# Global Common Output Gap

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**Abstract**

We build a reduced form multilateral open economy Phillips curve, which allows for internationally common components of time-varying output gaps, trend inflation rates and potential outputs. The estimated Phillips curve coefficients have the right signs. The output gap closely resembles that from the OECD Outlook for a number of leading economies, particularly the U.S. The common output gap accounts for much of the output gap in the U.S., Canada and Australia. However, over the sample period from 1970 to 2005, this common output gap has only limited influence on the domestic inflation in general. What contributes the most to the long term disinflationary phenomena in these economies is the decrease of trend inflation. We find a strong common component among the trend inflation rates across the economies.

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# 1 Introduction

In a closed frictionless economy, fluctuations in nominal expenditures are unlikely to have real effects. With nominal rigidity, however, even a nominal shock that is not purely random or transitory can influence the real economy (Woodford (2003), among many others). For example, due to sluggish price adjustments, an expansionary monetary policy may cause an output gap to appear. At the same time, the monetary expansion leads to inflation. So the Phillips curve, which relates inflation to the output gap, after controlling for inflation expectations, is a simple reduced form describing the more complicated underlying dynamics. Given long run neutrality, and possibly, long run superneutrality (King and Watson (1997)), the Phillips curve reflects cyclical or temporary effects of nominal shocks on the real economic activity.

As countries become increasingly integrated economically and financially through trade and investment, a nominal shock in one country can have rippling effects across national borders. Thus, foreign influences need to be accounted for in the Phillips curve relationship. This has important implications for the monetary policy as the output gap can play a central role in the monetary transmission mechanism. If inflation is related to not only the domestic real activity, but also the real activity elsewhere, then a Taylor rule (Taylor (1993)) using only inflation and domestic output gap to set the short term interest rate would not be sufficient.

In an ad hoc Keynesian setup, the international factor can be introduced into the traditional Phillips curve to make an open economy Phillips curve by including on the right hand side the import price change (Gordon (1998), Rich and Rissmiller (2000), Tootell (1998), Rudd and Whelan (2005b)) or measures of foreign output gaps (Corrado and Mattey (1997), Tootell (1998), Borio and Filardo (2006), Ihrig, Kamin, Lindner and Marquez (2007)). Another breed of open economy Phillips curve is based on the Woodford-Obstfeld-Rogoff New Keynesian model. Typically, these models relate inflation to expected inflation, output gap and terms-of-trade (Lane (2001), Yuen (2002), Razin and Yuen (2002), Loungani, Razin and Yuen (2001), Leith and Malley (2003), Rumler (2005), Benigno and Benigno (2006)).

Both traditional and New Keynesian open economy Phillips curves originate from two-country models. Theoretically, they can be extended to cover multi-country cases with relative ease. Empirically, the extension is less straightforward. Researchers have usually resorted to some aggregation scheme for the rest of the world so that the resulting open economy Phillips curve is essentially still in the two-country setting (Gerlach and Smets (1999), Borio and Filardo (2006), Ihrig, Kamin, Lindner and Marquez (2007)).

Our major contribution to the literature is to build an empirical multi-lateral open economy Phillips curve to account for the international influence on domestic inflation. We assume a country's output consists of trend and cyclical outputs. Similarly, its inflation consists of trend and cyclical inflation. Both the trend and cyclical outputs are further decomposed into common and idiosyncratic components. Same with the trend and cyclical inflation rates. We link the cyclical inflation and cyclical output by the Phillips curve along with all the common and idiosyncratic components. By definition, the trend output is the same as the potential output and the cyclical output is the same as the output gap.

Essentially, we adopt a common factor approach to extracting the internationally common components of time-varying output gaps, trend inflation rates and potential outputs. The model accounts for the effects on inflation not only from the so-called global output gap, but also from the common trend inflation rates, and indirectly, from the common potential outputs across different economies. Our work nests recent studies on several related but separate fronts—international common business cycles (Kose, Otrok and Whiteman (2003)), common inflation (Ciccarelli and Mojon (2005)), and foreign output gaps' influence on domestic inflation (Borio and Filardo (2006), Ihrig, Kamin, Lindner and Marquez (2007)). In addition, we introduce the concept of common potential output.

We choose to work with a generalized traditional Phillips curve, as opposed to a New Keynesian type of Phillips curve. Although the New Keynesian Phillips curve has more solid micro foundations theoretically, it has not been proved a clearly superior approach relative to the traditional Phillips curve empirically, as demonstrated by Rudd and Whelan (2006). Our generalized traditional Phillips curve offers great convenience in building the common factor model. We estimate the Phillips curve coefficients together with all the common and idiosyncratic components of output gaps, trend inflation rates and potential outputs. It is important that the estimated Phillips curve indeed reflect the relationship we would expect. Inflation should be up with a positive gap and down with a negative gap. This is clearly established by our estimated model.

The estimated output gap closely resembles that from the OECD Outlook for a number of leading economies, particularly the U.S. At the same time, the common output gap accounts for much of the output gap in the U.S., Canada and Australia. By definition, the output gap is the same as the cyclical movement. By the same token, the common output gap also depicts the common cyclical movement across countries. This corresponds to the recent study of the international common business cycles by Kose, Otrok and Whiteman (2003). They adopt a similar common factor approach. However, their common cycle is based on a statistical decomposition of each country's cyclical movement, defined either as simple log difference or HP filtered output series.

Here, we utilize the Phillips curve to pin down the countries' cycles, and simultaneously extract the common component of these cycles.

The cyclical inflation due to the output gap has not been a big contributor to the inflation movements in general, compared with the trend inflation, over the sample period from 1970 to 2005. This leaves even less for the common output gap to explain the general inflation. Instead, we focus on the decomposition of the cyclical inflation itself into a part due to the common output gap and a part due to the idiosyncratic gap. This is in line with Ciccarelli and Mojon (2005)'s common inflation factor at the business cycles frequencies, which also follows the common factor approach. They first use simple detrending methods, such as band pass and HP filters, on the inflation series. The resulting detrended inflation rates are then used to extract the common inflation component at the business cycles frequencies. In contrast, we rely on the Phillips curve and trend-cycle decomposition of the output to arrive at our cyclical inflation measure, part of which is further characterized as the common cyclical inflation.

We find a significant part of cyclical inflation can be attributed to the common output gap, but only in some of the countries, including the U.S., Canada and Australia. The finding is very much relevant to the current debate concerning the globalization's impact on monetary policy. Borio and Filardo (2006) argue that the global gap has affected the inflation rates of individual countries in a significant way. While Ihrig, Kamin, Lindner and Marquez (2007) reach the opposite conclusion, although using essentially the same approach. In both papers, a weighted average of all foreign output gaps enters the traditional Phillips curve, in addition to the domestic gap. The weights are explicitly determined. In our approach, the common output gap across countries can be also regarded as a function, albeit a complicated one, of the individual gaps, with the weights implicitly determined by the open economy Phillips curve model. Our common output gap is truly global in the sense that it reflects the influences from not only the domestic output gap, but also from all foreign output gaps.

With all the analysis done on the cyclical inflation, common or idiosyncratic, what contributes the most to the long term disinflationary phenomena in these economies is still the decrease of trend inflation. Among the trend inflation rates across the economies, we find a strong common component. This also concurs with the common inflation across countries found in Ciccarelli and Mojon (2005). However, they use demeaned year-over-year inflation rates and assume the common inflation component follows a simple AR(1). In essence, their common inflation largely reflects the common trend in the inflation series across the countries. Here, we specify the common trend inflation itself, which follows a random walk, using quarterly inflation rates.

The rest of the paper is organized as follows. Section 2 provides a quick review on the Phillips curve, particularly concerning the international influence. Section 3 proposes a multilateral open economy model in the traditional Phillips curve setting and details the common factor approach. Section 4 describes the state space model and data used in estimating the model. Section 5 reports the major findings. Section 6 discusses extensions of the base model. Section 7 concludes.

# 2 Phillips Curve

## 2.1 Closed Economy Phillips Curve

The traditional Phillips curve model has remained very popular and highly influential (Stock and Watson (1999), Kuttner (1994), Gerlach and Smets (1997), Apel and Janssen (1999), Camba-Mendez and Rodriguez-Palenzuela (2003)). The general form is

$$\pi_t = \alpha + A\left(L\right) x_{t-1} + B(L)\pi_{t-1} + \varepsilon_t$$

with $B(1) = 1$[1]. It relates current inflation $\pi_t$ to lagged inflation and the real sector forcing variable $x_t$, which typically is some gap measure such as the detrended output $y_t$. Because of the importance of lagged inflation, the model is susceptible to the Lucas critique (Lucas (1976), Lucas (1972) and Sargent (1971)). However, Rudd and Whelan (2005b) conclude that in practice the Lucas critique may not cause severe problems.

The New Keynesian Phillips curve is derived from an optimizing framework featuring rational expectations, monopolistic competition and nominal rigidity (Roberts (1995), Gali and Gertler (1999), Sbordone (2002), Kurman (2003) and Woodford (2003)). Usually the nominal rigidity takes the form of staggered pricing in the spirit of Calvo (1983) and Taylor (1980). In general, the New Keynesian Phillips curve states

$$\pi_t = \beta E_t \pi_{t+1} + \gamma x_t$$

with real sector forcing variable $x_t$[2]. The forcing variable typically is the real marginal cost $m_t$, which outperforms the simple detrended output $y_t$ (Gali and Gertler (1999), Sbordone (2002), Erieg,

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[1] Written in difference, the above model becomes

$$\triangle\pi_t = \alpha + A\left(L\right) x_{t-1} + \gamma(L)\triangle\pi_{t-1} + \varepsilon_t$$

In practice though, the constraint of $B(1) = 1$ is often dropped.

[2] The estimation methods for New Keyesian Phillips curves include GMM (Gali and Gertler (1999), Nelson and Neiss (2005)) and FIML (Linde (2005)).

Henderson and Levin (2000), Gali, Gertler and Lopez-Salido (2001)). On the other hand, Nelson and Neiss (2005) claim a theory-consistent output gap can fit the New Keynesian Phillips curve equally well.

Compared with the traditional Phillips curve, the New Keynesian Phillips curve has the advantage of having firm microeconomic foundations. It is also robust to the Lucas critique because it is purely forward looking. However, it fails to capture the inertia in inflation, which is evident in data, and is picked up by the traditional Phillips curve. To solve this persistence problem (Woodford (2003)), Gali and Gertler (1999) propose a hybrid New Keynesian Phillips curve by adding backward looking components. They and others (Gali, Gertler and Lopez-Salid (2005), Sbordone (2005)) find the hybrid New Keynesian Phillips curve with a dominant role for the forward looking behavior provides useful insights into the nature of inflation dynamics.

