New Dynamics of Consumption and Output[*]

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Abstract Since the mid-1980's, the volatility of major macro variables has decreased significantly, known as the Great Moderation. Even though a great deal of literature addressed the sources of the Great Moderation, its effects or changes in dynamics of macro variables have not been investigated rigorously. We report two empirical findings in this paper: i) a faster adjustment of consumption to new permanent income (as approximated by the random walk component of real output) in response to the shock to permanent income and ii) a faster adjustment of real output to its long-run random walk component since the mid-1980s. We interpret that the reduction in the persistence of transitory consumption appears to be responsible for the former and a faster technology diffusion process that results from improved information technology may be responsible for the latter. Our results suggest that with the onset of the Great Moderation, permanent shocks have become relatively more important than transitory shocks in the U.S. business cycle dynamics and policies that affect transitory consumption have become less effective.

Key Words Great Moderation, Dynamics of Consumption and Output, Persistence, Adjustment, Unobserved Component Model, Technology Diffusion

JEL Classification E21, E32, C32

1. Introduction

Since the mid-1980s, U.S. economy has been stabilized remarkably. McConnell and Perez-Quiros (2000) and Kim and Nelson (1999) showed that a structural break in U.S. output volatility occurred in the first quarter of 1984. This phenomenon was labeled as the Great Moderation and many previous studies have tried to explain the source of this moderation, including Clarida et al. (2000), Kahn, McConnell, and Perez-Quiros (2002), Stock and Watson (2002), Bernake (2004), Summers (2005), Dynan, Elmendorf, and Sichel (2006), Giannone, Lenza and Reichlin (2008), and Gali and Gambetti (2009). From these studies, several explanations for the source of the Great Moderation have been suggested: structural changes, better monetary policy, milder economic shocks (i.e., good luck), improved inventory management, and financial innovation.

Even though a great deal of literature addressed the sources of the Great Moderation, its effects or changes in dynamics of macro variables have not been investigated rigorously. However, as Kim et al. (2004) found that structural breaks in volatility and the persistence of inflation occurred simultaneously with output volatility changes, there may have been structural changes in the persistence (dynamics) of macro variables such as output and consumption as well as volatility. Campbell and Deaton (1989) argued that although the permanent income hypothesis (PIH) predicts the adjustment of consumption to permanent income, this adjustment is slower than predicted due to precautionary motives (i.e. excess smoothness of consumption). That is, consumers facing future income uncertainty will set part of their income aside as a buffer against income fluctuations. Thus it would be natural to expect a reduction in income volatility to encourage consumers to adjust their consumption so that it is in line with their permanent income more quickly.

Why is the change in the dynamics and volatility in consumption and output worth investigating? Morley (2007) argued that a slow adjustment of consumption to permanent income suggests habit formation in consumer preferences or the presence of a precautionary

savings motive. Habit formation in consumer preferences can help explain puzzling economic phenomena, including the asset-pricing anomalies and the gradual response of consumption and inflation to monetary policy. From this point of view, a change in the consumption persistence may indicate a change in habit formation and this may affect the response of consumption to monetary policy. Hence, tracking the changes in the dynamics of consumption and output during Great Moderation would be valuable for a more effective evaluation of monetary policy performance.

The purpose of this paper is to examine whether the dynamics of U.S. consumption and output has changed over the last three decades due to Great Moderation. To this end, we focus on the change in the dynamics of consumption and output. We extend the unobserved component (UC) model of Morley (2007) by incorporating a structural break around the mid-1980s for the covariance structure and an unknown break in the long-run growth into the UC model in order to investigate the long-run dynamics in U.S. consumption and output from 1954 to 2016.

We find that, since 1984, there has been reduction in the persistence of transitory consumption, resulting in the faster adjustment of consumption to new permanent income. We also find that since 1984, there has been a decrease in the persistence of transitory income and a faster adjustment of real output to its long-run random-walk component. Thus, we confirm that since 1984, the dynamics of consumption and output has changed.

We consider the implications and the interpretation of the change in dynamics of consumption and output in terms of consumption habit and the technology diffusion of production. We interpret that since the mid-1980s the weaker habit of consumption contributed to the reduction in the persistence of the transitory consumption and thus to the faster adjustment of consumption to new permanent income, while the faster technology diffusion process due to improved information technology resulted in the faster adjustment of real output to its long-run random walk component since the Great Moderation. The policy implication of our result is that the policy that intends to affect permanent income (for example, a permanent

tax cut) may have longer and deeper impact on consumption than the policy to take an effect to transitory income.

The structure of this paper is as follows. In Section 2 we model the dynamics of consumption and output based on a UC model and propose a bivariate model where consumption and output are considered in a unified framework. The estimation results are presented in Section 3 and the implications and interpretations of changes in the dynamics of consumption and output are suggested in Section 4. A summary and concluding remarks are provided in Section 5.

2. Model

Following Carroll (2009), suppose log consumption can be represented as follows:

$$\underline{Consumption\ dynamics}:$$

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\begin{aligned}
c_t &= x_t + z_{ct}, & (1) \\
x_t &= \mu + x_{t-1} + v_t & (2) \\
z_{ct} &= \psi_c(L)e_{ct}, & (3)
\end{aligned}
$$

where, c_t denotes the logarithm of consumption, x_t is the stochastic trend component of consumption, which can be interpreted as the permanent income and z_{ct} is the transitory component of consumption that is assumed to be stationary with $\psi_c(L) = 1 + \psi_{c,1}L + \psi_{c,2}L^2 + ...$

Similarly we specify output dynamics as follows:

$$\underline{Output\ dynamics}:$$

$$y_t = x_{yt} + z_{yt} \tag{4}$$

$$x_{yt} = \mu_y + x_{yt-1} + v_{yt} \tag{5}$$

$$z_{yt} = \psi_y(L)e_{yt}, \tag{6}$$

where x_{yt} is the stochastic trend component of output and z_{yt} is the cyclical component of output which is stationary with $\psi_y(L) = 1 + \psi_{y,1}L + \psi_{y,2}L^2 + \dots$.

Following Stock and Watson (1988) and Morley (2007), we assume that consumption and output are cointegrated and share a common stochastic trend. Carroll (2009) proved that the marginal propensity to consume out of permanent income must be 1 in the long run, even though in the short run it may be less than 1 in the presence of precautionary saving motive. Thus, we alternatively can specify x_{yt} as:

$$x_{yt} = x_t, \tag{7}$$

where x_t is specified in equation (2).

