Is the Taylor Rule Still an Adequate Representation of Monetary Policy in Macroeconomic Models?

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Abstract

Probably not. A benchmark Taylor Rule remains the consensus specification of monetary policy in macro models. However, unconventional monetary policies (UMP), plus a policy rate stuck at the zero lower bound (ZLB) from 2009-2015, suggest macro models may need more than a "tune-up" of their Taylor Rules. We update the literature by testing for an expected structural break in the Taylor Rule parameters around 2008 using three macro models. Significant breaks in Taylor Rule and non-policy structural parameters alter estimated shocks, dynamics, and output gaps. Using a "shadow rate" to incorporate UMP policy and circumvent the ZLB has little effect on the results. Deducing the cause(s) of structural breaks is challenging due to the breadth and complexity of unconventional monetary policies and to changes in non-policy structure.

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1 Introduction

More than a decade after the Global Financial Crisis (GFC) and implementation of new unconventional monetary policies (UMP), John Taylor's (1993) interest rate rule remains the consensus specification of monetary policy in most small- and medium-scale macroeconomic models. Prominent examples include the benchmark New Keynesian model in "Rebuilding Macro Theory" (Vines and Wills, 2018), textbooks at all levels, and even recent innovations in macro models with monetary policy.[1] The Federal Reserve Board itself still relies on a prototypical Taylor Rule for the short-term policy rate (federal funds) in its primary macro model, FRB/US:

$$r_t = \rho r_{t-1} + (1-\rho)(r + \pi_t + \phi_\pi(\pi_t - \pi^*) + \phi_x x_t) + \epsilon_t \tag{1}$$

where r is the "natural" (equilibrium) real rate, π is inflation, π^* is target inflation, $x_t = (y - y^*)$ is the real output gap from its potential, y^* (see Brayton et al. (2014)). While particular specifications vary, most macro models still include an equation close to this one.

In this paper, we address the title by testing for structural breaks in Taylor Rule and non-policy parameters between 1984-2007 (Great Moderation, or GM) and 2008-2020 (post-GFC). Identifying UMP is challenging, as explained in Rossi's (2021) excellent survey. As a first step, we use three benchmark macro models that do *not* include UMP but do vary in size and degree of structural restrictions for robustness: 1) a simple VAR with modest restrictions; 2) the three-variable New Keynesian (NK) model of Clarida, Gali, and Gertler (1999); and 3) the DSGE model of Smets and Wouters (2007). Rossi (2021) focuses on reduced-form models like our VAR and other creative strategies for identifying monetary shocks. We add two structural models in search of more detailed identification and understanding.

Although we focus on the latest hypothesized policy break in 2008, the structural-break analysis covers the full sample from 1960-2020 for completeness. Including 1960-1983 (pre-

[1] A *short* list of innovations includes Gabaix (2020), Barnichon and Mesters (2021), Laurays et al. (2021), and Fuhrer (2017)

Great Moderation) allows for comparison and updating of the literature, starting with the finding by Bernanke and Mihov (1998) that no single policy variable (fed funds rate or nonborrowed reserves) explains monetary policy from 1965-1995 without a structural break.[2] Previous studies with single-equation and VAR models typically find evidence of structural breaks occurring around changes in the Fed's operating procedure, preferences, and other factors influencing monetary policy. Likewise, the introduction of unconventional policies suggests the occurrence of a new structural break.[3]

Unlike prior research, however, using the standard Taylor Rule policy rate (federal funds) after 2008 poses econometric difficulties that must be addressed. First, the federal funds rate was stuck at (essentially) the zero lower bound (ZLB) for nearly seven years (2009-2015), and truncation of this key endogenous variable likely biases inference for potentially all parameters in the macro models.[4] To circumvent this problem, we set the policy rate as the "shadow" federal funds rate of Wu and Xia (2016); see also Krippner (2013) and Bauer and Rudebusch (2014). Using a shadow rate also indirectly introduces elements of unconventional policies via the term structure because Forward Guidance (FG) and Quantitative Easing (QE) (or large-scale asset purchases, LSAP)—the centerpiece of Quantitative Easing (QE)—affect longer term rates. This strategy alters the nature of contemporary structural break tests relative to past research by including elements of the very object (UMP) the test seeks to identify. Consequently, our structural break test is a joint test of the Taylor Rule and the sufficiency of the shadow rate specification of unconventional policy.

Despite using a shadow fed funds rate, we find statistically and economically significant evidence of structural breaks in the parameters of the Taylor Rule and non-policy equations. The post-GFC Taylor Rule shows the Fed is *less* responsive to changes in *both* inflation and

[2] A list of papers covering structural breaks in the Taylor Rule can be found in Table 1

[3] The COVID-19 pandemic and recession precipitated additional unconventional policies, such as the central bank purchase of commercial bonds and direct loans to small business for payroll expenses, which are new and still being investigated. It's too early to properly evaluate these new policies, so we leave this to future research.

[4] Many pre-GFC papers attempted to revise traditional macro models by introducing an explict ZLB constraint on the monetary policy rate. For leading examples, see Furher and Madigan (1997) and McCallum (2000)

the output gap after 2008. Many aspect of the non-policy structure of the economy changed significantly after 2008 as well. For examples, agents became more sensitive to changes in the real interest rate and expected inflation; steady state growth and inflation fell; and the Phillips Curve flattened. Some of these structural breaks probably are related to policy changes, as in the Lucas Critique. However, other coefficient breaks likely are not directly related to monetary policy, but they should influence the setting of optimal policy as well. Perhaps surprisingly, using the effective fed funds rate gives similar results, albeit with higher persistence, ρ.

Structural breaks also are manifest in economically important changes in three key characteristics of estimated models across subsamples. Structural shocks estimated over subsamples exhibit much smaller variances (in absolute terms) than the full-sample shocks because the coefficient breaks enable better model fits in the subsamples. However, the relative variances and autoregressive properties of the structural shocks estimated over subsample also change notably. The dynamic properties (impulse responses) of the estimated models also vary across subsamples. When all parameters are allowed to change across subsamples, the dynamic effects are qualitatively similar but modestly different quantitatively. Mainly, the GM period differs while the post-GFC subsample dynamics are closer to the pre-GM sample. Counterfactual simulations that alternatively hold the Taylor Rule and non-policy coefficients fixed at their full-sample values reveal additional differences in estimated model dynamics across subsamples. Finally, subsample breaks in the DSGE model parameters dramatically affect its estimates of the model-consistent output gap. The full-sample output gap deviates substantially from the Congressional Budget Office (CBO) output gap estimate, which is taken as data by the VAR and NK models. The break-adjusted DSGE output gap closely resembles the CBO gap.

Together, the results suggest that macro models with a non-structural proxy (shadow fed funds rate) may not sufficiently capture the richness of modern UMP for two reasons. First, the absence of explicit, comprehensive structure that fully incorporates UMP may represent an omitted variables (equations) problem that leads to apparent structural breaks in estimated parameters. The remedy is to specify macro models with complete UMP built into their structure but the effort to do so largely has been piecemeal thus far. Introduction of FG after 2008 mainly has been modeled and estimated (or calibrated) as the addition of policy announcement shocks to the Taylor Rule.[5] Modeling QE has occurred mainly in theoretical models that introduce banks and their balance sheets to capture bond holdings and bank reserve management.[6] One promising paper that combines these two strands is Wu and Zhang (2019), which microfounds a central bank's bond holdings in an effort to map unconventional policies into a single "shadow" fed funds rate to be used in a standard Taylor Rule. A second concern with the estimated models considered here is the prevalence of breaks in non-policy structural parameters. Perhaps the most important is steady state output growth and other variables related to time-variation in the natural rate of interest, which is an important extension of the benchmark Taylor Rule and potentially correlated with UMP.[7] Addressing both macro modeling development opportunities is an important line of future research.

2 Previous Literature

While the structure of the Taylor Rule has stayed largely constant, changes in the Taylor Rule coefficients have been well documented in the literature using a variety of different methods. A summary of these papers, methods, and findings can be seen in table 1. Regime-switching models and break point tests, like those in Estrella and Fuhrer (2003), Duffy and Engle-Warnick (2004), and Gonzalez-Astudillo (2018), consistently to show a regime change in the the late 1970s/early 1980s and another in the mid 1980s. This follows closely with the traditional narrative that the Federal Reserve undertook a "Monetarist experiment" in early

[5]For more on forward guidance, see Del Negro, et. al (2012), Bundick and Smith (2016), Campbell et. al (2017) and McKay et. al (2016).

[6]For examples on modeling QE, see the Gerler and Karadi (2011, 2013) and Joyce et. al (2012).

[7]Leading research on time-varying equilibrium real rates includes Holston et al. (2017) and Del Negro et al. (2017)

portion of the 1980s, wherein the Fed targeted the growth of a monetary aggregate rather than an interest rate. Bunzel and Enders (2010) use a single-equation model to find that these regimes appear in the Taylor Rule as a strong output gap and inflation response regime (1970s) and a gradual adjustment of the Fed Funds rate regime (post 1980s). However, Estrella and Fuhrer (2003) note that these regime changes could be caused by changes elsewhere in the economy that these smaller, single-equation models fail to estimate.

In response, researchers have attempted to find structural breaks in larger VAR models. Bernanke and Mihov (1998) find using a factor-augmented VAR find that no simple policy variable fully captures monetary policy from 1965-1996. Instead, they find regime switches in the Fed's operating procedure in roughly 1979 and 1982, similar to the single-equation break-point models. Moreover, Primiceri (2005) and Sims and Zha (2006) use structural VARs find similar timing of regime changes, but emphasize that monetary regime changes are characterised by changes in the *variance* of Taylor Rule coefficients, as well as changes in the coefficients themselves. In essence, they find the monetary policy after the mid-1980s is best characterized by more consistent responses to output and inflation.

Alternatively, researchers have attempted to estimate changes to the Taylor Rule in the context of a full structural model. Castelnuovo (2012) estimates a real business cycle model with money, splitting the sample into 1966-1982 and 1990-2006 subsamples. Interestingly, Castelnuovo finds that the parameters in the Taylor Rule are largely unchanged across subsamples, but the fed funds rate is less responsive to money growth in the second sample. Importantly for our results, Canova (2009) estimates the NK model in Clarida, Gali, Gertler (1999) using Bayesian methods, finding the Fed responds more strongly to inflation after 1982, largely driving the Great Moderation. Moreover, Ilbas (2012) estimates pre-crisis changes in the Taylor Rule in Smets and Wouters' (2007) model. Splitting the sample into 1966-1979 and 1983-2005 subsamples, Ilbass similarly finds the Fed is more responsive to inflation after 1983. Moreover, Ilbas finds a greater degree of interest rate smoothing and lower inflation target in this Great Moderation era of policy.

We build on this literature by estimating whether there has been an additional structural break in the Taylor Rule since the 2008 Financial Crisis. Rather than attempting to find the "proper" model to test for a structural break, we estimate 3 different classifications of models: a structural VAR, a 3-equation NK model, and a full DSGE model. In each case, we a structural break in the early-1980s, similar to previous papers in the literature and seen in Table 2. Moreover, our results show the structural break in a similar fashion to previous papers based on the model used: the VAR finds an decline in the variance of the estimated parameters, the NK and DSGE models find greater responsiveness to inflation.

