Examining Business Cycles and Optimal Monetary Policy in a Regional DSGE Model

Sacha Gelfer*

Abstract

I construct a dynamic stochastic general equilibrium (DSGE) model consisting of geographic regions and use state level data to estimate the effects that monetary policy and financial shocks have on the four census regions of the United States. The DSGE model I use is constructed around a centralized monetary authority and financial market with regional output, labor and investment markets and is a close variant of the FRBNY model (Del Negro et al. 2013). I use a combination of state level and national level data to estimate the regional and national parameters of the DSGE model. I find significant heterogeneity amongst the regional structural parameters of the model, creating different dynamics for the four regions in regard to national monetary and financial shocks. Simulating the estimated model, I find that monetary policy that considers the regional variation in output and inflation can significantly lower a central bank's loss function while also being Pareto improving to all four regions. The paper's results suggest that regional macroeconomic conditions should be considered in monetary policy decisions.

Keywords: Regional DSGE, Optimal Monetary Policy, U.S. Regional Dynamics
JEL: E3, E4, E5, R13

**Bentley University, Waltham, MA, USA. E-mail address: sgelfer@bentley.edu*

1 Introduction

There is a disparity between the acknowledgement of significant heterogeneities within the United States and its absence in the design of monetary policy and macroeconomic models. Regional business cycles have been found to exhibit significant variation across time and space.[1] Since the U.S. economy is ultimately an aggregation of these regional business cycles, including them in macroeconomic models have important implications on business cycle analysis and monetary policy decisions.

Recent literature has emerged that has examined regional business cycle variation in the context of aggregate business cycle analysis through various methodologies.[2] This paper builds upon those by conducting similar analysis by extending a predominant DSGE model that is fully estimated using both regional and national data. Fully estimating a multi-regional DSGE model allows for more detailed business cycle analysis at the national and regional levels. Further, a fully estimated multi-regional DSGE model for the United States allows for this paper to examine whether a central bank, interested in national variables, should react to regional economic developments within the country.

In order to conduct this investigation, I construct a DSGE model that is a close variant of the FRBNY model (Del Negro et al. 2013) that augments the New-Keynesian Model of Smets and Wouters (2007) with a financial accelerator. The model in the paper has n regions that are bonded together by a financial market, monetary policy and fiscal policy. Together the n regions aggregate up to determine the national variables of the model. The model is constructed around a centralized monetary authority and financial market with regional goods, labor and capital markets.

The regional economies are weighted by relative size to determine the aggregate values of the national macroeconomy. Since the micro-foundations and optimization objectives are identical across the n regions, each region of the model consists of linearized equations that only differ in their structural parameter values. The national monetary authority only responds to fluctuations in aggregate output and aggregate inflation in a Taylor-rule like

[1] See for example, Carlino and DeFina (1998, 1999), Owyang, Piger and Wall (2005), Del Negro and Otrok (2007), Owyang and Wall (2009), Dominguez-Torres and Hierro (2019).

[2] See for example, Mian and Sufi (2014), Jones, Midrigan, and Philippon (2018), Beraja, Hurst and Ospina (2019), Beraja, Fuster, Hurst, and Vavra (2019).

fashion. In the model there are five independent regional shocks for each region, productivity, investment, preference, wage and price shocks. In addition, there are four national shocks, finance, government, unexpected and expected monetary policy shocks.

I estimate the model using a combination of mixed-frequency state level and national level data. To be able to fully estimate the structural parameters of a regional DSGE model, I shrink the number of regions down to the four census regions of the United states: Midwest, Northeast, South and West. However, there still remains over 100 regional and national structural parameters that need to be estimated jointly. Given the dimensionality of the joint estimation, I employ a random walk Metropolis Hastings with a log adaptive proposals algorithm [Shaby and Wells (2010)] to ensure the posterior mode is found and searched around.

I find significant heterogeneity amongst the regional structural parameters of the model. In particular, price and wage frictions are estimated to be largest in the Midwest and Southern regions. As a result of these heterogeneous frictions, monetary policy shocks have a greater economic impact on output and investment in the Southern and Midwestern census regions while localized regional shocks have a greater economic impact on output and investment in the Northeast and Western census regions.