## 2.2 International Influences in the Phillips Curve

In an ad hoc Keynesian setup, one simple way to introduce the international factor into the traditional Phillips curve is to include the import price change as an explanatory variable. Examples include Gordon (1998), Rich and Rissmiller (2000), Tootell (1998), Rudd and Whelan (2005b)[3]. Most of these studies find the import price change helps the model fit but the contribution is small. Considering that foreign output gaps help to predict price changes in imported goods produced overseas, this approach essentially means that all foreign output gaps collapse into the single import price inflation measure. Alternatively, researchers can go one step further to directly include some aggregate measure of foreign output gaps in the traditional Phillips curve. Corrado and Mattey (1997), Tootell (1998), Borio and Filardo (2006), Ihrig, Kamin, Lindner and Marquez (2007) take that approach. Results vary concerning the effect on domestic inflation from the foreign gap measure. In summary, the traditional open economy Phillips curve essentially is a two-country model, treating the rest of the world as one entity, whose influence on the domestic inflation is reflected either through the import price inflation or the aggregate foreign gap measure.

Another breed of open economy Phillips curve is based on the Woodford-Obstfeld-Rogoff New Keynesian Phillips curve. Typically, these models relate inflation to expected inflation, output gap and terms-of-trade (Lane (2001), Yuen (2002), Razin and Yuen (2002), Loungani, Razin and Yuen (2001), Leith and Malley (2003), Rumler (2005), Benigno and Benigno (2006)). Particularly, Benigno and Benigno (2006) demonstrate that a country's domestic inflation is related to not only

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[3] Dexter, Levi and Nault (2005) even add real import share of consumption and real export share of production to strengthen the traditional Phillips curve relationship between unemployment and inflation.

its own output gap but also output gaps in the rest of the world. So the reduced form can be written as

$$\pi_t^H = \alpha^H \cdot y_t^H + \gamma^F \cdot y_t^F + \beta E_t \pi_{t+1}^H$$

where $\pi_t^H$ stands for inflation in the home country, $y_t^H$ for home output gap and $y_t^F$ for foreign output gap. This again is in a two-country setting. Theoretically, we can extend it to the multi-country case, so that

$$\pi_t^H = \alpha^H \cdot y_t^H + \sum_{i=1}^{n} \gamma_i^F \cdot y_{i,t}^F + \beta E_t \pi_{t+1}^H$$

where $y_{i,t}^F$ stands for the $i$th foreign country's output gap. To our knowledge, there has been little empirical work based on this form of open economy New Keynesian Phillips curve.

# 3 A Multilateral Open Economy Phillips Curve

As we have seen, so far, most empirical work on the open economy Phillips curve has been done on the single equation basis in a two-country setting. To model the interaction between real activities and inflation rates across multiple countries simultaneously, we need to essentially build a system of equations. This offers efficiency gains but involves too many coefficients to be estimated. To solve the problem, we take advantage of the symmetric appearance in the Phillips curve equations and build a reduced form multilateral open economy Phillips curve using common factors. Although it is based on the traditional Phillips curve, it uses insights from both the traditional and the New Keynesian Phillips curve that the domestic inflation rate is related to not only the domestic output gap but also the foreign output gap.

We use the traditional Phillips curve as opposed to the New Keynesian Phillips curve. There is little evidence at present that the New Keynesian Phillips curve's structural modelling of inflation in a rational expectations framework provides a clearly superior approach relative to traditional models of inflation dynamics in empirical studies. Particularly, Rudd and Whelan (2006) show the hybrid model New Keynesian Phillips curve fails to provide a useful empirical description of the inflation process relative to the traditional Phillips curve[4].

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[4] Rudd and Whelan (2006) uses the following traditional Phillips curve in the triangle form of

$$\pi_t = \alpha + \rho \pi_{t-1} + \sum_{k=1}^{N} \mu_k \triangle \pi_{t-k} + \lambda_1 y_{t-1} + \lambda_2 y_{t-2} + \varsigma \left(\pi_{t-1}^m - \pi_{t-1}\right) + \epsilon_t$$

with the difference (lagged) between import price inflation $\pi_{t-1}^m$ and domestic inflation $\pi_{t-1}$ as the supply shock variable. They find the traditional output gaps remain highly significant explanatory variables. The model remains surprisingly stable and proves useful in forecasting, even considering the possible shifts in monetary policy's effects

We adopt a more generalized form of the traditional Phillips curve, similar to Kuttner (1994), Gerlach and Smets (1997), Apel and Janssen (1999) and Camba-Mendez and Rodriguez-Palenzuela (2003). For country $i = 1...k$, the inflation $\pi_{i,t}$ (log difference of price level) and output $y_{i,t}$ (log level) follow

$$\pi_{i,t} = \pi^n_{i,t} + \theta_{i,0} \cdot c_{i,t} + \theta_{i,1} \cdot c_{i,t-1} + u^\pi_{i,t} \tag{1}$$

$$y_{i,t} = y^n_{i,t} + c_{i,t} + u^y_{i,t} \tag{2}$$

The Phillips curve relationship is established through the cyclical factor $c_{i,t}$, which enters both the inflation equation (both contemporaneously and with one lag) and the output equation. $\pi^n_{i,t}$ is the trend inflation and $y^n_{i,t}$ is the trend output. $u^\pi_{i,t}$ and $u^y_{i,t}$ are observation errors.

The cyclical factor $c_{i,t}$ also fits the conventional definition of the output gap. So in the following discussions, the terms "cyclical factor (or movement)" and "gap" are used interchangeably. Equations (1) and (2) amount to a multivariate approach to measuring the output gap. This approach has the advantage of being able to put theoretical restrictions on data fitting, compared with the ad hoc fashion of univariate decomposition or detrending approach to estimating the gap (Orphanides and van Norden (2002, 2004b)). It is also much less data dependent than the production function method of measuring the output gap. Most countries do have output and inflation statistics, even though the data quality varies from country to country. On the other hand, because the output measure often faces revisions, the output gap estimated by employing the Phillips curve is subject to significant and highly persistent revisions (Orphanides and van Norden (2002), Camda-Mendez and Rodriguez-Palenzuela (2003), Cayen and van Norden (2005)). Orphanides and van Norden (2004a, 2004b) conclude the ex post output gap measure is quite useful for predicting inflation, but the real time output gap is not. At this stage, we want to focus on the historical relationship between inflation and the output gap, so the data revision issue is less of a concern.

The international factor enters each country's Phillips curve through a common component $c^w_t$ that is shared by all $c_{i,t}$. The magnitude of its influence is controlled by the loading $\gamma^c_i$. The rest of $c_{i,t}$'s movement is picked up by an idiosyncratic part $c^I_{i,t}$ with a standardized loading of 1. Both $c^w_t$ and $c^I_{i,t}$ are assumed to follow AR(2) processes.

$$c_{i,t} = \gamma^c_i \cdot c^w_t + c^I_{i,t} \tag{3}$$

$$c^w_t = \rho^{cw}_1 \cdot c^w_{t-1} + \rho^{cw}_2 \cdot c^w_{t-2} + \varepsilon^{cw}_t \tag{3a}$$

$$c^I_{i,t} = \rho^{cI}_{i,1} \cdot c^I_{i,t-1} + \rho^{cI}_{i,2} \cdot c^I_{i,t-2} + \varepsilon^{cI}_{i,t} \tag{3b}$$

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on the reduced form.

The decomposition of cyclical indicator $c_{i,t}$ corresponds to the methodology of Kose, Otrok and Whiteman (2003). They, however, adopt a two-step approach. First, They define cyclical movements as either simple log difference or HP filtered output series. Then, they perform a statistical decomposition of the cyclical movements of individual countries into parts due to the world, regional and country-specific factors. In our model here, each $c_{i,t}$ is estimated under restrictions implied by the Phillips curve, and the common component $c_t^w$ is extracted at the same time.

The common cyclical component $c_t^w$ embodies all the information on the so-called global output gap, which reflects the global determinants of the domestic inflation through the Phillips curve in each country. Essentially, $c_t^w$ can be regarded as a function, albeit a complicated one, of all the individual gaps $c_{i,t}$, with each gap's weight implicitly determined by the model. Here, both domestic and foreign gaps are accounted for. In comparison, domestic gap and foreign output gaps enter the Phillips curve separately in Borio and Filardo (2006), and Ihrig, Kamin, Lindner and Marquez (2007). Both studies use simple weighted averages of gaps across foreign countries based on pre-determined weights.

The trend inflation $\pi_{i,t}^n$ is the inflation that would persist if the cyclical component is zero. It can be thought as reflecting the expected inflation in the traditional Phillips curve. It can also be interpreted as the frictionless inflation rate under the New Keynesian framework. It consists of two parts. One is due to the influence from a common trend inflation $\pi_t^w$ across countries, with loading $\gamma_i^\pi$ and the other part $\pi_{i,t}^I$ is idiosyncratic, with standardized loading of 1. We assume both $\pi_t^w$ and $\pi_{i,t}^I$ follow random walk processes.

$$\begin{aligned}
\pi_{i,t}^n &= \gamma_i^\pi \cdot \pi_t^w + \pi_{i,t}^I && (4)\\
\pi_t^w &= \pi_{t-1}^w + \varepsilon_t^{\pi w} && (4a)\\
\pi_{i,t}^I &= \pi_{i,t-1}^I + \varepsilon_{i,t}^{\pi I} && (4b)
\end{aligned}$$

Ciccarelli and Mojon (2005) propose a measure of the global inflation by breaking down the individual country's demeaned year-over-year inflation rate into a part attributable to the common global component, which follows a simple AR(1) process, and an idiosyncratic part. As they correctly point out, their approach may mix up the trend and cyclical parts of the inflation process. This concern leads to their further analysis of the inflation rates at the business cycle frequency only. In our current model, we instead model both trend and cyclical inflation based on quarter-over-quarter inflation rates. On one hand, we assume the underlying trend inflation needs to be decomposed into common and idiosyncratic components, both following random walk processes. On the other hand, the cyclical inflation captured by the Phillips curve relationship (1) is also divided into parts due to the global common output gap and the idiosyncratic gap.