Table 1: Summary of structural break literature

Paper	Sample	Break(s)	Taylor Rule Implications	Nonpolicy Implications
Clarida et al. (2000)	1960-1996	1979	$\uparrow \phi_\pi, \uparrow \phi_y$	Taylor Rule induces determinacy
Smets and Wouters (2007)	1954-2007	early-1980s	$\uparrow \phi_\pi, \downarrow \phi_y$	More flexible prices
Canova (2009)	1955-2002	1982	$\uparrow \phi_\pi$	Flatter IS Curve
Ilbas (2012)	1966-2005	early-1980s	$\uparrow \phi_r, \uparrow \phi_\pi$	Lower inflation target
Bunzel and Enders (2010)	1965-2007	early-1980s	$\uparrow \phi_r, \uparrow \phi_\pi$	NA
Coibion and Gorodnichenko (2011)	1960-2002	early-1980s	$\uparrow \phi_\pi, \uparrow \phi_{\Delta y}, \downarrow \phi_y$	Lower trend inflation
Sims and Zha (2006)	1959-2003	late-1970s, mid-1980s	$\downarrow$ variance of ϕ_π, ϕ_y	NA
Primiceri (2005)	1953-2001	early-1980s	$\downarrow$ variance of $\phi_\pi, \phi_y, \uparrow \phi_\pi$	NA
Mavroeidis (2010)	1961-2006	1979	TR cannot be accurately estimated after 1979	NA
Dean and Schuh	1960-2020	1984, 2008	1984: $\uparrow \phi_\pi$, 2008: $\downarrow \phi_\pi, \phi_y$	Flatter Phillips Curve, lower trend growth

3 Models

For this paper, we use three different macro models to estimate the Taylor Rule and test for structural breaks. For robustness of results, we chose models that vary in size—small-scale (SVAR, NK) and medium-scale (DSGE)—and in degree of structural, cross-equation restrictions (VAR least, DSGE most).

3.1 Taylor Rules

The macro models contain two slightly different variants of the Taylor Rule. The SVAR and NK models include a linearize specification of the FRB/US Taylor Rule in (1):

$$r_t = \rho r_{t-1} + (1-\rho)(\phi_\pi(\pi_t - \pi^*) + \phi_x x_t)) + \epsilon_t \tag{2}$$

The DSGE model adds an additional terms, the growth rate of the output gap, as Smets and Wouters (2007):

$$r_t = \rho r_{t-1} + (1-\rho)[\phi_\pi \pi_t + \phi_y(y_t - y_t^p)] + \phi_{\Delta y}[(y_t - y_t^p) - (y_{t-1} - y_{t-1}^p)] + \epsilon_t \tag{3}$$

Estimating these different Taylor Rules in different models provides evidence on the stability of the estimated structural break in monetary policy after 2008. However, none of these benchmark Taylor Rules or macro models incorporates UMP.

Some papers (Del Negro et al., 2012; Campbell et al., 2012; Cole, 2020) have incorporated forward guidance into a modified form of the Taylor Rule using the effective fed funds rate and forward guidance shocks to the future policy rate:

$$r_t = \rho r_{t-1} + (1-\rho)(\phi_\pi(\pi_t - \pi^*) + \phi_x x_t)) + \epsilon_t^{MP} + \sum_{l=1}^{L} \epsilon_{l,t-l}^R \tag{4}$$

where $\sum_{l=1}^{L} \epsilon_{l,t-l}^R$ are forward guidance shocks to the interest rate at time l, but realized at $t-l$ and ϵ_t^{MP} are standard monetary shocks. The forward guidance shock is modeled in the literature as an announcement by the central bank at time $t-l$ that the interest rate will change in time l. In other words, these papers model forward guidance as an expected shock to the future policy rate which extends the duration at the zero-lower bound. These policy rules do not account for the quantitative easing portion of unconventional policy. Because of this, we take a different approach, using the Wu-Xia Shadow Rate in a Taylor Rule.

This approach to a FG-augmented Taylor Rule, however, is mathematically similar to the forward guidance shock incorporated into the literature on QE and shadow rates. Wu and Zhang (2019) provide a mapping of QE into a standard NK model through the shadow rate. To do this, they assume the shadow rate, s_t, follows the balance sheet according to:

$$s_t = -\zeta(b_t^{CB} - b^{CB}) + \epsilon_t \tag{5}$$

where ζ maps the shadow rate to changes in the Fed's balance sheet from steady state, b_t^{CB} is the Fed's bond holdings in time t, b^{CB} is the steady state level of bond holdings, and ϵ_t is the difference between the shadow rate and the predicted shadow rate. As shown in Figure 1, the shadow rate tracks closely to the Fed's bond holdings, with key deviations: early 2010, early 2013, and 2014. As Wu and Zhang note, these deviations coincide with the Fed's changes in its forward guidance: the deviation in 2010 coincides with the Fed signaling it would unwind its lending facilities and the decline in 2014 coincides with the Fed extending its forecasted duration of the zero-lower bound. The spike in 2013 coincides with the "taper tantrum" and is presented as a traditional monetary shock. In other words, many of these deviations of the shadow rate from the Fed's balance sheet present themselves similar to the "forward guidance shock." (5) can be adjusted to incorporate forward guidance similar to the literature by decomposing ϵ_t into its forward guidance component and its traditional shock component:

$$s_t = -\zeta(b_t^{CB} - b^{CB}) + \epsilon_t^{FG} + \epsilon_t^{MP} \tag{6}$$

where ϵ_t^{FG} is the forward guidance shock and ϵ_t is a traditional monetary shock. In (6), ϵ_t^{FG} behaves similar to the forward guidance shock in the literature, extending the expected duration of the zero-lower bound and easing financial conditions contemporaneously.

Figure 1: The Wu-Xia Shadow Rate and the Fed's bond holdings

In short, by using the shadow rate we avoid the need to include the forward guidance augmented Taylor Rule in our estimation because s_t incorporates forward guidance. Moreover, s_t also includes the effect of quantitative easing, allowing us to incorporate both aspects of unconventional monetary policy. Henceforth, we refer to the interest rate as $\hat{r}_t$ where:

$$\hat{r}_t = \min(r_t, s_t) \tag{7}$$

3.2 Structural VAR

To start, we estimate a 3 variable structural VAR wherein the economy takes the form:

$$B_0 Y_t = \sum_{i=1}^{k} B_i Y_{t-1} + u_t \tag{8}$$

where $Y_t = [x_t, \pi_t, \hat{i}_t]'$ is a 3x1 vector using the output gap, inflation, and the federal funds rate, respectively. For consistency across subsamples, we estimate each SVAR with $k = 1$

lag on the 3 endogenous variables and impose a Cholesky decomposition of the form:

$$B_0 = \begin{bmatrix} 1 & 0 & 0 \\ \kappa & 1 & 0 \\ (1-\rho)\phi_x & (1-\rho)\phi_\pi & 1 \end{bmatrix} \tag{9}$$

while the covariance matrix, $\Sigma = u_t u_t\prime$ is diagonal: Intuitively, our restrictions allow the output gap to move the slowest. Inflation responds contemporaneously to the output gap. Lastly, the Fed responds to changes in output and inflation, similar to the standard Taylor Rule in (1). This identification originated with Sims (1980) but still is central to Rossi's (2021) latest analysis.

3.3 NK Model

Next, we estimate the structural parameters of Clarida, Gali, and Gertler's (1999) NK model, consisting of an IS equation, a forward-looking Phillips Curve, and a monetary policy rule described in equation (2):

$$x_t = \psi[\hat{i_t} - E_t\pi_{t+1}] + E_t x_{t+1} + \epsilon_{x,t} \tag{10}$$

$$\pi_t = \kappa x_t + \beta E_t \pi_{t+1} + \epsilon_{\pi,t} \tag{11}$$

where x_t is the output gap, π^* is the inflation target, β is the discount factor, ψ is the coefficient of relative risk aversion, κ is the slope of the Phillips Curve, and ρ, ϕ_π, and ϕ_x are the Taylor Rule coefficients. $\epsilon_{x,t}$, $\epsilon_{\pi,t}$, and $\epsilon_{x,t}$ are persistent shocks which follow an AR(1) process:

$$\epsilon_{x,t} = \rho_x \epsilon_{x,t-1} + \eta_{x,t} \tag{12}$$

$$\epsilon_{\pi,t} = \rho_\pi \epsilon_{\pi,t-1} + \eta_{\pi,t} \tag{13}$$

$$\epsilon_{i,t} = \rho_i \epsilon_{i,t-1} + \eta_{i,t} \tag{14}$$

where $0 < \rho_{x,t}, \rho_{\pi,t}, \rho_{i,t} < 1$ capture the persistence of shocks and $\eta_{x,t}, \eta_{\pi,t}, \eta_{i,t}$ are i.i.d. with zero mean and variances of σ_x^2, σ_π^2, and σ_i^2, respectively. Similar to the SVAR above, we use the CBO's estimated output gap, core PCE inflation, and the Federal Funds Rate. Altogether, the model has 9 total parameters: 6 structural parameters (β, ψ, κ, ρ, ϕ_π, ϕ_y) and 3 auxiliary parameters (ρ_x, ρ_π, ρ_i).

3.4 DSGE Model

Lastly, we estimate the DSGE model in Smets and Wouters (2007). The full linearized model is in Smets and Wouters (2007). The portion of the DSGE model that most closes matches the NK model are a consumption Euler equation and Phillips Curve:

$$c_t = c_1 c_{t-1} + (1 - c_1) E_t c_{t+1} + c_2(l_t - E_t l_{t+1}) - c_3(r_t - E_t \pi_{t+1} + \varepsilon_t^b) \tag{15}$$

$$\pi_t = \pi_1 \pi_{t-1} + \pi_2 E_t \pi_{t+1} - \pi_3 \mu_t^p + \varepsilon_t^p \tag{16}$$

Additionally, the Fed responds to changes in the output gap, the growth in the output gap, and inflation, as in equation (3).

The DSGE model is much more comprehensive than the NK model, allowing for additional structural complexity. For example, the IS Curve in the NK model (10) is obtained by linearizing the forward-looking consumption Euler equation while the Phillips Curve is the linearization of the firm's pricing decision. Alternatively, the DSGE model incorporates backward looking elements into the consumption Euler equation and Phillips Curve. It is also consistent with a steady-state growth path, incorporating investment decisions, and the pricing and accumulation of capital into its optimization problems.

The DSGE model also allows for a greater treatment of specific shocks than the NK model. While the NK model only has 3 shocks (demand, cost-push, and monetary), the DSGE model incorporates 7 different shocks (productivity, technology, risk premium, spending, monetary, price-markup, and wage-markup). This allows the estimation of the DSGE model to be more specific on the sources of economic variation than the NK model.

4 Data and Estimation

Data for each estimation come from the St. Louis FRED and runs from 1960:1 to 2020:1 (full sample). For the VAR and NK models, we use the CBO estimated output gap, core PCE inflation, and Wu-Xia Shadow Rate. For the DSGE model, we use the same data from Smets and Wouters' original estimation, but extended to 2020 and using the Wu-Xia Shadow Rate. This shadow rate is simply the fed funds rate when the target fed funds rate is above the effective lower bound. However, the shadow rate can go below the lower bound to reflect actions taken by the Fed while the target fed funds rate is at the lower bound. Thus, as noted in Rossi (2021), the shadow rate is the short-term interest rate implied by a model of the yield curve. The advantage of using the shadow rate in our estimation is it allows for us to easily compare the stance of monetary policy across conventional and unconventional policy periods.