We assume that the cyclical components of consumption and output can be approximated by AR(2) process. Then the model that consists of equations (1) - (6), form a bivariate model considered by Morley (2007). Furthermore, in order to consider the possibility of a structural break since the mid-1980s, we incorporate a dummy variable in the parameters of the model considered by Morley (2007) as given below:

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$$c_t = a_{S_t} + x_t + z_{ct}, \tag{8}$$

$$y_t = x_t + z_{yt}, \tag{9}$$

$$x_t = \mu_{S_t} + x_{t-1} + v_t, \tag{10}$$

$$z_{ct} = \phi_{c1,D_t} z_{ct-1} + \phi_{c2,D_t} z_{ct-2} + e_{ct}, \tag{11}$$

$$z_{yt} = \phi_{y1,D_t} z_{yt-1} + \phi_{y2,D_t} z_{yt-2} + e_{yt}, \tag{12}$$

$$\begin{bmatrix} v_t \\ e_{ct} \\ e_{yt} \end{bmatrix} \sim iid\ N\left(\begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix}, Q_{D_t} \right), \tag{13}$$

$$Q_{D_t} = \begin{bmatrix} \sigma_{v,i}^2 & \rho_{vc,i}\sigma_{v,i}\sigma_{c,i} & \rho_{vy,i}\sigma_{v,i}\sigma_{y,i} \\ \rho_{vc,i}\sigma_{v,i}\sigma_{c,i} & \sigma_{c,i}^2 & \rho_{cy,i}\sigma_{c,i}\sigma_{y,i} \\ \rho_{vy,i}\sigma_{v,i}\sigma_{y,i} & \rho_{cy,i}\sigma_{c,i}\sigma_{y,i} & \sigma_{y,i}^2 \end{bmatrix}, i = 0,\ 1 \tag{14}$$

$$D_t = \begin{cases} 0 & \text{for } t \leq 1983Q4 \\ 1 & \text{otherwise}, \end{cases}$$

$$\begin{bmatrix} a_{S_t} \\ \mu_{S_t} \end{bmatrix} = \begin{bmatrix} a_0 \\ \mu_0 \end{bmatrix} + \begin{bmatrix} \Delta a \\ \Delta \mu \end{bmatrix} S_t, \tag{15}$$

$$p = \Pr[S_t = 1 | S_{t-1} = 1]; q = \Pr[S_t = 0 | S_{t-1} = 0],$$

where D_t denotes a dummy variable, and S_t is the state variable.[1] The dummy variable is considered according to Kim (1999), and since there are researches to indicate the change of consumption growth in the 1990s, we also incorporate a regime switching in the model.

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[1] The state-space model for the equations (8) - (13) is outlined in Appendix C.

3. Estimation Results

3.1 Data

Following Morley (2007), we construct real consumption and real output quarterly data from 1954:Q1 to 2016:Q2. For real output data we use 100 times the natural logarithm of U.S. per capita real GDP. The per capita real GDP and per capita real consumption are downloaded from the FRED website [2]. The sample is divided into two subsamples based on the starting point of the Great Moderation: 1954:Q1 - 1983:Q4 and 1984:Q1 - 2016:Q2.

For the consumption data, we use 100 times the natural logarithm of U.S. per capita real consumption of non-durables and services. By dividing the nominal per capita consumption of non-durables with the chain-type price index, we obtain the per capita real consumption of non-durables. We construct the per capita real consumption of services exactly the same way. One aspect of the consumption data to be noted is, as pointed out in Whelan (2002), chain-type real data lack additivity. Following Whelan (2002)'s methodology, we construct the consumption of non-durables and services. Details of the construction of consumption data are provided in Appendix A.

3.2 A Faster Adjustment of Consumption to Permanent Income

The estimation results for the UC model with a structural break is shown in Table 1. According to the model, there are two structural breaks, one known structural break in the covariance matrix of the shocks, and one unknown structural break in the growth rate and cointegrating vector between the consumption and output. The estimated parameters with their standard errors for the first subsample is shown in the first column and those for the second subsample (Great Moderation period) in the second column.

The estimated persistence parameters for transitory consumption are 0.872 for $\hat{\phi}_{c1,0}$ and 0.058 for $\hat{\phi}_{c2,0}$ for the period of 1953:Q1 - 1983:Q4 and 0.841 for $\hat{\phi}_{c1,1}$ and -0.036 for $\hat{\phi}_{c2,1}$

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for the period of 1984:Q1-2016:Q2. This result indicates that the persistence of transitory consumption has decreased since 1984. In order to examine whether the persistence of transitory consumption has changed or not, we conduct the Wald test on the null hypothesis that $\phi_{c1,0} + \phi_{c2,0} = \phi_{c1,1} + \phi_{c2,1}$ and the test results are shown in Table 2. The null hypothesis that the persistence of transitory consumption has not changed is strongly rejected. $(p - value = 0)$.

In addition, the estimated standard deviation of the shock to transitory consumption, $\widehat{\sigma}_c$, is 1.385 for the period of 1953:Q1 - 1983:Q4 and 0.76 for the period of 1984:Q1 - 2016:Q2. The estimated correlation between the shock to permanent income and the shock to transitory consumption, $\widehat{\rho}_{vc}$, is -0.995 for the period of 1953:Q1 - 1983:Q4 and -0.98 for the period of 1984:Q1 - 2016:Q2. In order to investigate whether the magnitude of the correlation changed significantly, we conduct the Wald test and the null hypothesis, $\rho_{vc,0} = \rho_{vc,1}$, is not rejected at the conventional level.

How can the structural changes in consumption dynamics be measured? Carroll (2009) reported that optimizing consumers slowly adjust their consumption in response to changes in permanent income due to precautionary saving and this results in a negative correlation between the shocks to permanent income and transitory consumption. In other words, from the equations (1) - (3), v_t is negatively correlated with e_{ct}. As a result, we can look further into the future consumption in response to a permanent income shock. Consider the j-period ahead consumption response to permanent income shock:

$$\frac{\partial c_{t+j}}{\partial v_t} = 1 + \psi_{cj} \rho_{vc} \frac{\sigma_c}{\sigma_v}, \ j = 0, 1, 2, \ldots \tag{16}$$

where $\psi_{cj} = \frac{\partial z_{ct+j}}{\partial e_{ct}}$, $\psi_{c0} = 1$ and ρ_{vc} is the correlation between v_t and e_{ct} : $Corr\left(v_t, e_{ct}\right) = \rho_{vc}$.[3]

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[3] $\frac{\partial c_{t+j}}{\partial v_t} = \frac{\partial x_{t+j}}{\partial v_t} + \frac{\partial z_{t+j}}{\partial v_t} = \frac{\partial x_{t+j}}{\partial v_t} + \frac{\partial z_{t+j}}{\partial e_{ct}} \frac{\partial e_{ct}}{\partial v_t} = 1 + \psi_{cj} \rho_{vc} \frac{\sigma_c}{\sigma_v}$. For the specific derivation of $\frac{\partial e_{ct}}{\partial v_t}$ and for a simulation of the consumption adjustment path, refer to Appendix C.

