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Globalization and Inflation Dynamics

Empirical Evidence from a Time-varying New-Keynesian Phillips Curve

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Abstract There is a debate on whether globalization causes the flattening of Phillips curve. We explore this question by estimating a modified New-Keynesian Phillips curve (NKPC) in which inflation is determined by both domestic and foreign factors. Contrary to most of previous literature, we find that from 1983 to 2006, globalization raised the slope of the NKPC by about 0.025 in U.S economy. In addition, globalization shifts the NKPC downward by introducing cheaper imported goods. Our result is robust when we consider different maximization tools and potential heterogeneity. We conclude that globalization indeed changed the domestic inflation dynamics by steepening and shifting the NKPC.

Keywords: Globalization; New-Keynesian Phillips curve; Time-varying parameter model

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Contents

Introduction

A massive globalization process is a worldwide trend during the past decades. The formation of Euro zone and the emerging markets such as China and India being more open are notable episodes of globalization. In the meantime, inflation went down substantially all over the world. The annual CPI inflation rate among emerging markets and developing economies, which was around 40 percent in the early 1980s, came down to 13 percent towards the end of the 1990s and remained low until recent years (see Figure B.1). Similarly, global inflation and inflation levels among advanced economies, specifically U.S., have also experienced a downward trend and reduction in volatility (see Figure B.2).

Many researchers suggested that globalization might have contributed to the decline in inflation: as the production and competition of goods have been widely distributed around the world, global factors should play more and more significant role in determining the domestic price level and so inflation. In macroeconomics, inflation dynamic is usually described by the Phillips curve, a linear relationship that links inflation with domestic real economic activity. If globalization indeed affects domestic inflation, then the Phillips curve should be modified to incorporate one or more aspects of globalization. For example, some researchers add value of international trade to the original statistical Phillips curve (Ball, 2006), while others consider import penetration ratio (Gamber and Hung, 2001) or foreign output gap (Ihrig et al., 2010) as control variables. Despite the plausibility of their argument, these researchers fail to obtain a convincing conclusion about the importance of globalization. Regression analysis shows that the coefficients of the additional terms–e.g., value of international trade–are in most cases insignificant. Moreover, from the policy side, a number of people (Bean, 2006; Yellen et al., 2006) share a common opinion: globalization is a phenomenon to be copied with, whereas its impact on inflation and monetary policy need to be adequately evaluated. Ball (2006) and Mishkin (2009) further argue that globalization has very limited role in altering the determinants of inflation, and that better monetary policy and well-anchored inflation expectations are the main reasons for the low and stable inflation levels observed in the US during the 1990s. The overall situation is that evidence so far is too scattered to be conclusive.

We summarized that there are two drawbacks in the previous research that studies globalization and inflation dynamics. First, in most of these studies, on the right hand side of the Phillips curve the proxy variable for real economic activity is output gap, a variable that does not entirely co-moves with the marginal cost of production. As Galı and Gertler (1999) criticize, real marginal cost is likely to lag the movement of output gap, a violation of the New-Keynesian theory. This discrepancy usually leads to an insignificant slope of the Phillips curve. Most importantly, traditional OLS method only reveals the slope of a time-invariant Phillips curve, which is unsatisfactory in the sense that globalization is a long-term phenomenon and its impact is unlikely to be constant over time.

Inspired by both the conflicting argument and limitations in current studies, we attempt to explore the relationship between globalization and inflation using a time-varying New-Keynesian Phillips Curve (NKPC) in an open economy. First, we derive a refined NKPC following Sbordone (2007), Guerrieri et al. (2010), and Benigno et al. (2016), where the marginal cost of production is a proxy for real economic activity. The selection of independent variable addresses the co-movement problem. What's more, the refined NKPC also captures globalization's impact by introducing strategic pricing interaction between domestic and foreign producers. According to Benigno et al. (2016)'s prediction, as globalization proceeds, the NKPC is shifted and its slope becomes steeper. Finally, we allow all coefficients in the NKPC to be time-varying, endowing our model with more dynamic characteristics. When estimating the time-varying model, we employ a two-step error correction method to address the endogeneity issue, and this approach can be regarded as a dynamic extension of the traditional GMM approach. The result suggests that from 1984 to 2006, globalization increases the slope of the NKPC by around 0.015 in the U.S. economy. In addition, globalization imposed disinflation pressure through the difference between imported and domestic goods prices, and this channel is significantly positive in the entire sample period. To verify our findings, we first employ different maximization tools to obtain the maximum likelihood estimates, then we extend our model by allowing the volatility of error terms to be time-varying. The final results change only little with these adjustments, indicating that our baseline results are quite robust.

The remainder of the paper is structured as follows. Section 2 review previous literature about globalization and its impact on the Phillips curve. Section 3 derives the open-economy refined NKPC and illustrates how globalization can possibly affect domestic inflation. Section 4 introduces the two-step error correction estimation method, without which our baseline result will be biased. Data and our main result are discussed in section 5. Section 6 presents the result of robustness checks and discusses the implications of our findings. Section 7 concludes.

Literature Review

2.1 Globalization and Inflation

Interest in globalization and its influence on all aspects of economic life have been increasing during recent years. There is no single definition of globalization, the International Monetary Fund (IMF) classified globalization into four aspects: trade and transactions, capital and investment movements, labor force migration and movement, and knowledge dissemination. In economic literature, most of the researchers refer to globalization as trade and financial openness (Ball, 2006; Badinger, 2009). Trade openness is defined in various ways, e.g. average share of imports in GDP or GNP (Romer, 1993), an increase in the number of goods traded (Sbordone, 2007; Guerrieri et al., 2010; Benigno et al., 2016), or a fall in trade costs (Guilloux-Nefussi, 2020). Financial openness is usually measured in terms of Foreign Direct Investment (FDI) and the size of international capital markets (Calza, 2009). The definition of globalization reflects the possible channels through which globalization affects inflation. We summarized seven main channels based on the previous literature.

The first channel is known as the global competition effect. As globalization makes markets more competitive, it may spur productivity growth. Higher productivity growth can give rise to a fall in inflation since it directly lowers prices if monetary policy does not become more expansionary (Mishkin, 2009). It can decrease markups (price over costs) as well because greater competition from foreign producers makes it harder for domestic producers to raise prices (Helbling et al., 2006). The second channel works immediately through import prices. Lower price levels on imports from low-income countries, altogether with the increasing import shares of overall imports in high-income countries, have been shown to remarkably depress import prices and consumer price inflation (Chen et al., 2004).

The third channel operates through labor markets. The increase in available labor supply worldwide puts great pressure on wages in richer countries. Lower wages mean lower production costs and therefore lower prices for goods and services (Glatzer et al., 2006). Fourth, globalization can influence the balance between the demand and supply in global goods and services markets. As long as production of emerging economies expands more quickly than their demand, inflation would be supposed to be dampened globally (Gamber and Hung, 2001). Fifth, globalization may make capital and financial markets more liberalized and integrated, thus facilitating access to credit and reduce borrowing costs. Changes in aggregate demand affect aggregate price (Gnan et al., 2005). Sixth, the expansion of global value chains(GVCs), cross-national trade in intermediate goods and services, is another important channel proposed recently (Brouillette et al., 2017; Auer et al., 2017). Finally, these effect of globalization may change the ability (Romer, 1993) and incentives (Rogoff et al., 2003; Borio and Filardo, 2007) of central banks to temporarily boost output using monetary policy tools such as inflation surprises.

Under most circumstances, the above channels are interconnected with each other. In our paper, we mainly concentrate on the competition effect channel and the relative price channel which might result from strategic pricing or/and import prices. There is vast literature that directly explores the relationship between globalization and inflation. Swagel (1995) studies whether prices of imported goods affect domestic prices through the competing goods effect and finds a small but statistically significant impact in 10 out of the 19 industries. By contrast, Romer (1993) finds a negative relation between inflation and trade openness for a large cross-section of 114 countries during the period from 1973 to 1988 (except for the OECD subsample). Lane (1997) further demonstrates that this relationship hold for OECD countries when country size is controlled for. Gruben and McLeod (2004), Ciccarelli and Mojon (2010), and Mumtaz and Surico (2012) reach the similar conclusion employing different data and methods. However, the majority of research in this area tends to study globalization and inflation under the Phillips Curve framework. Next we will give a comprehensive introduction about it.

2.2 Phillips Curve

2.2.1 Statistical Phillips Curve

The original Phillips curve describes the inverse relationship between wage growth rate and unemployment rates (Phillips, 1958). Based on it, other researchers derived the connection between inflation and unemployment. Later on, researchers considered how inflation relates to other measures of real economic activity, and the most common measure for real economic activity is the output gap. A typical Phillips curve takes the following form:

$$\pi_t - \bar{\pi}_{t-1} = c + b\hat{y}_t + u_t \tag{2.1}$$

where π_t denotes current quarter's inflation, $\bar{\pi}_{t-1}$ denotes the previous year's average inflation, and $\hat{y}_t$ denotes the deviation of log-output from its steady state level. This statistical relation is also referred as the statistical Phillips curve. Estimating and understanding this statistical relationship is important for several reasons. For instance, central banks want to maintain both high employment rate and price stability but these two targets might be not consistent (Jordà and Nechio, 2018). The seemingly decreased sensitivity of inflation to economic conditions during the past years is usually called the flattening of the Phillips curve (Glatzer et al., 2006), because the coefficient of real economic activity (sometimes also referred as the slope of Phillips curve) is diminishing. The flattening may result from many economic factors. For instance, an improvement in the way monetary policy responds to economic activity and inflation: the rising credibility of central banks to anchor inflation expectations (Gürkaynak et al., 2010; Strohsal et al., 2016). Another possibility is that something fundamental in the economy has changed, e.g. the way firms set prices and wages or the openness of the economy to foreign trade (Occhino, 2019).

Evidence about the impact of globalization on the Phillips curve is mixed. On the one hand, Borio and Filardo (2007) estimate Phillips curve models for 16 OECD countries from 1985 to 2005 and find that the effect of weighted average foreign gaps on consumer price inflation is positive and statistically significant. Moreover, this positive effect is even greater than the effect of domestic output gaps and increases gradually. This means that as the coefficient for domestic output gap diminishes, the coefficient for foreign output gap increases. The result is also robust to the inclusion of extra independent variables, such as unit labor costs and import prices. Loungani et al. (2001), and Pain et al. (2006) provide further evidence that globalization can weaken the output–inflation trade-off. Romer (1993), Lane (1997), and Bowdler (2009) instead claim that trade openness increases the sensitivity of inflation to output. On the other hand, Ball (2006), Wynne and Kersting (2007), Gaiotti et al. (2010) and Ihrig et al. (2010) report weak or no relation at all using firm-level or aggregate data for different countries.

2.2.2 New Keynesian Phillips Curve

New-Keynesian Phillips curve (NKPC) is a forward-looking equation that links price inflation to the marginal costs and forward-looking inflation expectation of firms that follow a Calvo (1983) [1] staggered price setting scheme (Bianchi and Civelli, 2015):

$$\pi_t = \kappa \tilde{y}_t + \beta E_t \pi_{t+1} \tag{2.2}$$

Unlike the statistical Phillips curve, NKPC is derived from firms' profit-optimization problem, so is a structural relation (not just statistical relation) that reflects the micro-foundations of the economy. This structural relation is not affected by changes in the conduct of monetary policy (Occhino, 2019). The relationship between inflation and marginal cost, which is the key determinant of the slope of NKPC, depends on the frequency of price adjustments, but is also affected by strategic complementarity in price setting (Razin and Yuen, 2002). It is one of the main mechanisms that supports the 'globalization' argument, according to which the increase in the openness of the economy has influenced the sensitivity of inflation to output variations (Sbordone, 2007).

There is a large body of literature studying globalization and inflation using NKPC (Corsetti and Pesenti, 2005; Monacelli, 2005; Steinsson, 2008; Zaniboni, 2008). Specifically, Razin et al. (2005) employ a New Keynesian open economy model to show that both trade and financial openness lead policy makers to concentrate more on lowering inflation than on narrowing output gaps, thus flattening the trade-off between inflation and the real economic activity. Daniels and VanHoose (2006), Razin and Binyamini (2007), and Daniels and VanHoose (2009) also find that trade openness or capital mobility reduces the sensitivity of inflation to output under the imperfectly competitive open economy model. Furthermore, Woodford (2007) builds his analysis on Clarida et al. (2002) to study several channels through

[1] There are other sticky-price models that can also derive a NKPC, such as Rotemberg (1982).

which globalization might change the impact of monetary policy on domestic factors, and concludes that globalization is not likely to lessen central bank's ability to control domestic inflation.