For both the NK and DSGE models, we utilize Bayesian estimation. The selection of priors will have a significant bearing on the estimated parameters in the Bayesian estimation. Moreover, changing priors between subsamples can potentially bias results toward a structural break when one does not truly exist. To mitigate this bias and for consistency with earlier estimations, we use the same prior distribution, mean, and standard deviation in the full sample and all subsamples. Specifically, we use the same priors as Canova's (2009) estimation of the NK model and Smets and Wouters' (2007) original estimation of the DSGE model. A summary of parameters, their role in the model, and their priors can be found in the appendix.

On each subsample, we calculate the likelihood function through the Kalman filter. We then obtain the posterior density distribution from the calculated likelihood function and prior distributions, continuing until convergence is achieved. We then use the Metropolis-

Hastings algorithm to create 2,000 draws of the posterior distribution and approximate moments of the distribution.[8]

The output gap in Smets and Wouters (2007) is generated within the model and calculated as the deviation from the level of output that would prevail with flexible wages and prices, y_t^p. This generated output gap differs substantially from both the SVAR and NK models above, which simply use the CBO estimated output gap. For subsample estimation, this means Smets and Wouters' model generates an output gap based on the data in each subsample while the VAR and NK models use an output gap estimated from the entire sample.

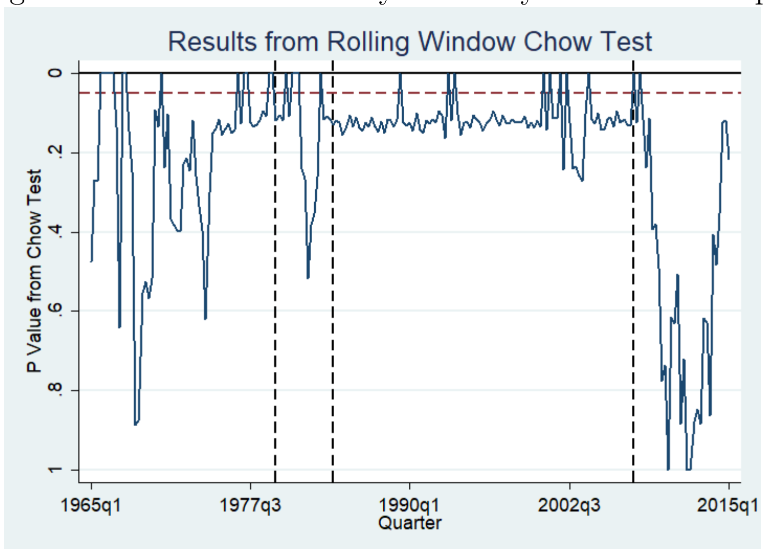
Importantly, we split the full sample into three subsamples: 1960Q1-1979Q3 (I), 1983Q1-2007Q2 (II), and 2007Q3-2019Q4 (III). For simplicity and ease, we denotes the subsamples as pre-Great Moderation, Great Moderation, and post-Financial Crisis. We use a priori reasoning when selecting these breaks. Our first subsample ends in 1979Q3 to correspond to the Fed's shift to targeting nonborrowed reserves. Similarly, our second subsample begins begins in 1983Q1, corresponding to the Fed switching its preferred instrument back to the interest rate. We omit the 1979Q4-1982Q4 period for two reasons: first, because the Fed targeted nonborrowed reserves, the Taylor Rule was dormant during this period; second, as noted in Table 1, many estimations in the literature place a structural break(s) in monetary policy between 1979-1984, but there is not broad agreement on the exact date. Finally, we begin our third subsample in 2007Q3 to correspond to the Fed's initial rate cuts, and the early events of the financial crisis, such as American Home Mortgage's bankruptcy, BNP Parabas noting a decline in liquidity, the Dow Jones Industrial Average's peak.

For robustness, we estimate a split-sample Chow test for our VAR to test for structural breaks across our sample periods. The p-value from the rolling window estimation can be seen in figure 2. The Chow test largely confirms our a priori reasoning on subsamples: there

[8] Estimations are performed using a modified version of Johannes Pfeifer's dynare code for Smets and Wouter's model. Pfeifer's code can be found at https://github.com/JohannesPfeifer/DSGE_mod/tree/master/Smets_Wouters_2007, and Dynare can be downloaded at https://dynare.org.

appears to be a structural break corresponding to the Fed's changes in operating procedure in 1979Q3 and 1983Q1, as well as one near the start of the financial crisis in 2007Q3.

Figure 2: Structural monetary shocks by model and sample



5 Structural Break Results

This section reports the results of estimating the three macroeconomic models and testing for structural breaks in model parameters. Table 2 contains coefficient estimates for the Taylor Rule, and Table 3 contains estimates for the remaining non-policy structural parameters. Both tables include columns with estimates for the full sample and each subsample (I-III), plus columns of coefficient changes between subsamples and their significance tests. Because our break-test results for subsamples I and II are generally consistent with the prior literature, as noted in Section 2, this section focuses on tests for breaks between subsamples II and III. Coefficient magnitudes may vary across models due to differences in model variables and structure, and thus should be compared mainly across subsamples within models.

5.1 Taylor Rule Coefficients

Estimates of the Taylor Rule during the Great Moderation for all three models are consistent with the prior literature, as shown in the subsample II column of Table 2. The inflation responses are notably larger than output responses ($\phi_\pi >> \phi_y$), indicating the Fed responds more to the inflation gap than the output gap (full employment) in setting interest rates. The difference in coefficients is largest in the DSGE model (1.97 versus .09). Interest rate persistence is similar across models but a bit lower in the NK model (.6 versus .8). All coefficients are statistically significant; the DSGE model also shows a significant response to output growth ($\phi_{\Delta y}$).

Table 2: Taylor Rule estimates by subsample and model

		Parameter Estimates					Changes		
	Parameter	Full	I	II	III$\hat{r}$	IIIr	I-II	II-III$\hat{r}$	II-IIIr
VAR	ϕ_π	3.55 (1.61)	1.43 (1.51)	2.67 (1.23)	-1.61 (1.77)	.24 (.89)	1.24	-4.28	-2.43
	ϕ_y	4.05 (.68)	1.26 (1.03)	3.10 (.45)	1.64 (.50)	1.37 (.06)	1.84	-1.43	-1.73
	ρ	.91 (.02)	.83 (.07)	.83 (.04)	.86 (.03)	.81 (.04)	.00	.03	-.12
NK	ϕ_π	1.37 [1.16,1.62]	1.27 [1.00,1.47]	2.41 [2.30,2.55]	1.31 [1.00,1.57]	1.24 [1.00,1.50]	1.14	-1.1	-1.17
	ϕ_y	.99 [.75,1.26]	.85 [.62,1.06]	.69 [.43,.99]	.64 [.38,.93]	.31 [.17,.44]	-.16	-.05	-.38
	ρ	.79 [.70,.88]	.63 [.50,.74]	.62 [.54,.68]	.78 [.68,.88]	.66 [.57,.76]	-.01	.16	.04
DSGE	ϕ_π	1.99 [1.57,2.41]	1.48 [1.26,1.69]	1.97 [1.58,2.36]	1.42 [1.27,1.57]	1.44 [1.23,1.47]	.49	-.55	-.53
	ϕ_y	.30 [.25,.34]	.15 [.09,.20]	.09 [.02,.17]	.21 [.14,.28]	.15 [.10,.20]	-.06	.12	.06
	ρ	.86 [.82,.89]	.80 [.74,.87]	.84 [.79,.88]	.75 [.65,.86]	.92 [.88,.96]	.04	-.09	.08
	$\phi_{\Delta y}$	.41 [.37,.44]	.17 [.13,.22]	.16 [.11,.21]	.20 [.12,.27]	.09 [.06,.13]	-.01	.04	-.07

Note: VAR estimates report the standard errors, and the NK and DSGE models report the 90% HPD confidence interval.

After the Financial Crisis, all models exhibit significant but heterogeneous structural breaks in their Taylor Rule coefficients, as shown in the columns for subsample III$\hat{r}$ (using shadow federal funds rate) and for II-III$\hat{r}$ Change in Table 2. In all three models, the Fed is less responsive to inflation (ϕ_π) but the decline is only economically large (-3.37) and significant in the VAR model. The response to output (ϕ_y) increases a modest (.12) and significant amount in the DSGE model, but declines a modest (-1.02 to $-.65$) and significant amount in the VAR and NK models. Persistence (ρ) rises (.16) significantly in the NK model but is essentially unchanged in the other models. Perhaps more importantly, ϕ_y in the NK model is no longer significantly different from zero during the post-Crisis period, suggesting that the Fed only responded to inflation. ϕ_π is no longer statistically significant in the VAR model and, importantly, now has the wrong sign (negative). In contrast, all four Taylor Rule coefficients in the DSGE model remain statistically significant after the Financial Crisis. While the decline in the response to inflation (ϕ_π) is economically large, it is not statistically significant. However, the response to output (ϕ_y) increases significantly. The combined changes in ϕ_π (decrease) and output ϕ_y (increase) in the DSGE model leads to an estimated Taylor Rule in which the Fed places relatively less (more) emphasis on responding to inflation (output) compared to the Great Moderation period. The Fed's response to output *growth* ($\phi_{\Delta y}$) remains significant and roughly the same.

Table 2 also provides estimates for two post-Financial Crisis (III) specifications: 1) using the shadow fed funds rate (III$\hat{r}$), which is the benchmark; and 2) using the traditional effective federal funds rate (IIIr), which was constrained by the zero lower bound for several years. Comparing estimates from these two specifications reveals the extent to which the shadow rate sufficiently reflects for the effects of unconventional monetary policies in the models or not.

The Taylor Rule estimates for subsample IIIr are strikingly similar to those for III$\hat{r}$ despite the effective federal funds rate being constrained by the ZLB for several years. Estimates for the VAR and NK models are very close quantitatively, so the structural break tests using IIIr are essentially the same as for III$\hat{r}$. Estimates for the DSGE model, however, capture a nuanced difference induced by the shadow rate. Interest rate persistence (ρ) is estimated to be higher with the effective federal funds rate stuck at the ZLB (.92 versus .75), naturally; likewise, the Fed's responses to output (ϕ_y) and output *growth* ($\phi_{\Delta y}$) are estimated to be a bit weaker (lower). As a result, the structural break tests are notably different with IIIr. The increase in the output response (ϕ_y) is smaller and no longer significant, while the other coefficients change significantly (but not all in the same direction).

5.2 Non-policy Coefficients

Estimates of the non-policy parameters also are generally, if roughly, consistent with the prior literature, as shown in the subsample II column of Table 3. In the NK model, the slope of the IS Curve (ψ) is negative and small in absolute value, implying a relatively high coefficient of relative risk aversion of about 50. The slope of the Phillips Curve (κ) and the expectations feedback are both positive and relatively high but significantly less than 1.0. In the DSGE model, there are many more parameters and too many to discuss individually, but these are roughly in line with Smets and Wouters (2007) and subsequent estimates of their model. Unlike the Taylor Rule parameters, it is more difficult to compare the NK and DSGE coefficients because the former is a highly restricted, non-nested, specification of the latter.