Given the estimate results, in order to investigate the speed of adjustment of consumption to the new long-run level of output in response to a shock to permanent income, we simulate the adjustment path of consumption when there is one-unit shock to the common stochastic trend. Figure 1a displays the simulation results for the consumption adjustment. Given the estimated parameters, we plot the adjustment path with equation (16) along with the one-standard deviation confidence band (1-SD band hereafter) using the Delta method. As illustrated in [Figure 1A], consumption adjusts to the new level of permanent income faster for the period 1984:Q1 - 2016:Q2 than for the period of 1953:Q1-1983:Q4. We measure the speed of adjustment for consumption in terms of the half-life of consumption to fully adjust to the new permanent income level; that is, the time taken for the half-adjustment of consumption to a shock of one unit to permanent income. The one-SD band for the half-life of consumption adjustment is 8-10 quarters in the years before 1984, but it becomes 3-4 quarters in the period since 1984.

3.3 A Faster Adjustment of Output to Its Long-run Random-walk Component Since the Mid-1980s

The estimated standard deviation of the shock to the permanent component of output is 1.866 for the period of 1953:Q1 - 1983:Q4 and 1.01 for the period of 1984:Q1 - 2016:Q2, implying that the variance in long-run output fluctuation has reduced to 1/3 of previous level. The estimated standard deviation of the shock to the transitory component of output has reduced from 1.42 to 0.627. These results confirm the earlier findings of Kim and Nelson (1999) and McConnell and Quiros (2000) that the U.S. output volatility reduced significantly since 1984.

The estimated correlation between the shock to permanent income and the shock to transitory income is -0.876 for the period of 1953:Q1-1983:Q4 and -0.929 for the period of 1984:Q1-2016:Q2 and both correlations are statistically significant at the 1% level. In order to investigate whether the magnitude of the correlation changed significantly, we conduct

the Wald test and the test results are summarized in the Table 2; the null hypothesis that $\rho_{vy,0} = \rho_{vy,1}$ is not rejected ($p - value = 0.376$). This result implies that a structural change in the correlation between the shock to permanent income and the shock to transitory income since 1984 is uncertain.

The estimated persistence parameters for transitory output are 0.675 for $\hat{\phi}_{y1,0}$ and 0.050 for $\hat{\phi}_{y2,0}$ for 1953:Q1-1983:Q4 and 0.696 for $\hat{\phi}_{y1,1}$ and -0.121 for $\hat{\phi}_{y2,1}$ for 1984:Q1 - 2016:Q2. The persistence of transitory output thus appears to have decreased since 1984. In order to examine whether the persistence of transitory output has changed or not since 1984, we conduct the Wald test for the null hypothesis $\phi_{y1,0} + \phi_{y2,0} = \phi_{y1,1} + \phi_{y2,1}$; the null hypothesis is rejected at the 10% level as shown in Table 2. The reduced persistence of transitory output possibly implies a "Good policy" story for the source of the Great Moderation.

As in the case of the change in the adjustment speed of consumption to new long-run level, we consider the adjustment path of output to its long-run level in response to the shock to permanent income. From the equations (4) - (6), we derive the future output path in response to a one-unit shock to permanent income (the shock to the random-walk component such as technology shock) as follows[4]:

$$\frac{\partial y_{t+j}}{\partial v_t} = 1 + \psi_{yj}\rho_{vy}\frac{\sigma_y}{\sigma_v}. \tag{17}$$

The adjustment path of output to its long-run level in equation (17) depends on mainly two parameters: the correlation between the shock to the random walk component and the shock to the transitory component ρ_{vy} and the persistence parameters of the transitory output ψ_{yj}.

In order to investigate the changes of adjustment speed of output to the long-run level of output given the estimated results for output, we simulate the adjustment path of output when there is a one-unit shock to the common stochastic trend. Figure 1B shows the simulation results. Output appears to adjust to the new long-run level of output more quickly for

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[4]The derivation of equation (16) is exactly the same as the case of consumption in the previous subsection 3.2.

the period of 1984:Q1-2016:Q2 than for the period of 1953:Q1-1983:Q4. The one-SD band of the full adjustment of output to its long-run level has reduced from 10-16 quarters to 5-6 quarters.

Figure 2 shows the filtered probability and the estimated long-run growth (μ_{S_t}) of the stochastic trend component of output. Although it appears that there have been a few cases for the structural change in the stochastic trend component of output before the mid-1990s, the significant change has occurred in the late-1990s. Thus, this result indicates that our specification for the structural change in the stochastic trend component of output (and consumption) would be valid.

4. The Implications of Changes in Consumption and Output Dynamics

4.1 Precautionary Savings and Persistence in Transitory Consumption

The permanent income hypothesis (PIH) implies that a representative consumer alters his consumption according not to his current income but to his permanent income. Hall (1978) showed that a rational representative agent's consumption follows a random walk under the PIH. Cochrane (1994) reported that aggregate income is largely predictable and the PIH describes aggregate consumption behavior well. Campbell and Deaton (1989), however, pointed out that permanent income is much more volatile than consumption and that the PIH does not explain the smoothness of consumption. They argue that the slow adjustment of consumption to changes in income results in the smoothness of consumption. Morley (2007) employed a new approach to the estimation of cointegrated systems and found that permanent income appears to be relatively volatile with the slow adjustment of consumption over time and thus the standard PIH appears to be rejected. His results suggest alternative theories of consumption behavior such as habit formation or precautionary savings.

Why do consumers adjust their consumption to their income so slowly? Although there

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have been a number of studies investigating the reasons behind the non-instantaneous adjustment of consumption to permanent income, one of the most likely explanations is a precautionary saving motive. The buffer-stock saving model of Deaton (1991), Carroll, Hall, and Zeldes (1992), and Carroll (2001) considered the idea of the PIH that households attempt to maximize utility by using savings as a buffer against income fluctuations (which is the core idea of Friedman, 1957) but modifies the PIH to allow for the precautionary saving motive, impatience, and restrictions on borrowing. The buffer-stock theory postulates that an impatient consumer facing income uncertainty and liquidity constraints tends to engage in buffer-stock saving behavior where he sets up a target wealth-to-permanent-income ratio and if his actual wealth-to-permanent-income ratio is lower than the target due to a positive shock to permanent income, he would build wealth by saving; the reverse is true for negative shocks.

Carroll (2009) stated that, in theory, if consumers are impatient and subject to transitory and permanent shocks, the optimal marginal propensity to consume out of permanent shocks (MPCP) is strictly less than one, because buffer-stock savers compare the actual wealth-to-permanent income ratio to the target wealth-to-permanent-income ratio. Carroll explained that optimizing agents facing an unexpected increase in their permanent income adjust their consumption to a level lower than the change in permanent income and set aside part of the unexpected permanent income as precautionary savings in the short run. Eventually, however, consumption must fully adjust to permanent income in the long run due to budget constraints.