In addition to nesting recent studies in the three related but separate fronts that we have discussed above, we introduce the common potential output. The trend output $y_{i,t}^n$ is interpreted as the potential output. It too can be decomposed into two parts. The first part due to a common potential output $y_t^w$ with loading $\gamma_i^y$. The other is an idiosyncratic component $y_{i,t}^I$ with standardized loading 1. Both $y_t^w$ and $y_{i,t}^I$ follow random walk with a drift, because of the obvious slope in the output series.

$$
\begin{aligned}
y_{i,t}^n &= \gamma_i^y \cdot y_t^w + y_{i,t}^I && (5)\\
y_t^w &= \beta^w + y_{t-1}^w + \varepsilon_t^{yw} && (5a)\\
y_{i,t}^I &= \beta_i^I + y_{i,t-1}^I + \varepsilon_{i,t}^{yI} && (5b)
\end{aligned}
$$

In summary, if we substitute equations (4) and (3) into equation (1), the observed inflation for $i = 1...k$ follows

$$\pi_{i,t} = \gamma_i^\pi \cdot \pi_t^w + \pi_{i,t}^I + \theta_{i,0} \cdot \gamma_i^c \cdot c_t^w + \theta_{i,0} \cdot c_{i,t}^I + \theta_{i,1} \cdot \gamma_i^c \cdot c_{t-1}^w + \theta_{i,1} \cdot c_{i,t-1}^I + u_{i,t}^\pi \qquad (6)$$

Substitute equation (5) and (3) into equation (2), the observed output for $i = 1...k$ follows

$$y_{i,t} = \gamma_i^y \cdot y_t^w + y_{i,t}^I + \gamma_i^c \cdot c_t^w + c_{i,t}^I + u_{i,t}^y \qquad (7)$$

## 4 State Space Model and Data Description

Equations (1) through (7) represent our base model, which we take to the data. Equations (4a) and (5a) lead to

$$
\begin{aligned}
\begin{pmatrix} \pi_t^w \\ y_t^w \end{pmatrix} &= \begin{pmatrix} 0 \\ \beta^w \end{pmatrix} + \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} \begin{pmatrix} \pi_{t-1}^w \\ y_{t-1}^w \end{pmatrix} + \begin{pmatrix} \varepsilon_t^{\pi w} \\ \varepsilon_t^{yw} \end{pmatrix}\\
S_t^w &= B^w + A \cdot S_{t-1}^w + \varepsilon_t^w && (8)
\end{aligned}
$$

Equations (4b) and (5b) lead to

$$
\begin{aligned}
\begin{pmatrix} \pi_{i,t}^I \\ y_{i,t}^I \end{pmatrix} &= \begin{pmatrix} 0 \\ \beta_i^I \end{pmatrix} + \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} \pi_{i,t-1}^I \\ y_{i,t-1}^I \end{pmatrix} + \begin{pmatrix} \varepsilon_{i,t}^{\pi I} \\ \varepsilon_{i,t}^{yI} \end{pmatrix}\\
S_{i,t}^I &= B_i^I + A \cdot S_{i,t-1}^I + \varepsilon_{i,t}^I && (9)
\end{aligned}
$$

for $i = 1...k$.

Equations (3a) and (3b) lead to

$$\begin{aligned}
\begin{pmatrix} c_t^w \\ c_{1,t}^I \\ ... \\ c_{k,t}^I \end{pmatrix} &= \begin{pmatrix} \rho_1^{cw} & & & \\ & \rho_{1,1}^{cI} & & \\ & & ... & \\ & & & \rho_{k,1}^{cI} \end{pmatrix} \cdot \begin{pmatrix} c_{t-1}^w \\ c_{1,t-1}^I \\ ... \\ c_{k,t-1}^I \end{pmatrix} + \begin{pmatrix} \rho_2^{cw} & & & \\ & \rho_{1,2}^{cI} & & \\ & & ... & \\ & & & \rho_{k,2}^{cI} \end{pmatrix} \cdot \begin{pmatrix} c_{t-2}^w \\ c_{1,t-2}^I \\ ... \\ c_{k,t-2}^I \end{pmatrix} + \begin{pmatrix} \varepsilon_t^{cw} \\ \varepsilon_{1,t}^{cI} \\ ... \\ \varepsilon_{k,t}^{cI} \end{pmatrix} \\
S_t^c &= \rho_1 \cdot S_{t-1}^c + \rho_2 \cdot S_{t-2}^c + \varepsilon_t^c \qquad (10)
\end{aligned}$$

Together, equations (8), (9) and (10) make up the state equation of the state space model.

$$\begin{aligned}
\begin{pmatrix} S_t^w \\ S_{1,t}^I \\ ... \\ S_{k,t}^I \\ S_t^c \\ S_{1,t-1}^I \\ ... \\ S_{k,t-1}^I \\ S_{t-1}^c \end{pmatrix} &= \begin{pmatrix} B^w \\ B_1^I \\ ... \\ B_k^I \\ 0 \\ 0 \\ ... \\ 0 \\ 0 \end{pmatrix} + \begin{pmatrix} A & & & & & & & & \\ & A & & & & & & & \\ & & ... & & & & & & \\ & & & A & & & & & \\ & & & & \rho_1 & & & & \rho_2 \\ & I & & & & & & & \\ & & ... & & & & & & \\ & & & I & & & & & \\ & & & & I & & & & \end{pmatrix} \cdot \begin{pmatrix} S_{t-1}^w \\ S_{1,t-1}^I \\ ... \\ S_{k,t-1}^I \\ S_{t-1}^c \\ S_{1,t-2}^I \\ ... \\ S_{k,t-2}^I \\ S_{t-2}^c \end{pmatrix} + \begin{pmatrix} \varepsilon_t^w \\ \varepsilon_{1,t}^I \\ ... \\ \varepsilon_{k,t}^I \\ \varepsilon_t^c \\ 0 \\ ... \\ 0 \\ 0 \end{pmatrix} \\
\alpha_t &= d + T \cdot \alpha_{t-1} + V_t \qquad (11)
\end{aligned}$$

with $V_t \sim N(0, Q)$. For identification, we follow Stock and Watson (1989) and specify $var(\varepsilon_t^{\pi w})$, $var(\varepsilon_t^{yw})$, and $var(\varepsilon_t^{cw})$ (in practice, the corresponding elements in the Choleski decomposition of $Q$) to be constant. Other variance terms in $Q$ are set free. In addition, all the covariance terms are assumed zero, except $cov\left(\varepsilon_t^{cw}, \varepsilon_t^{yw}\right)$ and $cov\left(\varepsilon_{i,t}^{cI}, \varepsilon_{i,t}^{yI}\right)$ for $i = 1...k$. So on one hand, we allow correlations between innovations to the gap measures and potential outputs. This gives more economic content to the trend-cycle decomposition compared with the orthogonality case (Clark (1987)). For example, shocks to the economy that increase output can also boost business investment via the accelerator mechanism, raising the capital stock and trend output, thus leading to a positive correlation between innovations to the potential output and output gap. In a real business cycle model, a persistent shock to the technology can have similar effects. On the other hand, shocks to trend inflation are not correlated with real shocks to either the potential or cyclical output. If we think a shock to the trend inflation (a random walk), which represents a permanent shift of the trend inflation, results from a change of the growth rate of the money, the independence between innovations to trend inflation and real shocks (permanent or temporary) is consistent with the long run superneutrality hypothesis.

Equations (6) and (7) make up the observation equation of the state space model.

$$
\begin{aligned}
\begin{pmatrix} \pi_{1,t} \\ y_{1,t} \\ \ldots \\ \pi_{k,t} \\ y_{k,t} \end{pmatrix}
&= \begin{pmatrix}
(\gamma_1^{\pi}\ 0) & (1\ 0) & & & (\theta_{1,0}\cdot\gamma_1^c\ \ \theta_{1,0}\ \ldots 0) & & & & (\theta_{1,1}\cdot\gamma_1^c\ \ \theta_{1,1}\ \ldots 0) \\
(0\ \gamma_1^{y}) & (0\ 1) & & & (\gamma_1^c\ \ 1\ \ldots\ 0) & & & & (0\ 0\ \ldots\ 0) \\
\ldots & \ldots & \ldots & \ldots & \ldots & \ldots & \ldots & \ldots & \ldots \\
(\gamma_k^{\pi}\ 0) & & & (1\ 0) & (\theta_{k,0}\cdot\gamma_k^c\ \ 0\ \ldots\theta_{k,0}) & & & & (\theta_{k,1}\cdot\gamma_k^c\ \ 0\ \ldots\theta_{k,1}) \\
(0\ \gamma_k^{y}) & & & (0\ 1) & (\gamma_k^c\ \ 0\ \ldots\ 1) & & & & (0\ 0\ \ldots\ 0)
\end{pmatrix} . \\
&\quad \begin{pmatrix} S_t^w \\ S_{1,t}^I \\ \ldots \\ S_{k,t}^I \\ S_t^c \\ S_{1,t-1}^I \\ \ldots \\ S_{k,t-1}^I \\ S_{t-1}^c \end{pmatrix}
+ \begin{pmatrix} u_{1,t}^{\pi} \\ u_{1,t}^{y} \\ \ldots \\ u_{k,t}^{\pi} \\ u_{k,t}^{y} \end{pmatrix} \\
Y_t &= Z\cdot\alpha_t + W_t \qquad (12)
\end{aligned}
$$

with $W_t \sim N(0,R)$, where $R$ is assumed to be diagonal, indicating no cross correlation among observation errors. We specify $\gamma_i^{\pi} > 0$, $\gamma_i^{y} > 0$ and $\gamma_i^{c} > 0$. Essentially, we force the idiosyncrasy in inflation and output of each economy to be explained by the idiosyncratic components in trend inflation, potential output and cyclical movements. Particularly, with $\gamma_i^c > 0$, $\theta_{i,0}$ and $\theta_{i,1}$ are likely to sum up to be positive, so that the Phillips curve relationship can be preserved empirically. We use maximum likelihood estimation of the state space model[5].

The sample data set includes quarterly data on real output (log level) and inflation (log difference) of 10 major economies from 1970 Q1 to 2005 Q4. All data are downloaded from the Haver database. They are seasonally adjusted (using the X12 seasonal adjustment procedure) if not originally so from Haver. Table 1 describes the data in detail, with the source indicating the name of the data set in Haver. We use the aggregate Euro area data, so the data actually covers 21 economic entities,

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[5] We use SsfPack 3.0 in OX, which is developed by Koopman, Shephard and Doornik (2002).

including not only developed economies but also two newly industrialized economies—Korea and Taiwan. The choice of these economies are based on real output, total trade volume and data availability. The country code and the subscript $i$ are used for identification. This sample data set is used in our base model first. Table 1 also includes two additional economies, China and India, whose data are used later in an expanded sample. The subscript $j$ is used for identification there for convenience, because the ordering of economies in the expanded sample is a little different.

# 5 Major Findings

Table 2 presents the coefficient estimates with standard errors, using the base model on the 10-country sample. The autoregressive coefficients $\rho_1^w$ and $\rho_2^w$, $\rho_{i,1}^{cI}$ and $\rho_{i,2}^{cI}$, of the cyclical output imply stationarity in most cases. However, for $i = 8$ (Switzerland), the idiosyncratic cyclical output is very close to a unit root process. The sum of the two coefficients $\theta_{i,0}$ and $\theta_{i,1}$ on the output gap in the inflation equation (1) remains positive for all countries, thus, preserving the traditional Phillips curve relationship between inflation and output gap. $\beta^w$ is negative, so the common potential output is downward sloping. This may reflect the shared slowing of economic growth among developed countries over the sample period. On the other hand, all $\beta_i^I$'s are positive, so the idiosyncratic potential output is upward sloping.

Table 3 presents the estimated variance and covariance terms in matrix $R$ and $Q$. The innovations to the common potential output and the common output gap are highly correlated. As we discussed earlier in the model specification, a positive correlation can arise in a number of situations. The correlation between the innovations to the idiosyncratic potential output and idiosyncratic output gap varies from -1 to +1, depending on the economy. Because of the decomposition into common and idiosyncratic components, and because of the usage of information from both the output and inflation processes, these correlations can be hard to interpret sometimes. Nonetheless, allowing for such correlations adds an element of economic reality and offers a more flexible model.

