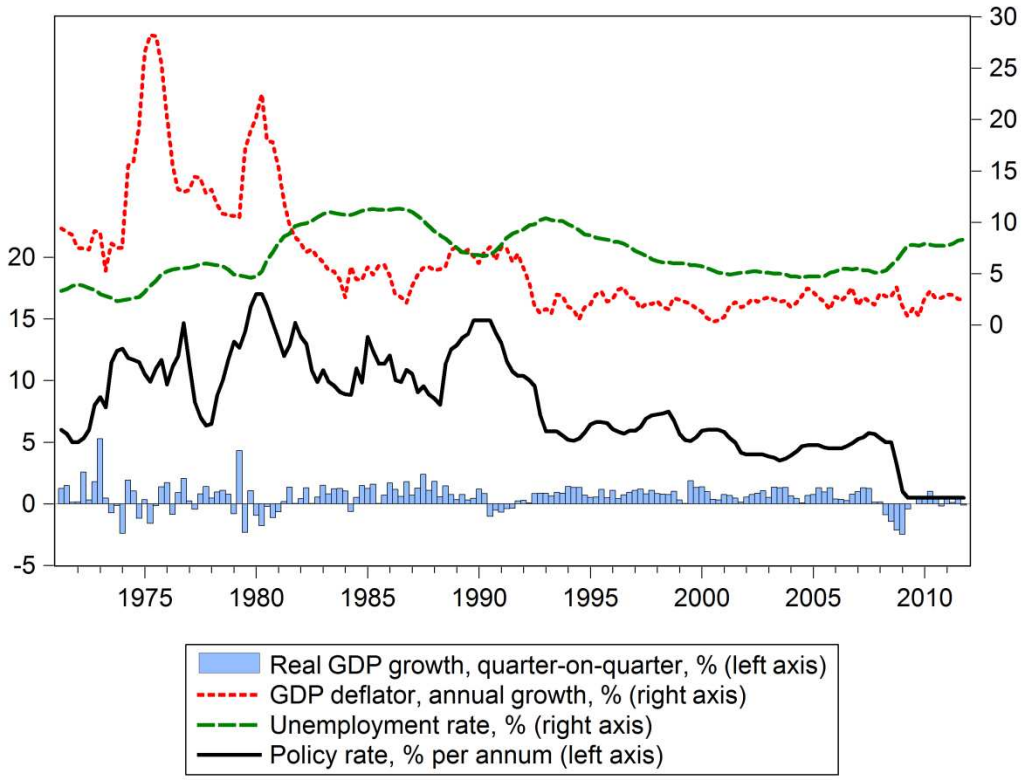
[4] The full statutory mandate of the FED includes `maximum employment, stable prices, and moderate long-term interest rates'. Recently some economists have proposed to switch the FED's mandate to an inflation targeting regime (see Labonte, 2014).

[5] King (1994, 2002) argues that `debt deflation' might have been the main cause of this recession in the UK.

Among the four countries studied in this paper, the UK was perhaps the second-most affected by the GFC after the US. The economy experienced five consecutive quarters of negative growth in 2008Q2–2009Q3, while unemployment increased from 5.1% in 2008Q1 to 8.3% in 2011Q4. The inflation rate fell below the target band of 1.5–3.5% to 0.9% in 2009Q2 and 2009Q4. As a result, the policy rate was pushed down sharply from 5% per annum in 2008Q3 to 0.5% per annum in 2009Q2, and stayed there until the end of 2011. Inflation did come back to the target band in 2009Q3, however unemployment kept increasing and GDP growth was low and unstable.

Figure 2 Key economic indicators in the UK, 1971Q2–2011Q4



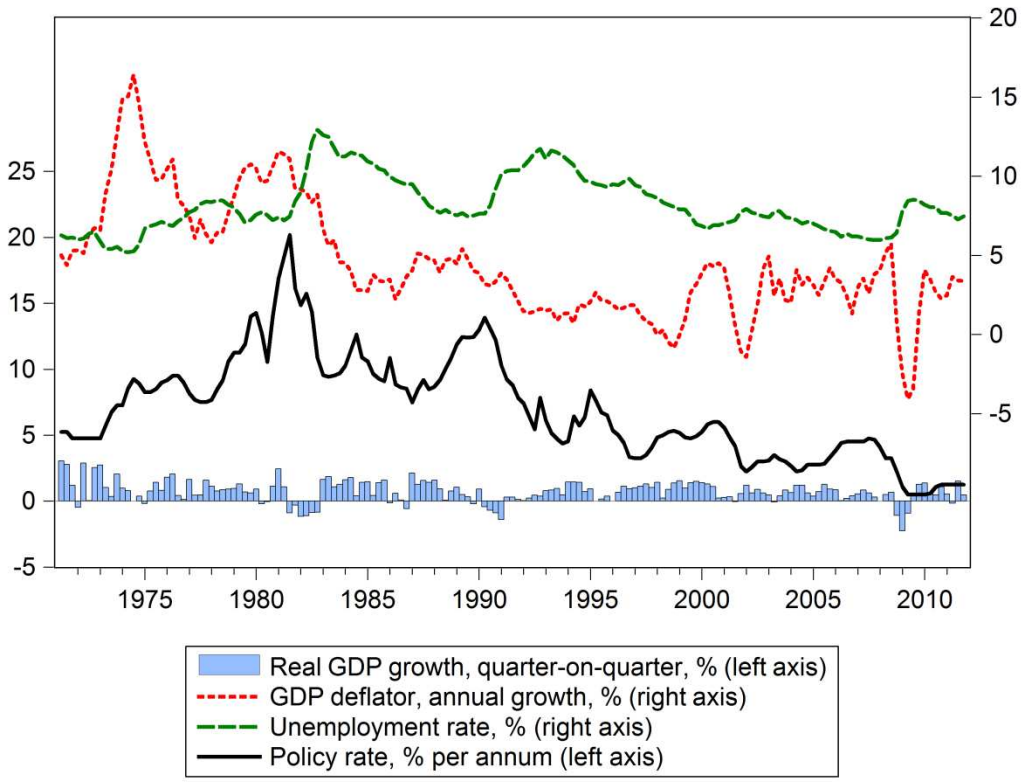
Sources: see Appendix A.

2.3. Canada

Figure 3 shows the macroeconomic indicators in Canada during the period 1971Q2–2011Q4. Similarly to the US and UK, the 1970s and early 1980s featured high and variable inflation, increasing unemployment, and unstable growth in Canada. The country

experienced six consecutive quarters of negative growth in 1981Q3–1982Q4. Inflation peaked at 15.1% in 1974Q2, then 11.4% in 1981Q2, while unemployment climbed to 12.9% in 1982Q4. The policy rate (the bank rate) was raised to 20.2% per annum in 1981Q3 to fight inflation, then was pushed down sharply to 9.4% per annum in 1983Q2 to counteract high unemployment and low economic growth.

Figure 3 Key economic indicators in Canada, 1971Q2–2011Q4



Sources: see Appendix A.

The Bank of Canada began to apply inflation targeting in February 1991, only second to New Zealand in the developed world. Just before that time, Canada suffered a recession from 1990Q2–1991Q1 and an increase in its unemployment rate since 1990Q2. During the Great Moderation, there were sub-periods when inflation fluctuated in Canada. Inflation fell to less than zero at some times (such as around 1998Q4 and 2001Q1), but also increased to 4.5–5% around 2001Q1 and 2003Q1. GDP growth was stable, and the unemployment rate kept declining right up until 2008Q2, when the GFC hit.

In 2008Q2 and 2008Q3, inflation climbed to 5.2% and 5.3% respectively, followed by a sharp fall to deep deflation of -4.1% in 2009Q2. Canada's economy went into recession for 2008Q4–2009Q2, while unemployment peaked again at 8.5% in 2009Q3. The policy interest rate was pushed down remarkably to 0.5% per annum in 2009Q2 and remained unchanged before being lifted to more than 1% per annum in late 2010.

2.4. Australia

In Australia (see Figure 4), the period 1971Q2–1993Q1 featured fluctuations in real GDP growth, inflation, and unemployment. Within 22 years, Australia experienced six periods of recession, the longest of which lasted four consecutive quarters from 1982Q3 to 1983Q2. Inflation ranged from 3.8% in 1984Q4 to a peak of 18.8% in 1974Q4, with many sub-periods of sharp rises or declines, before easing since 1991. Unemployment also climbed to 10.2% in 1983Q2. In response, the policy rate in this period changed with high frequency and variance. It ranged from 4.6% per annum in 1972Q4 to peaks of 18–19.5% per annum (in 1974Q2, 1982Q2, 1985Q4, and 1989Q4). During the short period from 1991Q3 to 1993Q1, Australia's GDP growth rate was positive, and inflation was low (less than 2%). However, unemployment was high, with a peak of 11.1% in 1992Q4. The RBA therefore had to decrease its policy rate from 10% per annum to around 5%. This move appeared to help bring down unemployment. The unemployment rate continued its downward trend for a long period until the recent GFC.

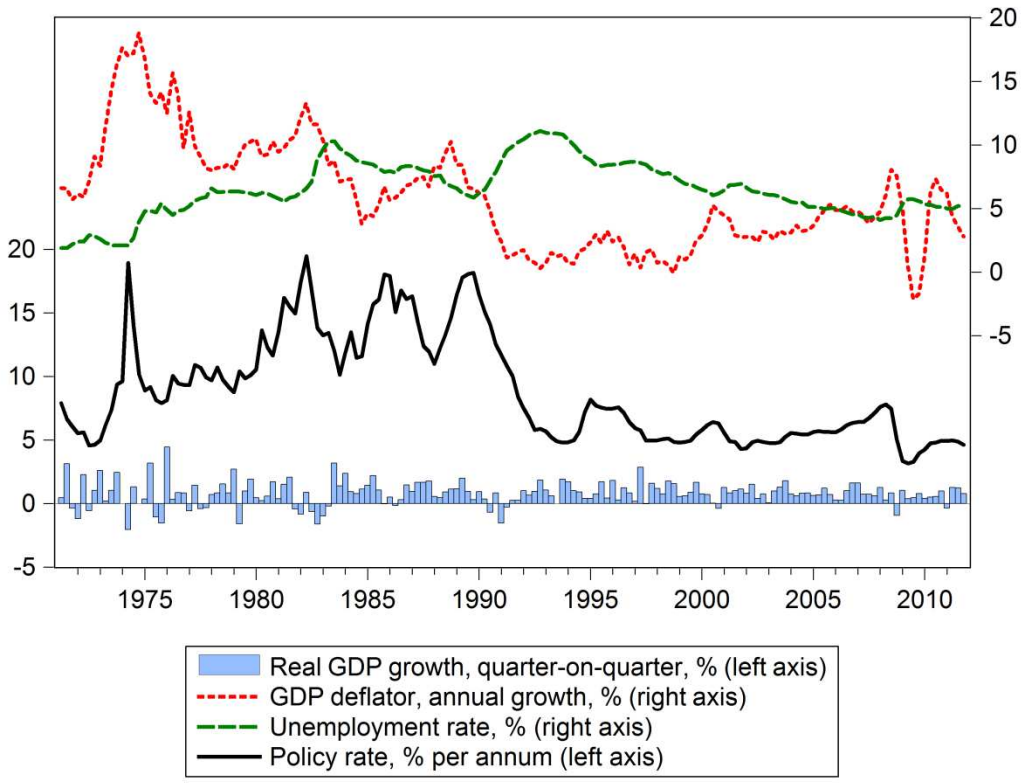
The Reserve Bank of Australia (RBA) began an inflation targeting regime in the middle of 1993 (see Stevens, 1999)[6], with an inflation target of 2–3%. As suggested by Stevens (1999), the regime might have brought decent economic outcomes as well as enhanced the RBA's credibility, and therefore equipped the RBA with more flexibility in its policy to deal with exogenous shocks. Australia's macroeconomic performance has generally been good since, with a long period of stable economic growth and no recession.

[6] Mishkin and Schmidt-Hebbel (2001) marked September 1994 as the official commencement of inflation targeting in Australia.

During 1997–1998, in response to the Asian financial crisis with some signals of disinflation (the inflation rate fell to 0.3% in 1997Q2), the RBA decreased its policy rate (the cash rate) from 5.8% to 5% per annum, then kept it steady at around 4% per annum for more than 2 years. Australia managed to escape the Asian financial crisis without a quarter of negative growth. In 1999Q4 inflation came back to 2.5%. However, inflation rose to 5.2% in 2000Q3, leading the RBA to raise its policy rate to 6.4% per annum, which once again helped bring inflation back to its target band.

During the recent GFC, the policy rate fell sharply from 7.4% per annum in 2008Q2 to 3.4% per annum in 2009Q1. Together with the fiscal stimulus packages in 2009 (see, for example, Leigh, 2012) as well as the effects of the `mining boom' (Day, 2011), Australia avoided the recession that most other OECD countries (including the other three countries in this paper) experienced. The unemployment rate was kept stable at around 4–5.5%, except for a short increase in 2009Q2.

Figure 4 Key economic indicators in Australia, 1971Q2–2011Q4



Sources: see Appendix A.

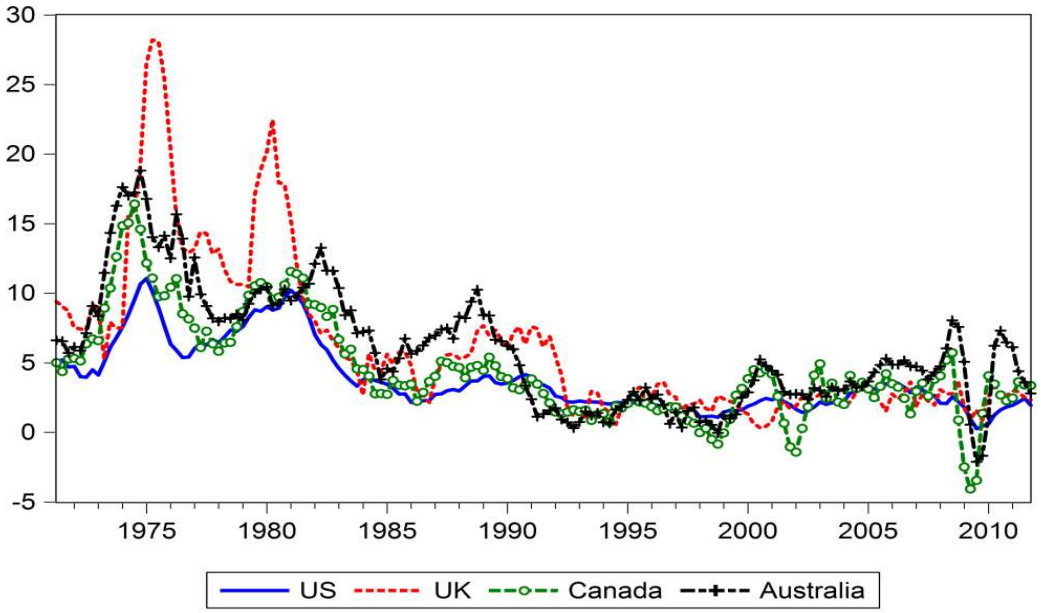
2.4. Similarities of key indicators across countries

Figures 5–7 show combined graphs of inflation, unemployment, and the policy rate respectively across the four countries. Tables 1–3 show pairwise correlation coefficients of inflation, unemployment, and the policy rate among the countries. All the correlation coefficients are significantly positive. The figures and tables indicate highly similar patterns for the movements of these variables across the four countries during the period of interest.