I compare the estimated regional DSGE model to the nested national model[3] which uses only national data to identify its structural parameters. I estimate wages, prices and employment changes to be more flexible when incorporating regional data into the estimation than when I use aggregate data alone. A finding similar to Beraja, Hurst and Ospina (2019). There is also a significant increase in the estimated capital share and investment adjustment costs when regionality is included in the model and the data. As a result there is a significant difference in business cycle dynamics and causes across the two models. The regional model uses mostly monetary and financial shocks to explain the business cycle while the national model mostly uses demand shocks to consumption and investment. I also find that the regional model does a better in-sample job of forecasting national macroeconomic variables than does the national model. In particular, the point and density in-sample forecasts of national GDP growth and inflation are more accurate in the regional model compared to the

[3]Del Negro and Schorfheide (2013,2015) SWFF model.

national model.

In the final section of the paper, I examine monetary policy loss function reductions that can be made by the central bank if the monetary authority reacted to regional data rather than national data. I also examine the decline in the monetary policy loss function that can be made if the monetary authority targets an average price indicator in which the weight assigned to each region is proportional to its degree of price stickiness as was illustrated in Benigno (2004). Using simulations under the estimated posterior of the model's parameter values, I find that the decline in the policy maker's loss function is significant and Pareto improving for all four regions when regional economic information is utilized by the monetary authority in the regional DSGE model. The decline in the policy maker's loss function is insignificant when regional dynamics and regional price rigidities are utilized by the monetary authority in the regional DSGE model and can result in an increase in the regional loss function.

1.1 Related Literature

This paper contributes to two types of literatures. First, the work contributes to the recent increase in papers that have examined regional variation and its impact on aggregate fluctuations and national policy. Jones, Midrigan, and Philippon (2018) exploit state-level variation to explore the extent to which household leverage had contributed to the Great Recession. Beraja, Hurst and Ospina (2019) use state-level data and show that variation in wages are driven by mostly changes in local economic conditions. Beraja, Fuster, Hurst, and Vavra (2019) use regional variation to explore the time varying aggregate effects of unconventional monetary policy.

Regional variation and data have also been used in forming and estimating structural models. Nakamura and Steinsson (2014) use a structural model to show how local government multipliers can inform aggregate multipliers. Adao, Arkolakis, and Esposito (2019) use a structural model to examine regional heterogeneity that exists in employment effects resulting from international trade shocks. Jones, Midrigan, and Philippon (2018) use regional data in an equilibrium dynamic macro model to study the Great Recession. Beraja, Hurst and Ospina (2019) construct and estimate a regional DSGE model to examine the role regional wage rigidities have on aggregate business cycles.

This paper is part of a growing recent literature showing how regional variation can expand aggregate structural models. Unlike previous studies, this paper is the first to fully estimate a stylized multi-regional DSGE model for the United States. Beraja, Hurst and Ospina (2019) use regional variation to capture variation in the labor market only, while Jones, Midrigan, and Philippon (2018) use state-level variation to capture heterogeneity in regional credit and employment.

Second, my work builds on the work related to monetary policy evaluation in a currency union. The vast majority of empirical research on this issue focuses on the European Union. Benigno (2004), use a two-country DSGE model to show that a central bank that relied on regional economic information and relative price rigidities was nearly optimal. Lombardo (2006) extends this analysis to the role of unequal degrees of competition. Bragoli et al. (2016) show that optimal policy is related to interactions of price stickiness, economic size, and the distribution of shocks across regions. Further, Gali and Monacelli (2008), Erceg and Linde(2010), Kolasa and Lombardo (2014) and Gilchrist et al. (2018) conduct similar optimal policy analysis on the European Union's currency union for a variety of issues.[4]

The monetary policy analysis of this paper is closely aligned to Angelini et al. (2008) who conducts policy analysis on the European Union using a small scale multi-country model. This paper contributes to the profound optimal policy in a currency union literature by evaluating monetary policy rules for a stylized multi-regional model that is built and estimated around the United States.

The remainder of this paper is structured as follows. Section 2 presents the log-linearized equations of the regional DSGE model and discusses the differences in dynamics between the regional model with homogeneous regions and the model with only one national region. Section 3 outlines the adaptive proposal estimation techniques I use in the paper. Also included in this section is a description of the priors for the structural parameters and an overview of the data series. Section 4 includes a summary of posterior estimates and discusses the business cycle dynamics associated with the estimated regional model. In this section, I compare the forecast accuracy of the regional and national model on the eight national data

[4]For a survey on optimal currency areas see Silva and Tenreyro (2010).

series the two models have in common. In Section 5, the importance of regional information in conducting monetary policy is evaluated by simulating the estimated regional model and comparing central bank loss functions under three different monetary policy rules. Section 6 concludes and discusses future extensions.