The NKPC in our paper is mostly related to the models in Sbordone (2007), Guerrieri et al. (2010), and Benigno et al. (2016). Sbordone (2007) studies the impact of greater competition, proxied as an increase in number of traded goods, on the firms' elasticity of demand and finds that the effect on the slope of the NKPC is not quantitatively significant. Guerrieri et al. (2010) follow a similar approach to estimate NKPC in the context of an open-economy model, and conclude that foreign competition has contributed to the lower inflation levels. Benigno et al. (2016), employing an extension of Dornbusch (1987)'s model, finds that globalization changes the slope and the position of the NKPC and also influences the degree of exchange-rate pass-through. We keep the strategic pricing and nominal rigidities components in these paper, and meanwhile extend the model by making the coefficients time-varying.

2.2.3 Time-Varying Phillips Curve

There are a number of papers testing whether the slope of Phillips curve is time-varying. Berger et al. (2016) use the stochastic model specification search method to detect time variation in the slope of the NKPC and find that it is not time-varying. On the contrary, Fu (2019) tests for time variation in the slope of the NKPC using various measures of inflation expectations and real economic activity. He concluded that slope of NKPC is time-varying. Karlsson and Österholm (2018) obtain similar results by applying a time-varying parameter Bayesian VAR approach. Atkeson et al. (2001), Roberts (2006), and Ball and Mazumder (2011) use split samples to estimate the statistical Phillips curve with constant coefficient and find that it is flattening in the more recent period. Stella and Stock (2013), Kim et al. (2014), and Chan et al. (2016) allow the slope of statistical Phillips curve to be time-varying, and they conclude that inflation is relatively less sensitive to unemployment. Lansing (2009) introduces bounded-rational inflation expectations to the traditional time-varying NKPC. He emphasizes the important role of inflation expectation instead of domestic economic activity in determining inflation and show that low-frequency fluctuations in the inflation levels are driven merely by expectational reaction.

Research on time-varying Phillips curve is abundant, however little of it is related to globalization and its impact on domestic inflation. Of this topic, the most relevant paper is Bianchi and Civelli (2015), which investigates the globalization hypothesis by employing a time-varying coefficients VAR model for many countries. They find that most countries (including U.S.) do not show a declining correlation between inflation and domestic output gap from the reduced-form estimates of the VAR, and for U.S. they notice a positive but decreasing correlation between inflation and foreign gap. Their conclusion is that globalization has not yet caused changes in openness large enough to explain significant decline in inflation dynamics.

Model

3.1 The Strategic Price-Setting

To begin with, it is helpful to decompose the relationship between consumer price inflation and domestic output, the one generally analyzed in the context of Phillips curve in empirical studies into three parts. Firstly, there is a linkage between the marginal cost of production and domestic output. Secondly, the relation between the marginal cost of production and domestic inflation, and finally the connection between domestic inflation and CPI inflation. We focus on the relation that captures how changes in marginal cost transform into fluctuations in domestic prices, which is most likely to be affected by the increased competition.

Our model setup is primarily related to those of Sbordone (2007), Guerrieri et al. (2010), and Benigno et al. (2016). Specifically, we follow Benigno et al. (2016), who build a refined model in spirit of Dornbusch (1987), claiming that the competitive pressure from abroad could increase the variations in the markups of domestic firms. These competitiveness effects arise because the elasticity of demand faced by domestic firms is linked to its market share, which depends on its price relative to its competitors, the relative number of goods traded, and the relative output. We then introduce these nonconstant elasticity preferences into a model of inflation dynamics where firms frequently re-optimize their prices at certain cost as in Rotemberg (1982). The following paragraphs summarize Benigno et al. (2016)'s model.

We consider a two-country model with the home economy indexed by h and the foreign economy indexed by f. There are various sectors, indexed by k, in each country. In home country, there are N differentiated goods in each sector, of which N_h are produced by firms residing in country h and the remaining N_f by firms residing in country f. Similarly, in each sector of the foreign country, there are N^* differentiated goods, of which N_h^* are produced by firms residing in country h and N_f^* by firms residing in country f. The optimal demand for good i in sector k, produced in country h, can be expressed as:

$$Q_i = (\frac{P_i}{P_k})^{-\sigma}(\frac{P_k}{P})^{-\theta}Q \tag{3.1}$$

where σ is the elasticity of substitution among different goods produced in one sector k, and θ is the elasticity of substitution across sectors. Q is defined as the overall demand in the economy, and P is the Dixit-Stiglitz economy-wide price index, P_i is the price of good i, and P_k is the aggregate price of the sector k, also defined by the

Dixit-Stiglitz aggregator:

$$P_k = (\sum_{i=1}^{N_h} P_i^{1-\sigma} + \sum_{j=1}^{N_f} P_j^{1-\sigma})^{\frac{1}{1-\sigma}} \tag{3.2}$$

where P_j denotes the price of good j in sector k, produced in country f.

Here we assume that firms are not small with respect to their sector, which implies that firms internalize the fact that they can influence the sectorial price in their pricing decisions. Therefore, given Eq.(3.1) and Eq.(3.2), for good i, the price elasticity of demand is not necessarily constant and is instead given by:

$$\frac{\partial Q_i}{\partial P_i}\frac{P_i}{Q_i} = -\sigma + \sigma\frac{P_i}{P_k}\frac{\partial P_k}{\partial P_i} - \theta\frac{P_i}{P_k}\frac{\partial P_k}{\partial P_i} \tag{3.3}$$

We can write the expression above in a more compact from:

$$\tilde{\sigma}_i \equiv \left|\frac{\partial Q_i}{\partial P_i}\frac{P_i}{Q_i}\right| = \sigma - (\sigma - \theta)\varphi_i \tag{3.4}$$

where φ_i denotes the market share of firm i in sector k, and can be expressed as:

$$\varphi_i \equiv \frac{P_i Q_i}{P_k Q_k} = \frac{P_i}{P_k}\frac{\partial P_k}{\partial P_i} \tag{3.5}$$

Since all firms in a sector face the same technology and optimization problem, the equilibrium would be symmetric. Therefore we could drop the index i and express the market share of firms as:

$$\varphi_i = \varphi_h = \frac{P_h Q_h}{N_h P_h Q_h + N_f P_f Q_f} \tag{3.6}$$

where P_h, P_f, Y_h, and Y_f denotes prices and output in country h of firms residing in country h and f, respectively.

The price elasticity of demand varies as the market share changes. However, under two conditions, the elasticity in Eq.(3.4) is constant and is simplified into the elasticity in monopolistic competition. Firstly, when all firms are quite small within the sector, i.e. when their market share φ_i approaches to zero, their influence on sectorial price setting gradually diminishes. Secondly, when the elasticity of substitution across different goods within sector (σ) is equal to that across different sectors (θ). The case we need to consider in empirical analysis is that the elasticity of substitution across different goods within sector, σ is larger than that across different sectors, θ, which thus implies that $\tilde{\sigma}_i$ is a decreasing function of firm i's market share.

Eq.(3.4) implies that variation in the market share can directly affect the elasticity and thus firms' markups. Since relative prices would influence the market shares as suggested in Eq.(3.6), firms tend to make their pricing-setting decisions considering its impact on the overall market equilibrium. We define globalization as the rise in the number of foreign products in the domestic market, that is, a increase in N_f. As shown in Eq.(3.4) and Eq.(3.6), such an increase decreases the market share of both domestic and foreign firms, and consequently increases the price elasticity of demand $\tilde{\sigma}_i$ and reduces the monopoly power. Next, in the context of producers' optimization problem, we introduce the New Keynesian Phillips curve to explore the model's implication for the sensitivity of prices to marginal costs and the relative price when prices are sticky.

3.2 Producers Optimization Problem

Under sticky prices, we consider that a firm i, producing and selling in country h, chooses P_i to maximize the present discounted value of profits:

$$E_t \sum_{\tau=t}^{\infty} R_{t,\tau} \left[P_{i,\tau} Q_{i,\tau} - \frac{W_\tau}{A_\tau} Q_{i,\tau} - \frac{\lambda}{2} \left(\frac{P_{i,\tau}}{P_{i,\tau-1}} - 1 \right)^2 P_{i,\tau} Q_{i,\tau} \right] \tag{3.7}$$

where λ, with $\lambda \geq 0$, is a parameter measuring the cost of adjusting prices, while $R_{t,\tau}$ is a nominal stochastic discount factor through which units of wealth are appropriately evaluated across time and states of nature.

The solution to the optimization problem present in Eq.(3.7) implies that prices need to be set as a time-varying markup over nominal marginal costs:

$$P_{i,t} = \tilde{\mu}_{i,t} \frac{W_t}{A_t} \tag{3.8}$$

where the markup is a function of past and future expected variations in prices as given by:

$$\tilde{\mu}_{i,t} = \frac{\tilde{\sigma}_{i,t}}{(\tilde{\sigma}_{i,t} - 1) \left[1 - \frac{\lambda}{2} (\pi_{i,t} - 1)^2 \right] + \lambda \pi_{i,t} (\pi_{i,t} - 1) - \Gamma_t} \tag{3.9}$$

with

$$\Gamma_t \equiv \lambda E_t \left\{ R_{t,t+1} \pi_{i,t+1} (\pi_{i,t+1} - 1) \frac{Q_{i,t+1}}{Q_{i,t}} \right\} \tag{3.10}$$

and

$$\pi_{i,t} \equiv P_{i,t} / P_{i,t-1} - 1 \tag{3.11}$$

We can then take a first-order approximation of Eq.(3.8) to obtain the following New Keynesian Phillips curve:

$$\pi_{h,t} = \left[\kappa \cdot mc_t + \frac{\sigma - \theta}{\bar{\sigma}} \frac{1}{N} \cdot \hat{\varphi}_{h,t} \right] + \beta E_t \pi_{h,t+1} \tag{3.12}$$

where $mc_t \equiv \left(\hat{W}_t - \hat{P}_{h,t} - \hat{A}_t \right)$ denotes the domestic real marginal costs, the slope κ is defined as $\kappa \equiv \frac{\bar{\sigma}-1}{\lambda}$, with $\bar{\sigma} \equiv \sigma - \frac{\sigma-\theta}{N}$. Variables with a hat denote log-derivation with respect to the steady-state.

As shown in Eq.(3.12), our model features both the real marginal costs variations in the market share for the domestic firms. Given Eq.(3.6), the market share can be approximated by the relative prices:

$$\hat{\varphi}_{h,t} = (\sigma - 1) \xi_f \left(\hat{P}_{f,t} - \hat{P}_{h,t} \right) \tag{3.13}$$

where $\xi_f = N_f/N$. Then by substituting Eq.(3.13) into Eq.(3.12), the Phillips curve can be re-written as follows:

$$\pi_{h,t} = \kappa \cdot \left[mc_t + k \cdot \xi_f \left(\hat{P}_{f,t} - \hat{P}_{h,t} \right) \right] + \beta E_t \pi_{h,t+1} \tag{3.14}$$

where $k = \frac{\sigma-1}{\bar{\sigma}-1} \frac{\sigma-\theta}{\bar{\sigma}} \frac{\lambda}{N}$.

We can briefly summarize two features that differentiate Benigno et al. (2016)'s NKPC from the traditional one and describe the effects of globalization on the aggregate supply equation. The first feature is the slope of the curve, which stands for the short-run relationship between inflation and domestic real marginal costs. We can clearly see that the slope κ now directly depends on the number of products present in the market N, which further depends on globalization (increasing N_f). In fact, $\bar{\sigma}$ is an increasing function of N. The higher the number of products, the higher is the steady-state elasticity of substitution and the higher is the response of inflation to movements in the real marginal costs. Therefore, from this point of view, higher competition steepens the NKPC and renders price more sensitive to domestic shocks.

The second feature is the direct impact of relative prices on inflation. This effect captures the novel aspect of strategic pricing featured by our model. When firms interact strategically, the aggregate supply equation shifts with the movements in the markup which are driven by variation in firms' market share (i.e. see Eq.(3.12)). When N goes to infinity, all firms become small in size, or when $\sigma = \theta$, the relative price channel disappears, the equation then nests the traditional New Keynesian Phillips curve:

$$\pi_{h,t} = \kappa mc_t + \beta E_t \pi_{h,t+1} \tag{3.15}$$

Since globalization is a gradual process, it is natural to study it with models whose parameters are time-varying. What's more, the subsample OLS result of Benigno et al. (2016) suggests that the slope of the U.S. NKPC has indeed increased from 1993 to 2010. Therefore we aim at estimating a time-varying version of Eq.(3.14):

$$\pi_t = \kappa_t mc_t + \gamma_t \left(\hat{P}_{f,t} - \hat{P}_{h,t} \right) + \beta_t E_t \pi_{t+1} \tag{3.16}$$

In the next section we derive our estimation strategy of Eq. (3.16) from previous empirical literature and summarize it in detail.