In the next section we will introduce the TVP-VAR model that we will use to gain insights into the policy rate reactions to changes of inflation and unemployment as well as the impulse response functions of inflation and unemployment to the policy rate shocks across the four countries, plus how these have changed over time.

Figure 5 Inflation rate in the four countries, 1971Q2–2011Q4

(Unit: %)



Sources: see Appendix A.

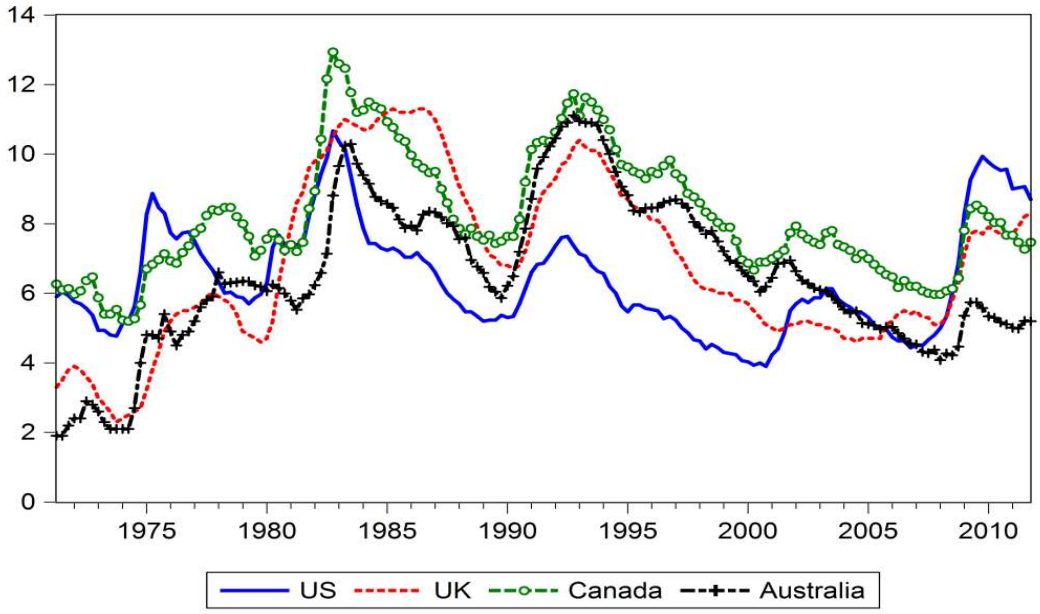
Table 1 Pairwise correlation of inflation in the four countries, 1971Q2–2011Q4

Country	US	UK	CAN	AUS
US	X			
UK	0.88***	X		
CAN	0.89***	0.77***	X	
AUS	0.82***	0.74***	0.90***	X

Notes: ***, **, * denote significance at 1%, 5%, and 10% respectively; 'X' = '1.00***'.

Figure 6 Unemployment rate in the four countries, 1971Q2–2011Q4

(Unit: %)



Sources: see Appendix A.

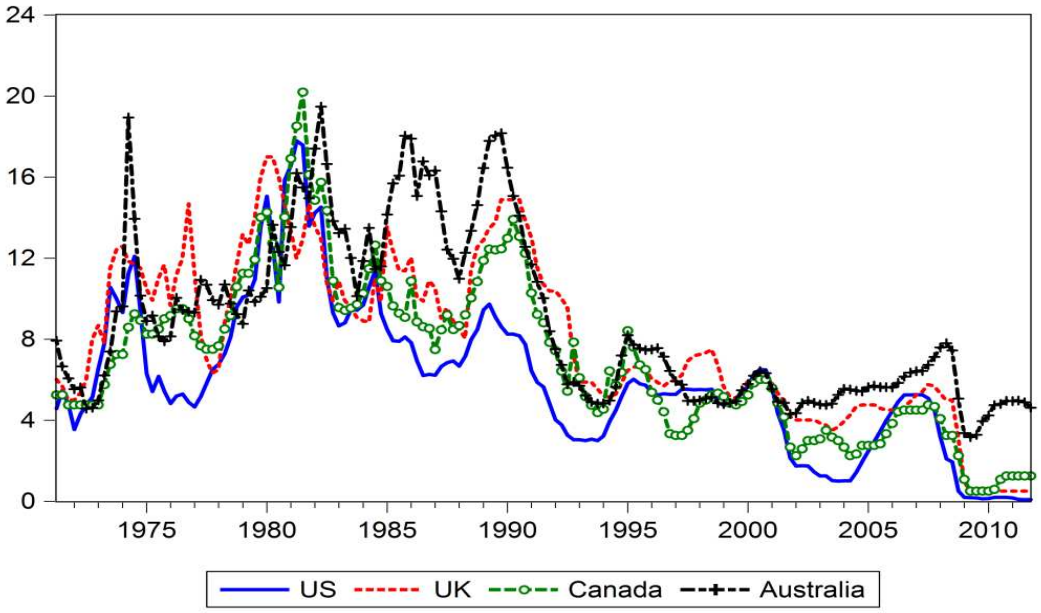
Table 2 Pairwise correlation of unemployment in the four countries, 1971Q2–2011Q4

Country	US	UK	CAN	AUS
US	X			
UK	0.48***	X		
CAN	0.47***	0.86***	X	
AUS	0.18**	0.79***	0.89***	X

Notes: ***, **, * denote significance at 1%, 5%, and 10% respectively; 'X' = '1.00***'.

***Figure** 7 Policy interest rate in the four countries, 1971Q2–2011Q4*

(Unit: % per annum)



Sources: see Appendix A.

Table 3 Pairwise correlation of the policy rate in the four countries, 1971Q2–2011Q4

Country	US	UK	CAN	AUS
US	X			
UK	0.83***	X		
CAN	0.91***	0.89***	X	
AUS	0.74***	0.78***	0.83***	X

Notes: ***, **, * denote significance at 1%, 5%, and 10% respectively; 'X' = '1.00***'.

3. The TVP-VAR model

3.1. The model

Led by Sims (1980), many papers employ VAR models to investigate the monetary policy transmission mechanism. Some summaries of the VAR literature can be found in Canova (1995), Bagliano and Favero (1998) and Christiano *et al.* (1999).

A limitation of VAR models is that they rely on an assumption of constant coefficients and constant variances throughout the period of interests. It means if structural breaks happened sometime during the period, the VAR estimates are not correct anymore. Therefore, a constant-parameter VAR analysis must be limited on free-structural-break periods only, which are normally not very long. To overcome this drawback, Cogley and Sargent (2001, 2005) propose a VAR model with time-varying coefficients. Primiceri (2005) follows with his influential paper introducing a VAR model allowing all parameters (coefficients, variances and co-variances, and parameters relating structural shocks) to be time-variant.

In this paper, we use parsimonious TVP-VAR models with stochastic volatility of the kind used by Primiceri (2005) and Nakajima (2011). The basic TVP-VAR model consists of three basic variables: inflation, unemployment, and policy interest rate. This simple three-variable model is similar to Gerlach and Smets (1995), Cogley and Sargent (2001), Primiceri (2005), and Nakajima (2011). As Australia is a small, open economy, the exchange rate is added into the TVP-VAR for Australia. Due to significant increases in complexity relating to priors of parameters, we leave larger models with more variables for future research.

In the TVP-VARs, we assume a recursive identification, in which the order of variables is similar to Primiceri (2005): inflation, unemployment, and policy interest rate. This order implies the identification assumption that a shock in the nominal policy interest rate affects unemployment and inflation only with a lag. At the same time, central bankers use a possible information set, which includes current inflation rate and unemployment rate (together with lags of all three variables), in deciding the policy rate. The order between inflation and unemployment turns out to be unimportant in the aspect that the main results are qualitatively unchanged if unemployment is placed in front of inflation in the TVP-VAR

models used in this paper. For the case of Australia, exchange rate locates last (behind the policy rate).

TVP-VAR models are built on basic structural VAR (SVAR) models as follows:

$$Ay_t = F_1 y_{t-1} + \cdots + F_s y_{t-s} + u_t \ , t = s+1, \ldots, n, \quad (1)$$

where y_t is a $k \times 1$ vector of variables, $A, F_1, \ldots, F_s$ are $k \times k$ matrices of coefficients, and u_t is a $k \times 1$ vector of structural shocks. Assume $u_t \sim N(0, \Sigma\Sigma')$, where

$$\Sigma = \begin{bmatrix} \sigma_1 & 0 & \cdots & 0 \\ 0 & \ddots & \ddots & \vdots \\ \vdots & \ddots & \ddots & 0 \\ 0 & \cdots & 0 & \sigma_k \end{bmatrix}.$$

The simultaneous relations of the structural shock are identified using a recursive assumption, therefore A is a lower-triangular matrix:

$$\mathrm{A} = \begin{bmatrix} 1 & 0 & \cdots & 0 \\ a_{21} & \ddots & \ddots & \vdots \\ \vdots & \ddots & \ddots & 0 \\ a_{k1} & \cdots & a_{k,k-1} & 1 \end{bmatrix}.$$

The reduced form of (1) is $y_t = B_1 y_{t-1} + \cdots + B_s y_{t-s} + A^{-1}\Sigma\varepsilon_t$, where $\varepsilon_t \sim N(0, I_k)$, $B_i = A^{-1}F_i$ for $i = 1, \ldots, s$. Stacking the elements in the rows of the B_is to form β ($k^2 s \times 1$ vector), and defining $X_t = I_k \otimes (y'_{t-1}, \ldots, y'_{t-s})$, in which $\otimes$ denotes the Kronecker product, the VAR model then can be written as

$$y_t = X_t \beta + A^{-1}\Sigma\varepsilon_t. \quad (2)$$

The time-invariant model (2) is extended to TVP-VAR by allowing the parameters to be time-varying. It means now the model becomes:

$$y_t = X_t \beta_t + A_t^{-1}\Sigma_t\varepsilon_t, \quad (3)$$

so that β_t, A_t, and Σ_t are time-varying parameters.

Following Primiceri (2005), let $a_t = (a_{21}, a_{31}, a_{32}, \ldots, a_{k,k-1})'$ be a stacked vector of the lower-triangular elements in A_t; $h_t = (h_{1t}, \ldots, h_{kt})'$ with $h_{jt} = \log \sigma_{jt}^2$ for $j = 1, \ldots, k$ and $t = s+1, \ldots, n$.

Assuming that the parameters in (3) follow a random walk process:

$$\beta_{t+1} = \beta_t + u_{\beta t},\ a_{t+1} = a_t + u_{at},\ h_{t+1} = h_t + u_{ht},$$

$$\begin{pmatrix} \varepsilon_t \\ u_{\beta t} \\ u_{at} \\ u_{ht} \end{pmatrix} \sim N\left(0, \begin{pmatrix} I & O & O & O \\ O & \Sigma_\beta & O & O \\ O & O & \Sigma_a & O \\ O & O & O & \Sigma_h \end{pmatrix}\right),$$

for $t = s+1, \ldots, n$, where $\beta_{s+1} \sim N(\mu_{\beta_0}, \Sigma_{\beta_0})$, $a_{s+1} \sim N(\mu_{a_0}, \Sigma_{a_0})$, and $h_{s+1} \sim N(\mu_{h_0}, \Sigma_{h_0})$. As in Nakajima (2011), Σ_a and Σ_h are also assumed to be diagonal matrices.

3.2. The estimation

Let $y = \{y_t\}_{t=1}^n$, and $\omega = (\Sigma_\beta, \Sigma_a, \Sigma_h)$. The estimation of TVP-VAR models are based on Bayesian econometric principles. The prior probability density of ω is set as $\pi(\omega)$. Given data y, samples are drawn from the posterior distribution $\pi(\beta, a, h, \omega|y)$ using the following Markov chain Monte Carlo (MCMC) algorithm:

(1) Initialise $\beta, a, h,$ and ω,

(2) Sample $\beta|a, h, \Sigma_\beta, y$,

(3) Sample $\Sigma_\beta|\beta$,

(4) Sample $a|\beta, h, \Sigma_a, y$,

(5) Sample $\Sigma_a|a$,

(6) Sample $h|\beta, a, \Sigma_h, y$,

(7) Sample $\Sigma_h|h$,

(8) Go to step (2).

The specific sampling process is illustrated as follows:

3.2.1. β sampling

In order to sample β from the conditional posterior distribution, the state space model is defined as:

$y_t = X_t\beta_t + A_t^{-1}\Sigma_t\varepsilon_t,$

$\beta_{t+1} = \beta_t + u_{\beta_t}$, where $t = s+1, \dots n$, $\beta_s = \mu\beta_0$, $u_{\beta_s} \sim N(0, \Sigma_0)$.

The simulation smoother requires a more general-form state space model as in de Jong and Shephard (1995):

$y_t = X_t\beta + Z_t\alpha_t + G_t u_t, \ t = 1, \dots n,$

$\alpha_{t+1} = T_t\alpha_t + H_t u_t, \ t = 1, \dots n,$

$X_t\beta = 0_k, \qquad Z_t = X_t, \qquad G_t = (A_t^{-1}\Sigma_t, O_{k_\beta}),$

$T_t = I_{k_\beta}, \qquad H_t = (O_k, \Sigma_\beta^{1/2}), \qquad H_0 = (O_k, \Sigma_{\beta_0}^{1/2}),$

where k_β is the number of rows of β_t.