One of crucial aspects of precautionary savings is how they are affected by income uncertainty. Carroll (1994) found that consumers with greater income uncertainty tend to have lower current consumption. Using panel data from the National Longitudinal Survey (NLS), Kazarosian (1997) showed that income uncertainty is positively correlated with the target wealth-to-permanent-income ratio. Based on this, greater income uncertainty tends to result in a stronger precautionary motive and thus we conjecture that the significant reduction in

the volatility of U.S. income since 1984 may have resulted in a change in the precautionary motive.

According to the buffer-stock theory, when there is positive shock to permanent income, a precautionary saving consumer sets aside part of the unexpected permanent income as buffer against income fluctuation in the short run, which indicates that the marginal propensity to consume out of permanent income (MPCP) is strictly less than one:

$$\frac{\partial c_t}{\partial v_t} = 1 + \rho_{ve_c} \frac{\sigma_{e_c}}{\sigma_v} < 1, \tag{18}$$

which implies that:

$$Corr\left(v_t, e_{ct}\right) = \rho_{ve_c} < 0. \tag{19}$$

The magnitude of the negative correlation $\rho_{v_p e_c}$ approximates the percentage of increased permanent income which is set aside as precautionary saving. Moreover, since $\lim_{j \to \infty} \frac{\partial c_{t+j}}{\partial v_t} = 1$, consumption fully adjusts to permanent income in the long run.[5]

Equation (16) indicates that the consumption adjustment path for the shock to permanent income depends on two parameters: the negative correlation between the shock to permanent income and the shock to transitory consumption, ρ_{ve_c}, and the Wold representation parameters of transitory consumption, $\{\psi_{cj}\}_{j=1}^{\infty}$. The latter decides the duration of consumption adjustment in response to the change in permanent income. Equation (16) suggests two implications for the adjustment of consumption to permanent income. First of all, as transitory consumption becomes less persistent, it takes shorter for consumption to fully adjust to the change in permanent income. Secondly, the smaller the magnitude of ρ_{ve_c}, the smaller the fraction of instantaneous precautionary savings in the presence of a one-unit shock to permanent income and the shorter it takes for consumption to fully adjust to the new permanent income level. As the estimation results in subsection (3.2) indicate that there is no statistical

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[5]The stationarity of $z_{c,t}$ implies that $\lim_{j \to \infty} \psi_{c,j} = 0$.

evidence on the structural break of ρ_{vc} over two different periods but the null hypothesis that $\phi_{c1,0} + \phi_{c2,0} = \phi_{c1,1} + \phi_{c2,1}$ is rejected, we interpret that since mid-1984, the decrease in the persistence of transitory consumption has mainly contributed to the faster adjustment of consumption to new permanent income level.

4.2 Technology Diffusion and Output Dynamics

A number of studies decompose real output into a trend component and a cyclical component (stationary process) where the former is driven by technology and the later by demand shocks. Beveridge and Nelson (1981), Harvey (1985), Clark (1987), Campbell and Mankiw (1987), and Morley (2007) assumed that the trend component follows a random walk process. Lippi and Reichlin (1994), however, pointed out that imposing a random walk restriction on the trend component implies that technical innovations are adopted by different firms simultaneously, but this does not take typical property of technology diffusion into account.[6] Incorporating the fact that different firms absorb technical innovation differently, they propose a more dynamic trend that follows an ARIMA process where the trend has a serial correlation in its difference:

$$y_t = \tau_t + \tilde{z}_{yt}, \tag{20}$$

$$\tau_t = \mu + \tau_{t-1} + \psi_\tau(L)\eta_t, \tag{21}$$

$$\tilde{z}_{yt} = \tilde{\psi}_y(L)\varepsilon_{yt}, \tag{22}$$

where y_t is a real output, τ_t is the trend component of output which is driven by the technology shock η_t, z_{yt} is the cyclical component of output driven by demand shock, ε_{yt}, and ε_{yt} is

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[6] A well-known feature of technology diffusion is its S-shaped diffusion path. Schumpeter (1943) is the first to refer to S-shaped technology diffusion. Schumpeter emphasizes the importance of two features of technology: learning inside firms and diffusion across firms. Griliches (1957) studied the use of hybrid seed coin in the United States, and found that the process of adopting and distributing a particular invention in different markets has a typical S-shaped pattern because any innovation is absorbed by different firms throughout the economy.

potentially correlated with η_t. If technology diffusion is instantaneous, $\psi_\tau(L) = 1$ and there is no serial correlation in $\Delta\tau_t$; otherwise, the slower the speed of technology diffusion, the larger the serial correlation in $\Delta\tau_t$.[7] Ma and Wohar (2013) found that the serial correlation in $\Delta\tau_t$ is statistically significant, supporting the gradual technology diffusion proposed by Lippi and Reichlin (1994). Morley, Nelson and Zivot (2003) and Morley (2007) found that, with the decomposition of output into a random walk trend component and a transitory component, there is a negative correlation between the shocks to the random walk component and the shocks to transitory component. What follows explains the source of their negative correlation.

Using Beveridge Nelson decomposition, we can decompose τ_t in equation (21) into a random walk component (x_{yt}) and a stationary component $(\psi_\tau^*(L)\eta_t)$ as follows[8]:

$$\tau_t = x_{yt} - \psi_\tau^*(L)\eta_t, \tag{23}$$

$$x_{yt} = \mu_y + x_{yt-1} + \psi_\tau(1)\eta_t, \tag{24}$$

where $\psi_\tau^*(L) = \psi_{\tau 0}^* + \psi_{\tau 1}^* L + \psi_{\tau 2}^* L^2 + \cdots$, $\psi_{\tau j}^* = \sum_{i=j+1}^{\infty} \psi_{\tau i}$. Here, we specify that x_{yt} is the long-run level of output and $-\psi_\tau^*(L)\eta_t$ is the transitory component of productivity driven by the technology shock. The basis of equations (23) and (24) is that the shock to technology is decomposed into a shock to the random walk component and a shock to the transitory component and, in the case of the non-instantaneous diffusion of technology, the transitory effect of the technology shock in the permanent component τ_t would be absorbed by the cyclical component and thus both the random walk and the cyclical components contain

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[7]Except for technology diffusion, there is an another strand of papers supportive of a more dynamic permanent trend component. In their influential work, Kydland and Prescott (1982) propose the "time-to-build" effect, which features the non-instantaneous construction of new productive capital. Since the construction of new productive capital takes several periods (i.e., the short-run elasticity of capital is low), income does not immediately adjust to a change in permanent income.

[8]According to Beveridge-Nelson decomposition, if $\sum_{j=1}^{\infty} j|\psi_j| < \infty$, then $\psi(L)$ can be decomposed into a permanent and a transitory components as follows: $\psi(L) = \psi(1) - \psi^*(L)(1-L)$ where $\psi(1) = \sum_{j=0}^{\infty} \psi_j$, $\psi^*(L) = \sum_{j=0}^{\infty} \psi_j^* L^j$, and $\psi_j^* = \sum_{k=j+1}^{\infty} \psi_k$.

the technology shock. In other words, if technology is adopted by all firms instantaneously, $-\psi_\tau^* (L)$ becomes 0. On the other hand, if technology diffusion is not instantaneous, τ_t is not a random walk but follows a process which has serial correlations in difference.