Methods

4.1 Model specification

4.1.1 A case of traditional NKPC

Let's start with the traditional version of NKPC:

$$\pi_t = \kappa mc_t + \beta E_t \pi_{t+1} + \epsilon_t \tag{4.1}$$

where π_t denotes inflation, mc_t marginal cost of production, and $E_t \pi_{t+1}$ agent's expectation of next period's inflation. One challenge is that we only have ex post data of π_t and mc_t, while $E_t \pi_{t+1}$ remains unknown. Galı and Gertler (1999) suggests that if Rational Expectation hypothesis [1] is true, the prediction error of π_{t+1} should be uncorrelated with information up to date t. That is, we can decompose the above equation as:

$$\begin{aligned} \pi_t &= \kappa mc_t + \beta \pi_{t+1} + \beta [E_t(\pi_{t+1}) - \pi_{t+1}] + \epsilon_t \\ &= \kappa mc_t + \beta \pi_{t+1} + e_t \end{aligned} \tag{4.2}$$

Now, the new equation only consists of observed variables. However, e_t is correlated with π_{t+1}, and thus direct estimation of Eq.(4.2) will suffer from severe endogeneity bias. To address the problem we need instrumental variables (IVs). Since past information is uncorrelated with the prediction error $E_t(\pi_{t+1}) - \pi_{t+1}$ and exogenous shock ϵ_t, it should be uncorrelated with e_t. In addition, empirical studies indicate that inflation has strong inertia, which means that past information, especially lagged inflation, will be correlated with future inflation π_{t+1}. Therefore, lagged variables can be the IVs for future inflation in this model. In fact, Galı and Gertler (1999) suggests the following generalized method of moments (GMM):

$$E_t\{(\pi_t - \kappa mc_t - \beta \pi_{t+1}) z_t\} = 0 \tag{4.3}$$

where z_t is a vector of four lags of inflation, the marginal production cost, the output gap, the long-short interest rate spread, wage inflation, and commodity price inflation. According to Rudd and Whelan (2005), since the NKPC is linear, Eq.(4.3) is equivalent to a two-stage least squares (2SLS) estimation approach. That is, first regress π_{t+1} on z_t:

$$\pi_{t+1} = \delta z_t + v_t \tag{4.4}$$

[1] Rational Expectation (RE) hypothesis is a fundamental assumption in most of the monetary economics literature. It assumes that agents will utilize all past information he has when predicting future economic performance.

and obtains the fitted values $\hat{\pi}_{t+1}$. Then, replace π_{t+1} by $\hat{\pi}_{t+1}$ when estimating the Phillips curve:

$$\pi_t = \kappa mc_t + \beta\hat{\pi}_{t+1} + \epsilon_t \tag{4.5}$$

Applying the above strategies, Galı and Gertler (1999) obtains a Phillips curve whose slope is significantly positive. Compared to previous studies this is a great progress, as estimated Phillips curve in previous studies has either nonsignificant or significantly negative slope, which is considered inconsistent with the theory. Thus we decide to adopt Galı and Gertler (1999)'s idea in our paper and come up with the following model.

4.1.2 Generalized time-varying NKPC

First, we consider a TVP Phillips curve in an open economy derived before:

$$\begin{aligned}
\pi_t &= \kappa_t mc_t + \gamma_t\left(\hat{P}_{f,t} - \hat{P}_{h,t}\right) + \beta_t E_t\pi_{t+1} + m_t \\
\kappa_t &= \kappa_{t-1} + \eta_t, \quad \eta_t \sim \mathrm{N}(0, \sigma_\eta^2) \\
\gamma_t &= \gamma_{t-1} + \xi_t, \quad \xi_t \sim \mathrm{N}(0, \sigma_\xi^2) \\
\beta_t &= \beta_{t-1} + \zeta_t, \quad \zeta_t \sim \mathrm{N}(0, \sigma_\zeta^2)
\end{aligned} \tag{4.6}$$

where π_t is observed inflation at period t; mc_t is observed marginal cost of production at period t; κ_t and β_t are time-varying coefficients of mc_t and $E_t\pi_{t+1}$, respectively. Each coefficient is assumed to satisfy a random walk process. With this assumption, we reduce the number of unknown hyperparameters so that our model is easier to estimate, and in addition, we allow potential regime shift over time.

Note that the first expression in Eq.(4.6) can be rewritten as:

$$\begin{aligned}
& \pi_t = \kappa_t mc_t + \gamma_t\left(\hat{P}_{f,t} - \hat{P}_{h,t}\right) + \beta_t\pi_{t+1} + \beta_t(E_t\pi_{t+1} - \pi_{t+1}) + m_t \\
\Leftrightarrow \quad & \pi_t = \kappa_t mc_t + \gamma_t\left(\hat{P}_{f,t} - \hat{P}_{h,t}\right) + \beta_t\pi_{t+1} + e_t, \quad e_t \sim \mathrm{N}(0, \sigma_e^2)
\end{aligned} \tag{4.7}$$

We cannot estimate Eq.(4.7) with ex post data directly, since the error term e_t is correlated with realized future inflation π_{t+1}. To deal with the endogeneity issue, we need instrumental variables (IVs):

$$\begin{aligned}
\pi_{t+1} &= Z_t'\delta_t + v_t, \quad v_t \sim \mathrm{N}(0, \sigma_v^2) \\
\delta_t &= \delta_{t-1} + \mu_t, \quad \mu_t \sim \mathrm{MN}(0, \Sigma_\mu)
\end{aligned} \tag{4.8}$$

π_{t+1} is observed inflation at period $t+1$; Z_t is a 8×1 vector of instrumental variables, which includes four lags of inflation π and four lags of industry marginal cost mc, respectively; δ_t is the corresponding 8×1 vector of coefficients; v_t is a stochastic error term.

Since both Eq.(4.8) and Eq.(4.7) contains inflation series $\{\pi_t\}_{t=1,\ldots,T}$, we distinguish them by denoting $X_T \equiv \{\pi_{t+1}\}_{t=1,\ldots,T-1}$ and $Y_T \equiv \{\pi_t\}_{t=1,\ldots,T-1}$, respectively. Their elements are indexed by x_t and y_t, e.g., $x_t = \pi_{t+1}$ and $y_t = \pi_t$. The model then becomes:

Step 1:

$$\begin{aligned} x_t &= Z_t'\delta_t + v_t, \quad v_t \sim \mathrm{N}(0, \sigma_v^2) \\ \delta_t &= \delta_{t-1} + \mu_t, \quad \mu_t \sim \mathrm{MN}(0, \Sigma_\mu) \end{aligned} \tag{4.9}$$

Step 2:

$$\begin{aligned} y_t &= \kappa_t mc_t + \gamma_t \left(\hat{P}_{f,t} - \hat{P}_{h,t}\right) + \beta_t x_t + e_t, \quad e_t \sim \mathrm{N}(0, \sigma_e^2) \\ \kappa_t &= \kappa_{t-1} + \eta_t, \quad \eta_t \sim \mathrm{N}(0, \sigma_\eta^2) \\ \gamma_t &= \gamma_{t-1} + \xi_t, \quad \xi_t \sim \mathrm{N}(0, \sigma_\xi^2) \\ \beta_t &= \beta_{t-1} + \zeta_t, \quad \zeta_t \sim \mathrm{MN}(0, \sigma_\zeta^2) \end{aligned} \tag{4.10}$$

In summary, the time-varying coefficients are δ_t, κ_t, γ_t and β_t. Among them, we are interested in κ_t and γ_t: κ_t is the time-varying slope of Phillips curve, and γ_t is the coefficient of relative price channel ($\hat{P}_{f,t} - \hat{P}_{h,t}$). According to Benigno et al. (2016), increase in the number of imported goods will make domestic price more sensitive to marginal production cost, and low imported good prices generate disinflation pressure. If κ_t increases over time, while γ_t gradually becomes statistically significant, then we can conclude that globalization indeed steepens and shifts the NKPC. Both Eq.(4.9) and Eq.(4.10) can be estimated with Kalman Filter.

One may be inclined to follow Galı and Gertler (1999), by first estimating Eq.(4.9) with Kalman Filter, obtaining the smoothed estimates (fitted values) $\pi_{t+1|T}$, substituting it into Eq.(4.10) and then estimating Eq.(4.10) with Kalman Filter again. However, in this way the result will be biased as $\pi_{t+1|T}$ is a generated regressor. In a time-invariant-parameter 2SLS model, values of coefficients are unaffected by generated regressors, only the variance-covariance matrix of coefficients needs to be adjusted. But in time-varying-parameter (TVP) models, generated regressors will have a direct impact on the inference of the coefficients. This is because generated regressors affect the conditional variance of observed variables, which appears in the log-likelihood function. To see this, suppose we first estimate Eq.(4.9) and substitute the smoothed estimates $\pi_{t+1|T}$ into Eq.(4.10):

$$\pi_t = \kappa_t mc_t + \gamma_t \left(\hat{P}_{f,t} - \hat{P}_{h,t}\right) + \beta_t \pi_{t+1|T} + \epsilon_t \tag{4.11}$$

The innovation ϵ_t will be:

$$\epsilon_t = e_t + \beta_t(\pi_{t+1} - \pi_{t+1|T}), \tag{4.12}$$

which is conditional heteroskedastic on $\{\pi_t\}_{t=1,\ldots,T}$.

To obtain unbiased inference, we need to address this issue. Fortunately, Kim and Nelson (2006) comes up with a two-step error correction method that solves the problem. The main innovation of our paper is that we introduce the econometric method proposed in Kim and Nelson (2006) to estimate our time-varying NKPC model. Kim and Nelson (2006)'s method enables us to estimate a purely forward-looking NKPC with ex post data. That is, we don't need any additional variable to proxy the expected future inflation, only realized inflation data is enough for the estimation of the NKPC. What's more, Kim and Nelson (2006)'s approach can be regarded as a state-space extension of the GMM method proposed by Galı and

Gertler (1999), whose approach has been widely used in practice. Therefore, by employing Kim and Nelson (2006)'s strategy in estimating the NKPC, we extend the application range of a classical econometric approach, and at the same time modify it so that it is suitable for more dynamic models. Our estimation procedure is described in the next subsection.

4.2 Estimation

Step 1: Firstly, we can express Eq.(4.9) as the following state-space model to be estimated:

$$\begin{gathered} x_t = [Z_t' \quad 1] \begin{bmatrix} \delta_t \\ v_t \end{bmatrix} \\ \left(\Longrightarrow x_t = W_t \tilde{\delta}_t \right) \end{gathered} \tag{4.13}$$

$$\begin{gathered} \begin{bmatrix} \delta_t \\ v_t \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} \delta_{t-1} \\ v_{t-1} \end{bmatrix} + \begin{bmatrix} \mu_t \\ v_t \end{bmatrix}, \quad \begin{bmatrix} \mu_t \\ v_t \end{bmatrix} \sim N\left(\begin{bmatrix} 0 \\ 0 \end{bmatrix}, \begin{bmatrix} \Sigma_\mu & 0 \\ 0 & \sigma_v^2 \end{bmatrix} \right) \\ \left(\Longrightarrow \tilde{\delta}_t = F\tilde{\delta}_{t-1} + \tilde{U}_{2,t}, \quad \tilde{U}_{2,t} \sim \mathrm{N}\left(0, Q\right) \right) \end{gathered} \tag{4.14}$$

Let:

$$\begin{aligned} d_{t|t-1} &= E_{t-1}(\tilde{\delta}_t) \\ P_{t|t-1} &= E[(\tilde{\delta}_t - d_{t|t-1})(\tilde{\delta}_t - d_{t|t-1})'] \\ \hat{x}_{t|t-1} &= E_{t-1}(x_t) \\ R_{t|t-1} &= E[(x_t - \hat{x}_{t|t-1})(x_t - \hat{x}_{t|t-1})'] \end{aligned}$$

The Kalman Filter then proceeds as:

$$\begin{aligned} d_{t|t-1} &= F d_{t-1|t-1} \\ P_{t|t-1} &= F P_{t-1|t-1} F' + Q \\ \hat{x}_{t|t-1} &= W_t d_{t|t-1} \\ R_{t|t-1} &= W_t P_{t|t-1} W_t' \\ d_{t|t} &= d_{t|t-1} + P_{t|t-1} W_t' R_{t|t-1}^{-1} (x_t - \hat{x}_{t|t-1}) \\ P_{t|t} &= P_{t|t-1} - P_{t|t-1} W_t' R_{t|t-1}^{-1} W_t P_{t|t-1} \end{aligned} \tag{4.15}$$

The corresponding Kalman Smoother proceeds as follows:

$$\begin{aligned} d_{t|T} &= d_{t|t} + P_{t|t} F' P_{t+1|t}^{-1} (d_{t+1|T} - F d_{t|t}) \\ P_{t|T} &= P_{t|t} + P_{t|t} F' P_{t+1|t}^{-1} (P_{t+1|T} - P_{t+1|t}) [P_{t|t} F' P_{t+1|t}^{-1}]' \quad t = T-1, ..., 1 \end{aligned} \tag{4.16}$$

In step 1, the likelihood function to be estimated is

$$\begin{aligned} f(X_T) &= \prod_{t=1}^{T} f(x_t | X_{t-1}) \\ &= \prod_{t=1}^{T} (2\pi)^{-k/2} |R_{t|t-1}|^{-1/2} \exp\left(-\frac{1}{2}(x_t - \hat{x}_{t|t-1})' R_{t|t-1}^{-1} (x_t - \hat{x}_{t|t-1})\right). \end{aligned} \tag{4.17}$$

The relevant hyperparameters are variance-covariance matrices Σ_μ and the standard deviation σ_v .