3.2.2. a sampling

The state space model used to sample a is written as follows:

$\hat{y}_t = \hat{X}_t a_t + \Sigma_t \varepsilon_t, \qquad t = 1, \dots n,$

$a_{t+1} = a_t + u_{a_t}, \qquad t = s, \dots n-1,$

where $a_s = \mu a_0$, $u_{a_s} \sim N(0, \Sigma_{a_0})$, $\hat{y}_t = y_t - X_t\beta_t$, and

$$\hat{X}_t = \begin{bmatrix} 0 & \cdots & & & & & & 0 \\ -\hat{y}_{1t} & 0 & 0 & \cdots & & & & \vdots \\ 0 & -\hat{y}_{1t} & -\hat{y}_{2t} & & & & & \\ 0 & 0 & 0 & -\hat{y}_{1t} & \cdots & & & \\ \vdots & & & & \ddots & 0 & \cdots & 0 \\ 0 & \cdots & & & 0 & -\hat{y}_{1t} & \cdots & -\hat{y}_{k-1,t} \end{bmatrix}, \quad t = s+1, \dots n.$$

The correspondences for the simulation smoother are defined as

$X_t\beta = 0_k, \qquad Z_t = \hat{X}_t, \qquad G_t = (\Sigma_t, O_{k_a}),$

$T_t = I_{k_a}, \qquad H_t = (O_k, \Sigma_a^{1/2}), \qquad H_0 = (O_k, \Sigma_{a_0}^{1/2}),$

where k_a is the number of rows of a_t.

3.2.3. h sampling

It is assumed that Σ_h and Σ_{h_0} are diagonal matrices. Therefore the inference for elements of the stochastic volatility h, $\{h_{jt}\}_{t=s+1}^{n}$, is made separately for $j\ (=1,\dots,k)$. Denote y_{it}^{*} as the i-th element of $A_t\hat{y}_t$, then:

$$y_{it}^{*} = \exp(h_{it}/2)\varepsilon_{it}, \quad t = s+1,\dots n,$$

$$h_{i,t+1} = h_{it} + \eta_{it}, \qquad t = s,\dots n-1,$$

$$\begin{pmatrix}\varepsilon_{it}\\ \eta_{it}\end{pmatrix} \sim N\left(0, \begin{pmatrix}1 & 0\\ 0 & v_i^2\end{pmatrix}\right),$$

where $\eta_{is} \sim N(0, v_{i_0}^2)$, v_i^2 and $v_{i_0}^2$ are the i-th diagonal elements of Σ_h and Σ_{h_0} respectively, and η_{it} is the i-th element of u_{ht}.

3.2.4. ω sampling

Components of ω (Σ_β, Σ_a, and Σ_h) are sampled separately as per their specified prior distributions.[7] Given the data, the following priors are assumed for the i-th diagonals of the covariance matrices: $(\Sigma_\beta)_i^{-2} \sim Gamma(20, 10^{-4})$, $(\Sigma_a)_i^{-2} \sim Gamma(4, 10^{-4})$, and $(\Sigma_h)_i^{-2} \sim Gamma(4, 10^{-4})$.

More details on the estimation process of the TVP-VAR model can be found in Nakajima (2011).

4. Data

For the purpose of this paper, 163 observations of quarterly data for the period 1971Q2–2011Q4 are used.[8] Since the parameters are allowed to time-vary, the recent GFC since 2007Q3 is included in the analysis of this paper. However, my emphasis will be on the

[7] Some other technical aspects of the TVP-VAR modelling such as degrees of freedom and the priors are discussed in more detail by Primiceri (2005). Chapters 4 and 6 of this thesis concentrate on empirically applying the TVP-VAR models used by Primiceri (2005) and Nakajima (2011) in examining monetary policy and transmission in specific countries. For a recent summary on specification searches for TVP-VARs, see Eisenstat *et al.* (2015).

[8] Real-time data (the data that were available at the time policy decisions are made) might also be employed for monetary policy reaction analysis, as suggested by Orphanides (2001), Croushore and Evans (2006), and Lee *et al.* (2012).

pre-GFC sub-period (1971Q2–2007Q2) because the recent GFC features the problem of a zero lower bound in the policy interest rates and an increasing role of unconventional monetary policy, especially in the US and UK. The time period stops at 2011 to avoid the biases of a prolonged period of near-zero policy interest rates in the countries. For more details on the effects of unconventional monetary policy in the context of the recent GFC, see the work of Baumeister and Benati (2013).

The TVP-VAR models are estimated with a two-lag structure, as also done by Primiceri (2005), Baumeister and Benati (2013), and others. A detailed list of data sources is provided in Appendix A. Inflation is calculated by the annual growth rate of the GDP deflator. The unemployment rate is measured for the whole labour force in each country. The effective Federal Funds rate is used as the policy rate for the US, while the discount rate, the bank rate, and the 90-day bank accepted bill rate are used for the UK, Canada, and Australia respectively. For the UK, Canada, and Australia, the logs of the USD/local currency rates are added for the movement of the exchange rates. To estimate the 4-variable TVP-VARs, the matrix Σ_β is set to be diagonal. The simulations are based on 20,000 iterations of the Gibbs sampler using MATLAB codes developed by Nakajima (2011). The convergence of the Markov chain Monte Carlo algorithm for all estimations is provided in Appendix B.

5. Results

5.1. How monetary policy has changed over time across countries?

As reviewed in Boivin and Giannoni (2006) and Gali and Gambetti (2009), monetary policy reactions might provide insights into how aggressive monetary policy has been against unemployment and inflation/deflation over time. This section explores monetary policy reactions to unemployment and inflation respectively. Unlike Primiceri (2005), in this paper the changes of inflation/unemployment are assumed to be temporary rather than permanent. The policy reactions are therefore short-run reactions rather than being close to long-run parameters in the Taylor rule. The size of a temporary shock in unemployment/inflation is assumed to be a one percentage point increase.

The policy reaction functions here are estimated simply from the parsimonious TVP-VARs rather than a formal Taylor rule estimation. Suggestions for more comprehensive

estimation of `meta' Taylor rules for the cases of the US, UK, and Australia can be found in the works of Lee *et al.* (2011, 2013).

5.1.1. Monetary policy reaction to unemployment

The posterior means of the monetary policy reaction to a one percentage point increase in unemployment in the four countries are presented in Figure 8 (for a 30-quarter horizon) and Figure 9 (at the 4th, 8th, and 12th quarter). Table 4 provides the pairwise correlation of the policy responses to unemployment among the countries for two sub-periods: 1971Q2–2007Q2 (pre-GFC) and 2007Q3–2011Q4 (since GFC) at the 4th, 8th, and 12th quarters. Three main patterns can be observed from Figures 8 and 9 and Table 4, as follows.

First, comovements in the monetary policy reactions to unemployment across the countries are observed for the pre-GFC period, especially over short-run horizons. Most of the pairwise correlation coefficients at the 4th quarter are significantly positive.

Second, it is observable that the policy rate responds immediately and expectedly to unemployment in all four countries. The policy rate falls in response to a one percentage point increase in unemployment and remains under its steady state level at the 4th, 8th, and 12th quarters.

Third, the policy rate appears to react slightly more aggressively against unemployment over time. This pattern is evidenced by the downward trend of the policy responses at the 4th quarter.

In addition to the graphs of responses for the whole period, we also selected several time points to illustrate the changes of the monetary policy reactions over time in the four countries. Six time points are chosen: the second quarters of 1975, 1985, 1993, 1998, 2003, and 2008. 1975Q2 is in the centre of the oil price shock period of the 1970s, 2008Q2 is at the early days of the current GFC, while the other four points are picked somewhat arbitrarily so that there is a distance of at least 5 years between them, with priority given to more recent years. These six time points are used throughout the paper.

The posterior means of the policy responses to unemployment at the six chosen time points shown in Figure 10 and Figure 11 support the three main patterns observed from Figures 8 and 9 and Table 4. In response to a one percentage point increase in unemployment, the policy rate declines immediately by around one percentage point per annum in all of the

four countries. The policy rate keeps decreasing by a peak of around 2–5 percentage points per annum after about 4–8 quarters.

A more aggressive trend in recent years is most notable in the US and UK. The US and UK also seem to demonstrate higher levels of reaction against unemployment compared to the other two countries. This result for the US is similar to the more aggressive trend of monetary policy against unemployment in the US found by Primiceri (2005), Judd and Rudebusch (1998), Clarida *et al.* (2000), Cogley and Sargent (2001, 2003), and Lubik and Schorfheide (2004).

Figure 8 Posterior means of the policy responses to a one percentage point increase in unemployment, 1971Q2–2011Q4 (30-quarter horizon)

(Unit: percentage point)

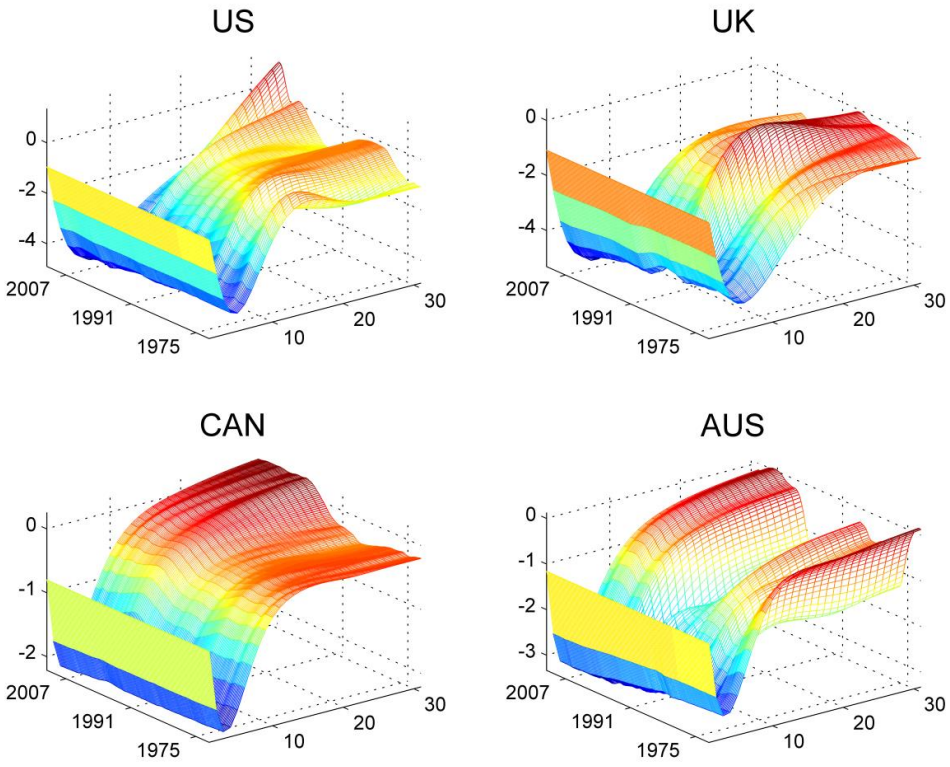
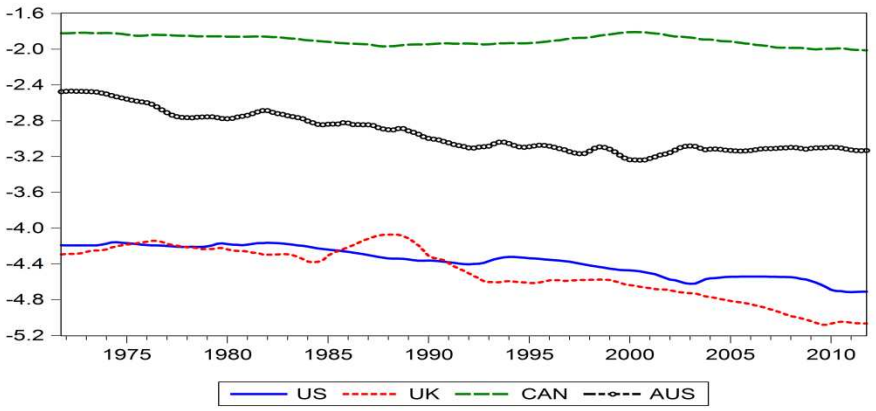


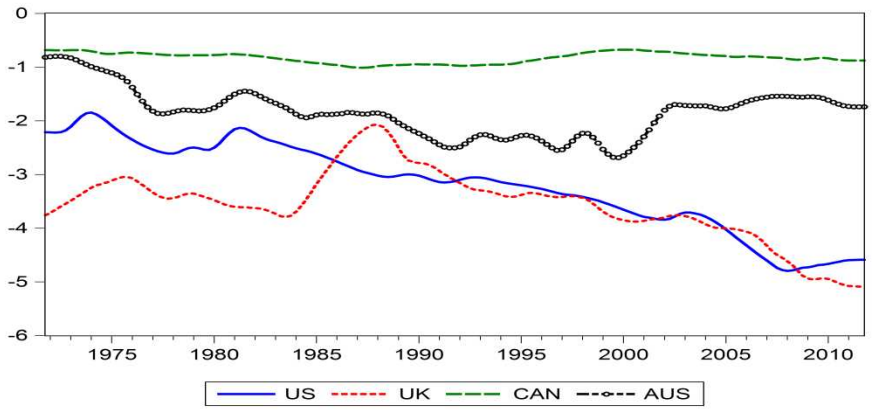
Figure 9 Posterior means of the policy responses to a one percentage point increase in unemployment, 1971Q2–2011Q4 (at 4th, 8th, 12th quarters)

(Unit: percentage point)

4th quarter



8th quarter



12th quarter

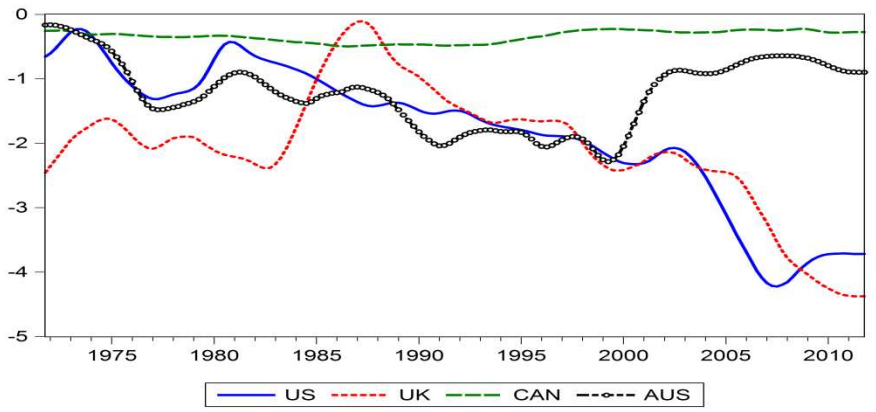


Table 4 Pairwise correlation of the policy rate responses to a one percentage point increase in unemployment, 1971Q2–2011Q4

Time	Country	1971Q2–2007Q2			2007Q3–2011Q4		
		US	**UK**	**CAN**	**US**	**UK**	**CAN**
4th quarter	**US**	X			X		
	UK	***0.83******	X		***0.79******	X	
	CAN	***0.26******	0.12	X	***0.73******	***0.77******	X
	AUS	***0.86******	***0.78******	***0.37******	***0.49******	0.29	***0.73******
8th quarter	**US**	X			X		
	UK	***0.39******	X		0.***79******	X	
	CAN	0.02	-0.65***	X	0.***77******	0.***64******	X
	AUS	***0.50******	-0.10	***0.38******	-0.94***	-0.61***	-0.87***
12th quarter	**US**	X			X		
	UK	***0.39******	X		***0.86******	X	
	CAN	-0.39***	-0.80***	X	***0.91******	***0.72******	X
	AUS	***0.17*****	-0.24***	***0.30******	-0.83***	-0.66***	-0.97***

Notes: ***, **, * denote significance at 1%, 5%, and 10% respectively; significantly positive correlations are in bold italics; 'X' = '1.00***'.