Combining equations (20) and (22) with equations (23) and (24), we can rewrite y_t as the sum of a random walk plus a transitory component:

$$y_t = x_{yt} + z_{yt}, \tag{25}$$

$$x_{yt} = \mu_y + x_{yt-1} + \psi_\tau (1) \eta_t, \tag{26}$$

$$z_{yt} = \tilde{z}_{yt} - \psi_\tau^* (L) \eta_t. \tag{27}$$

By rewriting equations (25) - (27), we have the following UC model for output as in equations

(28) - (30):

$$y_t = x_{yt} + z_{yt}, \tag{28}$$

$$x_{yt} = \mu_y + x_{yt-1} + v_t^\tau, \tag{29}$$

$$z_{yt} = \psi_y (L) e_{yt}, \tag{30}$$

where $v_t^\tau \equiv \psi_\tau (1) \eta_t$, $\psi_y (L) e_{yt} \equiv \tilde{\psi}_y (L) \varepsilon_{yt} - \psi_\tau^* (L) \eta_t$, and the joint distribution of the shock to technology and the shock to the transitory component follows normal distribution:
$$\begin{bmatrix} v_t^\tau \\ e_{yt} \end{bmatrix} \sim N \left(\begin{bmatrix} 0 \\ 0 \end{bmatrix}, \begin{bmatrix} \sigma_{v^\tau}^2 & \rho_{v^\tau e_y} \sigma_{v^\tau} \sigma_{e_y} \\ \rho_{v^\tau e_y} \sigma_{v^\tau} \sigma_{e_y} & \sigma_{e_y}^2 \end{bmatrix} \right)$$ where $\rho_{v^\tau e_y}$ denotes the correlation
between the shock to the trend component and the shock to transitory component of output. Suppose that technology diffusion is instantaneous, i.e. $\psi_\tau (1) = 1$, then $\psi_\tau^* (L) = 0$. Otherwise, when technology diffusion is not instantaneous, the shock to the random walk component decreases while that to the transitory component increases, resulting in a negative correlation between these two shocks. In other words, $\rho_{v^\tau e_y} < 0$ due to $\psi_\tau^* (L) \eta_t$ in

equation (26). Stock and Watson (1988) explained that real shocks such as technology shocks immediately shift the long-run path of output upward, leaving actual productivity below the long-run path of productivity. Thus, when we decompose the real output into a random walk component and a transitory component, the transitory component consists of the original business cycle and the temporal productivity adjustment toward the long-run level and this transitory adjustment would be the source of the negative correlation between the random walk and the transitory component of real GDP[9]. Morley et al (2003) show that the estimated correlation in a univariate UC model framework is around -0.9.

Given similar estimations for the correlations $\rho_{vy,0}$ and $\rho_{vy,1}$, equation (17) indicates that if output adjusted to the new long-run level of output more quickly after 1984, the main reason appears to be the reduction in the persistence of transitory output as in the case of the change in the adjustment speed of consumption to new long-run level in response to the shock to permanent income. As discussed earlier, we conjecture that the faster technology diffusion process due to an improvement in information technology industry induced a decrease in the persistence of output cycle since the mid-1980s and thus resulted in the faster adjustment of output to new permanent income level.

4.3 Policy Implication

Alessie and Lusardi (1997) showed that the closed form solution for consumption under the assumption of the habit formation and certainty equivalence, is basically a weighted average of past consumption and permanent income. According to their result, the stronger the habit, the more weight will be put on past consumption. Furthermore, they show that the stronger the habit, the lower the effect of income uncertainty on consumption. As the persistence in the transitory consumption has reduced since the 1984, we interpret that since 1984, the habit formation of the consumption has been weaker and less persistent and thus the consumption

---

[9]Morley (2007) stated that since it takes a few quarters for the effects of the productivity to fully propagate due to time-to-build effect (Kydland and Prescott 1982), movements in the permanent and transitory components of real GDP should be negatively correlated.

has been much closer to the permanent income.

The reduction in the persistence of transitory consumption and output has an important policy implication. Our results indicate that the policy that temporarily increases income (thus consumption) results in shorter effect since 1984 than before. For example, the impact of the tax rebate in 2008 to give one-time tax rebates of $78 billion by sending individual taxpayer $600 check in the second quarter of the year would have shorter effect compared to it being legislated before the Great Moderation. Thus, our results suggest that with the onset of the Great Moderation, permanent shocks have become relatively more important than transitory shocks in the U.S. business cycle dynamics. Besides, a faster adjustment of consumption to permanent income may imply that policies that affect transitory consumption have become less effective.

5. Conclusions

Since 1984, the volatility of U.S. real GDP has decreased significantly and this phenomenon, known as the Great Moderation, has received a great deal of attention. To our knowledge, however, no previous study has tried to examine whether this reduction in volatility affected the dynamics of consumption and output during the Great Moderation period. For example, the reduction in output uncertainty tends to reduce precautionary saving and thus change consumers' behavior, while improvements in the information technology industry may quicken technology diffusion and decrease the persistence of the transitory component of output.

This paper examines whether there has been a structural change in the dynamics of consumption and output over the periods 1953:Q1 - 2016:Q2. In our empirical study, we extend a bivariate UC model of Morley (2007) by incorporating a structural break in the mid-1980s for the covariance structure and an unknown structural break in the consumption growth into the UC model. We report two empirical findings in this paper. First of all, there

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has been a faster adjustment of consumption to new permanent income level (as approximated by the random-walk component of real output) since the mid-1980s. The main reason for the faster adjustment of consumption appears to be the reduction in the persistence in the transitory consumption since the mid-1980s. Secondly, there has been a faster adjustment of real output to its long-run random-walk component since the Great Moderation. As in the case consumption, the main reason for the faster adjustment of output is the reduction in the persistence in transitory output.

We look at the cause and the implication of the faster adjustments of consumption and output in terms of the permanent income hypothesis, the buffer-stock theory of consumption, the consumption habit, and the technology diffusion theory of production. We interpret that the weaker habit of the consumption has resulted in the reduction in the persistence of transitory consumption and thus closer relationship between the consumption and the permanent income since the mid-1980s. As a result, the consumption tends to have faster adjustment to new long-run income level in response to the shock to the permanent income. Furthermore, the improvement in the information technology industry induced faster technology diffusion process and better inventory management, resulting in the lower persistence of the transitory component of output. Eventually, these contributed to the faster adjustment of output to new long-run level of output over the Great Moderation period.