Step 2: In Eq.(4.10), x_t is correlated with the error term e_t. To address the endogeneity issue, the error term e_t should be corrected at each iteration. We thus decompose x_t into two components, the predicted component and the prediction error component:

$$x_t = \hat{x}_{t|t-1} + v_{t|t-1}, \tag{4.18}$$

where $v_{t|t-1}$ is the prediction error of x_t given information no later than period $t-1$. And assume further:

$$v_{t|t-1} = [\sigma^2_{v,t|t-1}]^{\frac{1}{2}} v^*_t, \quad v^*_t \sim i.i.d.\mathrm{N}(0,1) \tag{4.19}$$

Following Kim and Nelson (2006), we assume the distribution of v^*_t and e_t satisfy:

$$\begin{bmatrix} v^*_t \\ e_t \end{bmatrix} \sim \mathrm{N}\left(\begin{bmatrix} 0 \\ 0 \end{bmatrix}, \begin{bmatrix} 1 & \rho\sigma_e \\ \sigma_e\rho & \sigma^2_e \end{bmatrix} \right) \tag{4.20}$$

Applying Cholesky decomposition to the variance-covariance matrix yields:

$$\begin{bmatrix} v^*_t \\ e_t \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ \sigma_e\rho & \sigma_e\sqrt{1-\rho^2} \end{bmatrix} \begin{bmatrix} \omega_t \\ \epsilon_t \end{bmatrix}, \begin{bmatrix} \omega_t \\ \epsilon_t \end{bmatrix} \sim \mathrm{N}\left(\begin{bmatrix} 0 \\ 0 \end{bmatrix}, \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \right). \tag{4.21}$$

The above equation allows us to decompose e_t into two components: ω_t which is correlated with x_t and ϵ_t which is uncorrelated with x_t. In this way we address the endogeneity issue. Then the measurement equation can be written as:

$$y_t = \kappa_t mc_t + \gamma_t \left(\hat{P}_{f,t} - \hat{P}_{h,t} \right) + \beta_t x_t + \sigma_e \rho v^*_t + \epsilon^*_t \tag{4.22}$$

where $\epsilon^*_t \sim \mathrm{N}(0, (1-\rho^2)\sigma^2_e)$. Now the decomposed error term ϵ^*_t is uncorrelated with π_{t+1}, and we can estimate equation (20) with standard Kalman Filter. Stack the measurement and state equations into matrix form:

$$\begin{gathered} y_t = \begin{bmatrix} mc_t & \left(\hat{P}_{f,t} - \hat{P}_{h,t} \right) & x_t & 1 \end{bmatrix} \begin{bmatrix} \kappa_t \\ \gamma_t \\ \beta_t \\ \epsilon^*_t \end{bmatrix} + \sigma_e \rho v^*_t \\ \left(\Longrightarrow y_t = S_t \tilde{\beta}_t + \sigma_e \rho v^*_t \right) \end{gathered} \tag{4.23}$$

$$\begin{gathered} \begin{bmatrix} \kappa_t \\ \gamma_t \\ \beta_t \\ \epsilon^*_t \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} \kappa_{t-1} \\ \gamma_{t-1} \\ \beta_{t-1} \\ \epsilon^*_{t-1} \end{bmatrix} + \begin{bmatrix} \eta_t \\ \xi_t \\ \zeta_t \\ \epsilon^*_t \end{bmatrix}, \quad \begin{bmatrix} \eta_t \\ \xi_t \\ \zeta_t \\ \epsilon^*_t \end{bmatrix} \sim \mathrm{N}\left(\begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \end{bmatrix}, \begin{bmatrix} \sigma^2_\eta & 0 & 0 & 0 \\ 0 & \sigma^2_\xi & 0 & 0 \\ 0 & 0 & \sigma^2_\zeta & 0 \\ 0 & 0 & 0 & (1-\rho^2)\sigma^2_e \end{bmatrix} \right) \\ \left(\Longrightarrow \tilde{\beta}_t = G\tilde{\beta}_{t-1} + \tilde{V}_t, \quad \tilde{V}_t \sim N(0, \tilde{\Phi}) \right) \end{gathered} \tag{4.24}$$

We further define:

$$\begin{aligned} b_{t|t-1} &= E_{t-1}(\tilde{\beta}_t) \\ J_{t|t-1} &= E[(\tilde{\beta}_t - b_{t|t-1})(\tilde{\beta}_t - b_{t|t-1})'] \\ \hat{y}_{t|t-1} &= E_{t-1}(y_t) \\ H_{t|t-1} &= E[(y_t - \hat{y}_{t|t-1})(y_t - \hat{y}_{t|t-1})'] \end{aligned}$$

Then, the standard Kalman Filter proceeds as:

$$\begin{aligned}
b_{t|t-1} &= Gb_{t-1|t-1} \\
J_{t|t-1} &= GJ_{t-1|t-1}G' + \tilde{\Phi} \\
\hat{y}_{t|t-1} &= S_t b_{t|t-1} + \sigma_e \rho v_t^* \\
H_{t|t-1} &= S_t J_{t|t-1} S_t' \\
b_{t|t} &= b_{t|t-1} + J_{t|t-1} S_t' H_{t|t-1}^{-1}(y_t - \hat{y}_{t|t-1}) \\
J_{t|t} &= J_{t|t-1} - J_{t|t-1} S_t' H_{t|t-1}^{-1} S_t J_{t|t-1}
\end{aligned} \tag{4.25}$$

After obtaining $b_{t|t}$ and $J_{t|t}$ for all periods, we can continue with the Kalman smoother. Starting from period $T-1$, the Kalman smoother moves backward:

$$b_{t|T} = b_{t|t} + J_{t|t}G' J_{t+1|t}^{-1}(b_{t+1|T} - Gb_{t|t}), \quad t = T-1, ..., 1 \tag{4.26}$$

However, when smoothing the conditional variance of $\tilde{\beta}_t$ and deriving the likelihood function, we cannot directly employ the conditional variance of y_t from the Kalman Filter. This is because the above Kalman Filter provides us with $b_{t|t}$, $H_{t|t-1}$ and $J_{t|t}$ based on both information until $t-1$ and the error correction terms. Correct conditional variance of $\tilde{\beta}_t$ and y_t should not be based on the error correction terms. Thus, to get correct inference of conditional variance of y_t and $\tilde{\beta}_t$, we refer to the following equations:

$$\begin{aligned}
H_{t|t-1}^* &= S_t J_{t|t-1} S_t' + \rho^2 \sigma_e^2 \\
J_{t|t}^* &= J_{t|t-1} - J_{t|t-1} S_t' H_{t|t-1}^{*-1} S_t J_{t|t-1} \\
J_{t+1|t}^* &= GJ_{t|t}^* G' + \tilde{\Phi}
\end{aligned} \tag{4.27}$$

The corresponding Kalman smoother then is as follows:

$$J_{t|T}^* = J_{t|t}^* + J_{t|t}^* G' J_{t+1|t}^{-1*}(J_{t+1|T}^* - J_{t+1|t}^*)[J_{t|t}^* G' J_{t+1|t}^{-1*}]', \quad t = T-1, ..., 1 \tag{4.28}$$

The likelihood function to be maximized is:

$$\begin{aligned}
f(\tilde{Y}_T) &= \prod_{t=1}^{T} f(y_t|\tilde{Y}_t) \\
&= \prod_{t=1}^{T} (2\pi)^{-k/2} |H_{t|t-1}^*|^{-1/2} \exp\left(-\frac{1}{2}(y_t - \hat{y}_{t|t-1})' H_{t|t-1}^{*-1}(y_t - \hat{y}_{t|t-1})\right)
\end{aligned} \tag{4.29}$$

Empirical Analysis

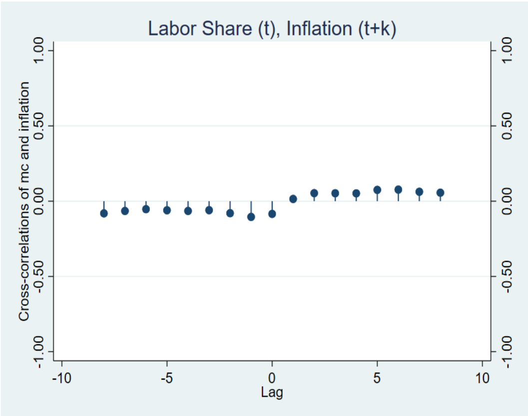
5.1 Data

We construct the empirical data set following Guerrieri et al. (2010)'s approach. Guerrieri et al. (2010) come up with a benchmark New Keynesian Phillips curve that is almost equivalent to Benigno et al. (2016)'s: current inflation is determined by not just real marginal cost and expected future inflation, but also the relative import price. First of all, we need to choose the time span of our empirical analysis. As shown in Figure B.3, there is a sharp rise in import and export shares of GDP from 1960s to early 2000s. Then, a sudden drop appears after the financial crisis, and the rebound occurs very soon, whereas the decline then lasts after 2010. A similar but more dramatic trend is observed if we only consider the goods sector (see Figure B.4). Since "de-globalization" is not of our interest, our study focuses on the period before 2007. In addition, the evolution of monetary policy regimes in the U.S. is of critical importance as it directly influences the inflation dynamics (Bae et al., 2012; Davig and Doh, 2014). To avoid policy regime shift, we restrict our analysis on Volcker–Greenspan period, which ranges from 1983 to 2006.

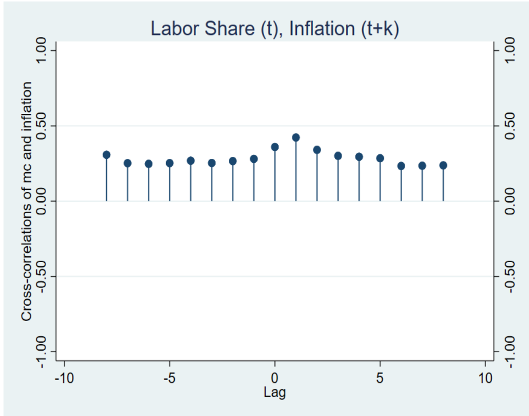
Table 5.1: Summary Statistics

Variable	Observation	Mean	Standard Deviation	Min	Max
Inflation	96	0.0021	0.0047	-0.0090	0.0143
Labor Share	96	-0.0022	0.0183	-0.0378	0.0339
Relative Price	96	0.0872	0.0784	-0.0529	0.2405

In Guerrieri et al. (2010), domestic inflation is measured by subtracting the exported goods price index from an overall goods prices index. Figure B.5 displays the inflation data of Guerrieri et al. (2010). The proxy variable for real marginal cost is the labor share in the U.S. non-farm business, defined as the logarithm of nominal labor compensation divided by nominal output. This definition is consistent with Galı and Gertler (1999) and Sbordone (2002). Figure B.6 plots the real marginal cost along with the inflation in Guerrieri et al. (2010). The real marginal cost co-moves with the inflation during most time, except for the beginning and the end of the 1990s. Relative import prices is defined as the logarithm of price deflator for non-oil imported goods divided by the logarithm of domestic goods price deflator. From Figure B.7, we notice that relative prices are positively correlated with inflation, falling to a lower level between 1990 and 2000, and then trending upwards after 2001. Summary statistics of these variables are presented in Table 5.1.



(a) Benigno et al. (2016)



(b) Guerrieri et al. (2010)

Figure 5.1: Dynamic Cross Correlation

Next, it is worthwhile discussing why we adopt Benigno et al. (2016)'s theoretical model but not their data. Benigno et al. (2016)'s data is described in detail in Appendix A. Figure 5.1 presents the dynamic cross correlation between inflation and marginal cost. In Benigno et al. (2016), the current labor share is positively correlated with future inflation but negatively correlated with lagged inflation. In other words, the marginal cost leads over the inflation, which contradicts the New-Keynesian Phillips curve theory. This unsatisfying characteristic has been criticized by Galı and Gertler (1999): when marginal cost leads over inflation, the slope of NKPC will be negative, a contradiction to the New Keynesian theory. In fact, we indeed obtained a downward-sloping NKPC by adopting Benigno et al. (2016)'s data. On the other hand, Guerrieri et al. (2010)'s measure of marginal cost has no such flaw: current marginal cost correlates with both leads and lags of inflation, which is consistent with the New Keynesian theory. Therefore, we implement our empirical strategy with Guerrieri et al. (2010)'s data. All variables are demeaned so that the steady state of each variable centers at zero. Besides, to make our argument more valid, we test for a structural break including inflation, marginal cost, and relative prices using Benigno et al. (2016)'s subsample data. A p-value of 0.5771 from Wald test indicates that it is necessary to consider a time-varying parameter model.