Figure 10 Posterior means of the policy responses to a one percentage point increase in unemployment across six specific time points

(Unit: percentage point; 30-quarter horizon)

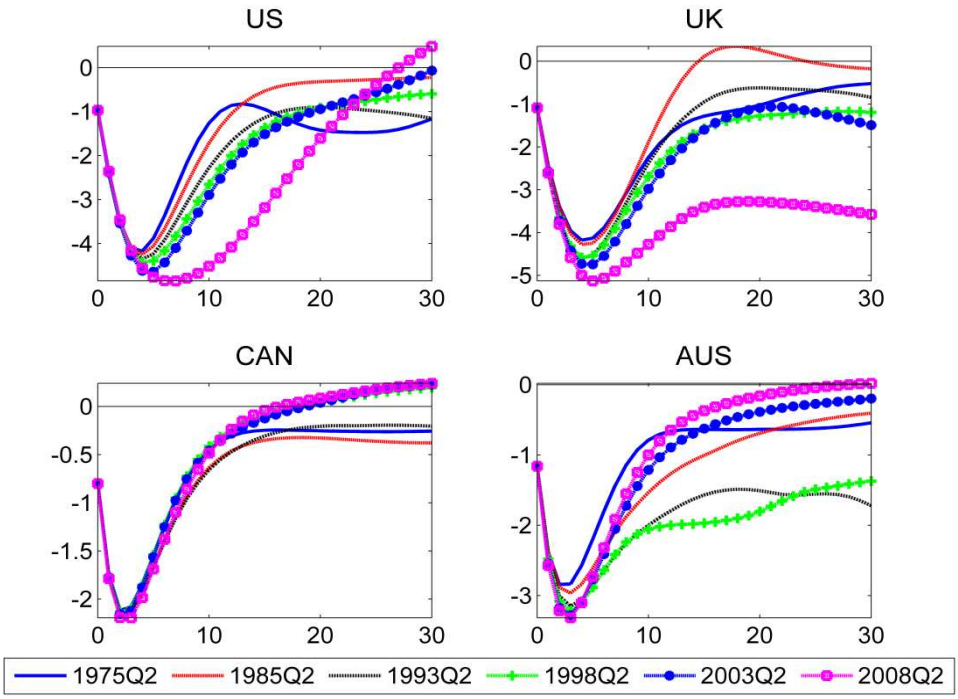
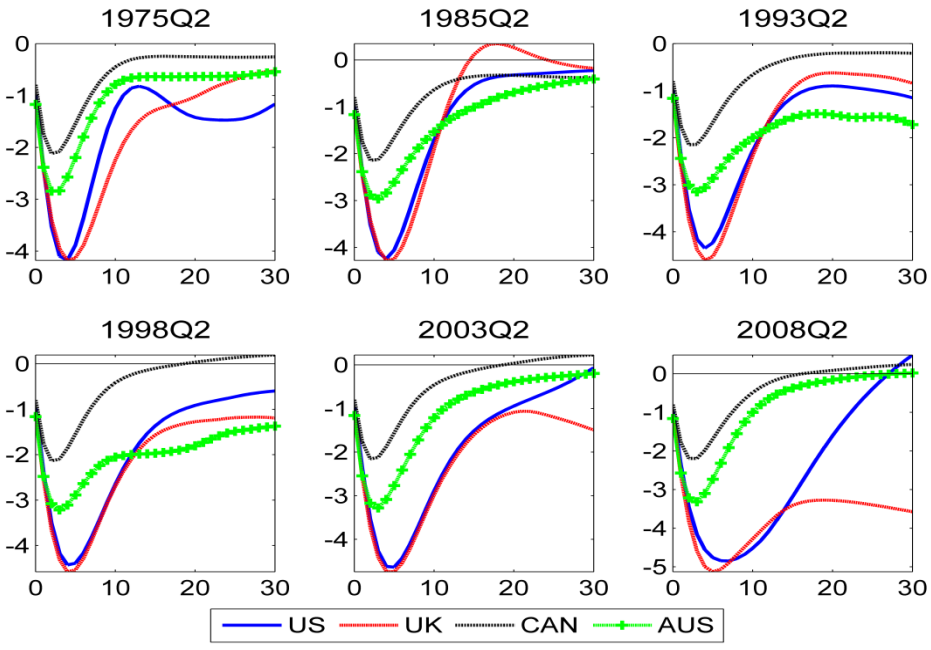


Figure 11 Posterior means of the policy responses to a one percentage point increase in unemployment at six specific time points across countries

(Unit: percentage point; 30-quarter horizon)



5.1.2. Monetary policy reaction to inflation

Figures 12 and 13 show the posterior means of the policy rate reactions to a one percentage point increase in inflation in the four countries for the whole 30-quarter horizon and at the 4th, 8th, and 12th quarters. Table 5 provides pairwise correlations of these policy rate responses across countries. From Figures 12 and 13 and Table 5, some key patterns can be observed.

First, the movements of the policy rate reactions to inflation seem not to be similar across the countries. Before the GFC, the policy rate responses in the US and UK are different compared to the ones in Canada and Australia. The pairwise correlation coefficients between the US and UK are significantly positive at the 4th, 8th, and 12th quarters, as are the correlations between Canada and Australia. However, the policy rate reactions of the two groups negatively correlate.

Second, although the changes in the monetary policy reactions are not similar across countries, it seems that the policy rate responds to inflation shocks in an expected way in all countries. An increase in inflation is followed by an increase in the policy rate. The policy rate remains below its steady level at all 4th, 8th, and 12th quarters.

Third, the US might show the most aggressive monetary policy reactions to inflation. For the whole period, the policy rate in the US appears to react most strongly to inflation, at all of the three specific horizons (4th, 8th, and 12th quarters). This pattern might relate to the fact that the US is the only country in this analysis that has not moved to an inflation-targeting regime. However, this hypothesis requires further study to be formally confirmed.

Notice that the assumption of a one percentage point increase in inflation is being imposed. During the recent GFC, inflation was not an issue in developed countries (unlike in some Asian developing countries; see, for example Tang, 2014). Therefore the term `inflation' here should be understood as `inflation or deflation'. Becoming more aggressive against deflation means the policy rate declines by a higher margin when price levels drop. As King (1994, 2002) suggests, deflation is as bad as inflation in certain circumstances,

therefore central banks should also be as aggressive against severe deflation as they should be against high inflation.

Figure 14 illustrates the posterior means of the monetary policy reactions to inflation at the (combined) six time points in each of the four countries, while Figure 15 shows the posterior means of the monetary policy reactions (combined) across the countries at each of the six time points. Figures 14 and 15 support the main features of Figures 12 and 13 and Table 5. In response to a one percentage point increase in inflation, the policy rate increases immediately and remains higher than its steady level over long horizons. Figures 14 and 15 also seem to emphasise the high level of aggressiveness of the monetary policy reactions in the US, which appears to stand out compared to the other countries.

The more aggressive monetary policy against inflation over time in the US is similar to what has been found by Judd and Rudebusch (1998), Clarida *et al.* (2000), Cogley and Sargent (2001, 2003), Lubik and Schorfheide (2004), and Primiceri (2005).

In general, there are comovements in the monetary policy reactions to unemployment across countries at the short horizons. However, the movements of the monetary policy reactions to inflation are not so similar and seem to be divided into two groups. The policy rate seems to react expectedly to changes in inflation and unemployment. The policy rate appears to respond more aggressively over time to changes in unemployment, and the US demonstrates the more aggressive policy reactions to inflation than the three inflation-targeting countries.

The more aggressive trend of monetary policy might reflect the fact that central banks have become more independent over time. Furthermore, it might also be because central banks switched from money and credit growth targets to using interest rates as their primary policy instrument after the oil price shocks in the 1970s (Labonte, 2014).

Figure 12 Posterior means of the policy rate responses to a one percentage point increase in inflation, 1971Q2–2011Q4 (30-quarter horizon)

(Unit: percentage point)

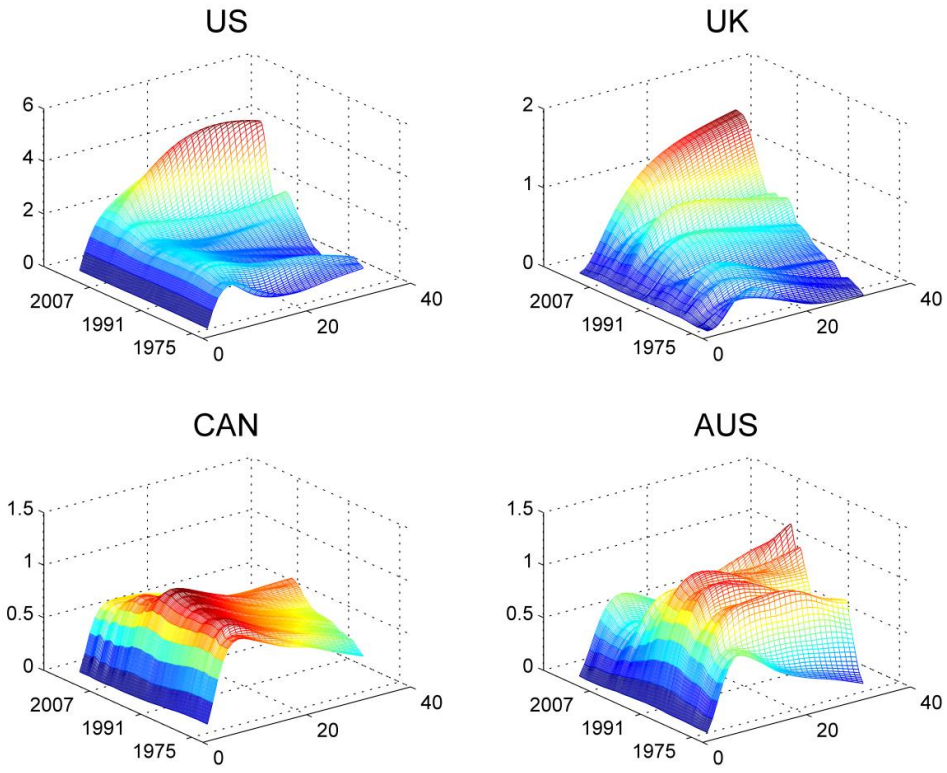
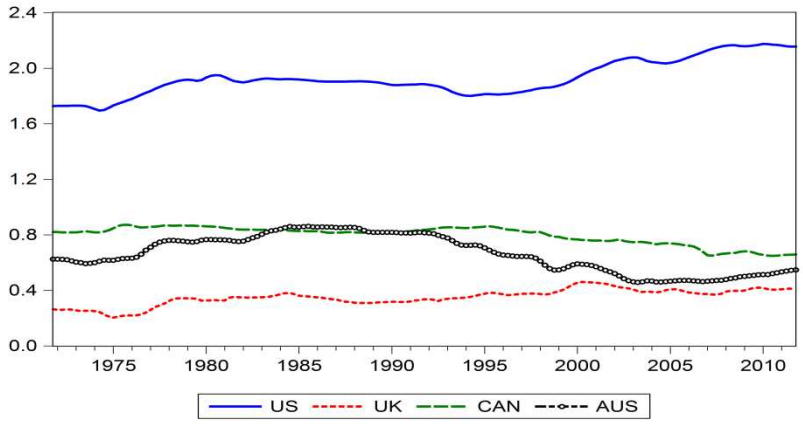


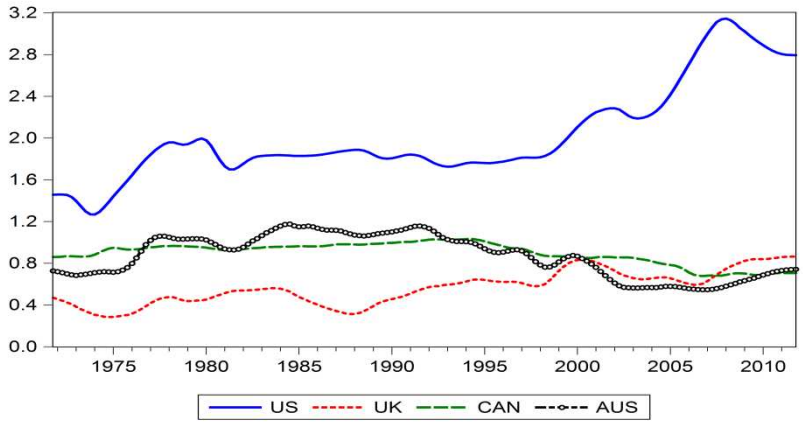
Figure 13 Posterior means of the policy rate responses to a one percentage point increase in inflation, 1971Q2–2011Q4 (at 4th, 8th, 12th quarters)

(Unit: percentage point)

4th quarter



8th quarter



12th quarter

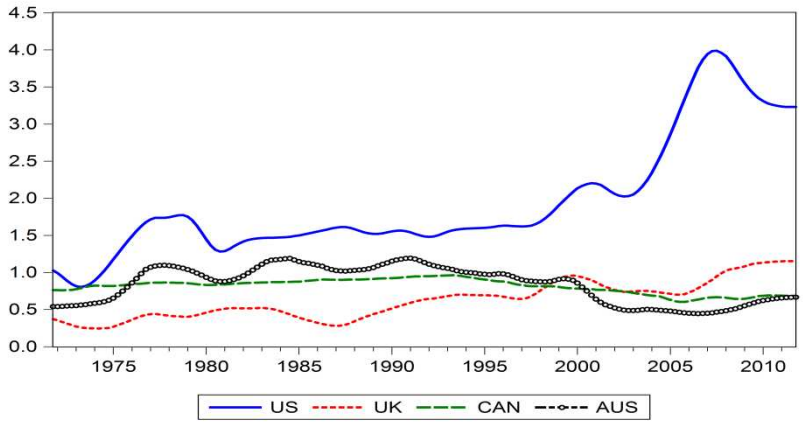


Table 5 Pairwise correlation of the policy rate responses to a one percentage point increase in inflation, 1971Q2–2011Q4

Time	Country	1971Q2–2007Q2			2007Q3–2011Q4		
		US	**UK**	**CAN**	**US**	**UK**	**CAN**
4th quarter	**US**	X			X		
	UK	***0.71******	X		-0.41*	X	
	CAN	-0.72***	-0.55***	X	***0.77******	-0.10	X
	AUS	-0.34***	-0.30***	***0.71******	0.11	-0.28	***0.47*****
8th quarter	**US**	X			X		
	UK	***0.56******	X		***0.63******	X	
	CAN	-0.65***	-0.36***	X	***0.92******	***0.65******	X
	AUS	-0.40***	-0.32***	***0.85******	-0.99***	-0.54**	-0.88***
12th quarter	**US**	X			X		
	UK	***0.63******	X		***0.80******	X	
	CAN	-0.67***	-0.37***	X	***0.96******	***0.66******	X
	AUS	-0.45***	-0.27***	***0.88******	-0.99***	-0.74***	-0.98***

Notes: ***, **, * denote significance at 1%, 5%, and 10% respectively; significantly positive correlations are in bold italics; 'X' = '1.00***'.