After the Financial Crisis, the NK and DSGE models exhibit significant structural breaks in their heterogeneous non-policy coefficients, as shown in the columns for subsample III and II-III Change in Table 3. In the NK model, ψ increased so the IS Curve is more sensitive (negatively related) to the real interest rate as the coefficient of relative risk aversion falls to about 9. Also, κ declined considerably, flattening the Phillips Curve as inflation remained steady throughout the period despite an improving economy. Inflation expectations (β) increased as well, moving closer to the rational benchmark of 1.0.

In the DSGE model, several coefficient changes were significant. In terms of long-run factors, steady state growth ($\overline{\gamma}$) and hours ($\bar{l}$) fell by economically significant amounts, with annual growth dropping from 1.9 to 1.4 percent. In contrast, steady state inflation ($\overline{\pi}$) essentially was unchanged. The capital share (α) also declined by almost half. The external habit (λ) increased notably (.51 to .83) and the Calvo price parameter declined a bit. The

Table 3: Structural Estimates from New Keynesian and Bayesian DSGE Model

	Parameter Output						Change	
	Parameter	Parameter Role	Full	I	II	III	I-II Change	II-III Change
VAR	κ	Phillips Curve	.01 (.03)	-.01 (.04)	-.02 (.04)	.13 (.05)	.02	.11***
NK	ψ	IS Curve	-.02 [.01,.03]	-.07 [.01,.12]	-.03 [.01,.06]	-.19 [.01,.38]	-.04	.16
	κ	Phillips Curve	.02 [.01,.03]	.02 [.01,.03]	.38 [.32,.42]	.03 [.01,.04]	.36	-.35
	β	Inflation feedback	.70 [.61,.79]	.69 [.53,.87]	.91 [.87,.95]	.82 [.61,.99]	.21	-.09
DSGE	$100(\beta^{-1}-1)$	Time Preference	.25 [.16,.34]	.18 [.07,.30]	.17 [.06,.29]	.23 [.09,.37]	-.01	.06
	$\bar{\pi}$	Steady State Inflation	.65 [.55,.73]	.70 [.51,.86]	.68 [.56,.84]	.65 [.53,.78]	-.02	-.03
	$\bar{\gamma}$	Steady State Growth	.33 [.28,.36]	.27 [.17,.38]	.48 [.42,.53]	.21 [.16,.27]	.21	-.27
	$\bar{l}$	Steady State Hours	-1.94 [-3.41,-.54]	2.72 [1.28,4.33]	.79 [-1.36,2.46]	-3.52 [-4.76,-2.38]	-1.93	-4.31
	ρ	Investment Adjustment	7.95 [6.04,9.55]	4.70 [3.11,6.19]	6.38 [4.14,8.66]	6.31 [4.28,8.13]	1.68	-.07
	σ_c	Risk Aversion	1.53 [1.22,1.83]	1.64 [1.25,1.98]	1.25 [.81,1.75]	.93 [.72,1.13]	-.39	-.32
	λ	External Habit Degree	.74 [.68,.80]	.67 [.60,.75]	.52 [.39,.67]	.82 [.76,.89]	-.15	.30
	ξ_w	Calvo: Wages	.93 [.91,.95]	.75 [.67,.83]	.69 [.52,.89]	.73 [.63,.89]	-.06	.04
	σ_l	Frisch Elasticity	2.62 [1.75,3.31]	1.97 [1.09,3.09]	2.20 [1.16,3.37]	.97 [.25,1.75]	.23	-1.23
	ξ_p	Calvo: Prices	.83 [.80,.87]	.55 [.50,.60]	.81 [.74,.88]	.71 [.60,.83]	.26	-.10
	ι_w	Wage Indexation	.72 [.62,.82]	.48 [.28,.67]	.46 [.17,.74]	.41 [.17,.65]	-.02	-.05
	ι_p	Price Indexation	.20 [.10,.32]	.37 [.16,.62]	.35 [.12,.60]	.33 [.13,.52]	-.02	-.02
	ψ	Capacity Utilization Cost	.55 [.42,.69]	.28 [.12,.42]	.68 [.46,.88]	.71 [.54,.91]	.4	.03
	Φ	Fixed Cost Share	1.69 [1.59,1.80]	1.55 [1.40,1.68]	1.53 [1.32,1.70]	1.42 [1.27,1.57]	-.02	-.13
	α	Capital Share	.22 [.20,.25]	.24 [.19,.28]	.21 [.15,.26]	.12 [.07,.16]	-.03	-.09
	r^*	Real Interest Rate	3.04 $(\cdot)$	2.50 $(\cdot)$	3.09 $(\cdot)$	1.71 $(\cdot)$	.59	-1.38

Note: VAR estimates report the standard errors, and the NK and DSGE models report the 90% HPD confidence interval.

DSGE model also estimates the natural real interest rate as a function of the the rate of time preference, β, and risk aversion, σ_c.[9] While these estimates are considerably above those traditionally estimated in the literature, they are in-line with Smets and Wouters (2007) original estimate. Nevertheless, these estimates show a similar trend to other estimates of the natural real interest rate: it has declined significantly since the financial crisis. The remaining DSGE coefficients did not change statistically significantly.

5.3 Discussion

The basic goal of this paper is to test the null hypothesis of a structural break in the Taylor Rule parameters around 2008 due to unconventional monetary policy. The evidence in this section indicates that we *cannot* reject the null hypothesis of a structural break. However, this break test cannot verify econometrically whether such policy is responsible for the break. For that, a clear alternative model that includes unconventional monetary policies is needed, which we discuss more in Section 7.2.

Nevertheless, it is helpful to summarize the results thus far and assess whether they may suggest evidence of changes in monetary policy. At least three comparisons provide useful if not identifying information:

- *Parameter types* – The results reveal structural breaks in both types, not just the Taylor Rule (policy). This finding makes it even more difficult to isolate the effects of omitted policies on the Taylor Rule. Because the policy and non-policy parameters are estimated jointly, changes in the latter can influence estimates of the former.

- *Subsamples* – Structural breaks after the Financial Crisis (II-III) are not always consistent with breaks in the Great Moderation (I-II). For some parameters, breaks are statistically significant in only one period while for others it is significant in both (or

[9] The natural real interest rate is calculated as in Smets and Wouters (2007): $\bar{r} = (\frac{\gamma^{\sigma_c}\Pi}{\beta} - 1)100$. Because of the nonlinear calculation of r^*, we are still working to get estimates for the standard error and will update the paper accordingly.

neither). Furthermore, for some parameters the structural breaks change signs, making the post-Financial Crisis coefficients look similar to those in pre-Moderation and hard to explain.

- *Models* – Structural breaks are hard to compare between the very parsimonious small models (VAR, NK) and the larger, richer DSGE model. While none of the models includes unconventional policies, the DSGE model has more variables that are likely to be influenced (directly or indirectly) by unconventional policies. Thus, it is difficult to identify whether the coefficient changes, especially non-policy, are due to omitted monetary policies or to changes in the private-sector economic structure.

Ultimately, it hard to discern from the comprehensive and heterogeneous evidence of structural breaks presented thus far whether unconventional monetary policy is responsible for the observed breaks in the Taylor Rule and model parameters.

6 Additional Regression Diagnostics

Motivated by the evidence on heterogeneity and complexity of structural breaks, this section examines the estimation results using additional regression diagnostics: 1) characteristics of the estimated structural shocks; 2) dynamic responses to the structural shocks; and 3) implications for the estimation of output gaps. Together, these measures provide further evidence of structural breaks and a fuller understanding of the economic nature of the observed changes.

6.1 Structural shocks

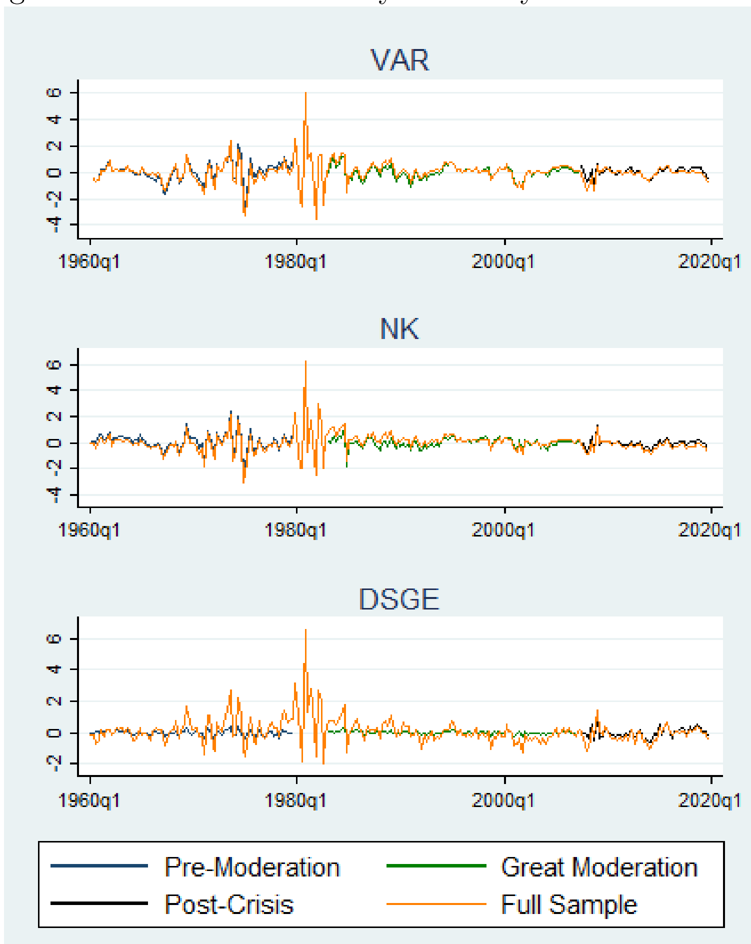
One way to summarize the comprehensive impact of the parameter structural breaks is to examine the time series characteristics of each model's estimated structural shocks. Figure 1 plots the monetary policy shocks estimated from the full sample and for each subsample.

Perhaps the most striking feature of the monetary shocks is the discrepancy between the relatively large variances of the full sample shocks compared with the less variable subsample shocks. This discrepancy is greatest in the pre-Moderation sample (I), which the literature suggests was the most volatile time for U.S. monetary policy. All three models exhibit a similarly large decline in monetary turbulence during the Great Moderation, and only a moderate increase after the Financial Crisis. The correlations of monetary shocks between models is uniformly positive for each sample period, but the magnitudes vary widely.

Large discrepancies in the variances and autoregressive properties of the full sample and subsample estimated shocks reflect economically meaningful structural breaks in models' Taylor Rule and non-policy parameters. The discrepancies are most evident in the DSGE model, which contains many more parameters and thus more opportunities to capture and interpret the breaks. Given that the magnitude of the Taylor Rule coefficient changes were modest compared to changes in the non-policy coefficients, the structural breaks in the latter appear to be at least as important as changes in the Taylor Rule.

Most other estimated structural shocks exhibit similar qualitative features and thus are presented and discussed separately in the Appendix. Discrepancies exist between the full sample and subsamples estimates in terms of volatility and persistence of the shocks. The appendix quantifies these results with figures and tables of estimated variances and autoregressive parameters.