2 The Model

The model is an extension of the FRBNY DSGE model (Del Negro et al. 2013) with the addition of n regions that are tied together by a central monetary and fiscal authority. In addition, national entrepreneurs buy and sell regional capital in the n regions using a national zero-profit banking system. In all, the model can be thought of as a multi-region DSGE model operating under a currency union with regional and national shocks. In this section, I outline the agents of the DSGE model and present its log-linearized equations. I then proceed to compare the Regional DSGE model with two homogeneous regions to a "National DSGE" model where there is only one region.

2.1 General Outline of the Model

The model involves a number of regional exogenous shocks, economic agents, and market frictions. The regional agents include households, firms and capital producers. The regional variables are aggregated up and weighed by economic size to create national variables. These national variables are used in determining national monetary policy and national financial spreads.

Regional Households supply household-specific labor to regional employment agencies. Households maximize a CRRA utility function over an infinite horizon with additively separable utility in consumption, leisure and money. Utility from consumption includes a habit persistence measure. Regional Households are subject to a exogenous preference shocks that can be viewed as a shock in the regional consumer's consumption and savings decisions.

Regional Employment Agencies package and sell labor bought from the household to intermediate-firms. Employment agencies are perfectly competitive but must buy specialized labor from households who hold some monopoly power over wages. Households and

Employment Agencies may only renegotiate wages with a certain probability but are subject to inflation indexation. Regional Employment agencies are subject to wage mark-up shocks that capture exogenous changes in the monopolistic power regional households hold over their specialized labor.

Regional Firms come in two forms, intermediate good producing firms and final good producing firms. There is a continuum of regional intermediate good firms, who supply intermediate goods in a monopolistically competitive market. Intermediate firms produce differentiated goods, decide on regional labor and regional capital inputs, and set prices in a Calvo (1983) manner. As with wages, those firms unable to change their prices, are able to partially index them to past inflation rates. Intermediate firms face two exogenous shocks, the first is a productivity shock that affects their production ability and the second is a price mark-up shock. The price mark-up shock captures the degree of competitiveness in the intermediate goods market. Final goods use regional intermediate goods in production and are produced in perfect competition.

Regional Capital Producers control the creation of new capital (Investment), a process that requires both the newly bought regional consumption output and the previous stock of regional capital in the economy. The investment procedure is subject to regional adjustment costs and capital producers are subject to investment shocks that affect the marginal efficiency of investment.

National Aggregation The regional variables of output, investment, consumption, inflation, labor, wage inflation, capital and capital prices are all proportionally weighed to create a national measure or level of each variable. These national variables are used in determining a national monetary policy, and impacting the national financial and banking markets.

Financial Sector centers around two national economic agents, banks and entrepreneurs. Entrepreneurs must use their net worth and an agreed upon loan from the bank to buy regional capital from the regional capital producers. Once the capital is bought they are subject to idiosyncratic national risk shock that can decrease or increase their overall level of the aggregate regional capital just purchased. The entrepreneur must optimize its regional utilization rate of the new level of regional capital and rent it out to the regional intermediate firms. If entrepreneurs received enough revenue they pay back the agreed upon loan with interest to the bank. Banks incorporate the risk of default by charging entrepreneurs an interest rate higher than the deposit rate paid to households. This risk premium that entrepreneurs must pay creates a financial friction resulting in real and exogenous fluctuations to the national capital stock and thus regional and national output.

Government Agencies are composed of a monetary authority and a fiscal authority. The short term nominal interest rate is determined by the monetary authority, which is assumed to follow a generalized Taylor Rule that reacts to the national variables of output and inflation and is subject to anticipated and non-anticipated monetary policy shocks. The fiscal authority sets fiscal policy and is subject to exogenous government spending shocks. The fiscal stimulus/contraction is proportioned amongst the n regions.

2.2 Log Linear Equations

The model is linearized around the non-stochastic steady state and variables denoted with a hat are defined as log deviations around the steady state. $\left(\hat{Y}_t = log\left(\frac{Y_t}{Y}\right)\right)$ Variables denoted without a time script are steady state values. Variables and parameters denoted with subscript s denote a variable or parameter specific to region s. In all, the model is reduced to $9n$ regional equations, three national equations and eight aggregation equations. There are $5n$ idiosyncratic exogenous shocks that encompass both a regional and national disturbance. There are three national shocks and five anticipated national monetary policy shocks, all of which are listed in this section.