Our result has important policy implications. Our results suggest that with the onset of the Great Moderation, permanent shocks have become relatively more important than transitory shocks in the U.S. business cycle dynamics. Besides, a faster adjustment of consumption to permanent income may imply that policies that affect transitory consumption have become less effective. From this point of view, our results would deserve further research. Since the economy may recover the steady state equilibrium more quickly in response to the macroeconomic shock when the persistence in output and consumption is lower, we expect that the economy may return to stable equilibrium path more quickly in response to monetary policy shock in order to stabilize the economy. Thus, we conjecture that monetary

policy is more effective in the lower persistence of consumption and output. We leave this issue to future research.

Appendix A: Data construction

We follow Whelan (2002) to construct the real per capita consumption of non-durables and services as follows. Denote personal consumption expenditure per capita on nondurable goods as $N_1(t)$ and personal consumption expenditures per capita on services as $N_2(t)$ and the corresponding chain-type price index as $p_1(t)$ and $p_2(t)$. Then calculate the real per capita consumptions by dividing the nominal values with the price index:

$$q_i(t) = \frac{N_i(t)}{p_i(t)}, \quad i = 1, 2.$$

Next, use the chain-type quantity index for per capita consumption of non-durables and services which can be calculated using the following Fisher approximation:

$$
\frac{Q(t)}{Q(t-1)} = \sqrt{\frac{p_1(t)\, q_1(t) + p_2(t)\, q_2(t)}{p_1(t)\, q_1(t-1) + p_2(t)\, q_2(t-1)}}
$$
$$
\times \sqrt{\frac{p_1(t-1)\, q_1(t) + p_2(t-1)\, q_2(t)}{p_1(t-1)\, q_1(t-1) + p_2(t-1)\, q_2(t-1)}}
$$

The first term on the right side of the equation is called the Paasche index, which uses period t prices as weight and the second term is the Laspeyrex index, which uses period $t-1$ prices as weight. The gross growth rate of the real aggregate at time t is a geometric average of the Paasche and Laspeyrex index.

Appendix B: State-space model with a dummy

The state-space model is as follows:

$$
\begin{bmatrix} c_t \\ y_t \end{bmatrix} = \begin{bmatrix} 0 \\ a_{s_t} \end{bmatrix} + \begin{bmatrix} 1 & 1 & 0 & 0 & 0 \\ b & 0 & 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} x_t \\ z_{c,t} \\ z_{c,t-1} \\ z_{y,t} \\ z_{y,t-1} \end{bmatrix}
$$

$$
\tilde{Y}_t = A_{s_t} + H\beta_t
$$

$$
R = 0
$$

$$
\begin{bmatrix} x_t \\ z_{c,t} \\ z_{c,t-1} \\ z_{y,t} \\ z_{y,t-1} \end{bmatrix} = \begin{bmatrix} \mu \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} + \begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & \phi_{c1,S_t} & \phi_{c2,S_t} & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & \phi_{y1,S_t} & \phi_{y2,S_t} \\ 0 & 0 & 0 & 1 & 0 \end{bmatrix}
$$

$$
+ \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} v_t \\ e_{ct} \\ e_{yt} \end{bmatrix}
$$

$$
\beta_t = \tilde{\mu}_{S_t} + F\beta_{t-1} + IE_t
$$

$$
Cov\left[e_t\right] = Q_{S_t}
$$

where Q_{S_t} is given in (14).

Appendix C: Simulation of the adjustment path

Here, we will describe the simulation of Figure 1 based on the estimates given in Table 1. The adjustment paths of consumption and output to their long-run levels are given in (16) and (17). We rewrite the adjustment path of consumption and output to a one unit permanent shock as follows:

$$\frac{\partial c_{t+j}}{\partial v_t} = \frac{\partial x_{t+j}}{\partial v_t} + \frac{\partial z_{c,t+j}}{\partial e_{ct}} \frac{\partial e_{ct}}{\partial v_t}$$

$$\frac{\partial y_{t+j}}{\partial v_t} = \frac{\partial bx_{t+j}}{\partial v_t} + \frac{\partial z_{y,t+j}}{\partial e_{yt}} \frac{\partial e_{yt}}{\partial v_t}$$

The first two terms in the right side of equation are obvious. Since x_t follows a random walk process, $\frac{\partial x_{t+j}}{\partial v_t} = 1$. Also $\frac{\partial z_{c,t+j}}{\partial e_{ct}}$ and $\frac{\partial z_{y,t+j}}{\partial e_{yt}}$ depend on the Wold coefficients of transitory consumption and output.

In order to get $\frac{\partial e_{ct}}{\partial v_t}$ and $\frac{\partial e_{yt}}{\partial v_t}$, we use the following Cholesky decomposition.

$$\begin{bmatrix} v_t \\ e_{ct} \\ e_{yt} \end{bmatrix} \sim i.i.d.N \left(\begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix}, Q \right)$$

where

$$Q = \begin{bmatrix} \sigma_v^2 & \rho_{vc}\sigma_v\sigma_c & \rho_{vy}\sigma_v\sigma_y \\ \rho_{vc}\sigma_v\sigma_c & \sigma_c^2 & \rho_{cy}\sigma_c\sigma_y \\ \rho_{vy}\sigma_v\sigma_y & \rho_{cy}\sigma_c\sigma_y & \sigma_y^2 \end{bmatrix}$$

By defining $v_t^* \equiv \frac{v_t}{\sigma_v}$, $e_{ct}^* \equiv \frac{e_{ct}}{\sigma_c}$, $e_{yt}^* \equiv \frac{e_{yt}}{\sigma_y}$, we can rewrite the original shock vector $\begin{bmatrix} v_t \\ e_{ct} \\ e_{yt} \end{bmatrix}$

as a linear combination of these standardized shocks:

$$
\begin{bmatrix} v_t \\ e_{ct} \\ e_{yt} \end{bmatrix} = \begin{bmatrix} \sigma_v & 0 & 0 \\ 0 & \sigma_c & 0 \\ 0 & 0 & \sigma_y \end{bmatrix} \begin{bmatrix} v_t^* \\ e_{ct}^* \\ e_{yt}^* \end{bmatrix}
\tag{B-1}
$$

where $\begin{bmatrix} v_t^* \\ e_{ct}^* \\ e_{yt}^* \end{bmatrix} \sim i.i.d.N \left(\begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix}, \Omega \right)$ and $\Omega = \begin{bmatrix} 1 & \rho_{vc} & \rho_{vy} \\ \rho_{vc} & 1 & \rho_{cy} \\ \rho_{vy} & \rho_{cy} & 1 \end{bmatrix}$ are the correlation matrix.