We compare our output gap measure with the OECD Outlook's gap measure $gap^{oecd}$ in all the countries for which data are available (Figure 1). The first column of table 4 calculates the correlation between the two. In the OECD Outlook, the output gap is defined as the difference between the actual and potential GDP as a percent of potential GDP. We follow this definition by calculating $100 \cdot \left( y_{i,t} - y_{i,t}^n \right)$ because our output equation (2) is in log[6]. The estimated output gap measure closely resembles the OECD Outlook gap for the U.S., Euro Area and Canada. Particularly,

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[6] Considering the observation error in our output equation (2), this is equivalent to $100 \cdot \left( c_{i,t} + u_{i,t}^y \right)$.

the U.S. gaps from two sources appear almost identical. The two measures are also somewhat close for Australia and Sweden. On the other hand, our estimated output gaps for the U.K. and Japan behave very much differently from the OECD Outlook's. Particularly, the estimated Japanese output gap shows many high frequency movements (the AR(2) coefficients $\rho_{i,1}^{cI}$ and $\rho_{i,2}^{cI}$ for Japan in Table 2 already signify this). Additionally, in the late 1990s and early 2000s, the Japanese economy appears to be operating above the potential judging from the estimated gap, while in fact, we know Japan is under persistent deflationary pressure in that period. Indeed, after Japan's fast growth period from the 1970s and 1980s (despite oil shocks), its prolonged economic slump in the 1990s coupled with several deflation episodes presents a unique experience among major economies in our sample period. There may be some structural characteristics of the Japanese economy that our model fails to fully account for. In this regard, the OECD outlook gap measure for Japan may also fall short. With all these considered, nonetheless, we think in general our output gap measure captures the essence of the deviation of actual GDP from potential GDP for most of the leading economies. This gives us more confidence in several interesting findings based on the model.

There is strong evidence of a common output gap, which also depicts the common cyclical movement across countries, in line with the recent study of the international business cycles by Kose, Otrok and Whiteman (2003). Figure 2 presents the common output gap $c_t^w$. The magnitude of the common output gap measure is not important. What counts is the common output gap's contribution, now denoted by $y_{i,t}^{cw} = \gamma_i^c \cdot c_t^w$, to each individual country's gap measure $c_{i,t}$. As we have discussed earlier, the common output gap $c_t^w$ is actually a weighted average of each individual economy's gap measure $c_{i,t}$, with the weights determined implicitly by the state space model. Among all possible factors, the size and the openness to trade and investment of a particular economy are likely to be the leading ones in determining the relative weight assigned to its gap measure $c_{i,t}$ in calculating the common output gap $c_{i,t}^w$. Now equation (3) becomes

$$\begin{aligned} c_{i,t} &= \gamma_i^c \cdot c_t^w + c_{i,t}^I \\ &= y_{i,t}^{cw} + c_{i,t}^I \end{aligned} \tag{3'}$$

with $\gamma_i^c$ implicitly determined. Figure 3 compares $y_{i,t}^{cw}$ (called "common gap" in short) with $c_{i,t}$. The second column of table 4 reports the correlation between the two. We can see that the two are closely correlated in several countries including the U.S., Canada and Australia. The U.S. is the dominant economy in both size of the economy and aggregate volumes in trade and investment. Both Canada and Australia are big raw material exporters, whose business cycles very much reflect the international business climate. In addition, Canada's economy is closely aligned with the

U.S. economy. The correlation between $y_{i,t}^{cw}$ and $c_{i,t}$ is weaker for Japan, U.K., Sweden, Korea and Taiwan. Their own gap measures $c_{i,t}$ reflect rather important idiosyncratic movements in their business cycles. The correlation between $y_{i,t}^{cw}$ and $c_{i,t}$ is even lower for the Euro Area and Switzerland, both of which seem to have a large part of the cyclical movement due to domestic reasons. However, we have to take some caution in explaining the result for the Euro Area, because it may also reflect data aggregation problems, particularly in the early sample period before the Euro came into existence.

Next we consider the impact of this common output gap on the domestic inflation. We define the cyclical inflation, which represents the response to the output gap in the Phillips curve, as $\pi_{i,t}^{c} = \theta_{i,0} \cdot c_{i,t} + \theta_{i,1} \cdot c_{i,t-1}$. From equations (1) and (3), $\pi_{i,t}^{c}$ can be redefined as the sum of $\pi_{i,t}^{cw}$, the part due to the common output gap, and $\pi_{i,t}^{cI}$, the part due to the idiosyncratic output gap

$$\begin{aligned} \pi_{i,t}^{c} &= \left(\theta_{i,0} \cdot \gamma_i^c \cdot c_t^w + \theta_{i,1} \cdot \gamma_i^c \cdot c_{t-1}^w\right) + \left(\theta_{i,0} \cdot c_{i,t}^I + \theta_{i,1} \cdot c_{i,t-1}^I\right) \\ &= \pi_{i,t}^{cw} + \pi_{i,t}^{cI} \end{aligned}$$

So equation (1) becomes

$$\begin{aligned} \pi_{i,t} &= \pi_{i,t}^{n} + \pi_{i,t}^{c} + u_{i,t}^{\pi} \\ &= \pi_{i,t}^{n} + \pi_{i,t}^{cw} + \pi_{i,t}^{cI} + u_{i,t}^{\pi} \qquad (1') \end{aligned}$$

Figure 4 shows the decomposition of inflation $\pi_{i,t}$ into the trend inflation $\pi_{i,t}^{n}$ and the cyclical inflation $\pi_{i,t}^{c}$ (observation error $u_{i,t}^{\pi}$ is not included). Table 5 reports the correlations between $\pi_{i,t}^{n}$ and $\pi_{i,t}$, and between $\pi_{i,t}^{c}$ and $\pi_{i,t}$. The evidence suggests that the trend inflation $\pi_{i,t}^{n}$ accounts for most of the disinflationary movements in most leading economies during the sample period. Relatively, only a small part of the disinflation phenomena can be attributed to the cyclical inflation $\pi_{i,t}^{c}$. This seems only natural when the cyclical inflation is meant to capture deviations of the actual inflation from the trend inflation. This also leaves even less for the part of $\pi_{i,t}$ to be explained by $\pi_{i,t}^{cw}$. Instead, we focus on the decomposition of the cyclical inflation $\pi_{i,t}^{c}$ into $\pi_{i,t}^{cw}$ and $\pi_{i,t}^{cI}$. This corresponds to Ciccarelli and Mojon (2005)'s analysis of the common inflation factor at the business cycles frequencies. Figure 5 compares $\pi_{i,t}^{cw}$ with $\pi_{i,t}^{c}$. Table 5 also reports the correlation between the two. The common component accounts for much of the cyclical inflation in the U.S., Canada and Australia, less for Japan, Sweden, Korea and Taiwan, and even less for the U.K., Euro Area and Switzerland. The ordering generally follows the ranking of how much the common output gap accounts for the gap measure in each economy.

It is interesting to compare our findings with the recent studies on the foreign gaps' influence on domestic inflation. Borio and Filardo (2006) argue foreign gaps have significant effects on domestic inflation using data of 16 industrialized economies from 1985 to 2005. Ihrig, Kamin, Lindner and Marquez (2007), however, find that result not robust. Based on our model, for the countries where the common gap's contribution to cyclical inflation is low, it is safe to say that the foreign output gaps don't have significant effects on the cyclical inflation. However, it is not simply the opposite for the countries where the common gap's contribution is high. For example, the U.S. cyclical inflation is largely explained by the common output gap. But we cannot jump to the conclusion that foreign gaps matter for the U.S. cyclical inflation because the common output gap measure may depend heavily on the U.S. gap itself. Instead of distinguishing between the domestic gap and foreign gap, we propose using the common output gap measure, which covers not only the foreign gaps, but also the domestic gap. In this sense, the common output gap is a true global measure.

As we have seen above, the decrease in trend inflation $\pi^n_{i,t}$ accounts for lower inflation in most of the countries during the sample period. To see how much of the decrease in $\pi^n_{i,t}$ is commonly shared by all economies, we define the portion of trend inflation $\pi^n_{i,t}$ that is due to the international common trend inflation as $\pi^{nw}_{i,t} = \gamma^\pi_i \cdot \pi^w_t$. Thus equation (4) becomes

$$\begin{aligned} \pi^n_{i,t} &= \gamma^\pi_i \cdot \pi^w_t + \pi^I_{i,t} \\ &= \pi^{nw}_{i,t} + \pi^I_{i,t} \qquad \text{(4')} \end{aligned}$$

Figure 6 shows $\pi_{i,t}$, $\pi^{nw}_{i,t}$ and $\pi^I_{i,t}$. Table 5 also reports the correlation between $\pi^{nw}_{i,t}$ and $\pi^n_{i,t}$. We find a strong common trend inflation $\pi^w_t$, which accounts for much of the recent decrease of the trend inflation $\pi^n_{i,t}$ (and $\pi_{i,t}$, in turn). This concurs with the common inflation, which largely reflects the common trend in the inflation series across countries, found by Ciccarelli and Mojon (2005) based on the breakdown of the demeaned year-over-year inflation rates. Meanwhile, the estimated $\pi^I_{i,t}$ appears to be constant for the U.K., Euro Area, Australia, Switzerland, Korea and Taiwan. It also remains quite stable over the sample period for Canada and Sweden. For these countries, the trend inflation $\pi^n_{i,t}$ can be regarded a simple markup to $\pi^{nw}_{i,t}$. However, the U.S. idiosyncratic trend inflation actually moves up in the 1970s and 1980s, but stabilizes in the 1990s and 2000s. The Japanese idiosyncratic trend inflation also shows some fluctuations in the late 1970s and around the 2000s.

Last but not least, figure 7 suggests that compared with the common output gap, the commonly shared decrease in the trend inflation has been a much more important contributor to the disinflation phenomena across the economies during our sample period. This is also evident from table 5, which reports too the correlation between $\pi^{cw}_{i,t}$ and $\pi_{i,t}$, and between $\pi^{nw}_{i,t}$ and $\pi_{i,t}$. In the current discussion of the globalization's influence on the determination of inflation, the level of resource utilization in the world as a whole is one of the potential venues for such influence (Bernanke (2007)). Our model, however, suggests this has not been a major channel. In the meantime, the evidence of a strong common trend inflation does seem to suggest some kind of convergence across various economies over time. This may be due to better macroeconomic, particularly, monetary policies, across the countries. This may be also related to other aspects of global economic integration. Further research is called for in this regard.

# 6 Extension of the Base Model

## 6.1 Time-varying $\beta$ Model

We extend the base model in two ways. First, we consider an alternative model which allows $y^w_t$ and $y^I_{i,t}$ to follow random walk with a time varying drift $\beta$. As we have observed in the base model, the estimated Japan and UK gaps are not very satisfactory. These may be due to the rigidity of a constant $\beta$. A time-varying $\beta$ may help us in that regard. The appendix presents the state space model under time-varying $\beta$.

The correlation between our gap measure and the corresponding OECD Outlook gap measure is higher for Japan, UK and Sweden than what is reported in table 4, but still only Sweden's estimated output gap measure closely resembles the OECD Outlook gap. On the other hand, the correlation is lower for the U.S., Euro Area, Canada and Australia. In the U.S. case, the output gap turns positive in most of the 1990s, contrary to what we find in the base model and from the OECD Outlook. In general, the magnitude of the estimated gap is much lower than the OECD Outlook's gap measure, particularly for the U.S., U.K., Canada and Australia. Compared with the constant $\beta$ model, the time-varying $\beta$ model seems to push too much of the output movement into the underlying potential and leave too little for the gap measure to pick up. We find the common potential output is upward sloping, contrary to the base model with constant $\beta$. So depending on the assumption, the common component of potential outputs can be either upward or downward sloping. Nonetheless, we get very similar results concerning the contributions to inflation from different factors. The decrease in trend inflation $\pi^n_{i,t}$ still accounts for lower inflation in most of the countries during the sample period and the common trend inflation $\pi^w_t$ accounts for much of the recent decrease of the trend inflation $\pi^n_{i,t}$. Only a small part of the disinflation phenomena can be attributed to the cyclical inflation $\pi^{cI}_{i,t}$.