Figure 14 Posterior means of the policy rate responses to a one percentage point increase in inflation across six specific time points

(Unit: percentage point; 30-quarter horizon)

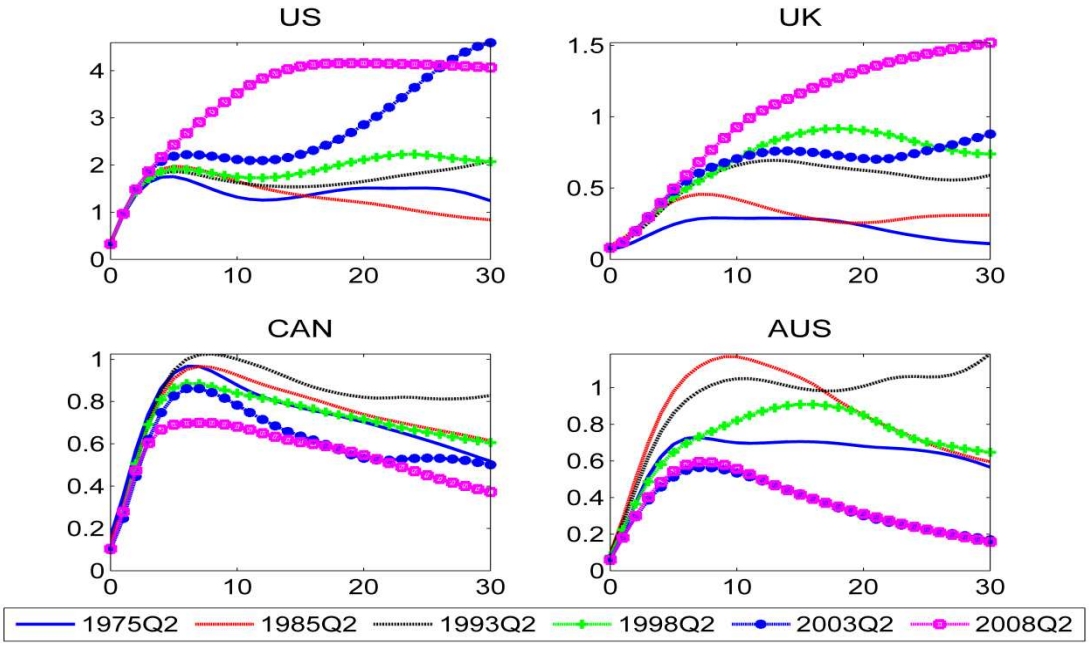
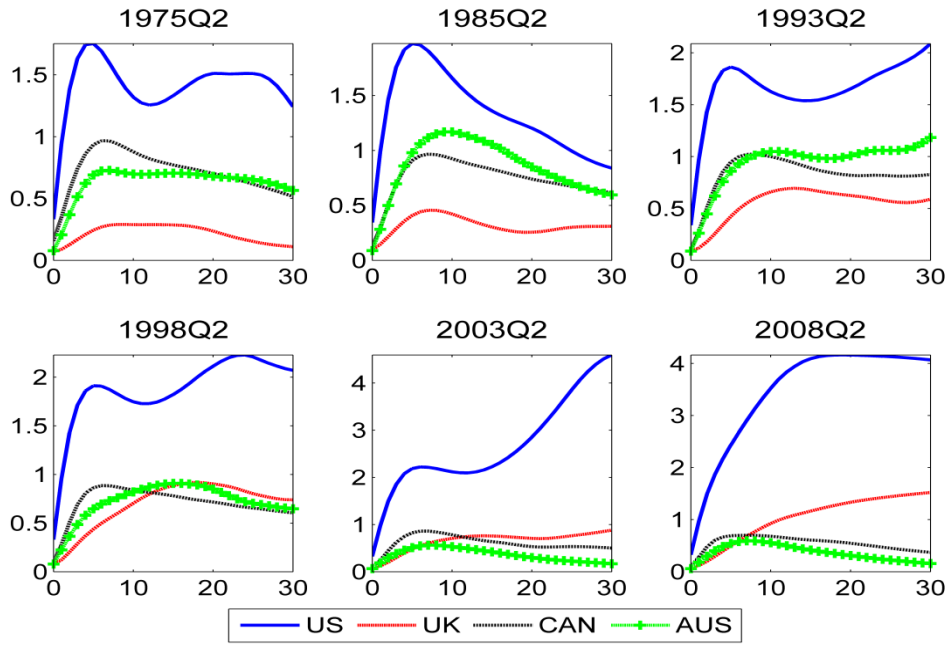


Figure 15 Posterior means of the policy rate responses to a one percentage point increase in inflation at six specific time points across countries

(Unit: percentage point; 30-quarter horizon)



5.2. How monetary transmission has changed over time across countries?

We now turn to answering the question of how the effects of monetary policy shocks on inflation and unemployment have changed over time in the four developed countries. The first step is to observe the monetary policy shocks in the countries obtained from the TVP-VARs. The next step is to examine the impulse responses of unemployment and inflation to monetary policy shocks, assuming the same-size policy rate shocks across countries.

5.2.1. Monetary policy shocks

As argued by Primiceri (2005), in the setup of the parsimonious TVP-VAR models, it seems natural to measure the relative importance and changes of monetary policy shocks by the time varying standard deviations of the residuals of the policy rate equation. Figure 16 shows the posterior means together with 95% confidence intervals of this policy shocks measure in the four countries.

It is observable from Figure 16 that the variance of the policy rate shocks was high during the times of oil price shocks (middle 1970s and early 1980s), but has remained small since the mid-1980s in the US, the early 1990s in the UK and Australia, and the late 1990s in Canada, only picking up slightly during the recent GFC (specifically 2008Q4 or 2009Q1). The generally-decreasing standard deviation of the policy rate shocks might reflect the fact that central banks have become more independent over time, reacting more sensitively to changes in unemployment and inflation, therefore there are not many chances for `monetary policy mistakes' or `unpredicted policy shocks' over time in the TVP-VAR system that already includes unemployment and inflation. In other words, Taylor-type rules might closely approximate monetary policy reactions in the four countries during the Great Moderation (see, for example, Primiceri, 2005).

Particularly in the US, the standard deviations of the policy rate residuals exhibit a substantially high variance of monetary policy shocks for the period 1979–1983 (under the Volcker chairmanship of the Federal Reserve). This pattern is consistent with what is found by Bernanke and Mihov (1998), Sims (1999, 2001), Sims and Zha (2006), Primiceri (2005), and Canova and Gambetti (2009).

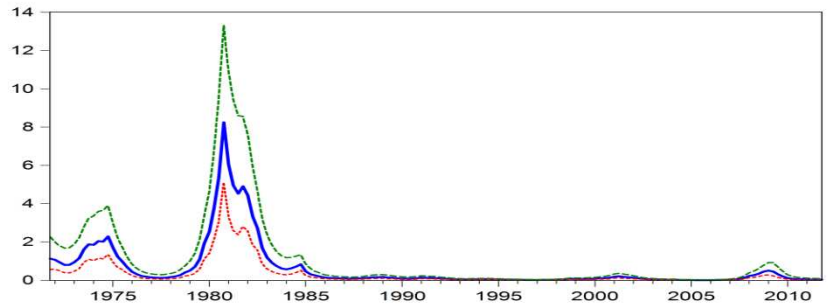
Table 6 shows the pairwise correlations of the standard deviations of the policy rate residuals. All the correlation coefficients are significantly positive, ranging from 0.24 to 0.71. The correlations suggest that there are comovements in the policy rate shocks across countries over time. However, as Figure 16 suggests, the size of the policy rate shocks seem to become smaller in the later part of the period.

Next we turn to comparing the effects of the policy rate on unemployment and inflation across the countries. In order for the impulse responses to be comparable across countries, same-size policy rate shocks are imposed. The policy shocks are assumed to be a 25 basis point temporary increase in the policy interest rate for all countries.

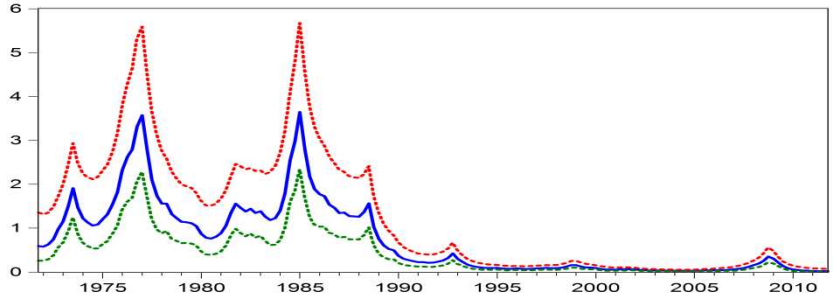
***Figure** 16 Posterior standard deviations of residuals of the policy rate equations, 1971Q2–2011Q4*

(Unit: percentage point)

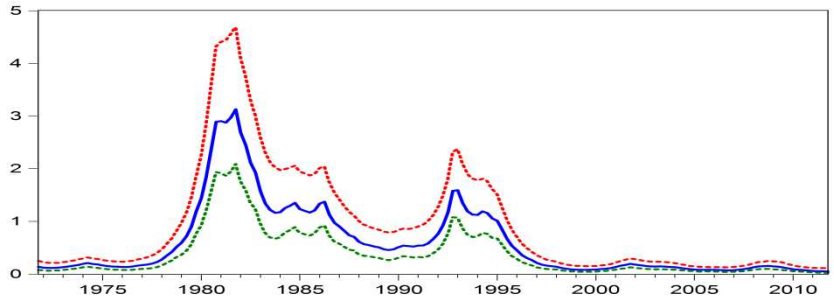
US



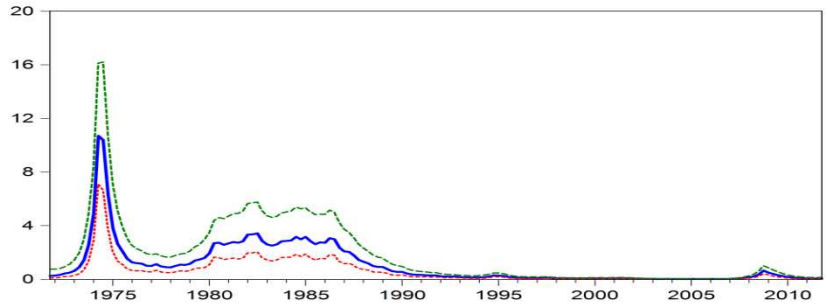
UK



Canada



Australia



Notes: Solid lines: posterior means; dashed lines: 95% confidence intervals.

Table 6 Pairwise correlation of the standard deviations of residuals of the policy rate equations, 1971Q2–2011Q4

Country	US	UK	CAN	AUS
US	X			
UK	0.24***	X		
CAN	0.71***	0.30***	X	
AUS	0.52***	0.54***	0.39***	X

Notes: ***, **, * denote significance at 1%, 5%, and 10% respectively; 'X' = '1.00***'.

5.2.2. Unemployment responses

The posterior means of the unemployment impulse responses to a 25 basis point increase in the policy rate are shown in Figure 17 (for the whole 30-quarter horizon) and Figure 18 (at the 4th, 8th, and 12th quarters). Table 7 shows the pairwise correlations of the unemployment responses at the 4th, 8th, and 12th quarters. Some features can be observed from Figures 17 and 18 and Table 7.

First, comovements in the unemployment responses to the policy shocks across countries exist for the pre-GFC period, especially over short horizons. All of the correlation coefficients at the 4th and 8th quarters are significantly positive, ranging from 0.26 to 0.95. Most of the correlations at the 12th quarter are also significantly positive. The correlation coefficients have not been so high since the GFC.

Second, in general, unemployment seems to respond expectedly to the policy shocks. Unemployment increases in response to a 25 basis point shock in the policy rate. However, the responses are observed to be slightly declining over time. This pattern is reflected in the downward trend of the unemployment responses.

When the six chosen time points are considered in Figures 19 and 20, the key features seen in Figures 17 and 18 can also be observed. There were comovements in the unemployment impulse response functions across the countries at the five earlier time points (pre-GFC). The responses at the last time point of 2008Q2 show dissimilarities. In response to a 25 basis point increase in the policy rate, unemployment increases by 0.15–0.2

percentage points at peak. However, the responses seem to decline for the more recent time points.

Primiceri (2005) reports a similar finding of a declining trend in the monetary policy effects on unemployment in the US. Using output rather than unemployment, Boivin and Giannoni (2006) and Gali and Gambetti (2009) also find decreasing output responses to policy rate shocks for the case of the US.