5.2 Main Result

We report estimation results of hyper-parameters in Table B.1. The first column displays estimates of the error term standard deviations in Step 1. The standard deviation of most of the error terms are quite small. Since step 1 equations reflect agent's prediction of future inflation, the minor standard deviations indicate that agents' expectation of future inflation was stable during 1983-2006. Also, agents rely more heavily on latest information when making predictions about future inflation: from $\Sigma_{\mu,1}^{\frac{1}{2}}$ (0.0000) to $\Sigma_{\mu,2}^{\frac{1}{2}}$ (0.0356) and from $\Sigma_{\mu,5}^{\frac{1}{2}}$ (0.0000) to $\Sigma_{\mu,8}^{\frac{1}{2}}$ (0.0256), there is a clear ascending pattern among the standard deviations of error terms, implying an increase in corresponding prediction uncertainty. The second column reports estimates of the error term standard deviations in Step 2 equations. The standard deviation for marginal cost shock is 0.0044, the standard deviation for the exogenous inflation shock in the NKPC is 0.0038, while the standard deviation for the shock in relative price and shock in discount factor are close to zero. The correlation coefficient ρ in the Cholesky decomposition equals -0.4410, suggesting that ignoring error correction will result in severe bias in the estimation results. One of the weaknesses of our estimation is that we didn't obtain the standard deviations of these estimates, thus we cannot justify the significance of them. The estimation of standard deviations involves complex iteration and loops of information matrix elements and we leave it to future research.

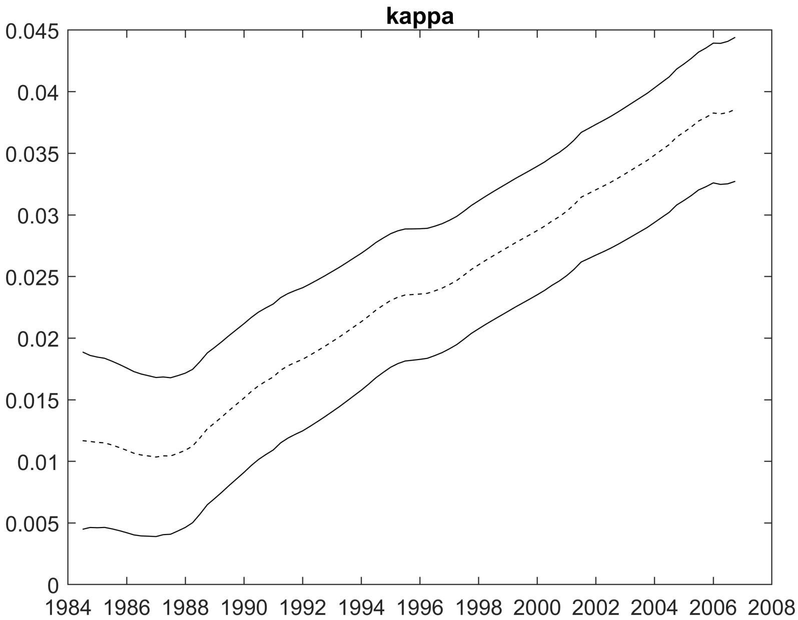


Figure 5.2: Inflation's response to domestic marginal cost and 95% confidence bands

Conditional on these hyperparameters, we estimate the state variables with Kalman Filter. Since Benigno et al. (2016)'s model predicts that inflation has an impact on κ and γ, we focus on these two coefficients. Figure 5.2 shows the response of inflation rate to the domestic marginal cost of production, which is traditionally regarded as the slope of NKPC. As discussed earlier, the slope of NKPC is: $\kappa \equiv \frac{(\bar{\sigma}-1)}{\lambda}$, where $\bar{\sigma} \equiv \sigma - \frac{\sigma-\theta}{N}$. σ is the elasticity of substitution among different varieties produced in the generic sector, while θ is the elasticity of substitution across sectors. Holding σ and θ constant, as globalization proceeds, the number of products in the market N is expected to grow, as a result, $\bar{\sigma}$ increases and the slope κ also increases. Benigno et al. (2016) considered two sample periods: 1993-1999 and 1999-2012, and they found that the slope of NKPC jumped from 0.001 in the first period to 0.1 in the second period but in both periods the slopes are statistically insignificant. Our result suggests that the mean of slope of U.S. NKPC has increased from less than 0.02 in 1980s, to more than 0.035 toward the end of 2006. More importantly, the slope is statistically significant in the whole sample period. Therefore, we conclude that globalization changed the U.S. inflation dynamics by making inflation more sensitive to marginal cost of production.

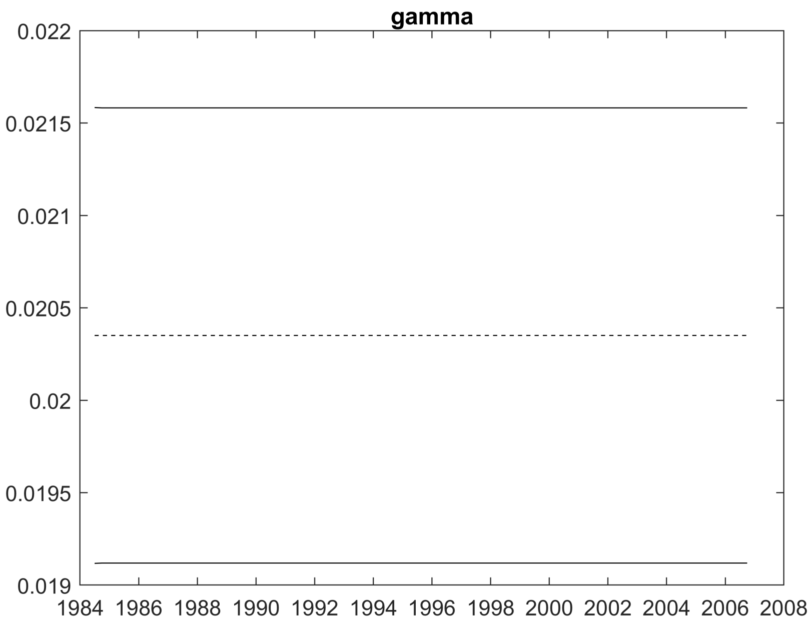


Figure 5.3: Inflation's response to relative prices and 95% confidence bands

Figure 5.3 and Figure B.8 shows the impacts of the relative import prices and expected future inflation on current inflation, respectively. To our surprise, these two estimates don't vary over time. This is because the standard deviations of their corresponding error terms, $\sigma_\xi(0.0000)$ and $\sigma_\zeta(0.0002)$, are close to zero, just as indicated in Table B.1. The mean of γ in Figure 5.3 is around 0.0204, while the mean of β in Figure B.8 is around 0.4417. According to the theoretical model, $\gamma \equiv \frac{\sigma-1}{\lambda}\frac{\sigma-\theta}{\bar{\sigma}}\frac{N_f}{N^2}$. Holding σ, θ and λ constant, the magnitude of γ will be determined by the number of imported goods N_f and total number of goods in the market N. Suppose Benigno et al. (2016)'s model is correct, as $N = N_f + N_h$ increases, to keep γ constant, N_f must grow much faster than N, which implies that the number of domestically produced goods N_h must decrease. Because of missing data we are unable to test this hypothesis at this moment, but it is worth testing in the future, since it is consistent with one aspect of globalization: more goods are produced abroad due to global division of labor. As for the discount factor β, Benigno et al. (2016) fixed it at 0.99, but our estimate of β is lower: only 0.4417. The magnitude of this estimate is consistent with the value in Oinonen and Paloviita (2014). They estimate a time-varying NKPC in Euro area, but also include backward-looking price setters, and obtain a time-varying β which ranges from 0.4 to 0.6. Therefore, to improve our model and possibly obtain time-varying β, researchers may add a lagged inflation term π_{t-1} to the right hand side of Phillips curve, making it a hybrid NKPC.

Figure B.9 plots the exogenous inflation shock. It seems that the volatility of exogenous shock is lower during 1996-2001 compared to other periods. One may criticize that our model fails to account for the potential heterogeneity in exogenous shocks. In the next section, we will prove that this concern is unnecessary, and our model is quite robust when considering time-varying volatility.

The most striking finding in our paper is the increasing slope of NKPC, rather the flattening one found in most of the previous studies. For example, Boivin and Giannoni (2006) employ the minimum distance estimation method to estimate the structural VAR model and find that the coefficient of marginal cost in NKPC decrease from 0.011 in pre-1980 sample to 0.008 in post-1980. Similarly, Smets and Wouters (2007), using Bayesian likelihood approach in a DSGE model, show that the slope of Phillips curve is higher in 1966-1979 sample period compared to that in 1984-2004 period. However, these studies aim at linking the change in output-inflation trade-off to the evolution in monetary policy in the early 1980s, not globalization. They also emphasize that only large and persistent fluctuations in the marginal cost will have an effect on inflation as the slope of Phillips curve is quite small.

On the other hand, Borio and Filardo (2007) relate variations in the slope of the Phillips curve to globalization. Specifically, they estimate a statistical Phillips curve for many countries over the two periods 1980-1992 and 1993-2005, and find that there is a decline in both inflation persistence and the sensitivity of inflation to domestic output gap in the more recent period. In particular, for the U.S, there is a drop in the estimated coefficient of lagged inflation from 0.92 to 0.82 across the two samples, and a decline in the slope from 0.13 to 0.09. The seemingly inconsistency between our results and their findings results from the different types of Phillips curve estimated. As we argued in section 2.2, the reduced-form relationships in traditional Phillips curve are about statistical correlations and not necessarily about exact structural relationships. The derivation of our NKPC fully reflects how globalization affects the slope through the strategic complementarity in price setting, and the empirical results support the theoretical predictions. Furthermore, Bianchi and Civelli (2015) find that the slope of NKPC is small and does not vary significantly, their results are not comparable to ours since they study the globalization effect by simply adding foreign output gap and import price inflation into the original NKPC. Theoretical models of Razin et al. (2005) and Daniels and VanHoose (2006) exhibit new Keynesian features such as imperfect competition and nominal rigidity. They claim that globalization makes NKPC flatter, whereas our model differs from theirs fundamentally, e.g. their model assumes constant elasticity. It does not make much sense to directly compare our results to those in previous literature without understanding the different micro-foundations of the models.

Another innovative finding is the relative import price channel proposed in the model. Contrary to the argument in Ball (2006), we indeed show that there is a positive and statistically significant effect of relative price on inflation dynamics. The magnitude of the effect is around 0.0204. Benigno et al. (2016) also find that this effect increases from 0.0025 in 1993-2000 sample period to 0.037 in 2001-2008 period. This finding is consistent with that in Pain et al. (2006) and Bianchi and Civelli (2015), e.g. foreign economic condition can affect the domestic inflation through the import prices. To sum up, our empirical results indicate that globalization influences inflation by steepening and shifting the NKPC downwards.

Discussion

6.1 Robustness Check

6.1.1 Global Maximum

Our main result is valid only if we indeed found the global maximum of the log-likelihood function. Since the concavity of the log-likelihood function is unknown, it is possible that the optimal point we found is actually a local maximum or a saddle point. In these two cases, the estimated hyperparameters are not true MLEs. Therefore, in this subsection we verify our main result by maximizing the log-likelihood function with different global maximization tools and different random seeds. First, we fix random seed at 'default' and compare different global maximization tools. Table B.2 reports the results [1]. In each column, we present the estimated hyperparameters and corresponding log-likelihood functional values which are obtained by applying a specific optimization algorithm in both steps. Our main result in previous section is obtained by applying "GlobalSearch".

Focusing on $\log L$(Step 1) and $\log L$(Step 2), we can see that the maximum functional values searched by GS algorithm is close to the maximum functional values searched by other algorithms. In addition, among all the results, similar $\log L$ values correspond to similar hyperparameter estimates, indicating that the log-likelihood function is unlikely to have multiple maximum points. Therefore, we conclude that we indeed found the global maximum of the likelihood function.

Next, we test whether our main result is sensitive to the number of random seed. When running optimization algorithms such as GS and MS, the final result depends on the positions of start points, which further depend on the initial random seed number. Therefore, different random seeds will lead to different final results. To verify the stability of our main result, we run the GS algorithm with random seeds ranging from 1 to 100, and the corresponding final log-likelihood functional values are presented by Figure 6.1.