In general, the common output gap has affected the domestic inflation only to a limited extent.

## 6.2 The Base Model on 12-Country Sample

We also consider including two of the fastest growing economies in the world—China and India in our sample for the base model. However, extra caution has to be taken here. First, there are a large number of missing observations for these two countries' data series (Table 1). So they don't contribute to the estimation in the early sample period of the common components. In addition, even for the available sample period, the data quality is known to be rather poor. All these make it much harder to estimate the Phillips curve relationship and may affect the common components in unpredictable ways.

Note we change the subscript $i$ to $j$ for the expanded sample as the ordering of the observed country series is a little different. The autoregressive coefficients $\rho_1^w$ and $\rho_2^w$, $\rho_{j,1}^{cI}$ and $\rho_{j,2}^{cI}$, of the cyclical output imply mostly stationarity. However, for $j = 11$ (India), the process is very close to a unit root process. In addition, the sum of the two coefficients $\theta_{j,0}$ and $\theta_{j,1}$ on the output gap in the inflation equation (1) turns out to be negative for $j = 10$ (China) and 11 (India). This contradicts the traditional Phillips curve relationship between inflation and the output gap, which however holds for all the other 10 economies. Part of the failure to fit a satisfactory Phillips curve for China and India may lie in the poor data quality and short sample period available, as we have discussed earlier. More importantly, the traditional Phillips curve model relying solely on the output gap is simply not rich enough to pick up all the elements that can influence the inflation movement in a transition economy, such as price deregulation, trade liberalization and exchange rate reforms. This is consistent with previous studies such as Gerlach and Peng (2006). We also find that the correlation between $y_{j,t}^{cw}$ and $c_{j,t}$ is minimal for China and India. In fact, the correlation for China is negative. The implication is that both China and India have large idiosyncratic cyclical movements, which is not surprising as they are both large developing economies who have been going through major structural reforms, unlike the other developed and newly industrialized economies. We find the common potential output is upward sloping, contrary to the case with the 10-country sample. This may be due to the inclusion in our sample of China and India, whose growth rates remain high and may have been even increasing over the sample period. For the other 10 economies, the results concerning the contributions to inflation from different factors remain essentially the same.

# 7 Concluding Remarks

In this paper, we estimate a multilateral Phillips curve with common components of time-varying output gaps, trend inflation rates and potential outputs, to account for the international influence on domestic inflation. Our model nests recent studies on international business cycles, common inflation, and foreign output gaps' influence on domestic inflation. In addition, we introduce the concept of common potential output across countries.

In our base model, the estimated Phillips curve coefficients have the right signs using a 10-country data sample, which covers leading developed and newly industrialized economies. The estimated output gap closely resembles that from the OECD Outlook, particularly for the U.S. The common output gap accounts for much of the output gap in the U.S., Canada and Australia. However, over the sample period from 1970 to 2005, this common output gap has only limited influence on the domestic inflation in general. What contributes the most to the long term disinflationary phenomena in these economies is the decrease of trend inflation. We find a strong common component among the trend inflation rates across the economies.

To extend our base model, we first consider a time varying $\beta$ model. But it results in gap measures of too small magnitudes. We also expand our data sample to include China and India in estimating the base model. However, the estimated Phillips curve coefficients are of the wrong sign for these two countries. There is still ample opportunities for future exploration in either direction. For example, we may differentiate between countries in modelling the slope for potential output, or introduce additional idiosyncratic factors to better pick up the movement in inflation for certain countries. Although we are taking a historical perspective in analyzing the Phillips curve with international factors, the same framework may be of interest for forecast purposes. In that regard, special attention needs to be paid to the real time properties of the model.

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# A State Space Model Under Time-varying $\beta$

We assume the trend inflation rates, both common and idiosyncratic, follow a random walk with time varying drift. So we have

$$\begin{aligned}
y_{i,t}^{n} &= \gamma_i^y \cdot y_t^w + y_{i,t}^I & (5)\\
y_t^w &= \beta_{t-1}^w + y_{t-1}^w + \varepsilon_t^{yw} & (5a')\\
\beta_t^w &= \beta_{t-1}^w + \varepsilon_t^{\beta w} & (5b')\\
y_{i,t}^I &= \beta_{i,t-1}^I + y_{i,t-1}^I + \varepsilon_{i,t}^{yI} & (5c')\\
\beta_{i,t}^I &= \beta_{i,t-1}^I + \varepsilon_{i,t}^{\beta I} & (5d')
\end{aligned}$$

Equations (4a), (5a') and (5b') lead to

$$\begin{aligned}
\begin{pmatrix} \pi_t^w \\ y_t^w \\ \beta_t^w \end{pmatrix} &= \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 1 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \pi_{t-1}^w \\ y_{t-1}^w \\ \beta_{t-1}^w \end{pmatrix} + \begin{pmatrix} \varepsilon_t^{\pi w} \\ \varepsilon_t^{yw} \\ \varepsilon_t^{\beta w} \end{pmatrix} \\
S_t^w &= A \cdot S_{t-1}^w + \varepsilon_t^w & (8')
\end{aligned}$$

Equations (4b), (5c') and (5d') lead to

$$\begin{aligned}
\begin{pmatrix} \pi_{i,t}^I \\ y_{i,t}^I \\ \beta_{i,t}^I \end{pmatrix} &= \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 1 \\ 0 & 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} \pi_{i,t-1}^I \\ y_{i,t-1}^I \\ \beta_{i,t-1}^I \end{pmatrix} + \begin{pmatrix} \varepsilon_{i,t}^{\pi I} \\ \varepsilon_{i,t}^{yI} \\ \varepsilon_{i,t}^{\beta I} \end{pmatrix} \\
S_{i,t}^I &= A \cdot S_{i,t-1}^I + \varepsilon_{i,t}^I & (9')
\end{aligned}$$

for $i = 1 \ldots k$.

Equations (3a) and (3b) lead to

$$\begin{aligned}
\begin{pmatrix} c_t^w \\ c_{1,t}^I \\ \ldots \\ c_{k,t}^I \end{pmatrix} &= \begin{pmatrix} \rho_1^{cw} & & & \\ & \rho_{1,1}^{cI} & & \\ & & \ldots & \\ & & & \rho_{k,1}^{cI} \end{pmatrix} \cdot \begin{pmatrix} c_{t-1}^w \\ c_{1,t-1}^I \\ \ldots \\ c_{k,t-1}^I \end{pmatrix} + \begin{pmatrix} \rho_2^{cw} & & & \\ & \rho_{1,2}^{cI} & & \\ & & \ldots & \\ & & & \rho_{k,2}^{cI} \end{pmatrix} \cdot \begin{pmatrix} c_{t-2}^w \\ c_{1,t-2}^I \\ \ldots \\ c_{k,t-2}^I \end{pmatrix} + \begin{pmatrix} \varepsilon_t^{cw} \\ \varepsilon_{1,t}^{cI} \\ \ldots \\ \varepsilon_{k,t}^{cI} \end{pmatrix} \\
S_t^c &= \rho_1 \cdot S_{t-1}^c + \rho_2 \cdot S_{t-2}^c + \varepsilon_t^c & (10')
\end{aligned}$$

Together, equations (8'), (9') and (10') make up the state equation of the state space model.

$$\begin{aligned}\begin{pmatrix} S_t^w \\ S_{1,t}^I \\ ... \\ S_{k,t}^I \\ S_t^c \\ S_{1,t-1}^I \\ ... \\ S_{k,t-1}^I \\ S_{t-1}^c \end{pmatrix} &= \begin{pmatrix} A & & & & & & & & \\ & A & & & & & & & \\ & & ... & & & & & & \\ & & & A & & & & & \\ & & & & \rho_1 & & & & \rho_2 \\ & I & & & & & & & \\ & & ... & & & & & & \\ & & & I & & & & & \\ & & & & I & & & & \end{pmatrix} \cdot \begin{pmatrix} S_{t-1}^w \\ S_{1,t-1}^I \\ ... \\ S_{k,t-1}^I \\ S_{t-1}^c \\ S_{1,t-2}^I \\ ... \\ S_{k,t-2}^I \\ S_{t-2}^c \end{pmatrix} + \begin{pmatrix} \varepsilon_t^w \\ \varepsilon_{1,t}^I \\ ... \\ \varepsilon_{k,t}^I \\ \varepsilon_t^c \\ 0 \\ ... \\ 0 \\ 0 \end{pmatrix} \\ \alpha_t &= T \cdot \alpha_{t-1} + V_t \qquad (11')\end{aligned}$$

with $V_t \sim N(0, Q)$. For identification, we specify $var(\varepsilon_t^{\pi w})$, $var(\varepsilon_t^{yw})$, and $var(\varepsilon_t^{cw})$ to be constant. All other variances are set free in $Q$. All the covariance terms are zero, except $cov(\varepsilon_t^{cw}, \varepsilon_t^{yw})$ and $cov\left(\varepsilon_{i,t}^{cI}, \varepsilon_{i,t}^{yI}\right)$ for $i = 1...k$.

Equations (6) and (7) remain the same, with the restrictions $\gamma_i^\pi > 0$, $\gamma_i^y > 0$ and $\gamma_i^c > 0$. The observation equation is now

$$\begin{aligned}\begin{pmatrix} \pi_{1,t} \\ y_{1,t} \\ ... \\ \pi_{k,t} \\ y_{k,t} \end{pmatrix} &= \begin{pmatrix} (\gamma_1^\pi\ 0\ 0) & (1\ 0\ 0) & & & (\theta_{1,0} \cdot \gamma_1^c\ \ \theta_{1,0}\ ...0) & & & & (\theta_{1,1} \cdot \gamma_1^c\ \ \theta_{1,1}\ ...0) \\ (0\ \gamma_1^y\ 0) & (0\ 1\ 0) & & & (\gamma_1^c\ \ 1\ ...\ 0) & & & & (0\ 0\ ...\ 0) \\ ... & ... & ... & ... & ... & ... & ... & ... & ... \\ (\gamma_k^\pi\ 0\ 0) & & & (1\ 0\ 0) & (\theta_{k,0} \cdot \gamma_k^c\ \ 0\ ...\theta_{k,0}) & & & & (\theta_{k,1} \cdot \gamma_k^c\ \ 0\ ...\theta_{k,1}) \\ (0\ \gamma_k^y\ 0) & & & (0\ 1\ 0) & (\gamma_k^c\ \ 0\ ...\ 1) & & & & (0\ 0\ ...\ 0) \end{pmatrix} \cdot \\ & \quad \begin{pmatrix} S_t^w \\ S_{1,t}^I \\ ... \\ S_{k,t}^I \\ S_t^c \\ S_{1,t-1}^I \\ ... \\ S_{k,t-1}^I \\ S_{t-1}^c \end{pmatrix} + \begin{pmatrix} u_{1,t}^\pi \\ u_{1,t}^y \\ ... \\ u_{k,t}^\pi \\ u_{k,t}^y \end{pmatrix} \\ Y_t &= Z \cdot \alpha_t + W_t \qquad (12')\end{aligned}$$

with $W_t \sim N(0, R)$, where $R$ is assumed to be diagonal, indicating no cross correlation among observation errors.