Physical capital in region s, denoted $\bar{K}_{t,s}$ accumulates according to:

$$\hat{\bar{K}}_{t,s} = (1-\tau)\hat{\bar{K}}_{t-1,s} + \tau\hat{I}_{t,s} + \tau(1+\beta)S''_s\hat{\varepsilon}^I_{t,s} \tag{1}$$

where $\varepsilon^I_{t,s}$ is an AR(1) investment shock in region s and τ is the national depreciation rate and S''_s is a parameter that governs regional investment adjustment costs. A large S''_s implies that adjusting an investment schedule is costly in region s.

Regional labor demand is given by

$$\hat{L}_{t.s} = -\hat{w}_{t,s} + (1 + \tfrac{1}{\psi_s})\hat{r}^k_{t,s} + \hat{\bar{K}}_{t-1,s} \tag{2}$$

where $r^k_{t,s}$ is the real rental rate of capital in region s and ψ_s is a parameter that captures regional utilization costs of capital. A large ψ_s infers that capital utilization costs are high in region s. The regional economy's resource constraint and production function take the form:

$$\hat{Y}_{t,s} = C_{y,s}\hat{C}_{t,s} + I_{y,s}\hat{I}_{t,s} + \frac{r^k \bar{k}_{y,s}}{\psi_s}\hat{r}^k_{t,s} + g_s\hat{\varepsilon}^G_t \tag{3}$$

$$\hat{Y}_{t,s} = \phi_s\hat{\varepsilon}^a_{t,s} + \phi_s\alpha_s\hat{\bar{K}}_{t-1,s} + \frac{\phi_s\alpha_s}{\psi_s}\hat{r}^k_{t,s} + \phi_s(1-\alpha_s)\hat{L}_{t,s} \tag{4}$$

where $C_{y,s}$ and $I_{y,s}$ are the steady state ratio of regional consumption and regional investment to regional output. The national fiscal shock, ε^G_t is an AR(1) national shock that adds to regional demand proportionately, where g_s adds up to one for all s. In the production function ϕ_s resembles a regional fixed cost of production and is assumed to be greater than one, α_s is the share of capital used in production in region s and $\varepsilon^a_{t,s}$ is an AR(1) stationary productivity shock in region s.

The regional consumption and investment transition equations are:

$$\hat{C}_{t,s} = \frac{h_s}{1+h_s}\hat{C}_{t-1,s} + \frac{1}{1+h_s}E_t[\hat{C}_{t+1,s}] - \frac{1-h_s}{(1+h_s)\sigma_{c,s}}\left(\hat{R}_t - E_t[\hat{\pi}_{t+1,s}]\right) + \hat{\varepsilon}^b_{t,s} \tag{5}$$

$$\hat{I}_{t,s} = \frac{1}{1+\beta}\hat{I}_{t-1,s} + \frac{\beta}{1+\beta}E_t[\hat{I}_{t+1,s}] + \frac{1}{(1+\beta)S''_s}\hat{q}_{t,s} + \hat{\varepsilon}^I_{t,s} \tag{6}$$

where $\hat{\varepsilon}^b_{t,s}$ and $\hat{\varepsilon}^I_{t,s}$ are exogenous stochastic stationary processes that affect the short term dynamics of consumption and investment in region s. $q_{t,s}$ is the relative price of capital in region s, β is the national discount rate and h_s is a measure of habit consumption in region s. Finally, R_t is the national interest rate and $\pi_{t,s}$ is the inflation rate in region s.

The model yields a regional Phillips curve equal to:

$$\hat{\pi}_{t,s} = \frac{\beta}{1+\beta\iota_{p,s}} E_t[\hat{\pi}_{t+1,s}] + \frac{\iota_{p,s}}{1+\beta\iota_{p,s}} \hat{\pi}_{t-1,s} + \frac{(1-\beta\xi_{p,s})(1-\xi_{p,s})}{(1+\beta\iota_{p,s})\xi_{p,s}} (\alpha_s \hat{r}^k_{t,s} + (1-\alpha_s)\hat{w}_{t,s} - \hat{\varepsilon}^a_{t,s}) + \hat{\varepsilon}^p_{t,s} \tag{7}$$

where $\xi_{p,s}$ is the degree of price stickiness in region s, $\iota_{p,s}$ is the degree of price indexation to last period's inflation rate in region s and $\hat{\varepsilon}^p_{t,s}$ is an exogenous processes affects the price mark up over marginal cost in region s.