Figure 3: Structural monetary shocks by model and sample

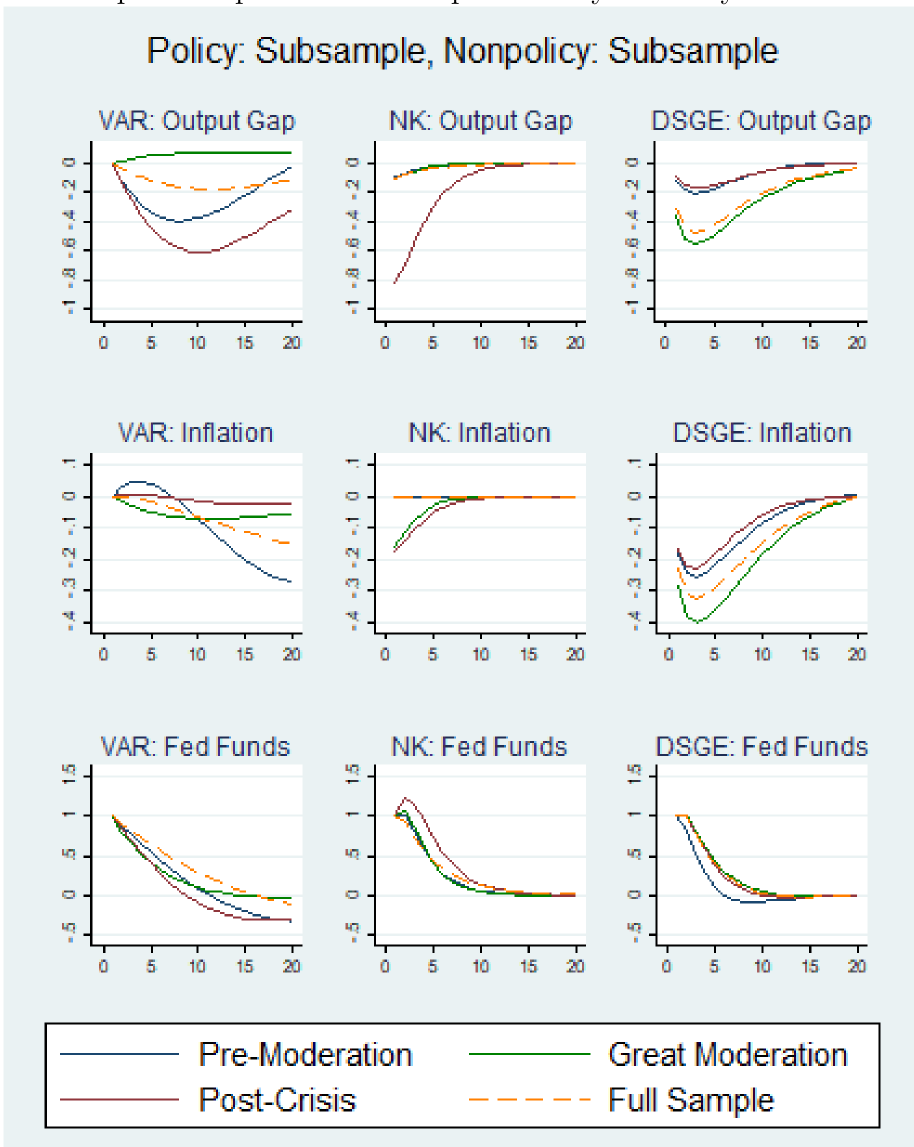


6.2 Impulse Response Functions

Structural breaks in the policy and non-policy parameters also affect the dynamic properties of macro models. Figure 4 shows the impulse responses to a 100-basis-point shock to the federal funds rate for the full sample and each subsample; recall that the post-Crisis (III) sample uses the shadow fed funds rate. These subsample impulse response functions (IRFs) are unrestricted, allowing all model parameters—both policy and non-policy—to change in each subsample.

The unrestricted dynamics are broadly consistent with prior evidence for each model type. With few exceptions, the IRFs are *qualitatively* similar across all models and samples. The monetary tightening produces a familiar, modest decline in both output and inflation,

Figure 4: Impulse response to a 100bp monetary shock by model and sample



followed by a slow return to steady state over 1-3 years in most cases. The fed funds rate paths are nearly the same, decaying slowly from 100 basis points in a similar fashion across models with only modest differences in the degree of persistence. Perhaps surprisingly, there is very little *qualitative* difference across subsamples for any model.

However, the output gap and inflation IRFs exhibit somewhat larger and more important *quantitative* differences across models and subsamples. For example, the output responses are larger (in absolute value) for the VAR and NK models, but smaller in the DSGE model.

The DSGE has notably larger (in absolute value) inflation responses than the other models, especially the NK model. The full sample responses are more notably muted for the NK model. No subsample response consistently matches the full-sample responses across models. A lack of consistency across models is perhaps to be expected given their different sizes and restrictions. But the relative inconsistency of subsample responses across models is striking. That is, the largest absolute response for each model is not associated with the same subsample.

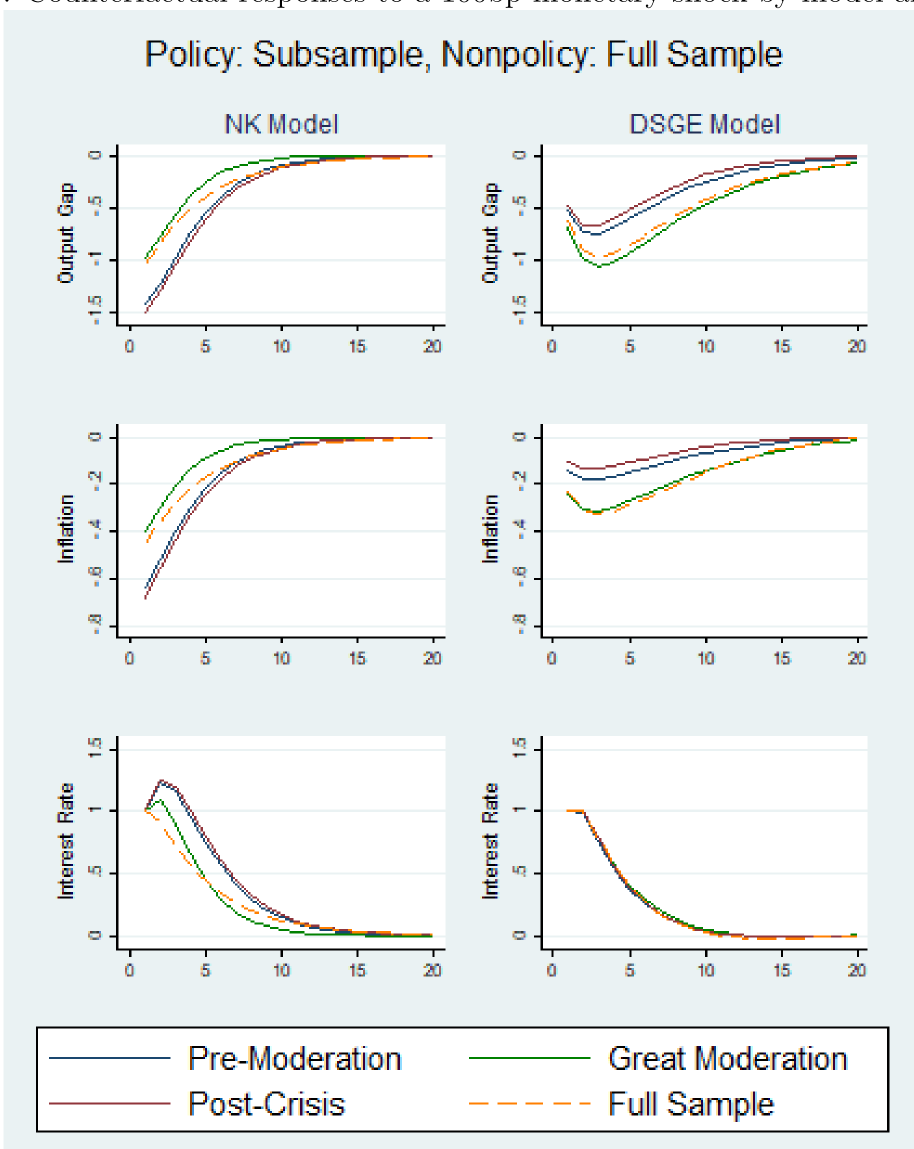
Although the subsample heterogeneity of IRFs provides additional evidence of structural breaks, most differences between responses are economically moderate for at least two reasons. First, as noted in Section 6.1, the variances and persistence of the structural shocks change considerably across subsamples, which impact the parameter estimates. Unlike the monetary shock fixed at 100 basis points, impulse responses based on shocks' estimated standard deviations would vary more. Second, data-consistent dynamics are the inherent goal of the model estimation procedures. Thus, while breaks in the economic structure may occur in some parameters (e.g., the Taylor Rule), offsetting breaks in other parameters (e.g., non-policy) may occur to maintain dynamic properties consistent with the data.

To better understand the effects of structural breaks in Taylor Rule parameters, we conducted a counterfactual exercise in which the non-policy parameters are held fixed at their full-sample estimates. Figure 5 shows impulse responses to a 100-basis point fed funds shock using models in which only policy parameters change across subsamples, thus better illustrating the effects of structural breaks to policy on model dynamics.[10] The counterfactual responses reveal three important insights. First, the absolute magnitudes are roughly two to three times larger than the unrestricted responses in Figure 4 for all but the DSGE inflation response (about the same). Second, the counterfactual responses are much more consistent across subsamples with smaller qualitative differences. Third, the Great Moderation (II) responses more consistently distinguish themselves from the very similar pre-Moderation (I)

[10]Figure 5 excludes the VAR model because the distinction between structure and reduced-form is less precise.

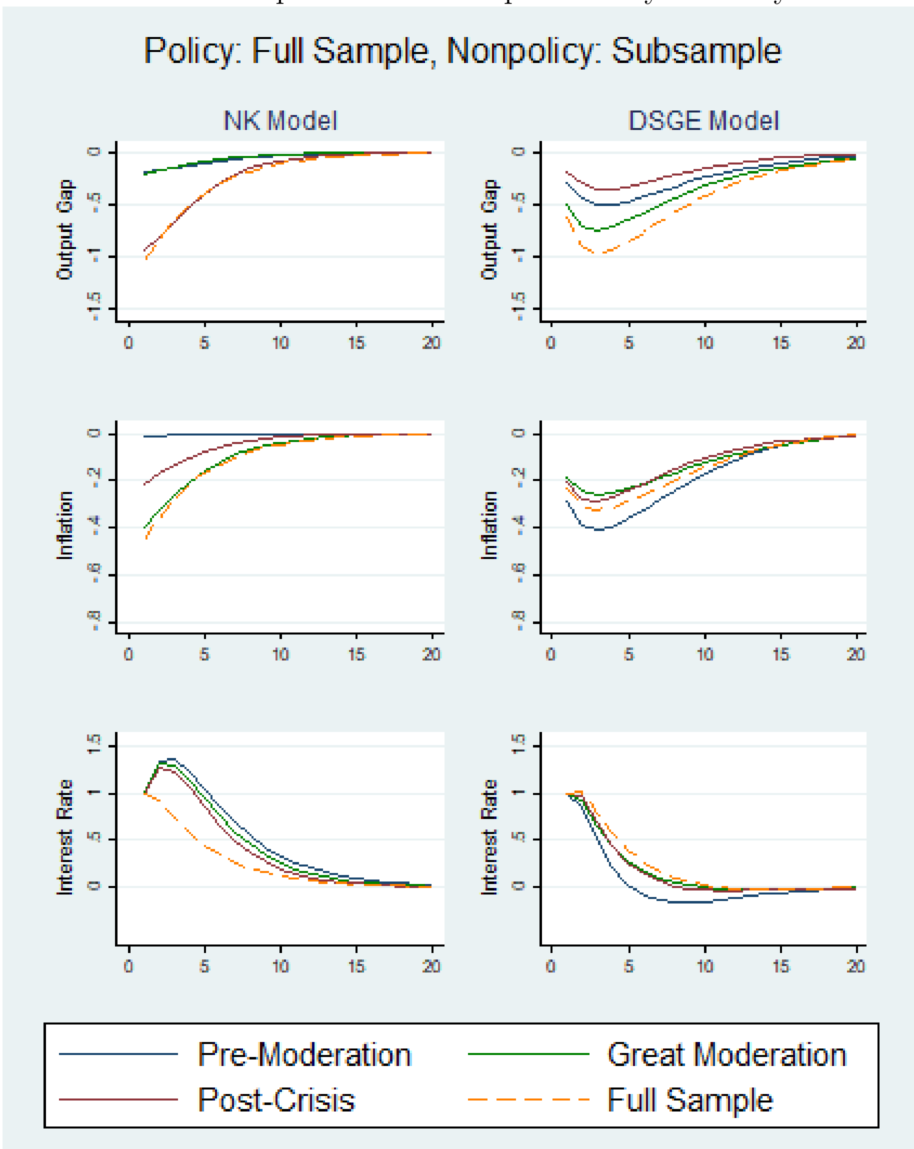
and post-Crisis (III) responses. The Great Moderation output and inflation responses are smaller (larger), that is less (more) negative, in the NK (DSGE) model. Except for the Great Moderation response, the NK fed funds rate responses exhibit a short-lived amplification after the shock while the DSGE responses do not. Overall, these counterfactual responses show that breaks in the non-policy parameters mute the volatility of responses differing only in Taylor Rules, and that differences in Taylor Rule estimates across samples and models have limited dynamic effects.