Table 1: Data Summary

|  | $i$ | $j$ | Code | Real GDP |  | Inflation (CPI) |  |
|---|---|---|---|---|---|---|---|
|  |  |  |  | Data source | Available period | Data source | Available period |
| U.S. | 1 | 1 | US | G10 | 47Q1– | G10 | 47Q1– |
| Japan | 2 | 2 | JP | OECD Outlook | 60Q1– | OECD Outlook | 60Q1– |
| U.K. | 3 | 3 | UK | OECD MEI | 60Q1– | OECD MEI | 60Q1– |
| Euro | 4 | 4 | ER | OECD MEI | 70Q1– | OECD Outlook | 60Q1– |
| Canada | 5 | 5 | CA | OECD MEI | 61Q1– | G10 | 21Q1– |
| Australia | 6 | 6 | AU | OECD MEI | 60Q1– | G10 | 48Q1– |
| Sweden | 7 | 7 | SW | OECD Outlook | 60Q1– | G10 | 55Q1– |
| Switzerland | 8 | 8 | SZ | OECD Outlook | 60Q1– | G10 | 21Q1– |
| Korea | 9 | 9 | KR | OECD MEI | 70Q1– | G10 | 55Q1– |
| Taiwan | 10 | 12 | TW | Emerging Market | 61Q1– | Emerging Market | 59Q1– |
| China |  | 10 | CH | OECD MEI | 95Q1– | G10 | 85Q1– |
| India |  | 11 | IN | OECD MEI | 96Q2– | OECD MEI | 88Q4– |

Table 2: Coefficient Estimates of the Base Model

| $i$ | $\gamma_i^\pi$ | $\gamma_i^y$ | $\gamma_i^c$ | $\theta_{i,0}$ | $\theta_{i,1}$ | $\rho_{i,1}^{cI}$ | $\rho_{i,2}^{cI}$ | $\beta_i^I$ |
|---|---|---|---|---|---|---|---|---|
| 1 | 0.5087 | 0.4126 | 0.0414 | 0.1812 | 0.0204 | 1.3426 | -0.4403 | 0.0124 |
| | (0.0603) | (0.7857) | (0.5146) | (0.2314) | (0.1004) | (0.5433) | (0.3319) | (1.4504) |
| 2 | 0.4709 | -0.2918 | 0.0311 | 0.9090 | -0.4183 | 0.6171 | 0.0897 | 0.0096 |
| | (0.0679) | (0.3626) | (0.3904) | (0.4636) | (0.2820) | (0.2841) | (0.0793) | (0.7358) |
| 3 | 0.4393 | 0.5984 | 0.0229 | 1.0656 | -0.5386 | 0.9844 | -0.1684 | 0.0159 |
| | (0.0582) | (0.1832) | (0.2871) | (0.6070) | (0.2952) | (0.1019) | (0.0708) | (3.0804) |
| 4 | 0.4313 | -0.3040 | 0.0368 | 0.2097 | -0.0896 | 1.1633 | -0.2949 | 0.0085 |
| | (0.0625) | (0.5085) | (0.4644) | (0.5758) | (0.6161) | (0.9543) | (0.7296) | (0.8004) |
| 5 | 0.4167 | -0.4892 | 0.0431 | -0.0507 | 0.2233 | 1.7063 | -0.9021 | 0.0143 |
| | (0.0571) | (0.1248) | (0.5410) | (0.2117) | (0.1476) | (0.0469) | (0.0720) | (2.0578) |
| 6 | 0.4181 | 0.4885 | 0.0273 | -0.2060 | 0.7081 | 1.7416 | -0.8057 | 0.0144 |
| | (0.0567) | (0.2349) | (0.3409) | (0.5570) | (0.7866) | (0.1481) | (0.1370) | (2.0470) |
| 7 | 0.4096 | -0.3261 | 0.0293 | 0.0794 | 0.1529 | 1.0935 | -0.3198 | 0.0081 |
| | (0.0441) | (0.4896) | (0.3693) | (0.2582) | (0.1993) | (0.2896) | (0.3856) | (0.9196) |
| 8 | 0.3223 | -0.0692 | 0.0481 | 0.0904 | -0.0009 | 1.7160 | -0.7160 | 0.0038 |
| | (0.0680) | (2.2093) | (0.6052) | (0.0556) | (0.0689) | (0.1353) | (0.1353) | (0.0478) |
| 9 | 0.5363 | 0.4525 | -0.0370 | -1.3075 | 1.4732 | 1.5366 | -0.5760 | 0.0227 |
| | (0.0577) | (0.3115) | (0.4634) | (0.5782) | (0.6188) | (0.2315) | (0.2069) | (1.7644) |
| 10 | 0.5379 | 0.7876 | 0.0227 | 1.5072 | -0.2367 | 1.0147 | -0.4203 | 0.0353 |
| | (0.0712) | (0.1453) | (0.2851) | (1.0096) | (1.1935) | (0.2535) | (0.3928) | (5.3266) |
| | | | | | | $\rho_1^w$ | $\rho_2^w$ | $\beta^w$ |
| | | | | | | 1.7901 | -0.8238 | -0.0280 |
| | | | | | | (0.0816) | (0.0750) | (8.5915) |

Note: The reported values for $\gamma_i^\pi$, $\gamma_i^y$ and $\gamma_i^c$ are the square roots.

Table 3: Variance-Covariance Estimates of the Base Model

| $i$ | $Var\left(u_{i,t}^{\pi}\right)$ | $Var\left(u_{i,t}^{y}\right)$ | $Var\left(\varepsilon_{i,t}^{\pi I}\right)$ | $Var\left(\varepsilon_{i,t}^{yI}\right)$ | $Var\left(\varepsilon_{i,t}^{cI}\right)$ | $Cov\left(\varepsilon_{i,t}^{cI},\ \varepsilon_{i,t}^{yI}\right)$ | $Corr\left(\varepsilon_{i,t}^{cI},\ \varepsilon_{i,t}^{yI}\right)$ |
|---|---|---|---|---|---|---|---|
| 1 | 5.2760e-6 | 9.7088e-6 | 1.0797e-6 | 3.8086e-7 | 1.7128e-5 | 2.5541e-6 | 1.0000 |
| 2 | 9.1299e-7 | 1.0939e-5 | 2.6409e-6 | 1.6895e-4 | 4.9348e-5 | -8.4771e-5 | -0.9284 |
| 3 | 2.3037e-16 | 3.2903e-6 | 3.1287e-20 | 1.3709e-4 | 4.5692e-5 | -6.1722e-5 | -0.7798 |
| 4 | 2.6885e-6 | 2.6435e-6 | 1.1414e-20 | 5.3810e-5 | 3.7690e-5 | -3.9799e-5 | -0.8837 |
| 5 | 1.1927e-5 | 8.1998e-19 | 2.4122e-7 | 4.7222e-5 | 2.1080e-6 | -9.9771e-6 | -1.0000 |
| 6 | 3.7264e-5 | 1.8368e-5 | 3.9834e-19 | 5.2663e-5 | 1.6286e-6 | 2.6296e-6 | 0.2839 |
| 7 | 3.7663e-5 | 3.6843e-5 | 2.9297e-7 | 1.1149e-4 | 4.3833e-5 | -5.8766e-5 | -0.8406 |
| 8 | 1.2479e-5 | 2.3042e-18 | 8.5983e-19 | 6.9006e-5 | 3.5023e-5 | -4.9161e-5 | -1.0000 |
| 9 | 6.9023e-5 | 2.2298e-17 | 3.7762e-18 | 2.0046e-4 | 3.3582e-5 | -1.2602e-5 | -0.1536 |
| 10 | 1.2877e-4 | 3.9622e-7 | 7.3909e-20 | 2.4833e-4 | 6.7078e-5 | -8.7592e-5 | -0.6786 |
|  |  |  | $Var\left(\varepsilon_{t}^{\pi w}\right)$ | $Var\left(\varepsilon_{t}^{yw}\right)$ | $Var\left(\varepsilon_{t}^{cw}\right)$ | $Cov\left(\varepsilon_{t}^{cw},\varepsilon_{t}^{yw}\right)$ | $Corr\left(\varepsilon_{t}^{cw},\varepsilon_{t}^{yw}\right)$ |
|  |  |  | 0.0001 | 0.0001 | 0.9994 | 9.9964e-3 | 0.9999 |

Table 4: Cross Correlation Analysis of Gap Measures in the Base Model

|  | $Corr\left(100 \cdot \left(\ y_{i,t} - y_{i,t}^{n}\right), gap^{oecd}\right)$ | $Corr\left(y_{i,t}^{cw}, c_{i,t}\right)$ |
|---|---|---|
| U.S. | 0.9762 | 0.8143 |
| Japan | 0.0650 | 0.5192 |
| U.K. | 0.2322 | 0.4990 |
| Euro Area | 0.7347 | 0.3923 |
| Canada | 0.7808 | 0.9111 |
| Australia | 0.5936 | 0.6477 |
| Sweden | 0.5219 | 0.5421 |
| Switzerland |  | 0.3040 |
| Korea |  | 0.5213 |
| Taiwan |  | 0.4575 |

Table 5: Cross Correlation Analysis of Inflation Measures in the Base Model

|  | $Corr\left(\pi_{i,t}^{c}, \pi_{i,t}\right)$ | $\left(\pi_{i,t}^{n}, \pi_{i,t}\right)$ | $\left(\pi_{i,t}^{cw}, \pi_{i,t}\right)$ | $\left(\pi_{i,t}^{nw}, \pi_{i,t}\right)$ | $\left(\pi_{i,t}^{cw}, \pi_{i,t}^{c}\right)$ | $\left(\pi_{i,t}^{nw}, \pi_{i,t}^{n}\right)$ |
|---|---|---|---|---|---|---|
| U.S. | 0.2128 | 0.8511 | 0.4374 | 0.7973 | 0.8148 | 0.9137 |
| Japan | 0.4567 | 0.8259 | 0.3698 | 0.7010 | 0.4177 | 0.8950 |
| U.K. | 0.7972 | 0.7908 | 0.2924 | 0.7908 | 0.3847 | 1.0000 |
| Euro Area | 0.2445 | 0.9669 | 0.1567 | 0.9669 | 0.3940 | 1.0000 |
| Canada | 0.4164 | 0.8695 | 0.4241 | 0.8462 | 0.9065 | 0.9769 |
| Australia | 0.5144 | 0.7303 | 0.3776 | 0.7303 | 0.6490 | 1.0000 |
| Sweden | 0.5037 | 0.8024 | 0.2231 | 0.7688 | 0.5462 | 0.9824 |
| Switzerland | 0.5524 | 0.5998 | 0.2611 | 0.5998 | 0.3042 | 1.0000 |
| Korea | 0.6809 | 0.6605 | 0.4474 | 0.6605 | 0.4652 | 1.0000 |
| Taiwan | 0.7741 | 0.4431 | 0.3787 | 0.4431 | 0.4437 | 1.0000 |