Suppose that the technology shock is the most exogenous shock and is not affected by the transitory consumption and output shocks, and suppose that the transitory output shock is the most endogenous one; we can then decompose the three shocks into a linear combination of independent shocks. According to the Cholesky decomposition, we have a unique lower triangular P such that $PP\prime = \Omega$ and

$$
\begin{aligned}
P &= \begin{bmatrix} 1 & 0 & 0 \\ \rho_{vc} & \sqrt{1 - \rho_{vc}^2} & 0 \\ \rho_{vy} & \frac{1}{\sqrt{1-\rho_{vc}^2}}\left(\rho_{cy} - \rho_{vc}\rho_{vy} \right) & \sqrt{\frac{1}{\rho_{vc}^2 - 1}\left(\rho_{cy} - \rho_{vc}\rho_{vy} \right)^2 - \rho_{vy}^2 + 1} \end{bmatrix} \\
&= \begin{bmatrix} p_{11} & 0 & 0 \\ p_{21} & p_{22} & 0 \\ p_{31} & p_{32} & p_{33} \end{bmatrix}
\end{aligned}
\tag{B-2}
$$

The standardized shock vector $\begin{bmatrix} v_t^* \\ e_{ct}^* \\ e_{yt}^* \end{bmatrix}$ can be represented as the product of p and a tri-

variate standard normal distribution:

$$
\begin{bmatrix} v_t^* \\ e_{ct}^* \\ e_{yt}^* \end{bmatrix} = \begin{bmatrix} p_{11} & 0 & 0 \\ p_{21} & p_{22} & 0 \\ p_{31} & p_{32} & p_{33} \end{bmatrix} \begin{bmatrix} \omega_{1t} \\ \omega_{2t} \\ \omega_{3t} \end{bmatrix}
$$

$$
\begin{bmatrix} \omega_{1t} \\ \omega_{2t} \\ \omega_{3t} \end{bmatrix} \sim i.i.d.N \left(\begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix}, \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \right)
$$

Thus by combining (B-1) and (B-2) we can decompose $\begin{bmatrix} v_t \\ e_{ct} \\ e_{yt} \end{bmatrix}$ into the linear combinations

of those standard normal shocks

$$
\begin{bmatrix} v_t \\ e_{ct} \\ e_{yt} \end{bmatrix} = \begin{bmatrix} \sigma_v & 0 & 0 \\ 0 & \sigma_c & 0 \\ 0 & 0 & \sigma_y \end{bmatrix} \begin{bmatrix} p_{11} & 0 & 0 \\ p_{21} & p_{22} & 0 \\ p_{31} & p_{32} & p_{33} \end{bmatrix} \begin{bmatrix} \omega_{1t} \\ \omega_{2t} \\ \omega_{3t} \end{bmatrix}
$$

$$
= \begin{bmatrix} \sigma_v p_{11} \omega_{1t} \\ \sigma_c p_{21} \omega_{1t} + \sigma_c p_{22} \omega_{2t} \\ \sigma_y p_{31} \omega_{1t} + \sigma_y p_{32} \omega_{2t} + \sigma_y p_{33} \omega_{3t} \end{bmatrix}
$$

Thus using the chain-rule and replacing p_{ij}s in (B-2) we get the following:

$$
\begin{aligned}
\frac{\partial e_{ct}}{\partial v_t} &= \frac{\partial e_{ct}}{\partial \omega_{1t}} \frac{\partial \omega_{1t}}{\partial v_t} = \frac{\sigma_c}{\sigma_v} \rho_{vc} \\
\frac{\partial e_{yt}}{\partial v_t} &= \frac{\partial e_{yt}}{\partial \omega_{1t}} \frac{\partial \omega_{1t}}{\partial v_t} = \frac{\sigma_y}{\sigma_v} \rho_{vy}
\end{aligned}
$$

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[Table 1] The Estimates of the UC model

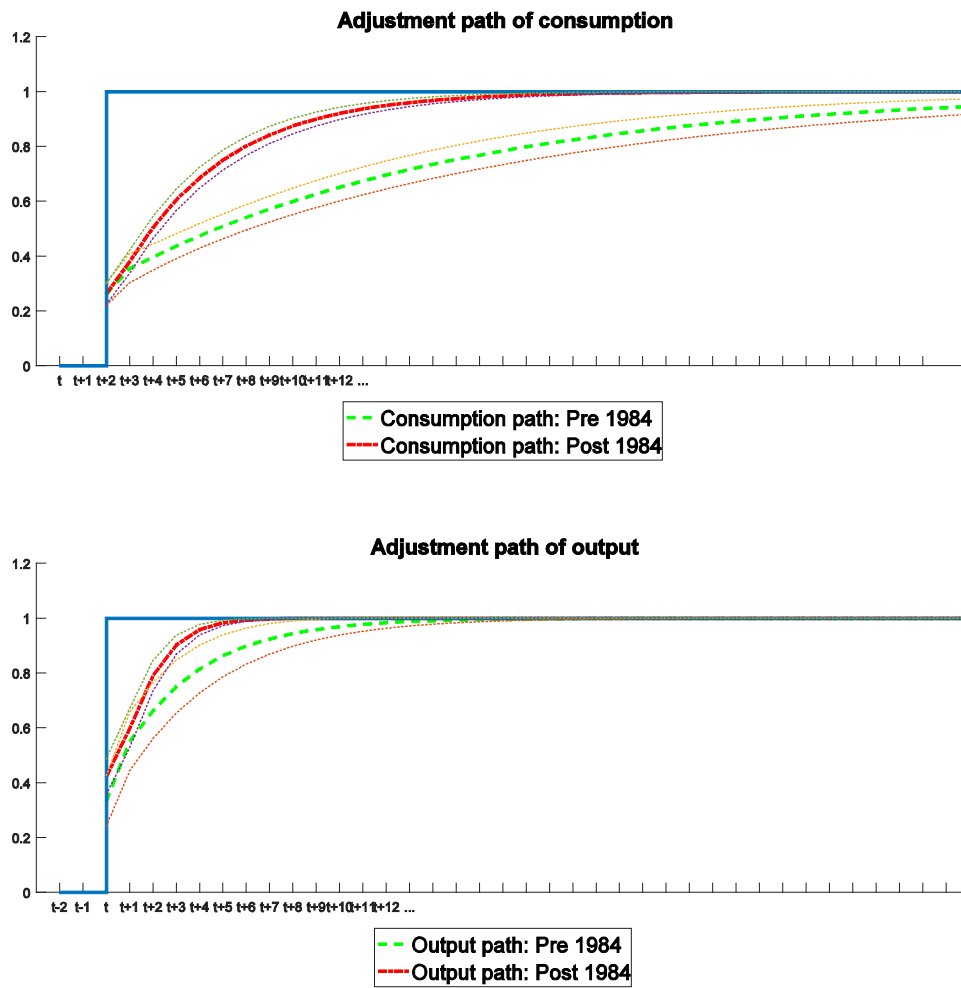| Parameters	Pre 1984		Post 1984	
ϕ_{c1}	0.8715(0.029)	***	0.841(0.041)	***
ϕ_{c2}	0.058(0.029)	*	-0.036(0.043)	
ϕ_{y1}	0.675(0.081)	***	0.696(0.070)	***
ϕ_{y2}	0.050(0.052)		-0.121(0.025)	***
σ_c	1.385(0.310)	***	0.76(0.130)	***
σ_y	1.420(0.341)	***	0.627(0.129)	***
σ_v	1.866(0.323)	***	1.010(0.136)	***
ρ_{cy}	0.826(0.078)	***	0.838(0.063)	***
ρ_{vc}	-0.995(0.006)	***	-0.981(0.010)	***
ρ_{vy}	$-0.876(0.053)$	***	-0.929(0.037)	***
μ	0.683(0.069)	***		
a	-50.57(0.259)	***		
$\Delta\mu$	-0.439(0.113)	***		
Δa	-0.405(0.306)			
Q	0.994(0.006)	***		