As random seeds vary from 1 to 100, for step 1, the maximum log-likelihood functional value oscillates around mean -367.4553, while for step 2, the maximum

[1] "GS" denotes "GlobalSearch", "MS" denotes "MultipleSearch", "PS" denotes "PatternSearch", "Surr" denotes "surrogateopt", "Part" denotes "Particleswarm", "Ga" denotes "GlobalSearch", and "CS" denotes "Csminwel". These are optimization algorithms that can be used for log-likelihood maximization.

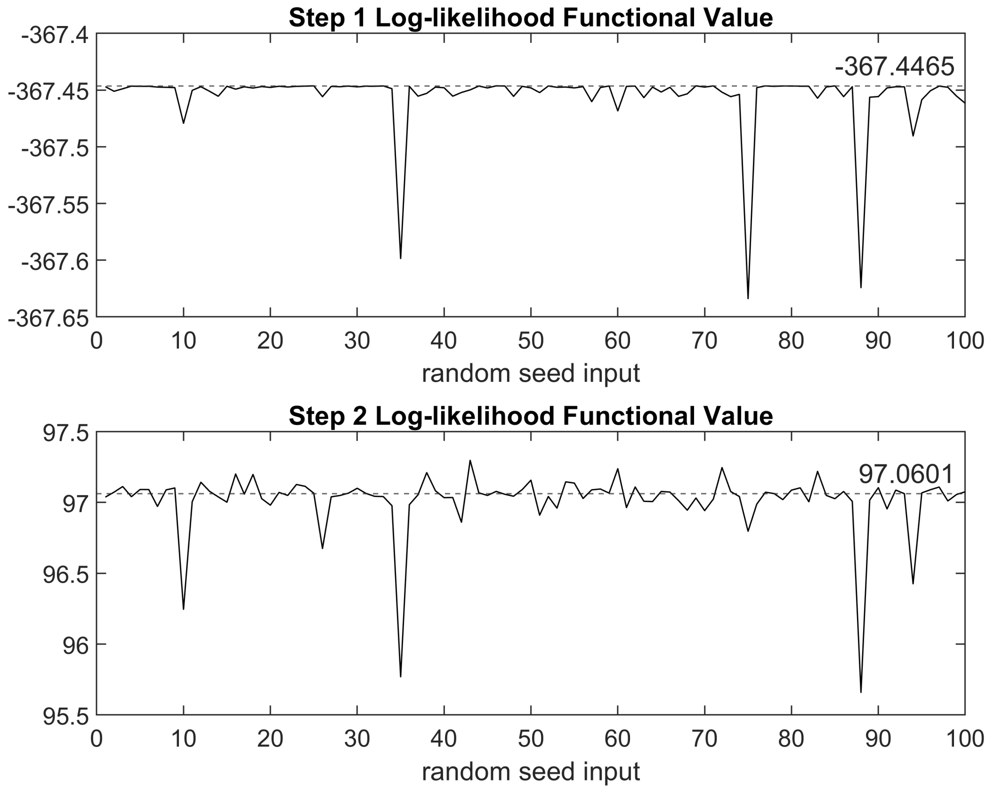


Figure 6.1: Random seed number and corresponding log-likelihood functional value

log-likelihood functional value oscillates around mean 97.0135. There is no sign for enormous deviation, thus random seed number has little effect on the final result. By setting random seed at option "default", our main result indicates that the step 1 maximum log-likelihood functional value equals -367.4465 and the step 2 maximum log-likelihood functional value equals 97.0601, both of which lie in the range of the varying-random-seeds sample. Therefore, we conclude that our main result is not an outlier, and is indeed the global maximum.

6.1.2 Heterogeneity

As Figure B.9 shows, the volatility of exogenous inflation shock seems to be time-varying: during 1996-2000, inflation is less volatile. In this subsection we modify our model so that the volatility of exogenous shocks are heterogeneous. To be more specific, the volatility of error terms v_t and e_t are no longer constant; instead, they are assumed to follow GARCH(1,1) processes:

$$\sigma_{v,t}^2 = a_0 + a_1 v_{t-1}^2 + a_2 \sigma_{v,t-1}^2 \tag{6.1}$$

$$\sigma_{e,t}^2 = \alpha_0 + \alpha_1 e_{t-1}^2 + \alpha_2 \sigma_{e,t-1}^2 \tag{6.2}$$

Note that v_{t-1}^2 and e_{t-1}^2 are unobserved. Following Harvey et al. (1992), we approximate v_{t-1}^2 and e_{t-1}^2 by their conditional means $E_{t-1}(v_{t-1}^2)$ and $E_{t-1}(e_{t-1}^2)$, respectively. After transformation, the GARCH(1,1) processes become:

$$\sigma_{v,t}^2 = a_0 + a_1 E_{t-1}(v_{t-1}^2) + a_2 \sigma_{v,t-1}^2 \tag{6.3}$$

$$\sigma_{e,t}^2 = \alpha_0 + \alpha_1 E_{t-1}(e_{t-1}^2) + \alpha_2 \sigma_{e,t-1}^2 \tag{6.4}$$

To estimate Eq.(6.3), note that the last element of $P_{t-1|t-1}$ is $E_{t-1}(v_{t-1}^2)$, and given $P_{t-1|t-1}, P_{t-2|t-2}, ..., P_{1|1}$, we can compute $\sigma_{v,t}^2$ recursively. For 6.4, since $e_t = \sigma_{e,t}\rho' v_t^* + \epsilon_t$, we have:

$$\begin{aligned}
\sigma_{e,t}^2 &= \alpha_0 + \alpha_1 E_{t-1}(e_{t-1}^2) + \alpha_2 \sigma_{e,t-1}^2 \\
&= \alpha_0 + \alpha_1 E_{t-1}[(E_{t-1}(e_{t-1}) + e_{t-1} - E_{t-1}(e_{t-1}))^2] + \alpha_2 \sigma_{e,t-1}^2 \\
&= \alpha_0 + \alpha_1 \{[E_{t-1}(e_{t-1})]^2 + E_{t-1}[(e_{t-1} - E_{t-1}(e_{t-1}))^2]\} + \alpha_2 \sigma_{e,t-1}^2 \\
&= \alpha_0 + \alpha_1 \{[\sigma_{e,t-1}\rho v_{t-1}^* + E_{t-1}(\epsilon_{t-1})]^2 + E_{t-1}[(\epsilon_{t-1} - E_{t-1}(\epsilon_{t-1}))^2]\} + \alpha_2 \sigma_{e,t-1}^2
\end{aligned} \tag{6.5}$$

In step 1 we already have the estimate v_{t-1}^*. $E_{t-1}(\epsilon_{t-1})$ is given by the last element of $b_{t-1|t-1}$. Its corresponding mean squared error $E_{t-1}[(\epsilon_{t-1} - E_{t-1}(\epsilon_{t-1}))^2]$ is given by the last diagonal element of $J_{t-1|t-1}$. In this way we are able to compute $E_{t-1}(\sigma_{e,t}^2)$ recursively, which will later be substituted into the last diagonal element of $J_{t|t-1}$. The Kalman Filter can thus proceed normally.

Estimation result is presented in Table B.3. As we can see, the coefficients for a_1, a_2, α_1 and α_2 all reach the lower bound 1×10^{-6} (whose 4th and 5th digit are zero), indicating that the variances of v_t and e_t are unlikely to be time-varying, and our main result is robust even when we consider heterogeneity.

6.2 Policy Implications

A famous claim by Milton Friedman - Inflation is always and everywhere a monetary phenomenon - well illustrates the crucial role of inflation in monetary policy. In the long run, the inflation rate is determined by monetary policy. However, in the short and medium runs, globalization can have an effect on the ability of central banks to stabilize prices and output, and thus to control inflation in two aspects. Firstly, the increasing integration of global economy might directly affect the level and volatility of output and inflation. Secondly, globalization has changed the sensitivity of inflation to the domestic output gaps, and thus to the domestic monetary policy.

Our paper primarily concentrates on the second aspect, that is, the slope of New-Keynesian Phillips curve in our model. We find that there is a slight increase in the slope over time, which implies increasing sensitivity of inflation to the domestic economic condition. Therefore, we conclude that globalization has not weaken the power of domestic monetary policy to stabilize output and inflation. In addition, we notice that the relative price channel enters the Phillips curve, and its coefficient estimated, though not large, is statistically significant all the time. This shift might temporarily affect the conduct of monetary policy. As Figure B.6 shows, relative price seems to be diminishing over time, implying that imported goods are becoming cheaper. In some periods, relative price was even negative. If our model is valid, then it indicates that globalization is laying an increasing downward pressure on domestic inflation, which may partially offset central banks' attempt to stimulate short-term inflation. Therefore, policy makers especially central banks should take global factor into consideration.

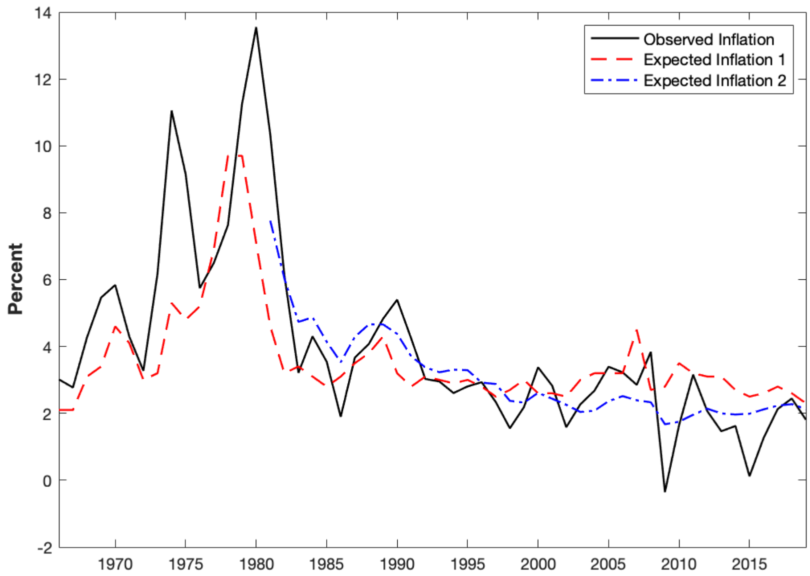


Figure 6.2: Annual Inflation Rates Comparisons

Whereas the slope of NKPC in our theoretical model should only reflect the effect of globalization on inflation through the global competition effect. Specifically, with respect to the monetary policy, since globalization increases competition, leading to greater price and wage flexibility, the ability of central banks to boost output using acceleration in inflation is weaken. That is, the Phillips curve will steepen. Consequently, central banks probably are less motivated to pursue expansionary monetary policy that results in higher inflation. Therefore, the global competition effect channel might account for part of the low inflation rates during recent years. Besides, there are other factors that may make the Phillips curve flatter and the inflation less persistent. A well-known example would be the better anchoring of inflation expectation as suggested in Roberts (2006), Mishkin (2007), and Stock and Watson (2007).

It is commonly recognized that expectation plays an increasing important role in understanding the economy and in determining monetary policy. When economic agents perceive that globalization will put a downward pressure on wages and prices, they naturally expect lower inflation in the future. Moreover, since central banks are more devoted to maintaining price stability, in particular during our sample period, i.e. Volcker-Greenspan rule period, and price stability is related to globalization, people also tend to expect lower inflation. Therefore, globalization dampens the inflation expectation, and in turn affects the way central banks anchor the expected inflation. Figure 6.2 traces how the inflation expectations evolve these years.

In summary, it is difficult but extremely crucial to disentangle different channels and the relationship among all the economic factors. Managing to do so will help the policy makers have a deep understanding of the mechanism about how globalization influence the economic activity and inflation dynamics, and hence make better policies.

6.3 Limitations and Improvements

In this part we briefly summarize the limitations and potential improvements of our paper. First, we could not guarantee that our model does not suffer from model misspecification. For example, we didn't check whether the coefficients of our NKPC have indeed varied over time. It is possible that a time-invariant NKPC has better performance than our model. To make our results more robust, we should conduct a Bayes factor test as in Fu (2019), which compares time-varying and time-invariant NKPC. Unfortunately, at this moment such test is beyond our knowledge.

Second, we didn't estimate the structural-form NKPC as Eq.(3.14). In Eq.(3.14) there are three parameters: the slope of NKPC κ, the hyperparameter k, and the fraction of imported goods ξ_f. Obviously, Eq.(3.14) is not linear in these parameters. Therefore, we let $\gamma = \kappa \cdot k \cdot \xi_f$ and estimate Eq.(3.16) instead. If one aims at obtaining estimates of k and s_f, he needs to apply first-order approximation to the NKPC so that these parameters are approximated by their conditional means. Details can be found in Harvey (1990) and Kim and Nelson (2006).