Figure 5: Counterfactual responses to a 100bp monetary shock by model and sample



For completeness, we also performed the converse counterfactual exercise in which the policy (Taylor Rule) parameters are held fixed at their full-sample estimates. Figure 6 shows impulse responses to a 100-basis point fed funds shock using models in which only non-policy parameters change across subsamples, thus better illustrating the effects of structural breaks to non-policy structure on model dynamics. The fixed-policy counterfactual responses of output and inflation also are larger (more negative) than the unrestricted responses, but not as much as when holding the non-policy parameters fixed. Variation in non-policy parameters holding the policy rule fixed also produces more heterogeneous impulse responses across subsamples, but the heterogeneity is not economically large.

Figure 6: Counterfactual responses to a 100bp monetary shock by model and sample



To summarize, structural breaks in model parameters have modest economic effects on model dynamics when all parameters are allowed change. Structural breaks in subsets of the parameter space do alter dynamic responses by magnitudes that are economically much larger and important. However, these dynamic effects in counterfactual simulations are largely offsetting when all model parameters are allowed to change.

6.3 Output Gap Implications

Different approaches across models to measuring the output gap offer further insights on the macroeconomic implications of the estimated structural breaks in Taylor Rule and non-policy coefficients. As mentioned previously, the VAR and NK models use the CBO's output gap, which is estimated continuously with data and a theoretical framework that are independent of the macro models. In contrast, the DSGE model generates an output gap from the estimation, so structural breaks can influence its measurement.

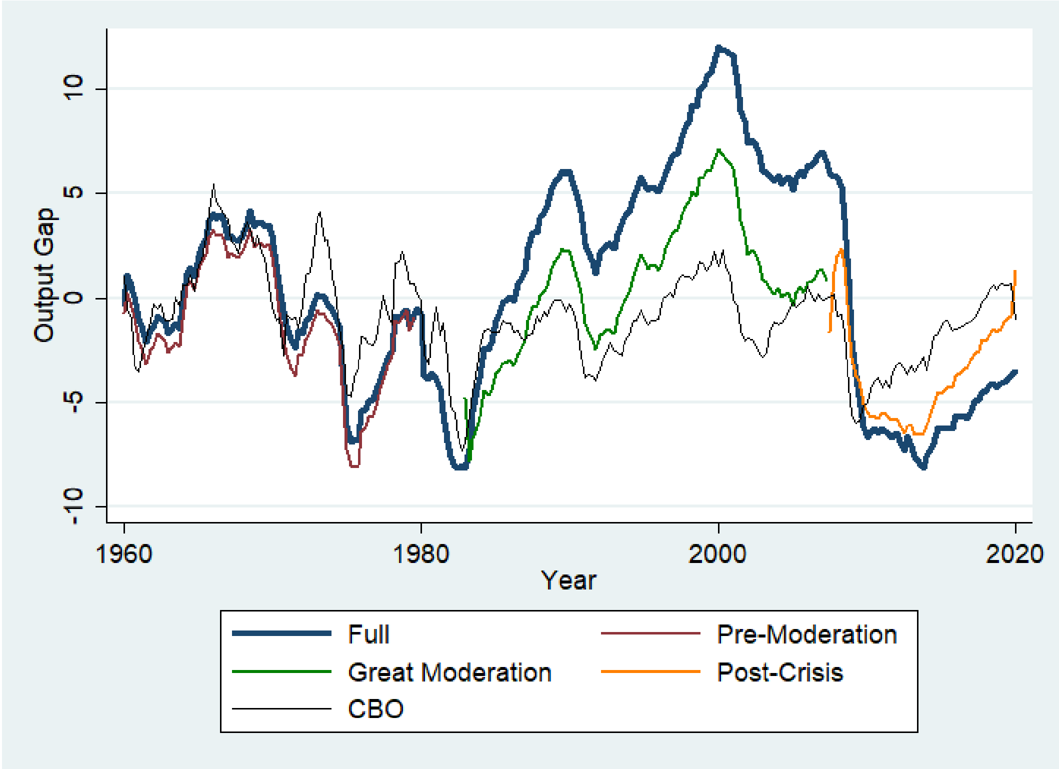
Figure 7 shows how the DSGE full sample output gap compares to the CBO gap for two different estimation samples. The CBO and full sample DSGE output gaps are qualitatively similar, positively correlated, and comparable levels until about 1970. After that, however, the full sample DSGE output gap begins to diverge by many percentage points and becomes very persistent, rarely crossing the zero line. The absolute magnitudes of this divergence are economically meaningful for monetary policy responses to output gaps in the Taylor Rule, and a concern for the DSGE model if the CBO output gap is a reliable estimate of slack in output.[11]

Figure 7 also shows that the DSGE output gap exhibits economically significant structural breaks across subsamples as well. The pre-Moderation subsample DSGE gap is similar to the one estimate over the full sample.[12] However, the DSGE subsample gap during the Great Moderation is roughly 5 percentage points below the full-sample gap, crossing the zero line multiple times. The DSGE output gap after the Financial Crisis follows a similar U-shaped path but, unlike the full-sample gap, returns to zero before 2020. Aside from a discontinuous jump in 2008, connecting the three subsamples of DSGE gaps yields an estimated output gap that looks considerably more like the CBO gap than the full-sample DSGE gap does.

[11] In the original Smets and Wouters (2007) estimation through 2004, the estimated output gap reflects more closely the CBO's output gap. However, extending the estimation sample drastically changes the DSGE output gap across the sample

[12] This similarity is not necessarily beneficial. Figure 7 shows the full-sample DSGE output gap during 1960-1983 is largely steady (without trend) but the estimated pre-Moderation subsample output gap exhibits a downward trend.

Figure 7: Estimated Output Gaps



The results in Figure 7 provide further evidence of valid structural breaks in the DSGE model. Upon deeper examination, the subsample instability appears to largely come from structural breaks in the estimated steady state growth rate. Full-sample estimation assumes a constant steady-state growth rate, while each subsample estimation allows sample-specific steady-state growth rates that enables the gap to better match the CBO. For example, the Great Moderation sub-period has a higher steady state growth rate than the full sample, causing the output gap to consistently increase throughout the period. On the other hand, the post-Crisis sub-period has a lower steady state growth rate than the full sample, biasing downward the output gap in the post-Crisis period. Overall, the estimated DSGE output gap exhibits strong evidence of subsample instability. Thus, the output gap estimated with the full sample tends to be biased upwards and downwards for long periods and subsamples.

7 Explaining Structural Breaks

The existence of multiple economically and statistically significant structural breaks in the Taylor Rule and non-policy structural parameters in macroeconomic models begs the question: what caused the breaks? Naturally, implementation of unconventional monetary policies that are not incorporated in the macroeconomic models creates an environment in which omitted variables (policy and non-policy) may bias existing coefficient estimates in ways that could manifest as structural breaks. Before turning to that central hypothesis of this paper, however, we discuss potential time variation in non-policy parameters that may be confounding efforts to identify causes of structural breaks in policy.

7.1 Time-varying Non-policy Parameters

The literature contains several branches that document and explain time variation in various aspects of macroeconomic models like the ones in this paper. A full literature review is beyond the scope of the paper. However, several key topics appear in our results and likely contribute to the observed structural breaks during the full sample.

Trend growth/productivity – The steady state (or trend) rate of growth changed. One likely reason is breaks in trend productivity growth (labor and/or TFP), as documented in Fernald (2014). Variation in trend growth/productivity may also cause variation in the marginal product of capital.

Natural rate of interest – The natural real interest rate, r in equation 1, is a fixed parameter. However, the observed real rate of interest varied widely over the full sample and is estimated to have declined at the end of the sample.[13] Indeed, our estimate shows a similar decline in period III. As noted above, while our estimate for the natural real interest rates are in line with Smets and Wouters (2007) original estimate of r^*, it is considerably above the traditional estimate in the literature. Holston et al (2018) estimated the natural rate of interest to be close to zero after the financial crisis, and Del Negro et al (2018) estimate

[13] See Kocherlakota (2018), Del Negro et al (2018), and Mertens and Johanssen (2018).

it to be slightly above one. Resolving these large inconsistencies around r^* is a key step to explaining structural breaks. Further, adding time-variation to the natural rate is warranted, as in the model of Laubach and Williams (2003) and others subsequently. Including their calculation of the natural real rate of interest, $r^* = \frac{1}{\sigma}\bar{\gamma} + \beta$, and its law of motion:

$$r_t^* = c\bar{\gamma}_t + z_t, \tag{17}$$

in a modified Taylor Rule would capture this variation where steady state growth ($\bar{\gamma}$) is allowed to vary over time ($\bar{\gamma}_t$). The other parameters also may vary over time, as seen in Section 5, but would need an economic theory to justify it.

Inflation target – The inflation target, $\overline{\pi}$, also is a fixed parameter by assumption. However, extreme variation in inflation during the "Great Inflation" and subsequent steady decline since (e.g., "opportunistic disinflation" in Orphanides and Wilcox, 2002) suggests that the target also may be time varying.