Figure 17 Posterior means of unemployment responses to a 25 basis point increase in the policy rate, 1971Q2–2011Q4 (30-quarter horizon)

(Unit: percentage point)

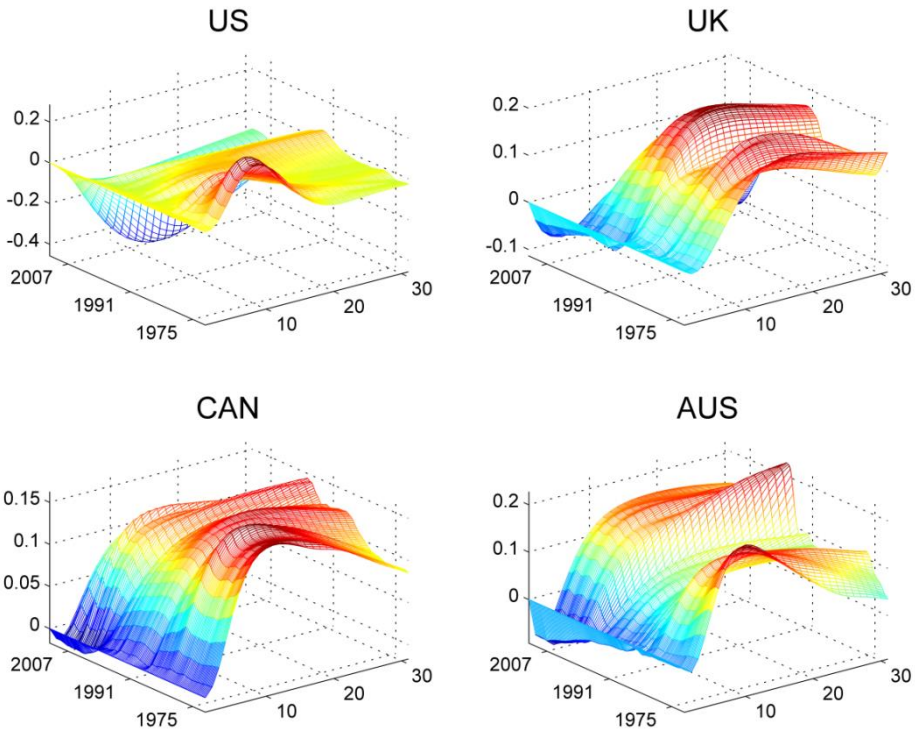
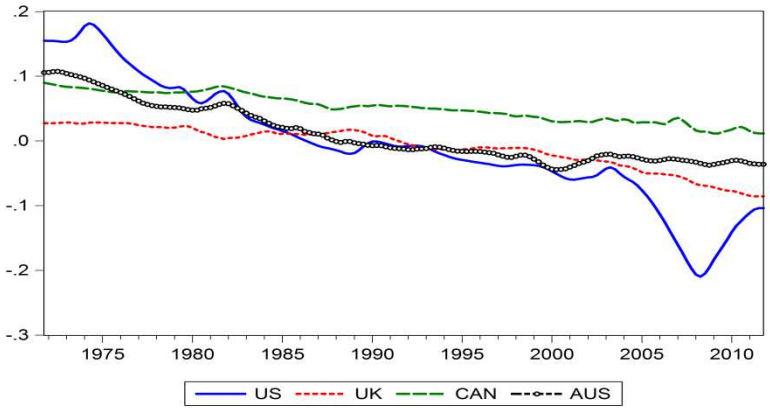


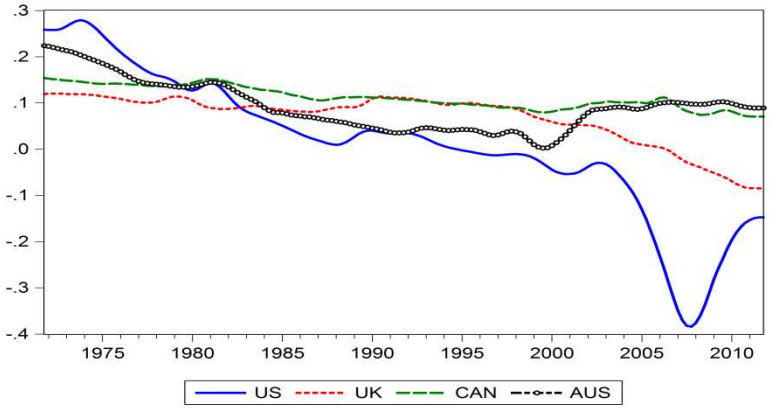
Figure 18 Posterior means of unemployment responses to a 25 basis point increase in the policy rate, 1971Q2–2011Q4 (at 4th, 8th, 12th quarters)

(Unit: percentage point)

4th quarter



8th quarter



12th quarter

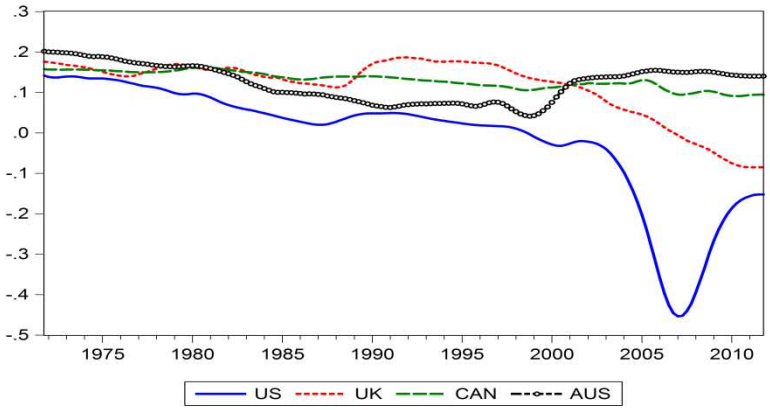


Table 7 Pairwise correlation of unemployment responses to a 25 basis point increase in the policy rate, 1971Q2–2011Q4

Time	Country	1971Q2–2007Q2			2007Q3–2011Q4		
		US	**UK**	**CAN**	**US**	**UK**	**CAN**
4th quarter	**US**	X			X		
	UK	***0.88******	X		***0.84******	X	
	CAN	***0.91******	***0.88******	X	0.17	0.40	X
	AUS	***0.95******	***0.82******	***0.95******	0.08	-0.09	-0.92
8th quarter	**US**	X			X		
	UK	***0.84******	X		***0.90******	X	
	CAN	***0.78******	***0.51******	X	***0.68******	***0.50*****	X
	AUS	***0.66******	***0.26******	***0.88******	-0.59***	-0.39	-0.99***
12th quarter	**US**	X			X		
	UK	***0.86******	X		***0.85******	X	
	CAN	***0.71******	***0.49******	X	***0.94******	***0.71******	X
	AUS	0.11	-0.19**	***0.59******	-0.89***	-0.63***	-0.99***

Notes: ***, **, * denote significance at 1%, 5%, and 10% respectively; significantly positive correlations are in bold italics; 'X' = '1.00***'.

Figure 19 Posterior means of unemployment responses to a 25 basis point increase in the policy rate across six specific time points

(Unit: percentage point; 30-quarter horizon)

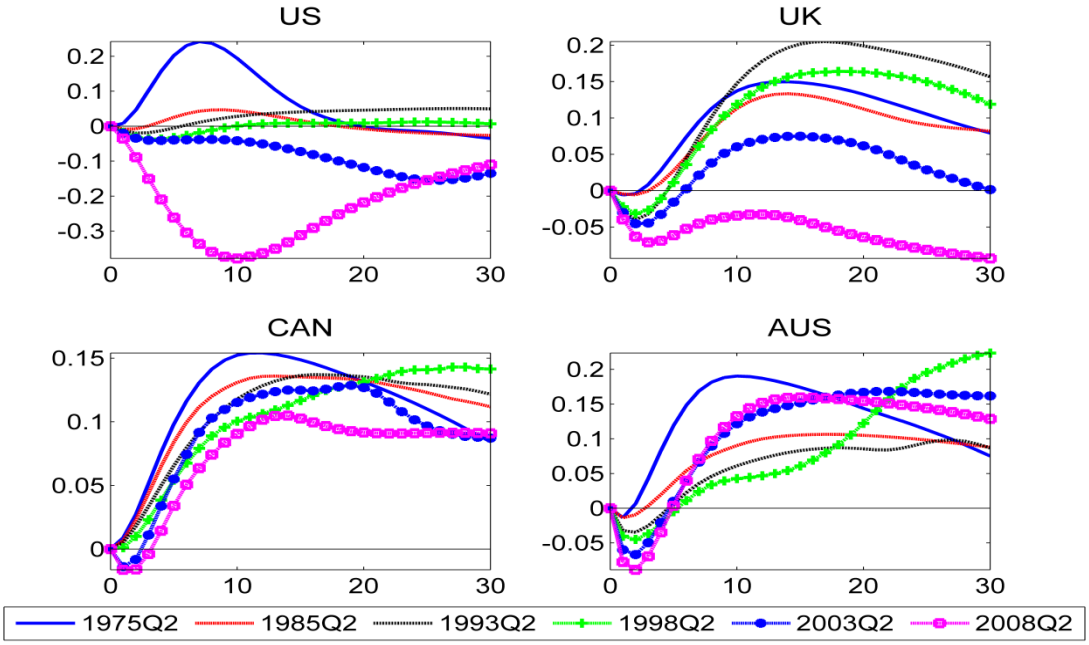
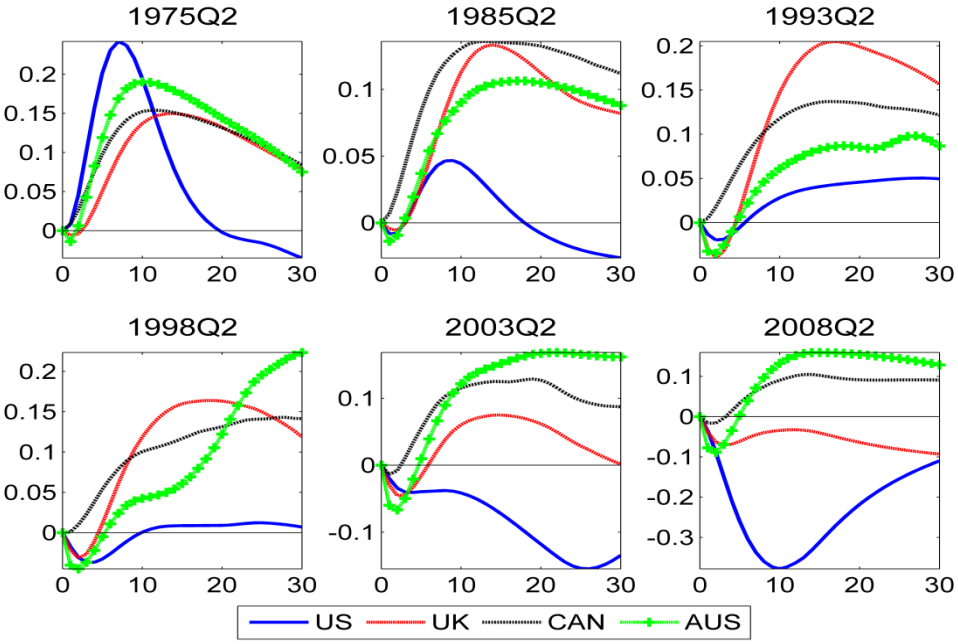


Figure 20 Posterior means of unemployment responses to a 25 basis point increase in the policy rate at six specific time points across countries

(Unit: percentage point; 30-quarter horizon)



5.2.3. Inflation responses

Figures 21 and 22 show the posterior means of the inflation impulse responses to a 25 basis point increase in the policy rate for the whole 30-quarter horizon and at the 4th, 8th, and 12th quarters. Table 8 provides the pairwise correlations of these responses for the pre-GFC period and since the GFC. Two key features are observed.

First, there were comovements in the inflation responses across countries for the pre-GFC period, especially at the 8th and 12th quarters. All the correlation coefficients are significantly positive at the 8th and 12th quarters, ranging from 0.71 to 0.91. The correlation coefficients are much lower since the GFC.

Second, it seems that the effects of the policy rate shocks on inflation were faster and stronger during the 1970s and 1980s and became slower and weaker during recent periods. This is evidenced by the upward trend in the inflation responses shown in Figures 21 and 22.

In addition, the `price puzzle' is observed for all countries, which might relate to the possible misspecification of the parsimonious 3- or 4-variable TVP-VAR models in this paper. Baumeister *et al.* (2013) find little evidence of the `price puzzle' for US data using a time-varying factor-augmented VAR model. Li *et al.* (2013) suggest that the `price puzzle' might be reduced with inclusions of the output gap and direct measures of expectations (such as survey measures of expected future inflation and output growth), which are outside the scope of this paper. However, the `price puzzle' might reaffirm the existence of a `cost channel', or `supply-side effects' in the monetary transmission mechanism as suggested by Barth and Ramey (2001), Ravenna and Walsh (2006), Chowdhury *et al.* (2006), Christiano *et al.* (2005), Gaiotti and Secchi (2006), Tillman (2008, 2009), and Ali and Anwar (2013). For the case of the US, Primiceri (2005) also finds the price puzzle using earlier data.

The posterior means of the inflation responses to policy shocks at the six chosen time points are shown in Figures 23 and 24. These figures are supportive of the above key observations. The responses indicate stronger effects of policy rate shocks on inflation at earlier time points, while the effects seem to decline at more recent time points in the four countries. The result of a weakening effect of monetary policy shocks on inflation in the US

is similar to the findings of Primiceri (2005), Boivin and Giannoni (2006), and Gali and Gambetti (2009).

Compared to Primiceri's (2005) results, the time-point unemployment and inflation responses estimated in this paper seem to be more time-variant. This difference might be explained by the fact that this paper uses more time points, spread out over the whole period, while Primiceri (2005) uses only three time points corresponding to the three different chairmanships of the Federal Reserve.