Wages in the economy evolve according to:

$$\hat{w}_{t,s} = \frac{\beta}{1+\beta} E_t[\hat{w}_{t+1,s}] + \frac{1}{1+\beta}\hat{w}_{t-1,s} + \frac{\beta}{1+\beta} E_t[\hat{\pi}_{t+1,s}] - \frac{1+\beta\iota_{w,s}}{1+\beta}\hat{\pi}_{t,s} + \frac{\iota_{w,s}}{1+\beta}\hat{\pi}_{t-1,s} - \frac{(1-\beta\xi_{w,s})(1-\xi_{w,s})}{(1+\beta)\left(1+\nu_{l,w}\frac{1+\lambda_w}{\lambda_w}\right)\xi_{w,s}} \left(\hat{w}_{t,s} - \nu_{l,s}\hat{L}_{t,s} - \frac{\sigma_{c,s}}{1-h_s}(\hat{C}_{t,s} - h_s\hat{C}_{t-1,s})\right) + \hat{\varepsilon}^w_{t,s} \tag{8}$$

where $\xi_{w,s}$ is the degree of wage stickiness in region s, $\iota_{w,s}$ is the degree of wage indexation to last period's inflation rate and $\hat{\varepsilon}^w_{t,s}$, is an exogenous process that affects monopoly power households hold over labor in region s.

The entrepreneurial return on capital is characterized by

$$\hat{\hat{R}}^k_t - \hat{\pi}_{t,s} = \frac{1-\tau}{1-\tau+r^k}\hat{q}_{t,s} + \frac{r^k}{1-\tau+r^k}\hat{r}^k_{t,s} - \hat{q}_{t-1,s} \tag{9}$$

Regional variables are aggregated up to create national variables using the following weighted linear averaging rule:

$$N\hat{A}T_t = \sum_{s=1}^{n} \omega_s R\hat{E}G_{t,s} \tag{10}$$

where $\sum_{s=1}^{n}\omega_s = 1$ and NAT_t and REG_t includes variables for output, investment, consumption, inflation, labor, wage inflation, capital stock and capital prices.

The Linearized Taylor Equation that determines the national nominal interest rate is:

$$\hat{R}_t = \rho \hat{R}_{t-1} + (1-\rho)\left[r_{\pi_1}\hat{\pi}_t + r_{y_1}\hat{Y}_t\right] + \hat{\varepsilon}_t^r + \sum_{k=1}^{5} \hat{\varepsilon}_{k,t-k}^r \tag{11}$$

where π_t is the national inflation rate expressed in deviation way from the central bank's objective of π, Y_t in the national output gap, $\hat{\varepsilon}_t^r$ is a standard unanticipated monetary policy shock, and $\hat{\varepsilon}_{k,t-k}^r$ are anticipated monetary policy shocks known to agents at time $t-k$.

The finance market is characterized by two equations, the first being the spread of the return on national capital over the risk free rate:

$$\hat{S}_t \equiv E_t\left[\hat{\tilde{R}}_{t+1}^k - \hat{R}_t\right] = \chi\left(\hat{q}_t + \hat{\bar{K}}_t - \hat{n}_t\right) + \hat{\varepsilon}_t^F \tag{12}$$

where χ is the elasticity of the spread with respect to the national capital to national net worth ratio and $\hat{\varepsilon}_t^F$ is a national finance shock that affects the riskiness of entrepreneurs and thus the riskiness of national banks being paid back in full.

The second financial equation contains the evolutional behavior of entrepreneur net worth:

$$\hat{n}_t = \delta_{\tilde{R}^k}(\hat{\tilde{R}}_t^k - \hat{\pi}_t) - \delta_R(\hat{R}_{t-1} - \hat{\pi}_t) + \delta_{qK}(\hat{q}_{t-1} + \hat{\bar{K}}_{t-1}) + \delta_n \hat{n}_{t-1} - \delta_\sigma \hat{\varepsilon}_{t-1}^F \tag{13}$$

where the δ coefficients are functions of the steady state values of the loan default rate, entrepreneur survival rate, the steady state variance of the entrepreneurial risk shocks, the steady state level of revenue lost in bankruptcy, and the steady state ratio of capital to net worth. The value of χ, which will be estimated, will determine the steady state level of the variance of the exogenous risk shock, the steady state value of the percentage of revenue lost in bankruptcy and the steady state level of leverage. Therefore, the value of χ will determine the values of the δ coefficients.