Another potential improvement of our model is to add lagged inflation to our NKPC, so that it incorporates both forward-looking and backward-looking components, as in Galı and Gertler (1999) and Rudd and Whelan (2005). Previous literature shows that this hybrid NKPC may outperform the traditional NKPC in explaining inflation behavior. It would also be interesting to further explore what happens if we replace the fully rational expectation hypothesis with the bounded-rationality hypothesis as suggested by Lansing (2009) and Ball and Mazumder (2011).

Conclusion

In this paper, we aim at evaluating globalization's impact on domestic inflation by estimating a modified time-varying NKPC whose coefficients can be affected by imported goods and their prices. When the number of imported goods increases, the domestic inflation becomes more sensitive to the marginal production cost, and the slope of the NKPC becomes steeper. More imported goods also intensify domestic competition, posing downward pressure on domestic price level. To verify the above two channels, we employ a two-step error correction method in the estimation. We find evidence of an increase in NKPC slope and the imported good prices indeed have a significant impact on domestic inflation. Thus we conclude that globalization has changed the domestic inflation dynamic. Our conclusion is robust when we consider different log-likelihood maximization methods and heterogeneous exogenous shocks.

Data Description

Guerrieri et al. (2010)'s data

Raw data to calculate traded good inflation and relative import prices are obtained from NIPA table 1.2.4 and 4.2.4 in BEA. Data in nonfarm business sector for computing labor share, a proxy for the real marginal cost, are obtained from BLS.

Benigno et al. (2016)'s data

All the data are on a quarterly basis. Inflation is calculated using Producer Price Index (PPI) in manufacturing industry, which is obtained from BLS. Marginal cost is defined as the difference between unit labor cost and demeaned home price, quarterly data or unit labor cost and price in manufacturing sector is available from BLS. Relative price is defined as the difference between demeaned import price and demeaned home price in manufacturing sector. Aggregate import price in manufacturing industry are constructed based on Harmonized System classification (HS) and its corresponding Relative Importance Index (see Table A.1). Raw data for import prices are on a monthly basis, and we take the average of three months to obtain the quarterly data.

Expected Inflation

The first expected inflation in Figure 6.2 is taken from **University of Michigan Surveys of Consumers**. The original data is on an annual basis: the survey asks a sample of US households about the change in prices they expect during the next year.

The second expected inflation in Figure 6.2 is obtained from **Survey of Professional Forecasters**. This survey asks a panel of professional forecasters for their expectations of one-year ahead inflation and is conducted on a quarterly basis. We average the values in four quarter to get the annual expectation.

Table A.1: HS sectors and the relative importance index

HS sectors	Description	Relative Importance
I	Live animals; animal products	1.392
II	Vegetable products	1.821
IV	Prepared foodstuffs, beverages, and tobacco	2.967
V	Mineral products	9.825
VI	Products of the chemical or allied industries	9.575
VII	Plastics and articles thereof; rubber and articles thereof	3.636
VIII	Raw hides, skins, leather, furskins, travel goods, etc	0.614
IX	Wood, wood charcoal, cork, straw, basketware and wickerwork	0.811
X	Woodpulp, recovered paper, and paper products	1.013
XI	Textile and textile articles	4.818
XII	Headgear, umbrellas, artificial flowers, etc.	1.374
XIII	Stone, plaster, cement, asbestos, ceramics, glass etc.	0.967
XIV	Pearls, stones, precious metals, imitation jewelry, and coins	2.899
XV	Base metals and articles of base metals	5.474
XVI	Machinery, electrical equipment, TV image and sound recorders, parts, etc.	30.251
XVII	Vehicles, aircraft, vessels and associated transport equipment	13.743
XVIII	Optical, photo, measuring, medical & musical instruments; & timepieces	4.059
XIX	Miscellaneous manufactured articles	4.433

Tables and Figures

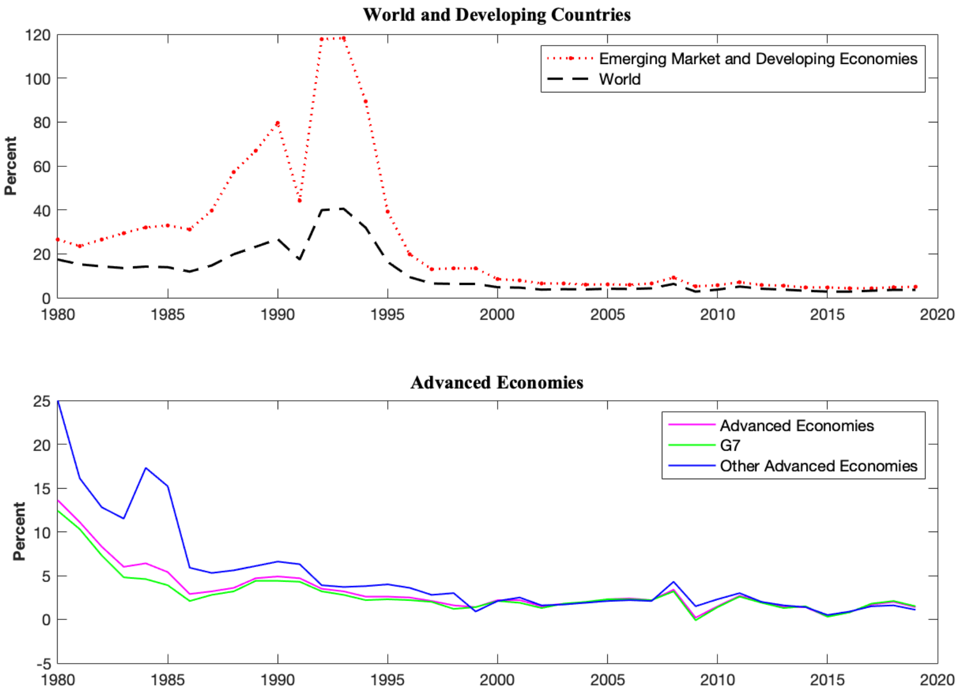


Figure B.1: Average Annual CPI Inflation Rates
Source: IMF, World Economic Outlook

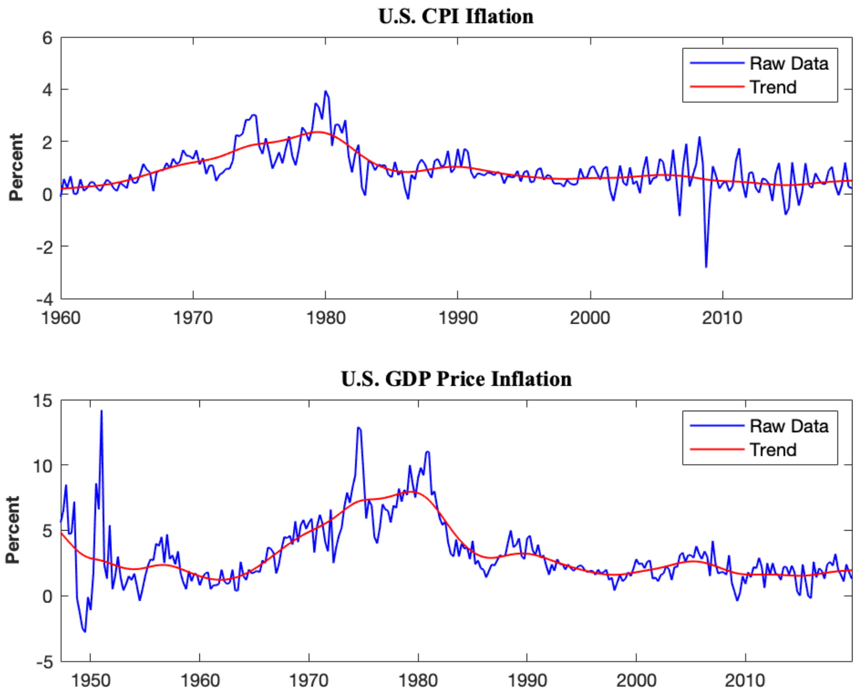


Figure B.2: Quarterly Inflation Rates in U.S. Economy[1]

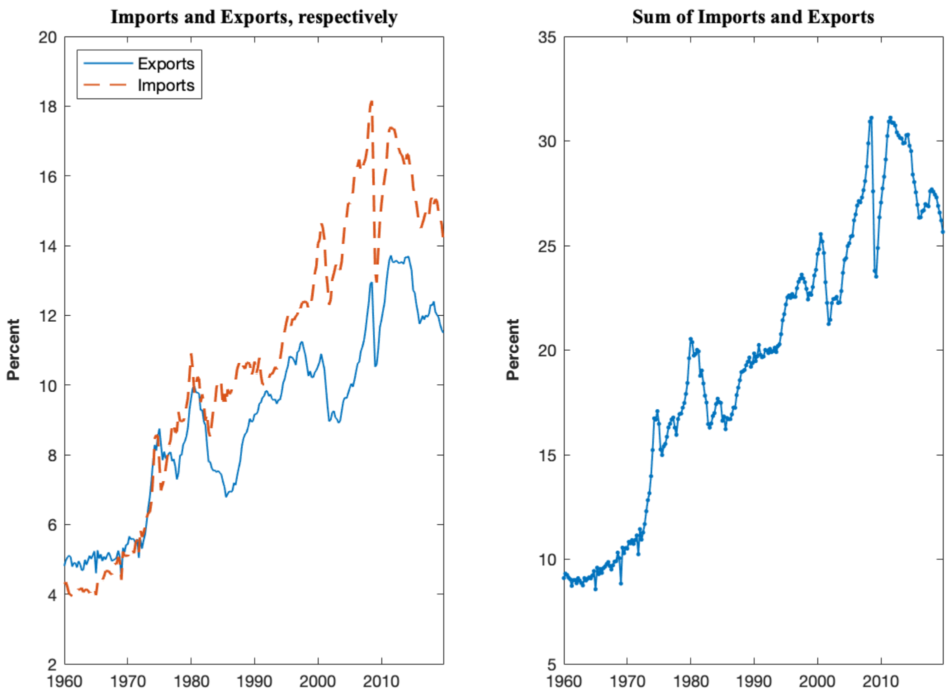


Figure B.3: Exports and Imports as a Share of GDP[2]

[1]Data for CPI inflation is obtained from BLS, not seasonally adjusted; data for GDP price inflation is from BEA, seasonally adjusted.

[2]Data Source: Survey of Current Business of the BEA.

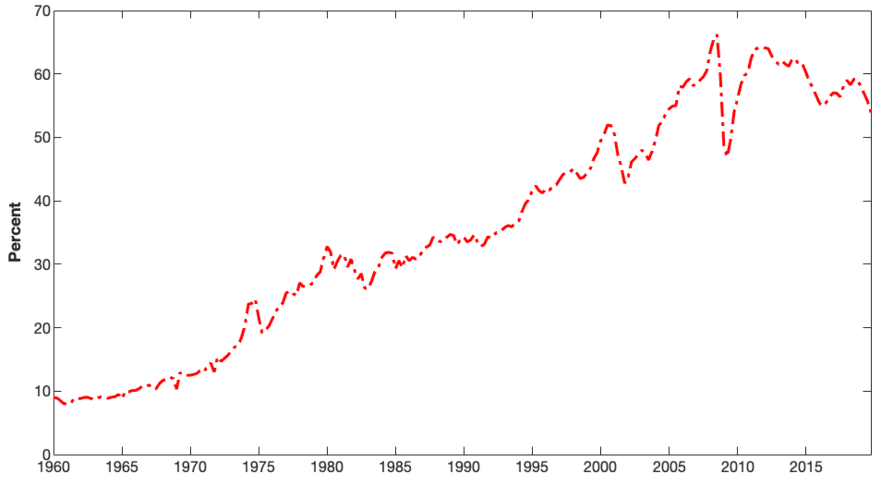


Figure B.4: Goods Imports Relative to Final Demands for Goods[2]

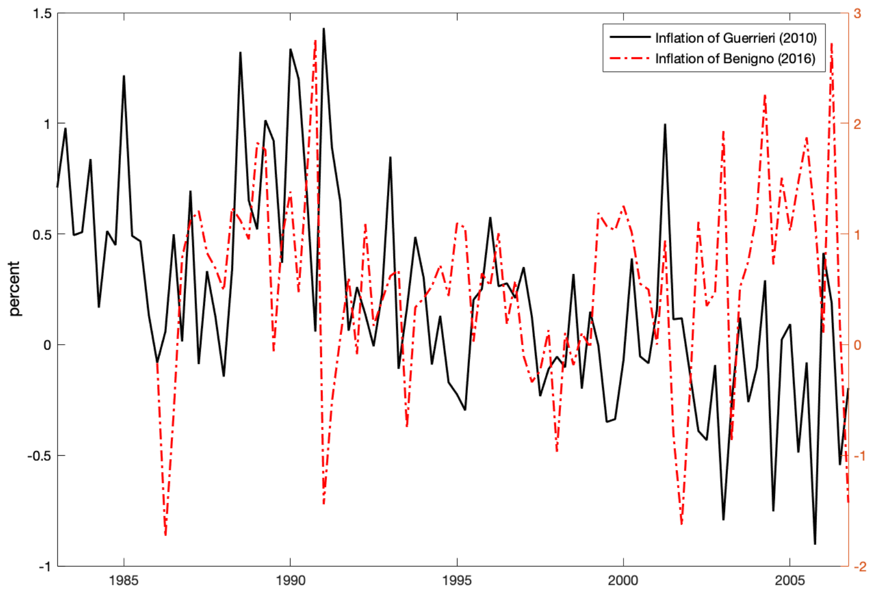


Figure B.5: Quarterly Inflation Rates[3]