Figure 21 Posterior means of the inflation responses to a 25 basis point increase in the policy rate, 1971Q2–2011Q4 (30-quarter horizon)

(Unit: percentage point)

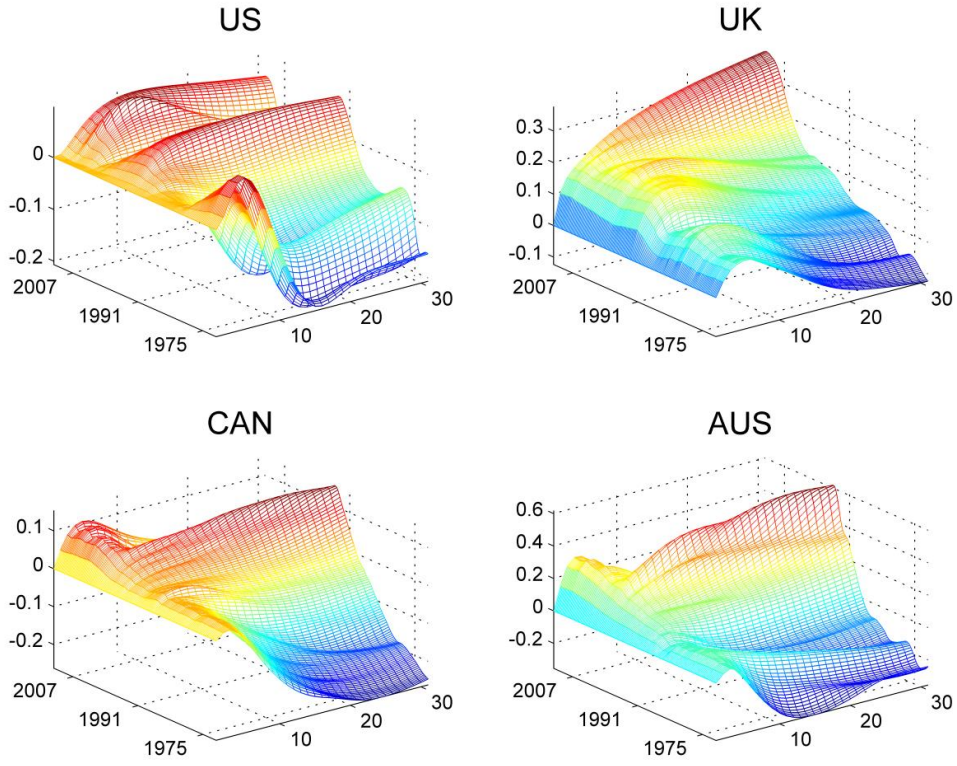
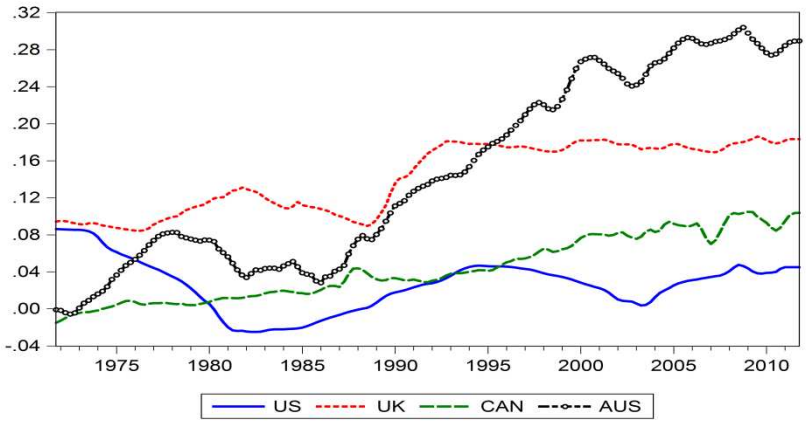


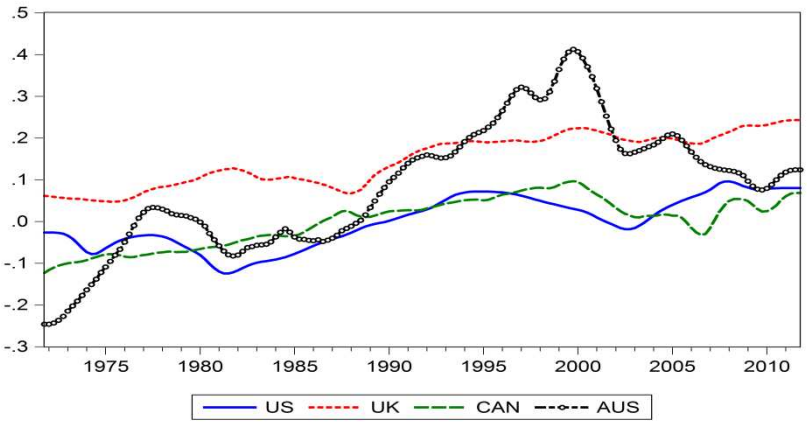
Figure 22 Posterior means of the inflation responses to a 25 basis point increase in the policy rate, 1971Q2–2011Q4 (at 4th, 8th, 12th quarters)

(Unit: percentage point)

4th quarter



8th quarter



12th quarter

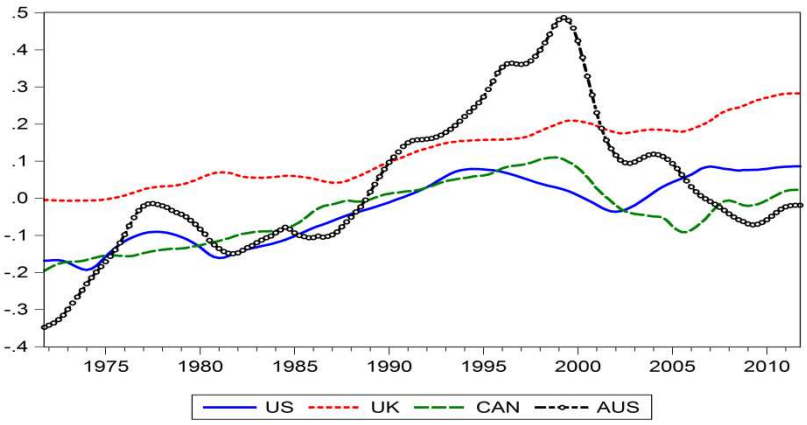


Table 8 Pairwise correlation of inflation responses to a 25 basis point increase in the policy rate, 1971Q2–2011Q4

Time	Country	1971Q2–2007Q2			2007Q3–2011Q4		
		US	**UK**	**CAN**	**US**	**UK**	**CAN**
4th quarter	**US**	X			X		
	UK	0.01	X		***0.70******	X	
	CAN	-0.11	***0.82******	X	-0.13	***0.54*****	X
	AUS	0.06	***0.88******	***0.95******	***0.53*****	***0.61******	0.30
8th quarter	**US**	X			X		
	UK	***0.72******	X		***0.68*****	X	
	CAN	***0.71******	***0.83******	X	-0.14	***0.50*****	X
	AUS	***0.76******	***0.91******	***0.89******	***0.63******	0.06	-0.79***
12th quarter	**US**	X			X		
	UK	***0.90******	X		***0.82******	X	
	CAN	***0.83******	***0.76******	X	0.28	***0.75******	X
	AUS	***0.82******	***0.81******	***0.86******	***0.88******	***0.93******	***0.66******

Notes: ***, **, * denote significance at 1%, 5%, and 10% respectively; significantly positive correlations are in bold italics; 'X' = '1.00***'.

Figure 23 Posterior means of the inflation responses to a 25 basis point increase in the policy rate across six specific time points

(Unit: percentage point; 30-quarter horizon)

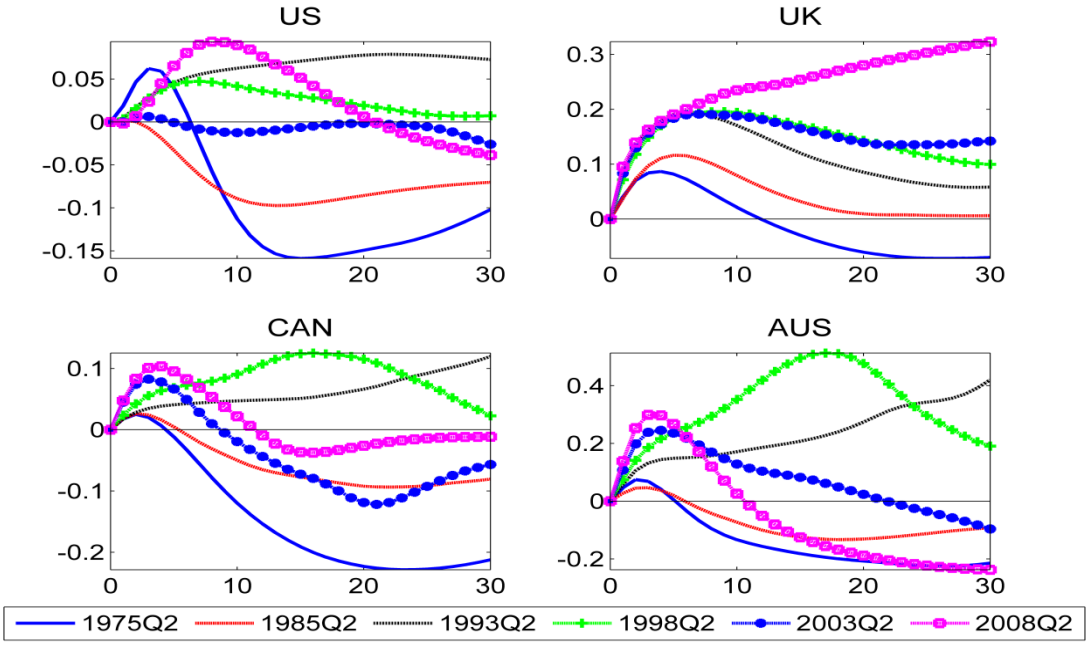
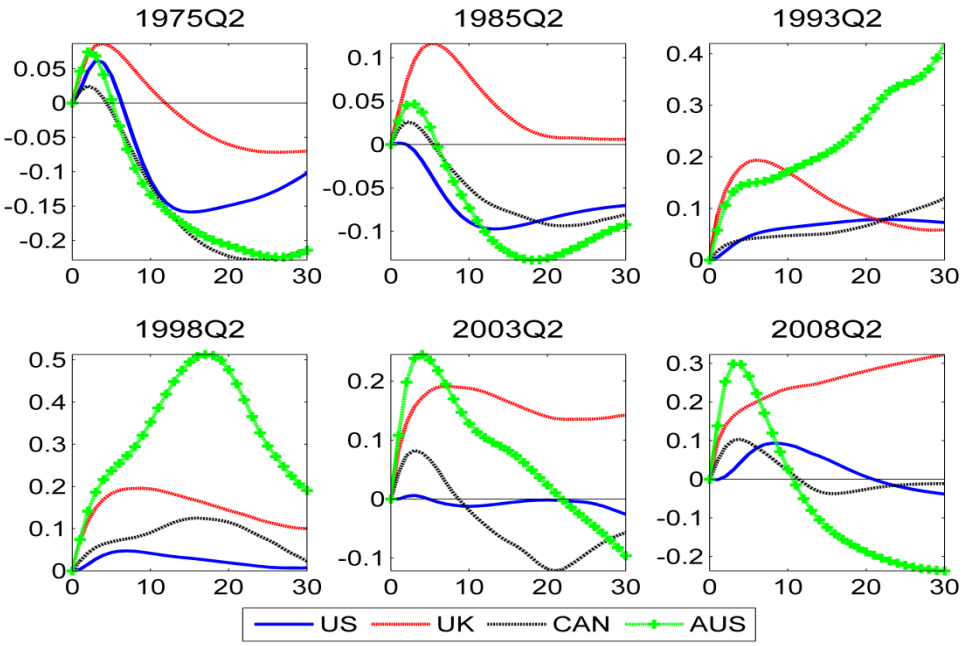


Figure 24 Posterior means of the inflation responses to a 25 basis point increase in the policy rate at six specific time points across countries

(Unit: percentage point; 30-quarter horizon)



In general, there were comovements in the effects of the policy rate shocks on unemployment and inflation across the countries for the pre-GFC period. Since the GFC, the responses are less similar. The movements of unemployment responses are more similar at short-run horizons, while the movements of inflation responses are similar over longer horizons. This pattern might be consistent with the consensus of slower responses of sticky prices compared to output/unemployment for VARs with monetary policy emphasis (see, for example, Christiano *et al.*, 1999).

The policy shock effects on both unemployment and inflation seem to decline over time. This pattern is consistent with the finding by Primiceri (2005), Boivin and Giannoni (2006), and Gali and Gambetti (2009) for the US.

6. Conclusion

This paper examines the changes of monetary policy and monetary transmission over time in four developed countries (the United States, the United Kingdom, Canada, and Australia) using time-varying vector autoregression (TVP-VAR) models. The results suggest that:

i) There were comovements in the monetary policy reactions against unemployment before the GFC. The policy interest rate seems to have become more aggressive against unemployment over time in the four countries, especially in the US and UK.

ii) Monetary policy reactions to inflation/deflation are observed to be divided into two groups, with the responses in the US and UK showing a different pattern to the responses in Canada and Australia. Monetary policy seems to be most aggressive against inflation/deflation in the US – the only non-inflation-targeting country among the four.

iii) There are comovements in the effects of monetary policy on unemployment and inflation across countries, with these effects appearing to have become weaker over time.

The results of this paper help shed light on the practice of monetary policy transmission. Knowing the similarities and dissimilarities of monetary transmission across countries might help central banks better understand the extent to which monetary policy has contributed to the dynamics of important macroeconomic variables such as unemployment and inflation.

The limitations of the parsimonious TVP-VARs suggest the possibility of expanding the models to bigger ones with more variables and structural relations. However, doing so might raise some technical issues, since the number of parameters to be estimated would increase exponentially, which in turns require tighter priors for the TVP-VAR to be estimated correctly. Another possible direction is to impose theory-consistent sign restrictions into the TVP-VARs to avoid the price puzzle and other unexpected responses. The investigation in this paper might also be expanded to cover other countries, especially for the European area when time series of data under the European Central Bank regime become long enough for a TVP-VAR analysis.

It could also be useful to know whether there are micro-level explanations for the comovements in monetary policy transmission across countries. However, a detailed analysis of this type might require a highly structural model as well as micro-level data rather than a small TVP-VAR system like the one used in this paper.

Furthermore, as Orphanides (2001), Croushore and Evans (2006), and Lee *et al.* (2012) suggest, real-time data (the data that were available at the time the policy decisions were made) should ideally be used when estimating monetary policy reaction functions. The exercises in this paper could be re-done when such real-time databases are available for all countries of interest.