Figure 1: The Estimated Output Gap in Comparison with the OECD Outlook's Gap Measure

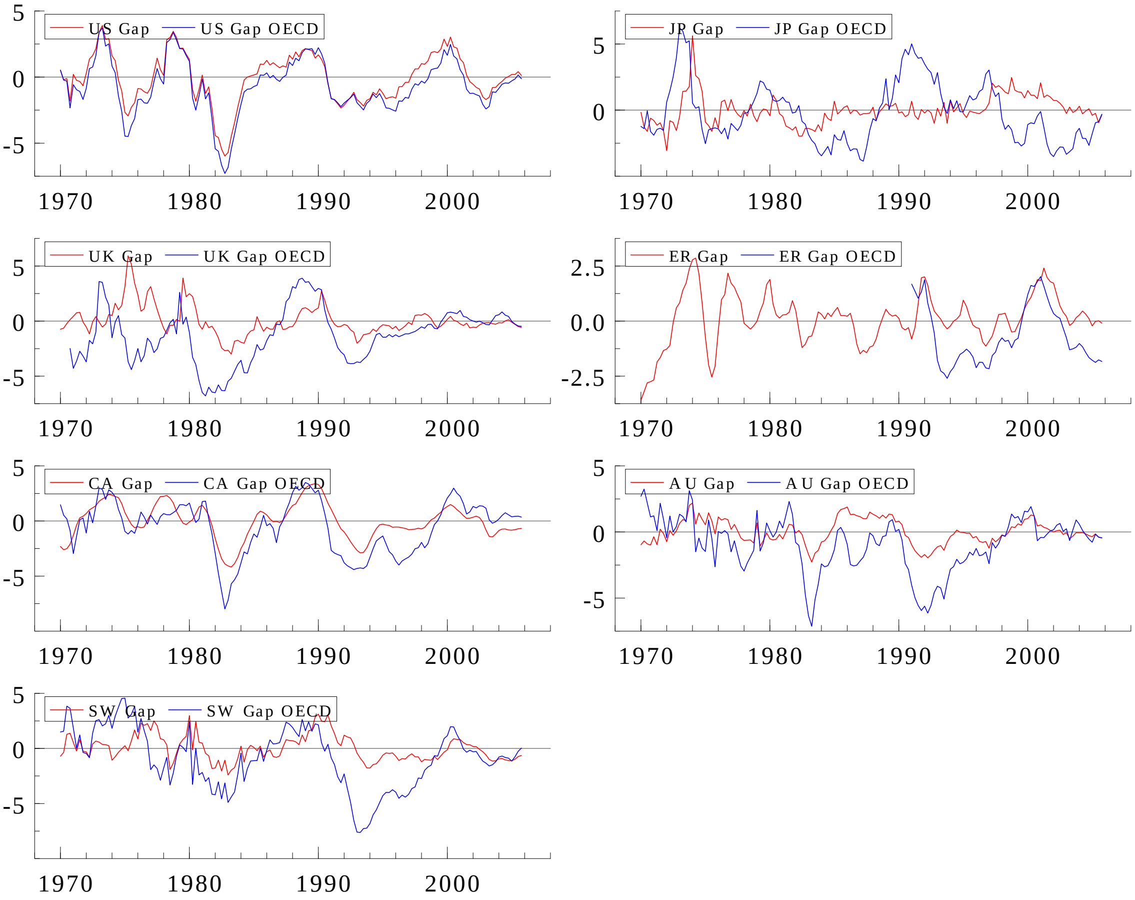

Figure 2: The Common Output Gap

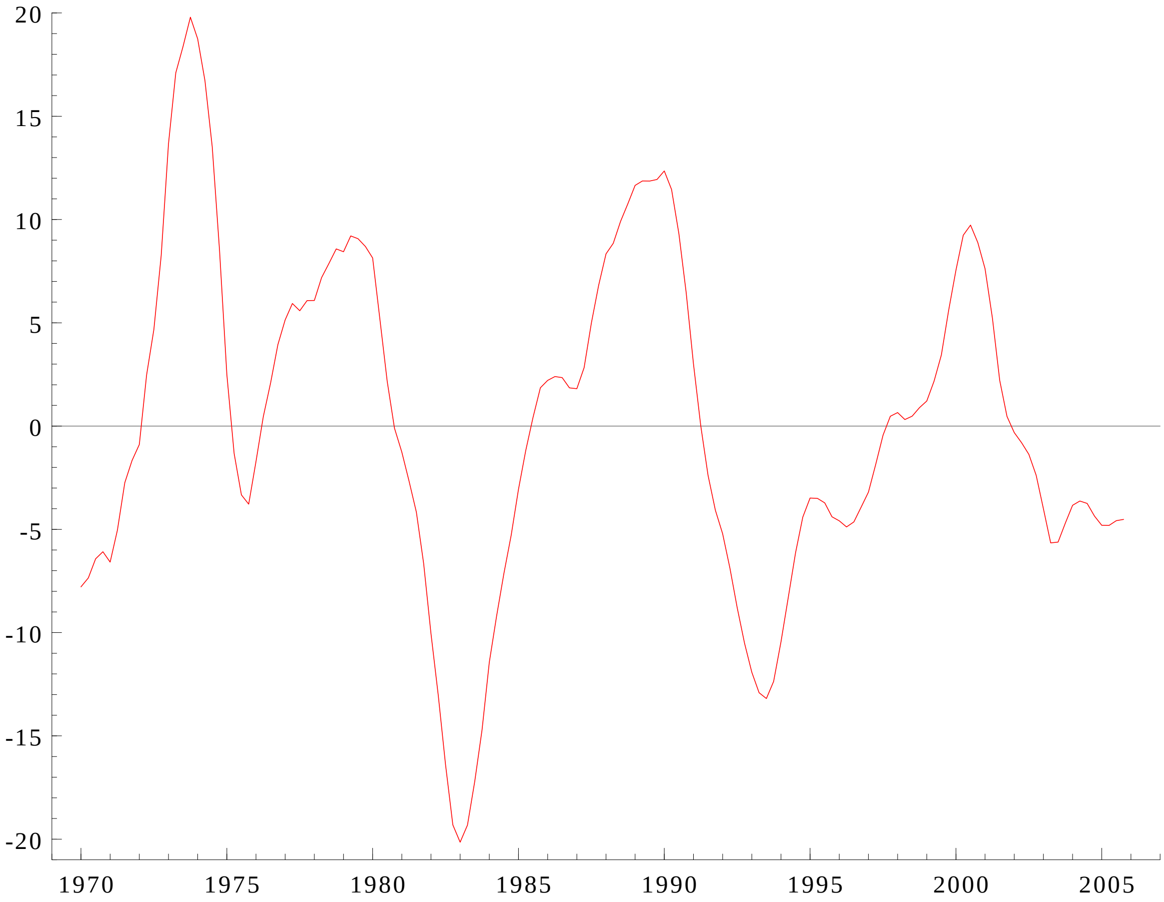

Figure 3: The Common Output Gap's Contribution to Each Gap Measure

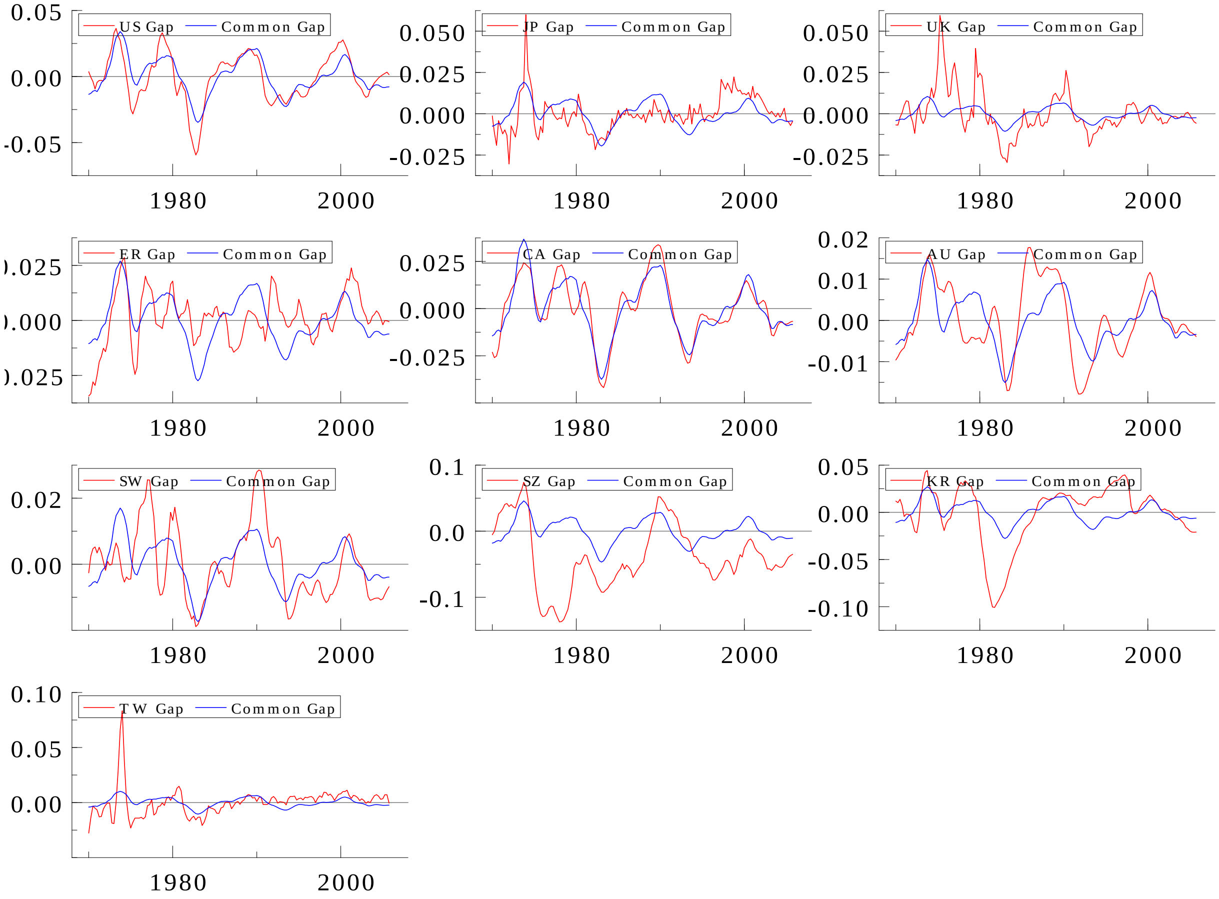

Figure 4: The Trend $\pi_{i,t}^{n}$ and Cyclical Inflation $\pi_{i,t}^{c}$ as Parts of the Actual Inflation $\pi_{i,t}$