[3]both series are not seasonally adjusted

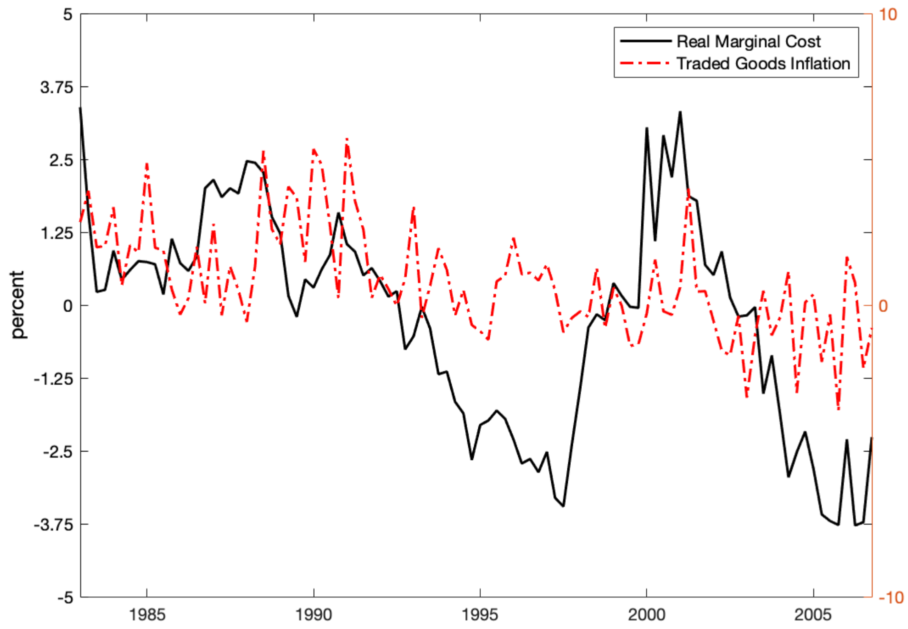


Figure B.6: The Real Marginal Cost and Inflation[4]

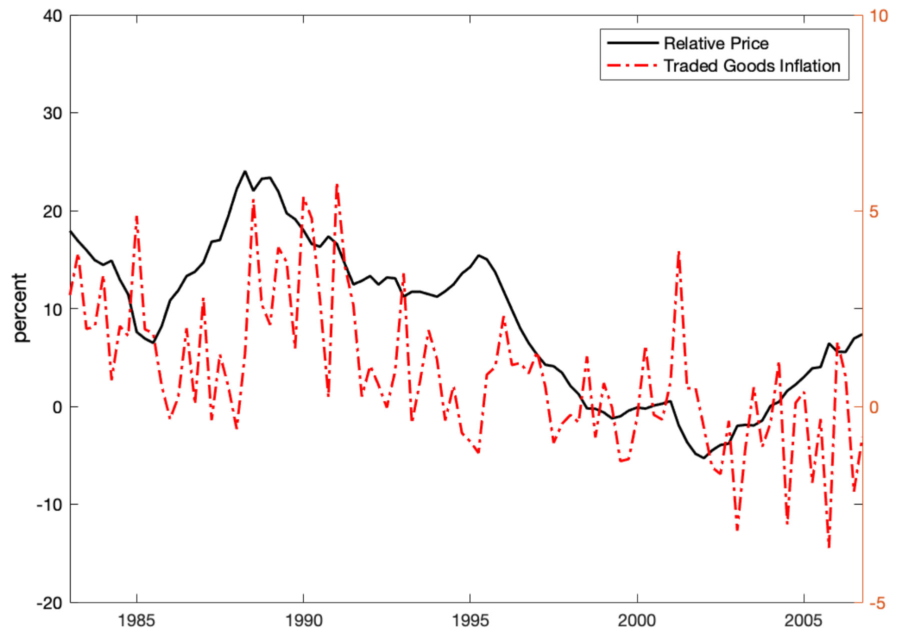


Figure B.7: Relative Price and Inflation[4]

[4]inflation are seasonally adjusted

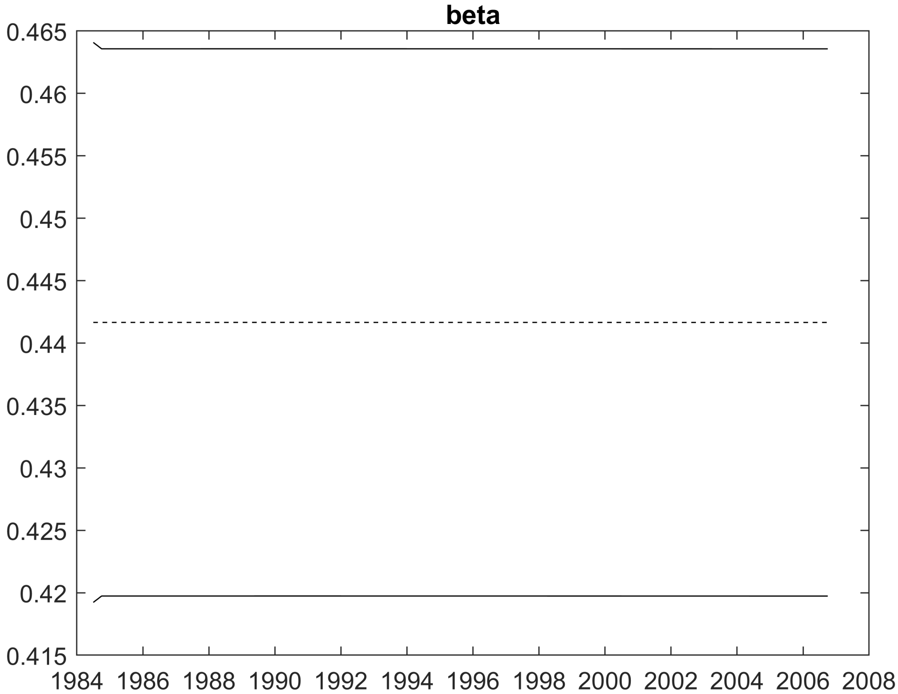


Figure B.8: Inflation's response to expected future inflation and 95% confidence bands

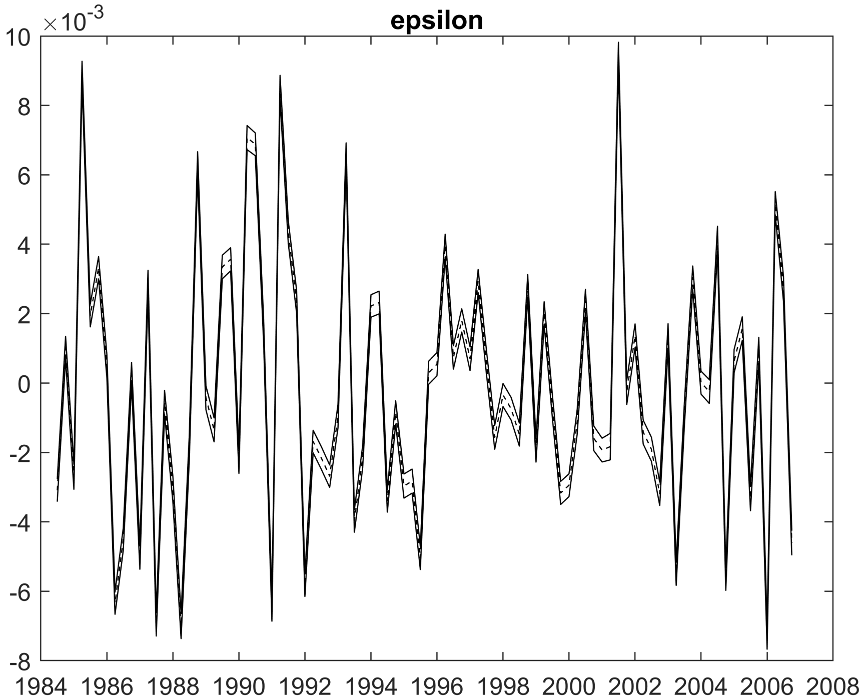


Figure B.9: Exogenous inflation shock and 95% confidence bands

Table B.1: Estimation of the hyperparameters

Step 1 Parameters	Estimates	Step 2 Parameters	Estimates
$\Sigma_{\mu,1}^{\frac{1}{2}}$	0.0000	σ_η	0.0044
$\Sigma_{\mu,2}^{\frac{1}{2}}$	0.0356	σ_ξ	0.0000
$\Sigma_{\mu,3}^{\frac{1}{2}}$	0.0002	σ_ζ	0.0002
$\Sigma_{\mu,4}^{\frac{1}{2}}$	0.0144	σ_e	0.0038
$\Sigma_{\mu,5}^{\frac{1}{2}}$	0.0000	ρ	-0.4410
$\Sigma_{\mu,6}^{\frac{1}{2}}$	0.0000	$\log L$	97.0601
$\Sigma_{\mu,7}^{\frac{1}{2}}$	0.0002		
$\Sigma_{\mu,8}^{\frac{1}{2}}$	0.0256		
σ_v	0.0038		
$\log L$	-367.4465		

Table B.2: MLE

Hyperparameters	GS	MS	PS	Surr	Part	Ga	CS
$\Sigma_{\mu,1}^{\frac{1}{2}}$	0.0000	0.0000	0.0000	0.0018	0.0000	0.0000	0.0000
$\Sigma_{\mu,2}^{\frac{1}{2}}$	0.0356	0.0344	0.0359	0.0702	0.0359	0.0369	0.0359
$\Sigma_{\mu,3}^{\frac{1}{2}}$	0.0002	0.0013	0.0000	0.0002	0.0000	0.0000	0.0000
$\Sigma_{\mu,4}^{\frac{1}{2}}$	0.0144	0.0157	0.0154	0.0004	0.0154	0.0076	0.0155
$\Sigma_{\mu,5}^{\frac{1}{2}}$	0.0000	0.0000	0.0000	0.0095	0.0000	0.0000	0.0000
$\Sigma_{\mu,6}^{\frac{1}{2}}$	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
$\Sigma_{\mu,7}^{\frac{1}{2}}$	0.0002	0.0001	0.0000	0.0015	0.0000	0.0000	0.0000
$\Sigma_{\mu,8}^{\frac{1}{2}}$	0.0256	0.0247	0.0254	0.0000	0.0254	0.0109	0.0254
σ_v	0.0038	0.0038	0.0038	0.0039	0.0038	0.0040	0.0040
$\log L$(Step 1)	-367.4465	-367.4471	-367.4462	-367.7984	-367.4462	-367.5630	-367.4462
σ_η	0.0044	0.0040	0.0044	0.0003	0.0044	0.0035	0.0044
σ_ξ	0.0000	0.0000	0.0000	0.0001	0.0000	0.0000	0.0000
σ_ζ	0.0002	0.0000	0.0000	0.0002	0.0000	0.0000	0.0000
σ_e	0.0038	0.0036	0.0038	0.0039	0.0038	0.0039	0.0038
ρ	-0.4410	-0.4371	-0.4403	-0.3272	-0.4403	-0.3787	-0.4402
$\log L$(Step 2)	97.0601	96.9804	97.0476	95.8618	97.0475	95.9023	97.0455

Table B.3: Estimation of the hyperparameters under time-varying volatility

Step 1 Parameters	Estimates	Step 2 Parameters	Estimates
$\Sigma_{\mu,1}$	0.0003	σ_η	0.0006
$\Sigma_{\mu,2}$	0.0427	σ_ξ	0.0000
$\Sigma_{\mu,3}$	0.0025	σ_ζ	0.0001
$\Sigma_{\mu,4}$	0.0134	ρ	-0.3685
$\Sigma_{\mu,5}$	0.0002	α_0	0.0000
$\Sigma_{\mu,6}$	0.0002	α_1	0.0000
$\Sigma_{\mu,7}$	0.0002	α_2	0.0000
$\Sigma_{\mu,8}$	0.0167	$\log L$	90.8850
a_0	0.0000		
a_1	0.0000		
a_2	0.0000		
$\log L$	-372.1540		

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