Note: Figures in the parentheses are standard errors and ***, **, * denote a statistical significance at the 1%, 5%, and 10% level respectively. Expected break in the long run growth rate is at 1996:Q3.

[Table 2] Wald Test

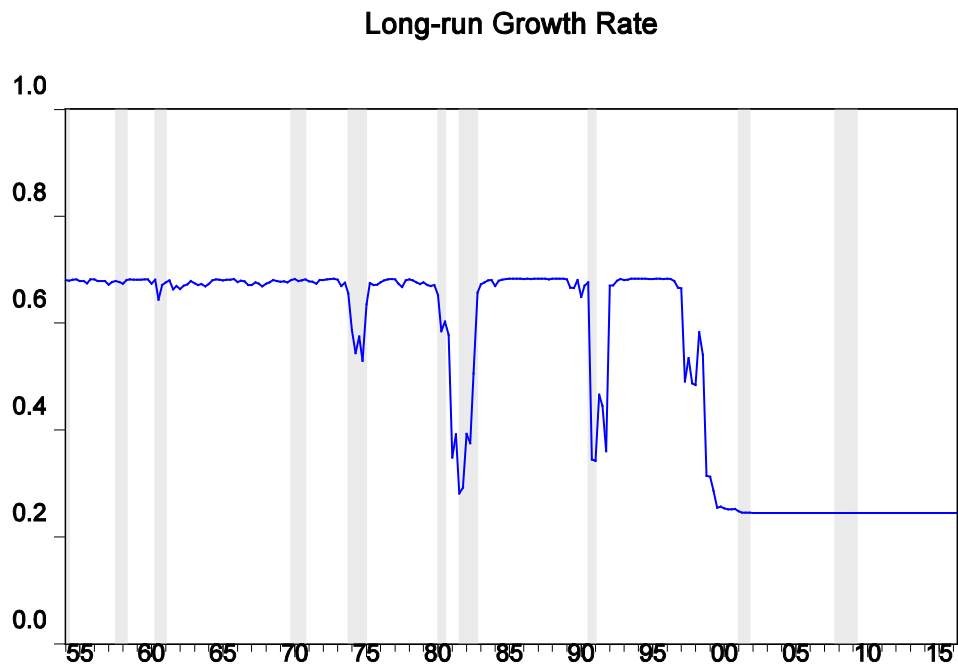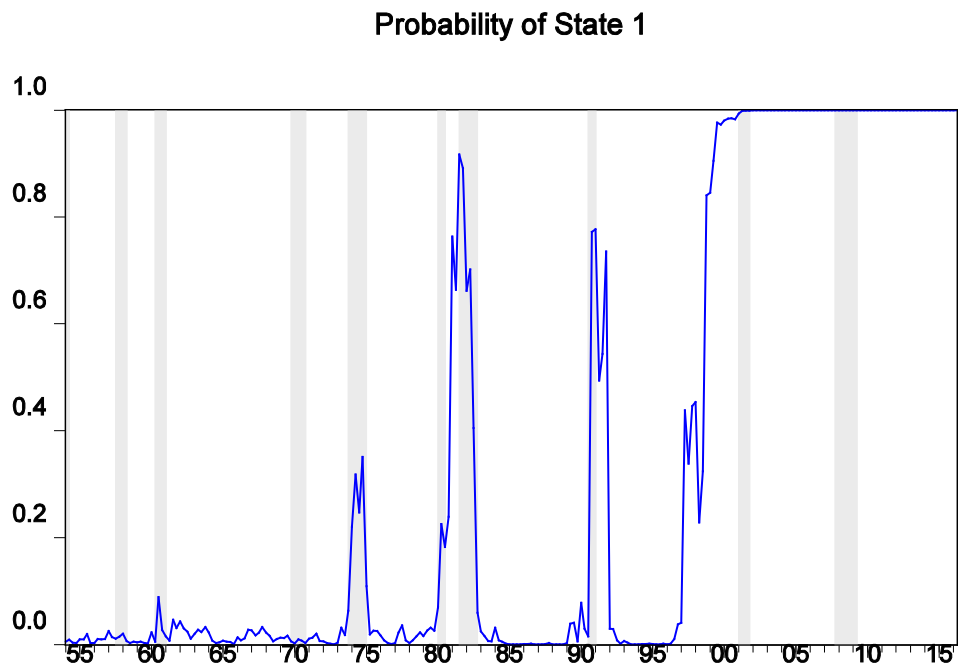| Null Hypothesis H_0	Pre 1984	Post 1984	Wald Test Statistics		P-value
$\phi_{c1,0} + \phi_{c2,0} = \phi_{c1,1} + \phi_{c2,1}$	0.93	0.805	25.73	***	0
$\phi_{y1,0} + \phi_{y2,0} = \phi_{y1,1} + \phi_{y2,1}$	0.725	0.575	3.306	*	0.069
$\sigma_{c,0} = \sigma_{c,1}$	1.385	0.76	3.868	**	0.049
$\sigma_{y,0} = \sigma_{y,1}$	1.42	0.627	4.821	**	0.028
$\sigma_{v,0} = \sigma_{v,1}$	1.866	1.009	6.615	**	0.01
$\rho_{cy,0} = \rho_{cy,1}$	0.826	0.838	0.018		0.894
$\rho_{vc,0} = \rho_{vc,1}$	-0.995	-0.98	1.456		0.228
$\rho_{vy,0} = \rho_{vy,1}$	-0.876	-0.929	0.784		0.376

Note: The subscripts "0" and "1" denote the subsample of 1954:Q1-1983:Q4 and the subsample of 1984:Q1-2016:Q2 respectively.

Figure 1. Adjustment Path of Consumption and Output

Adjustment path of consumption

Consumption path: Pre 1984
Consumption path: Post 1984

Adjustment path of output

Output path: Pre 1984
Output path: Post 1984

Figure 2 Filtered Probability and Long-run Growth

Probability of State 1

Long-run Growth Rate

The shaded area matches the NBER recession periods.