Appendix A. Data sources

Series	Sources
US	
Inflation	Annual growth rate of GDP deflator, GDPDEF, Federal Reserve Bank of St Louis, http://research.stlouisfed.org/fred2/
Unemployment	Unemployment rate, 16 years or over, LNS14000000, US Bureau of Labour Statistics
Policy rate	Effective Federal Funds rate, H15, Board of Governors of the Federal Reserve System
Real GDP growth rate	Gross Domestic Product by Expenditure in Constant Prices: Total Gross Domestic Product, Growth rate previous period, Federal Reserve Bank of St Louis, http://research.stlouisfed.org/fred2/
UK	
Inflation	Annual growth rate of GDP deflator, GBRGDPDEFQISMEI, Federal Reserve Bank of St Louis, http://research.stlouisfed.org/fred2/
Unemployment	Harmonised Unemployment Rate: All Persons for United Kingdom, GBRURHARMQDSMEI, Federal Reserve Bank of St Louis, http://research.stlouisfed.org/fred2/
Policy rate	Discount rate, INTDSRGBM193N, Federal Reserve Bank of St Louis, http://research.stlouisfed.org/fred2/
Exchange rate	Log of US/UK Foreign Exchange Rate, Federal Reserve Bank of St Louis, http://research.stlouisfed.org/fred2/
Real GDP growth rate	Gross Domestic Product by Expenditure in Constant Prices: Total Gross Domestic Product, Growth rate previous period, Federal Reserve Bank of St Louis, http://research.stlouisfed.org/fred2/
Canada	
Inflation	Annual growth rate of GDP deflator, CANGDPDEFQISMEI, Federal Reserve Bank of St Louis, http://research.stlouisfed.org/fred2/
Unemployment	Unemployment Rate: Aged 15 and Over: All Persons for Canada, LRUNTTTTCAQ156S, Federal Reserve Bank of St Louis, http://research.stlouisfed.org/fred2/
Policy rate	Bank rate, Data and Statistics Office, Bank of Canada
Exchange rate	Log of US/Canada Foreign Exchange Rate, Federal Reserve Bank of St Louis, http://research.stlouisfed.org/fred2/
Real GDP growth rate	Gross Domestic Product by Expenditure in Constant Prices: Total Gross Domestic Product, Growth rate previous period, Federal Reserve Bank of St Louis, http://research.stlouisfed.org/fred2/
Australia	
Inflation	Annual growth rate of GDP Implicit Price Deflator, AUSGDPDEFQISMEI, Federal Reserve Bank of St Louis, http://research.stlouisfed.org/fred2/
Unemployment	Unemployment rate, 6202.0 Labour Force, Australian Bureau of Statistics
Policy rate	90 days bank accepted bills, F1, Reserve Bank of Australia
Exchange rate	Log of US/Australia Foreign Exchange Rate, Federal Reserve Bank of St Louis, http://research.stlouisfed.org/fred2/
Real GDP growth rate	Gross Domestic Product by Expenditure in Constant Prices: Total Gross Domestic Product, Growth rate previous period, Federal Reserve Bank of St Louis, http://research.stlouisfed.org/fred2/

Appendix B. Convergence of the Markov chain Monte Carlo algorithm

For the US

Parameter	Mean	Stdev	95%U	95%L	Geweke	Inefficiency
sb1	0.0046	0.0018	0.0025	0.0093	0.113	119.91
sb2	0.0047	0.0018	0.0026	0.0092	0.142	84.07
sa1	0.0056	0.0016	0.0034	0.0097	0.479	51.31
sa2	0.0055	0.0015	0.0034	0.0092	0.054	44.17
sh1	0.0961	0.0316	0.0503	0.1747	0.002	95.21
sh2	0.0071	0.0039	0.0036	0.0180	0.597	191.06

For the UK

Parameter	Mean	Stdev	95%U	95%L	Geweke	Inefficiency
sb1	0.0023	0.0003	0.0018	0.0029	0.412	9.78
sb2	0.0023	0.0003	0.0018	0.0029	0.331	9.2
sa1	0.005	0.0013	0.0032	0.0079	0.629	28.42
sa2	0.0054	0.0015	0.0033	0.0092	0.391	46.95
sh1	0.18	0.0645	0.0876	0.335	0.082	137.8
sh2	0.0057	0.0018	0.0034	0.0102	0.383	70.47

For Canada

Parameter	Mean	Stdev	95%U	95%L	Geweke	Inefficiency
sb1	0.0023	0.0003	0.0018	0.0029	0.294	10.18
sb2	0.0023	0.0003	0.0018	0.0029	0.104	11.05
sa1	0.0052	0.0013	0.0033	0.0082	0.259	40.27
sa2	0.0055	0.0016	0.0034	0.0096	0.289	49.96
sh1	0.1203	0.0387	0.0619	0.2115	0.49	98.96
sh2	0.0069	0.0038	0.0036	0.0148	0.81	160.06

For Australia

Parameter	Mean	Stdev	95%U	95%L	Geweke	Inefficiency
sb1	0.0023	0.0003	0.0018	0.0029	0.196	7.23
sb2	0.0023	0.0003	0.0018	0.0029	0.416	8.03
sa1	0.0055	0.0016	0.0034	0.0094	0.997	39.40
sa2	0.0056	0.0016	0.0034	0.0098	0.348	50.28
sh1	0.2017	0.0496	0.1134	0.3069	0.337	68.76
sh2	0.0427	0.0169	0.0155	0.0814	0.139	123.04

Notes: Some of the inefficiency parameters are quite high, but arguably acceptable for 20,000 iterations.

REFERENCES

Ali, S.Z. and Anwar, S. (2013), 'Inflation and Interest Rates in the Presence of a Cost Channel, Wealth Effect and Agent Heterogeneity', *Economic Modelling*, 31, 286–296.

Bagliano, F.C. and Favero, C.A. (1998), 'Measuring Monetary Policy with VAR Models: An Evaluation', *European Economic Review*, 42(6), 1069−1112.

Barth, M. and Ramey, V. (2001), 'The Cost Channel of Monetary Transmission', *NBER Macroeconomic Annual (2001)*, ed. by B. Bernanke and K. Rogoff. Cambridge: MIT Press, 199−240.

Baumeister, C. and Benati, L. (2013), 'Unconventional Monetary Policy and the Great Recession: Estimating the Macroeconomic Effects of a Spread Compression at the Zero Lower Bound', *International Journal of Central Banking*, 9(2), 165–212.

Baumeister, C., Liu, P. and Mumtaz, H. (2013), 'Changes in the Effects of Monetary Policy on Disaggregate Price Dynamics', *Journal of Economic Dynamics and Control*, 37(3), 543–560.

Bernanke, B. and Mihov, I. (1998), 'Measuring Monetary Policy', *Quarterly Journal of Economics*, 113, 869–902.

Boivin, J. and Giannoni, M.P. (2006), 'Has Monetary Policy Become More Effective?', *Review of Economics and Statistics*, 88(3), 445–462.

Canova, F. (1995), 'VAR: Specification, Estimation, Testing and Forecasting', in Pesaran H. and Wickens M. (eds), *Handbook of Applied Econometrics*. John Wiley and Sons; 31−65.

Canova, F. and Gambetti, L. (2009), 'Structural Changes in the US Economy: Is There A Role For Monetary Policy?', *Journal of Economic Dynamics and Control*, 33, 477–490.

Cecioni, M. and Neri, S. (2011), 'The Monetary Transmission Mechanism in the Euro area: Has It Changed and Why?', *Banca D'Italia Working Paper*, 808.

Chatterjee, A. (2014), 'Globalization and Monetary Policy Comovement: Evidence from G-7 Countries', *Discussion Papers*, 2014-19, School of Economics, University of New South Wales.

Chowdhury, I., Hoffmann, M. and Schabert, A. (2006), 'Inflation Dynamics and the Cost Channel of Monetary Transmission', *European Economic Review*, 50, 995–1016.

Christiano, L., Eichenbaum, M. and Evans, C. (1999), 'Monetary Policy Shocks: What Have We Learned and to What End?', in Taylor, J.B. and Woodford, M. (eds), *Handbook of Macroeconomics.* Amsterdam, New York and Oxford: Elsevier Science, North-Holland; 65−148.

Christiano, L., Eichenbaum, M. and Evans, C. (2005), 'Nominal Rigidities and the Dynamic Effects of a Shock to Monetary Policy', *Journal of Political Economy*, 113(1), 1−45.

Ciccarelli, M. and Rebucci, A. (2006), 'Has The Transmission Mechanism of European Monetary Policy Changed in The Run-Up to EMU?', *European Economic Review*, 50, 737–776.

Clarida, R., Gali, J. and Gertler, M. (2000), 'Monetary Policy Rules and Macroeconomic Stability: Evidence and Some Theory', *Quarterly Journal of Economics*, 115 (1), 147–180.

Cogley, T. and Sargent, T.J. (2001), 'Evolving Post-World War II U.S. Inflation Dynamics', in *NBER Macroeconomics Annual*, Cambridge, MA: MIT Press, 331–373.

Cogley, T. and Sargent, T.J. (2003), 'Drifts and Volatilities: Monetary Policies and Outcomes in the Post WWII U.S.', *mimeo*, New York University.

Croushore, D. and Evans, C. (2006), 'Data Revisions and the Identification of Monetary Policy Shocks', *Journal of Monetary Economics*, 53, 1135–1160.

Day, C. (2011), 'China's Fiscal Stimulus and the Recession Australia Never Had: Is a Growth Slowdown Now Inevitable?', *Agenda*, 18(1), Australian National University.

Eisenstat, E., Chan, J. and Strachan, R. (2015), 'Stochastic Model Specification Search for Time-Varying Parameter VARs', *Econometric Reviews*, online published Oct 2015, doi: 10.1080/07474938.2015.1092808.

Fujiwara, I, Nakajima, J. and Phan, T. (2013), 'Comovements in Structural Change', paper presented at 2013 Southern Workshop in Macroeconomics (SWIM) at the Victoria University of Wellington.

Fujiwara, I. (2006), 'Evaluating Monetary Policy When Nominal Interest Rates Are Almost Zero', *Journal of the Japanese and International Economies*, 20, 434–453.

Gaiotti, E. and Secchi, A. (2006), 'Is There a Cost Channel of Monetary Policy Transmission? An Investigation into the Pricing Behavior of 2,000 Firms', *Journal of Money, Credit and Banking*, 38(8), 2013−2037.

Gali, J. and Gambetti, L. (2009), 'On the sources of the Great Moderation', *American Economic Journal: Macroeconomics*, 1(1), 26–57.

Gerlach, S., and Smets, F. (1995), 'The Monetary Transmission Mechanism: Evidence from the G-7 Countries', *BIS Working Papers* 26. Bank of International Settlements.

Iwata, S. and Wu, S. (2006), 'Estimating Monetary Policy Effects When Interest Rates Are Close To Zero', *Journal of Monetary Economics*, 53, 1395–1408.

Judd, J. and Rudebusch, G.D. (1998), 'Taylor's Rule and the Fed: 1970-1997', *Economic Review*, 3, 3–16, Federal Reserve Bank of San Francisco.

King, M. (1994), 'Debt Deflation: Theory and Evidence', *European Economic Review*, 38(3–4), 419–445.

King, M. (2002), 'The Inflation Target Five Years On', *Bank of England Quarterly Bulletin*, 37(4), 434–442.

Labonte, M. (2014), 'Monetary Policy and the Federal Reserve: Current Policy and Conditions', Report to US Congress members and Committees RL30354, Congressional Research Service, Washington D.C.

Lee, K.C., Morley, J. and Shields, K. (2011). 'The Meta Taylor Rule', *University of Nottingham Discussion Paper*, 1131, June.

Lee, K.C., Olekalns, N. and Shields, K. (2013), 'Meta Taylor Rules for the UK and Australia; Accommodating Regime Uncertainty in Monetary Policy Analysis Using Model Averaging Methods', *Manchester School*, 81, 28–53.

Lee, K.C., Olekalns, N., Shields, K. and Wang, Z. (2012), 'The Australian Real-Time Database: An Overview and an Illustration of its Use in Business Cycle Analysis', *Economic Record*, 88(283), 495–516.

Leeper, E. and Zha, T. (2002), 'Modest Policy Intervention', *NBER Working Papers*, 9192.

Leigh, A. (2012), 'How Much Did the 2009 Australian Fiscal Stimulus Boost Demand? Evidence from Household-Reported Spending Effects', *B.E. Journal of Macroeconomics*, 12(1), Article 4.

Li, S.M., Perera, R. and Shields, K. (2013), 'Misspecification, Identification or Measurement? Another Look at the Price Puzzle', *Department of Economics Working Papers Series*, 1169, University of Melbourne.

Lubik, T.A. and Schorfheide, F. (2004), 'Testing for Indeterminacy: An Application to U.S. Monetary Policy', *American Economic Review*, 94 (1), 190–217.

Mishkin, F.S. and Schmidt-Hebbel, K. (2001), 'One Decade of Inflation Targeting in the World: What Do We Know and What Do We Need to Know?', *Central Bank of Chile Working Papers*, 101.

Mojon, B. and Peersman, G. (2001), 'A VAR Description of the Effects of Monetary Policy in the Individual Countries of the Euro Area', *European Central Bank Working Paper Series*, 0092.

Nakajima, J. (2011), 'Time-Varying Parameter VAR Model with Stochastic Volatility: An Overview of Methodology and Empirical Applications', *Monetary and Economic Studies*, November, 107–142.

Nelson, E. (2005a), 'The Great Inflation of the Seventies: What Really Happened?', *Advances in Macroeconomics*, 5(1), 1297.

Nelson, E. (2005b), 'Monetary Policy Neglect and the Great Inflation in Canada, Australia and New Zealand', *International Journal of Central Banking*, 1(1), 133–179.

Orphanides, A. (2001), 'Monetary Policy Rules Based on Real-Time Data', *American Economic Review*, 91, 964–85.

Peersman, G. and Smets, F. (2003), 'The Monetary Transmission Mechanism in the Euro Area: More Evidence from VAR Analysis', in Angeloni, I., Kashyap, A. and Mojon B. (eds), *Monetary Policy Transmission in the Euro Area*. Cambridge: Cambridge University Press, 36−55.

Primiceri, G.E. (2005), 'Time Varying Structural Vector Autoregressions and Monetary Policy', *Review of Economic Studies*, 72(3), 821–852.

Ravenna, F. and Walsh, C.E. (2006), 'Optimal Monetary Policy with the Cost Channel', *Journal of Monetary Economics*, 53, 199–216.

Romer, D. (2005), 'Commentary on "Origins of the Great Inflation"', *Federal Reserve Bank of St. Louis Review*, 87(2), 177–186.

Sims, C.A. (1980), 'Macroeconomics and Reality', *Econometrica*, 48, 1−48.

Sims, C.A. (1999), 'Drift and Breaks in Monetary Policy', *mimeo*, Princeton University.

Sims, C.A. (2001), 'Comment on Sargent and Cogley's: "Evolving Post World War II U.S. Inflation Dynamics"' in *NBER Macroeconomics Annual*, Cambridge, MA: MIT Press, 373–379.

Stevens, G. (1999), 'Six Years of Inflation Targeting', address to the Economic Society of Australia. Available from http://www.rba.gov.au/speeches/1999/sp-ag-200499.html.

Suda, J. and Zervou, A.S. (2014), 'International Great Inflation and Common Monetary Policy', *Working paper* February 2014. Available from http://www.jaceksuda.com/

Tillman, P. (2008), 'Do Interest Rates Drive Inflation Dynamics? An Analysis of the Cost Channel of Monetary Transmission', *Journal of Economic Dynamics and Control*, 32, 2723–2744.

Tillman, P. (2009), 'The Time-Varying Cost Channel of Monetary Transmission', *Journal of International Money and Finance*, 28, 941–953.