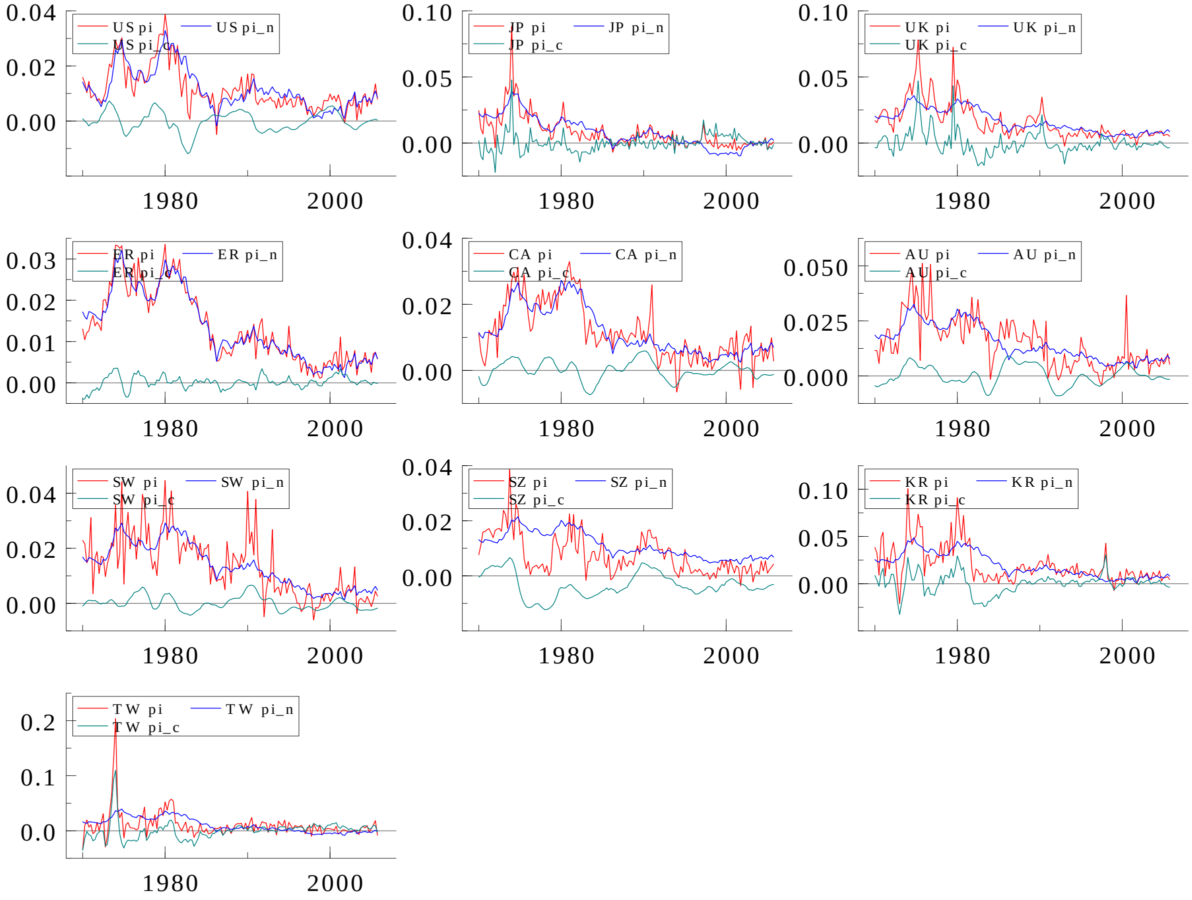

Figure 5: The Common Output Gap's Contribution $\pi_{i,t}^{cw}$ to the Cyclical Inflation $\pi_{i,t}^{c}$

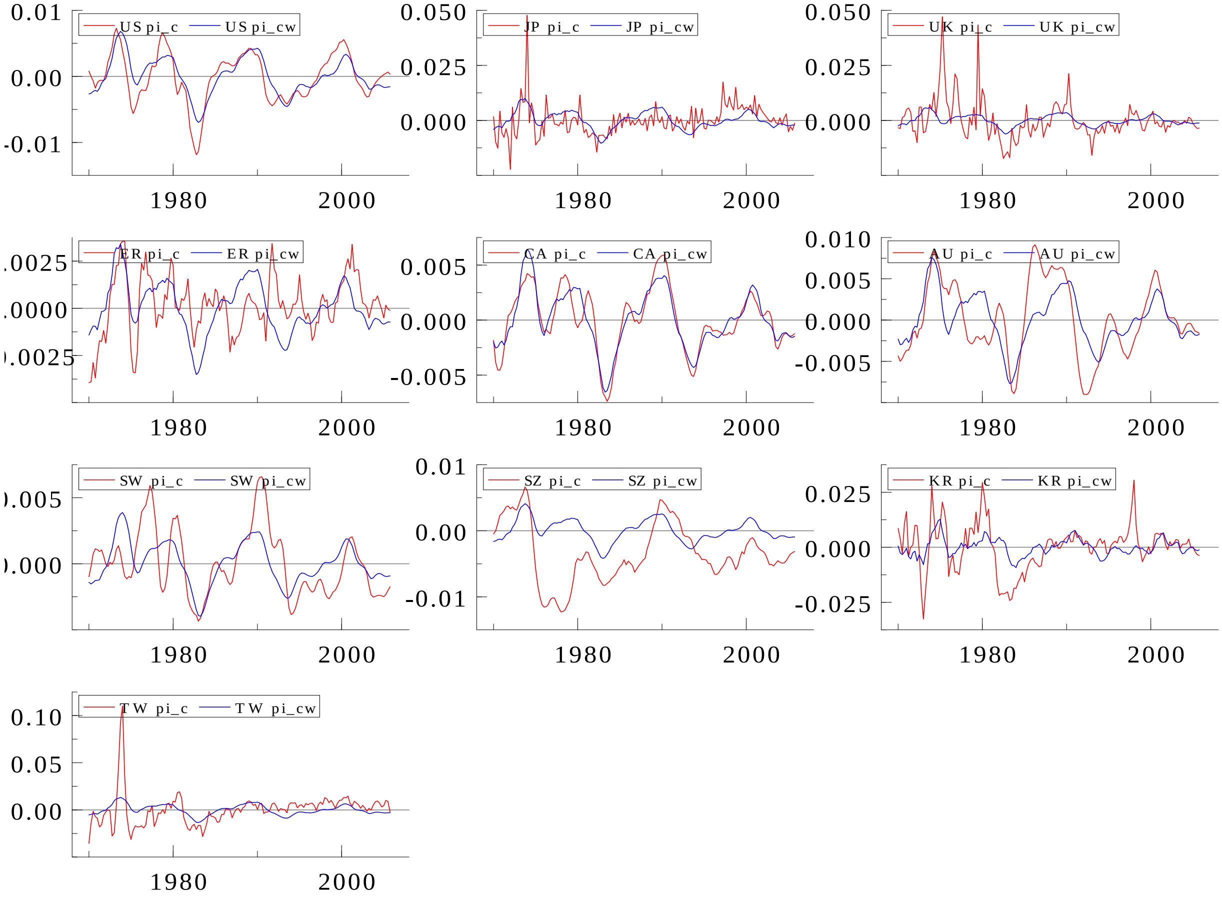

Figure 6: The Common and Idiosyncratic Trend Inflation's Contribution $\pi^{nw}_{i,t}$ and $\pi^{I}_{i,t}$ to Actual Inflation $\pi_{i,t}$

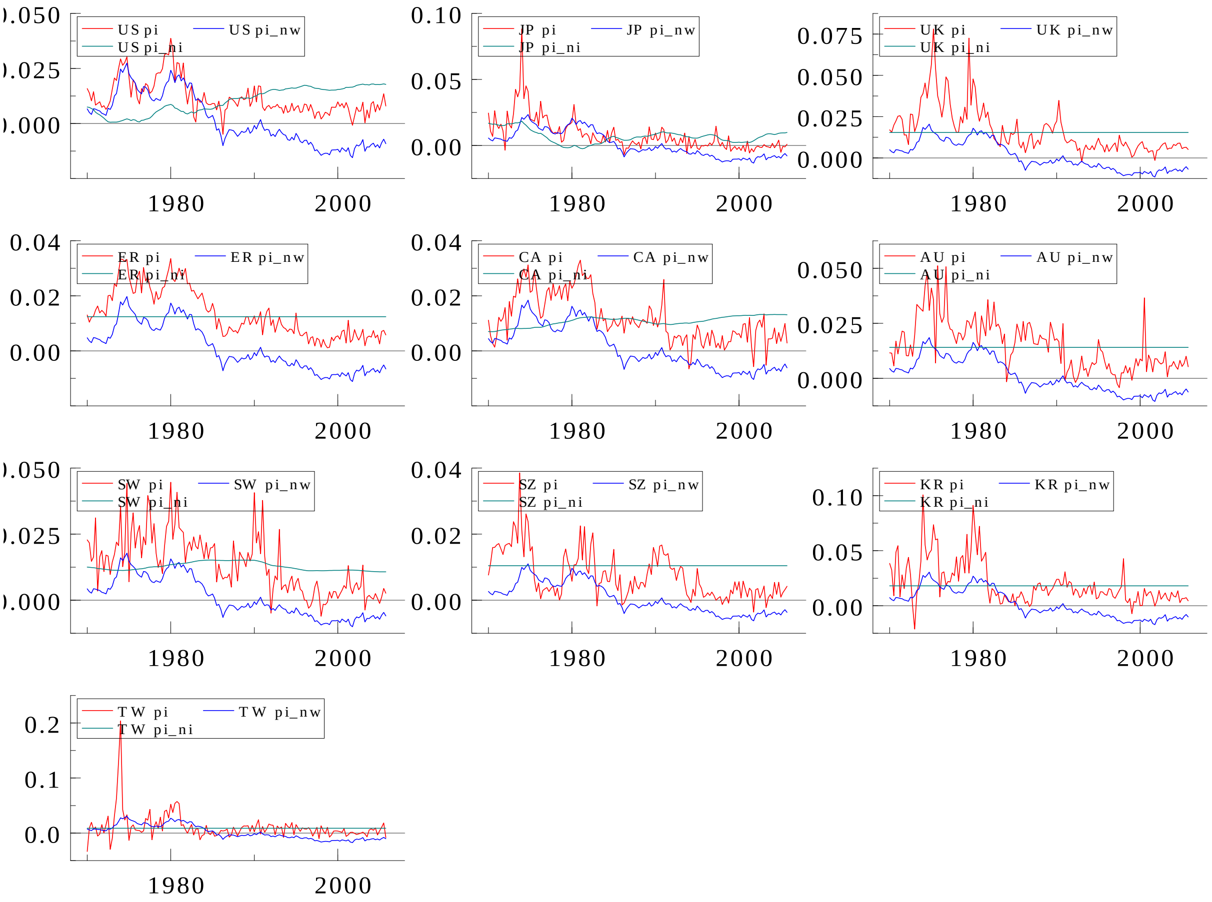

Figure 7: The Common Trend Inflation and Common Output Gap's Contribution $\pi^{nw}_{i,t}$ and $\pi^{cw}_{i,t}$ to Actual Inflation $\pi_{i,t}$