Policy maker preferences – The structural break in Taylor Rule coefficients during the Great Moderation (between subsamples I-II) has been described as a shift in the preferences of the Fed's FOMC members toward favoring inflation stability.[14]. Bordo and Istrefi (2018) examine the Fed's overall preference through the window of individual FOMC member's tendencies to place a higher weight on the inflation gap ("Hawk") or output gap ("Dove") in setting the interest rate and find the FOMC shifted significantly toward being dominated by Doves in the post-Crisis period. This observation is mildly consistent with the estimated Taylor Rules in the post-Crisis period (III), which generally show a small decline in the magnitude of ϕ_π relative to ϕ_y from the Great Moderation period (II).[15]

Phillips Curve/price stickiness – The slope of the NK Phillips Curve and the underlying degree of nominal stickiness (price and wage) changed. These phenomenon have been

[14]For examples, see Canova (2009), Castelnuovo (2012), Ilbas (2012), and Lakdawala (2016)

[15]Debortoli and Nunes (2014) caution against interpreting structural shifts in the policy rule as simply a change in preferences, noting that shifts in the policy rule can obscure differences between factors inside and outside a policymaker's control.

documented and discussed widely, as in (Kim et al., 2014; Jorgenson and Lansing, 2021). Developments such as information technology, declining influence of unions, and other factors likely have influenced nominal stickiness.

Rational expectations/policy transparency – The degree to which inflation responds to expected inflation increased. Several factors likely have contributed to this development, such as increasing awareness of the private sector of the importance of forming expectations that incorporate policy. However, U.S. monetary policy also has embraced the anchoring of inflation to expectations, and has become more transparent and cooperative with the private sector (Spencer et al., 2013). These developments likely influence coefficients of the simpler characterization of policy in the Taylor Rule.

Heterogeneous preferences – The degree of risk aversion in consumers declined. Given the challenges encountered in estimating this parameter, as shown in Calvet et al. (2021), it is hard to draw hard conclusions about the cause(s) of the estimated decline. Increased access to more sophisticated financial markets may be a contributing factor, but the macro models generally do not incorporate financial markets. The estimated rate of time preference is much larger than assumed in the fully rational exponential discounting model. However, a growing literature has shown the presence of notably heterogeneous preferences across consumers that rejects validity of the estimated time preference for all consumers[16].

For some or all of these reasons—and perhaps others not listed—it is possible that the observed structural breaks in the Taylor Rule may diminish or disappear if the macro models incorporated time-varying parameters or variable specifications. However, incorporating all or even some of these extensions is challenging and beyond the scope of the current paper.

7.2 Unconventional Monetary Policies

Around the time of the Financial Crisis, the Federal Reserve implemented a wide range of unconventional monetary policies that can be classified into three broad categories: 1)

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forward guidance (FG); 2) quantitative easing (QE); and 3) expanded liquidity facilities (ELF).[17] Each of these new policy tools suggests the need to modify the Taylor Rule and/or add variables and structural equations (including new policy rules) to the macro models to capture the effects of unconventional policy.

Forward Guidance (FG) – Developed during the (relatively) low-interest rate period of the early 2000s, FG was tested first during the subsequent increase of the federal funds rate in 2004. (Gürkaynak, et al., 2005) The main implementation of FG occurred during the Financial Crisis when the federal funds rate hit the ZLB for six years. Prototypical FG models add N-periods ahead expectations of the policy rate, i_{t+N}, or FG shocks to the Taylor Rule.[18] Such models find a "forward guidance puzzle" of excessively large responses to FG news. The shadow fed funds rates is designed to control for this FG effect. However, it may be necessary to introduce the FG-augmented policy rule, and one or more future policy rate variables (fed fund futures, survey expectations, etc.), to the macro model(s) to identify properly the effects on Taylor Rule parameters.

Quantitative Easing (QE) – From 2008-2014, the Fed substantially expanded its Open Market Operations (OMO) to conduct two types of large-scale asset purchases (LSAP): 1) mortgage-backed securities, to ease the bank risk and lower mortgage rates; and 2) longer term Treasury bonds, to increase maturity and long-term rates. This QE strategy essentially added a *de facto* long-term bond policy(ies) to the short-term interest rate policy characterized by the Taylor Rule. Thus, macro models may need either an explicit new rule(s), with commensurate objectives driving the setting of long-term rates, or asset-pricing equation(s) based on supply and demand for long-term bonds. Finally, QE policies stemmed from the Fed's inability to conduct traditional OMO in an period of "ample reserves" where banks held unusually high levels of excess reserves instead of converting reserves to new loans. Therefore, the expansion of OMO operations to QE affects the balance sheets of the entire

[17] For more details of these policies, see https://www.federalreserve.gov/monetarypolicy/policytools.htm.

[18] Del Negro et al., 2012; Campbell et al. 2012, Cole, 2020; This is called "forecast targeting" by Svensson (2017).

banking system, as modeled by Sims and Wu (2021) and others.[19]

Expanded Liquidity Facilities (ELF) – During the Financial Crisis and its aftermath, the Fed developed many new policy tools to provide liquidity and improve functioning of financial markets, which fall into two types. One type includes new short-term rates: 1) interest on excess reserves (IOER), which was replaced by interest on reserve balances (IORB) in 2021 after required reserves were eliminated; and 2) interest rate on overnight reverse repurchase agreements (ONRRP), which is a form of OMO. It is unclear whether more than one short-term rate is needed in a macro model. However, the new short-term rates are closely related to the fed funds rate and its target range, so leaving them out may be problematic. It has been suggested that IOER (IORB) should become the new policy instrument.[20] Because IOER (IORB) is the price that clears the market for bank (excess) reserves, it also is closely related to QE policies. A second type of new liquidity tool includes a variety of facilities that provide liquidity directly to banks, borrowers, and investors in key credit markets – some of which have expired.[21] These other liquidity facilities are mainly relevant during liquidity crises and the Fed has demonstrated a willingness to start and stop facilities as needed. Introduction of such intermittent policy tools seems particularly challenging for macro models.

To recap, observed structural breaks in the Taylor Rule may reflect the effects of omitting variables and equations associated with these unconventional policies. If so, then expanding the macro models to incorporate the policy and non-policy equations necessary to capture unconventional policies may diminish or eliminate the structural breaks documented in this paper. Recent research develops theoretical foundations for some types of the unconven-

[19]Modeling unconventional policy became more challenging in 2020 with two new responses to the COVID-19 pandemic: 1) expanded QE that included purchases of investment-grade corporate bonds via the Secondary Market Corporate Credit Facility (SMCCF) and short-term state and local government notes via the Municipal Liquidity Facility (MLF); and 2) new direct lending to small and medium-sized businesses via the Paycheck Protection Program Liquidity Facility (PPPLF) and the Main Street Lending Program.

[20]Former New York Fed President Bill Dudley argued recently the fed funds rate target (range) has become irrelevant so the Fed should drop it altogether and use the IOER (IORB) instead. See https://www.bloomberg.com/opinion/articles/2021-06-24/the-fed-s-interest-rate-target-is-obsolete

[21]See https://www.federalreserve.gov/monetarypolicy/policytools.htm

tional policies.[22] However, there is no comprehensive model that includes all elements of unconventional policy, and little or no estimation of models that incorporate portions of unconventional policy. Addressing these deficiencies is an important direction for future research.

8 Conclusions

Three classes of modern macroeconomic models exhibit significant structural breaks in their monetary policy and non-policy structural parameters around 2008. A structural break(s) was likely given the implementation of unconventional monetary policies during the Global Financial Crisis that are not captured in the macro models. Surprisingly, controlling for some unconventional policies and the zero lower bound of interest using a shadow rate does not alter the outcomes of the structural break tests much.

The observed structural breaks are heterogeneous and challenging to interpret well. Changes in the Taylor Rule (monetary policy) coefficients generally are statistically significant but reflect only an economically modest decline in the relative importance of inflation to the setting of the short-term policy rate after 2008. Changes in many non-policy coefficients also are statistically significant and often economically significant. Structural breaks after 2008 are not always consistent with the breaks documented during the period of the Great Moderation. In any case, allowing for structural breaks significantly impacts the volatility and persistence of estimated structural shocks, the magnitude of impulse responses, and the character of the estimated output gap.

In their benchmark forms, the estimated models cannot identify the impact of unconventional monetary policies on the Taylor Rule or non-policy parameters for at least two reasons. First, the literature suggests several reasons for time-variation in some non-policy parameters that probably are not directly related to unconventional policies. Independently controlling for this time-variation in the models is essential to properly identifying the effects

[22] Gertler and Karadi (2013), Hagedorn et al. (2019), Sims and Wu (2021)

of unconventional policies. Second, the effects of unconventional monetary policies in macro models do not work entirely through the Taylor Rule. Forward guidance, along with time-variation in the equilibrium real rate of interest, can be incorporated into the prototypical Taylor Rule. However, QE and ELP policies likely require explicit incorporation of additional policy tools, rules, and macro-prudential objectives. This task is a fruitful direction for future research.

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Appendix

A Additional Regression Diagnostics

A.1 Structural Shocks

In addition to the model parameters, the shock structure is highly variable between periods. The variance ratios of the shocks can be found in Table 4, and the autocorrelations are in Table 5. Time series graphs for the shocks in the NK model are seen in Figure 8. For the NK model, the output gap shock is smallest during the Great Moderation, and is significantly larger in the final subperiod. The output gap shock's persistence is largely stable between the Great Moderation and post-Crisis. Meanwhile, the inflation shock drops significantly in the final subperiod, as inflation was largely stable from 2008-2020. The inflation shock is highly persistent in each subperiod. The monetary shock declines between the first and second subperiod, but is consistent between periods II and III, as is the monetary shock's persistence.

For the DSGE model, the shock structure is similarly unstable between subperiods. The time series graphs for each DSGE shock are seem in Figure 9. Nearly each shock increases between periods II and III, with only the spending shock declining. The monetary shock changes most substantially between these periods, increasing by a factor of 3 from its period II value. The persistence of most shocks changes significantly in period III, with only the risk premium and investment shocks maintaining their Great Moderation persistence. The productivity, spending, price markup, and wage markup shocks become less persistent in the final subperiod, while the monetary shock becomes significantly more persistent. Taken together, this unstable monetary shock with increasing persistence leads to the high amount of subsample instability seen in Figure 3.

Figure 8: Structural shocks (η) from NK model

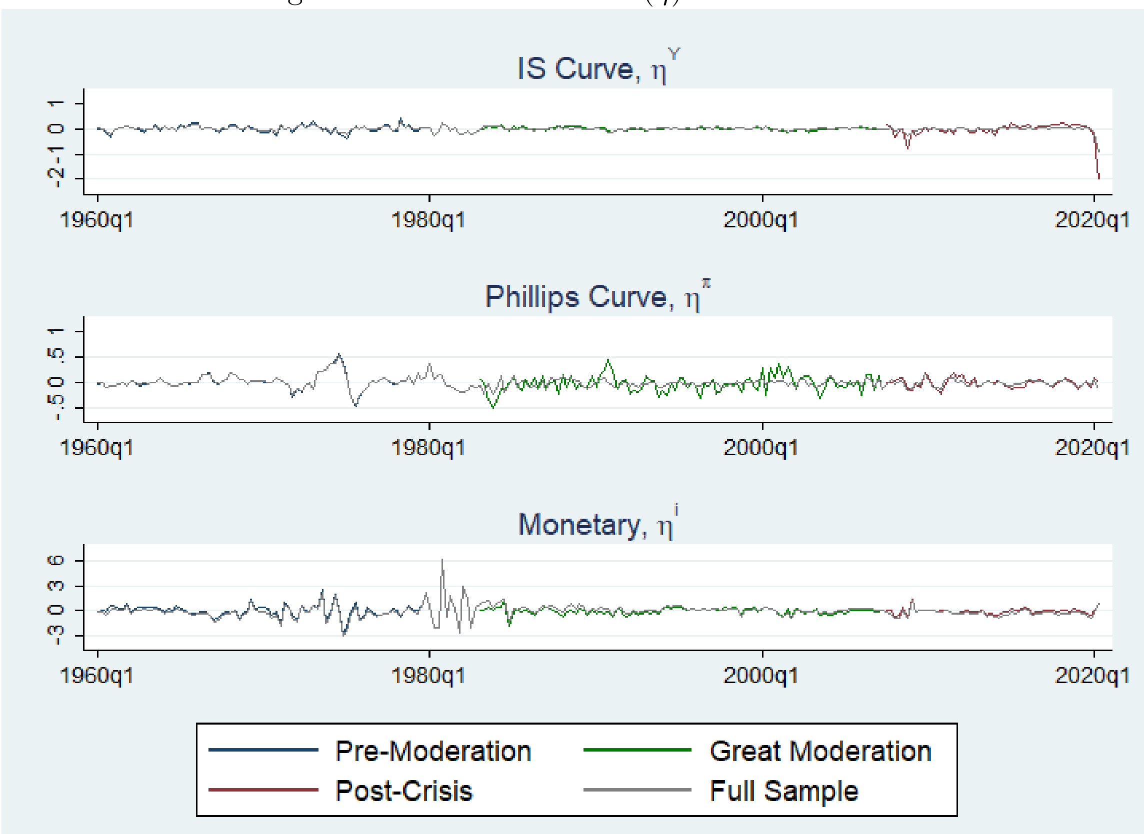

Table 4: Structural shock standard deviation

Model	Parameter	Role	FS	Ratio to FS		
				I	II	III
VAR	σ_t^y	Output Gap	.74 (.03)	1.25	.62	.78
	σ_t^π	Inflation	.31 (.01)	1.28	.63	.58
	σ_t^i	Monetary	.78 (.04)	1.43	.52	.41
NK	η_t^y	Output Gap	.10 [.06,.13]	1.42	.61	3.30
	η_t^π	Inflation	.11 [.08,.14]	1.36	1.63	.88
	η_t^i	Monetary	.80 [.74,.87]	.95	.50	.29
DSGE	ϵ_t^a	Productivity	.47 [.44,.51]	1.22	.78	.95
	ϵ_t^b	Risk Premium	.12 [.11,.13]	2.19	.76	1.13
	ϵ_t^g	Spending	.47 [.44,.50]	1.11	.85	.64
	ϵ_t^i	Investment	.40 [.34,.46]	1.20	.78	.95
	ϵ_t^m	Monetary	.85 [.78,.90]	.22	.14	.40
	ϵ_t^p	Price Markup	.14 [.13,.16]	1.21	.58	1.07
	ϵ_t^w	Wage Markup	.36 [.32,.39]	.48	.80	1.77

A.2 Estimation Priors

The prior distributions, means, and standard deviations used in estimation, given in Table 6, are similar to those used in Canova (2009) for the NK model. The slope of the IS curve, ψ, and Phillips Curve, κ, have gamma distributions with a prior mean of -.5 and 1, respectively. The inflation feedback parameter, β, has a beta distribution and a prior mean near a rational expectations benchmark at .98. The monetary parameters are set at $\rho = .8, \phi_y = .5$ and $\phi_\pi = 1.3$. Additionally, the prior for the inflation parameter, ϕ_π is truncated at 1 to not allow indeterminacy.

Figure 9: Structural shocks (ε) from DSGE model

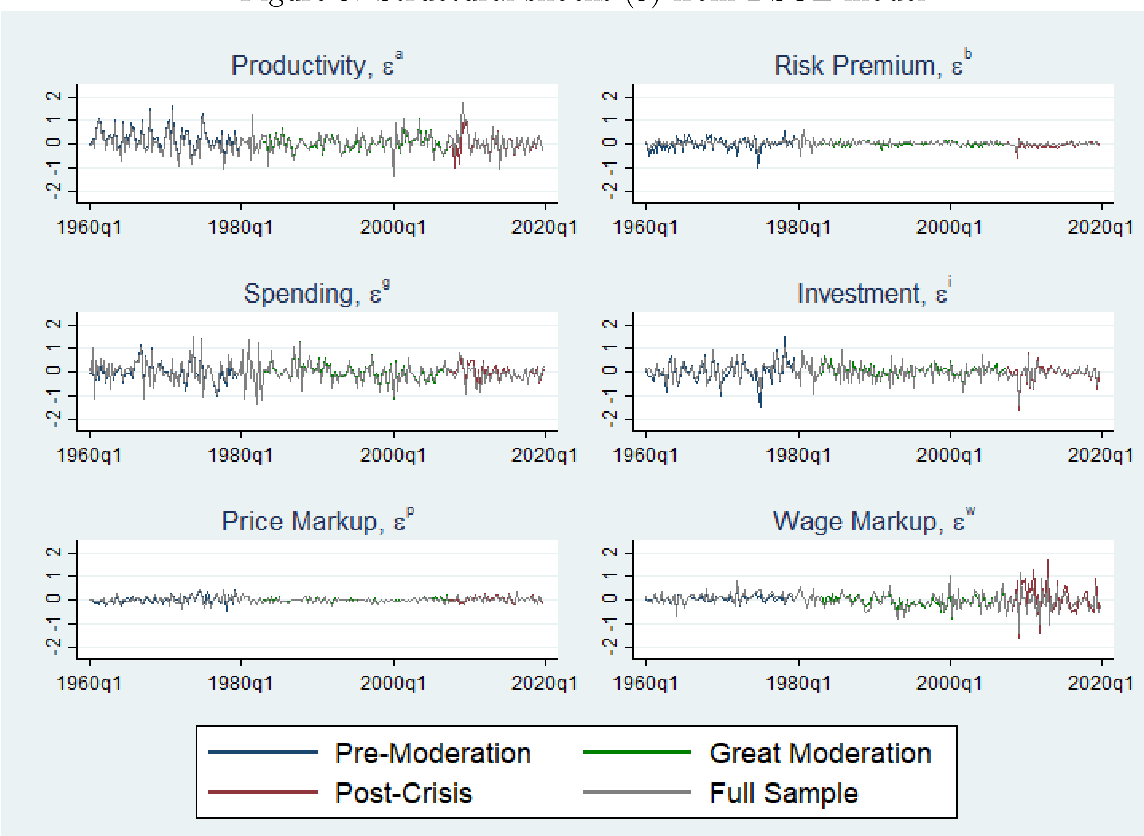

Table 5: Structural Shock Persistence

Model	Parameter	Parameter Role	Full	I	II	III	I-II Change	II-III Change
NK	ρ_Y	Output Gap Shock	.92 [.88,.95]	.90 [.84,.96]	.79 [.74,.85]	.87 [.78,.99]	-.11	.08
	ρ_π	Inflation Shock	.99 [.98,.99]	.99 [.97,.99]	.99 [.99,.99]	.65 [.42,.84]	0	-.34
	ρ_i	Monetary Shock	.34 [.13,.53]	.49 [.34,.64]	.60 [.42,.72]	.51 [.25,.81]	.11	-.09
DSGE	ρ_a	Productivity Shock	.99 [.99,.99]	.99 [.98,.99]	.92 [.87,.98]	.84 [.78,.91]	-.07	-.08
	ρ_b	Risk Premium Shock	.94 [.92,.95]	.24 [.07,.42]	.74 [.22,.93]	.79 [.72,.86]	.50	.05
	ρ_g	Spending Shock	.96 [.94,.98]	.90 [.84,.95]	.96 [.94,.99]	.78 [.63,.93]	.06	-.18
	ρ_i	Investment Shock	.72 [.64,.82]	.61 [.47,.78]	.70 [.55,.84]	.58 [.31,.82]	.09	-.12
	ρ_r	Monetary Shock	.14 [.05,.21]	.29 [.13,.45]	.31 [.13,.51]	.51 [.33,.68]	.02	.2
	ρ_p	Price Markup Shock	.93 [.89,.97]	.65 [.29,.99]	.75 [.55,.93]	.55 [.31,.81]	.10	-.2
	ρ_w	Wage Markup Shock	.30 [.16,.45]	.94 [.89,.99]	.78 [.50,.97]	.21 [.04,.37]	-.16	-.55

The VAR's shock persistence is simply the autoregressive parameter from each equation in the model.

For the DSGE model, we use the same priors as Smets and Wouters (2007), given in Table 7. The time preference rate is set at 0.25 (corresponding to $\beta = .9975$), the steady state inflation ($\bar{\pi}$) and growth rate ($\bar{\gamma}$) are set at 0.62 and and .4, respectively (corresponding to an annualized 2.5% inflation rate and 1.6% real growth rate). Steady state hours, $\bar{l}$, is set at 0, Firsh elasticity, σ_l, is 2, while risk aversion, σ_c, and habit formation, λ, are set at 1.5 and .7, respectively. The Calvo parameters, ξ_p and ξ_w, are both .5, and wage and price indexation, (ι_p, ι_w) are also .5. Finally, capacity utilization, ψ, is set at .5, and the fixed cost and capital shares (Φ and α) are 1.25 and .3, respectively. The monetary autoregressive parameter, ρ, is set at .75, and the monetary feedback parameters, $\phi_\pi, \phi_y, \phi_{\Delta y}$ are set at 1.5, .12, and .12, respectively, Similar to the NK model, the prior for ϕ_π is truncated at 1 to require determinacy.

Table 6: Estimation Priors

Model	Parameter	Parameter Role	Prior Distribution	Prior Mean
NK	ψ	IS curve slope	Gamma	-.50 (.35)
	κ	Phillips Curve slope	Gamma	1.00 (2.00)
	β	Inflation Expectation feedback	Beta	.98 (.05)
	ρ	Monetary smoothing	Beta	.8 (.25)
	ϕ_π	Taylor Rule: Inflation	Normal	1.3 (.5)
	ϕ_y	Taylor Rule: Output	Beta	.5 (.25)

Table 7: Estimation Priors

Model	Parameter	Parameter Role	Prior Distribution	Prior Mean
DSGE	$100(\beta^{-1}-1)$	Time Preference Rate	Gamma	.25 (.10)
	$\bar{\pi}$	Steady State Inflation	Gamma	.62 (.10)
	$\bar{\gamma}$	Steady State Growth Rate	Normal	.40 (.10)
	$\bar{l}$	Steady State Hours	Normal	.00 (2.00)
	ρ	Investment Adjustment Cost	Normal	4.00 (1.50)
	σ_c	Risk Aversion	Normal	1.50 (.37)
	λ	External Habit Degree	Beta	.70 (.10)
	ξ_w	Calvo Parameter: Wages	Beta	.50 (.10)
	σ_l	Frisch Elasticity	Normal	2.00 (.75)
	ξ_p	Calvo Parameter: Prices	Beta	.50 (.10)
	ι_w	Indexation to Past Wages	Beta	.50 (.15)
	ι_p	Indexation to Past Prices	Beta	.50 (.15)
	ψ	Capacity Utilization Cost	Beta	.50 (.15)
	Φ	Fixed Cost Share	Normal	1.25 (.12)
	α	Capital Share	Normal	.30 (.05)
	ρ	Monetary smoothing	Beta	.75 (.1)
	ϕ_π	Taylor Rule: Inflation	Normal	1.5 (.25)
	ϕ_y	Taylor Rule: Output	Normal	.12 (.05)
	$\phi_{\Delta y}$	Taylor Rule: Growth	Normal	.12 (.05)