In all, the regional DSGE model has five region specific exogenous processes in each region s. Each region specific process is made up of a regional specific AR(1) process ($\hat{u}_{s,t}^i$)

and a national exogenous AR(1) shock process ($\hat{\varepsilon}_t^i$). Thus each regional shock is modeled as:

$$\hat{\varepsilon}_{t,s}^i = \zeta \hat{\varepsilon}_t^i + \hat{u}_{s,t}^i \tag{14}$$

All regional processes ($\hat{u}_{s,t}^i$) are assumed to be AR(1) with i.i.d. shocks of mean zero and standard deviation $\sigma_{i,s}$ and autocorrelation parameters $\rho_{i,s}$, where $i = \{a, b, I, p, w\}$. With this setup the value of ζ encompasses the national model (when $\zeta = 1$ and all $\sigma_{i,s} = 0$). If however $\zeta = 0$, then each region is only tied together by the national financial sector, national fiscal and monetary policy.

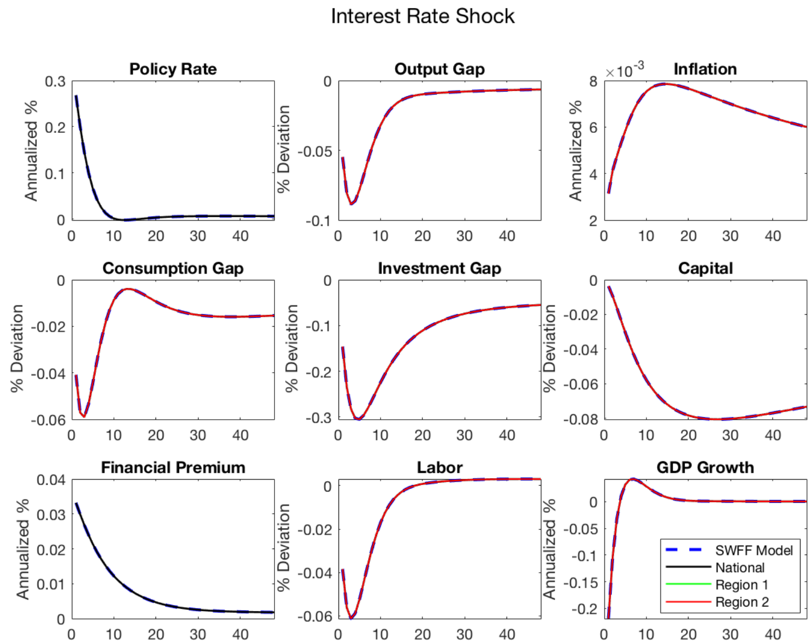
In addition there are three purely national shocks. Two of these shocks (finance and fiscal) are assumed to be AR(1) and the contemporaneous unanticipated monetary policy shock is assumed to be white noise with a standard deviation equal to σ_r. Finally, there are five anticipated monetary policy shocks which are assumed to have a mean of zero and a standard deviation equal to $\frac{\sigma_r}{5}$.

2.3 Comparing the Regional model to a "National" DSGE Model

The SWFF model of Del Negro and Schorfheide (2013) is nested inside the above regional DSGE model if one assumes all regions are of equal size and homogeneous. If I assume that there are two homogeneous regions of equal size, then all national shocks will have the same effect and magnitude on national values as they would have on the SWFF model. Further, both regions would have reacted to the national shocks in the same way as the aggregated national variables would. This is illustrated in Figure 1 which plots the impulse response functions (IRFs) of the Regional DSGE model and the nested national SWFF DSGE model for a monetary shock when both models are calibrated to the posterior mean estimates of Del Negro and Schorfheide (2015). The regional DSGE model is assumed to have two identical regions of equal size ($n = 2$ & $\omega_1 = \omega_2 = .5$).

The Homogeneous regional DSGE model dynamics differ when there is a regional shock to one of the regions. Figure 2 plots the IRFs of a positive regional investment shock to region 1 and compares it to a positive investment shock in the SWFF model. We see that the positive regional investment shock to region 1 creates an economic boom in region 1

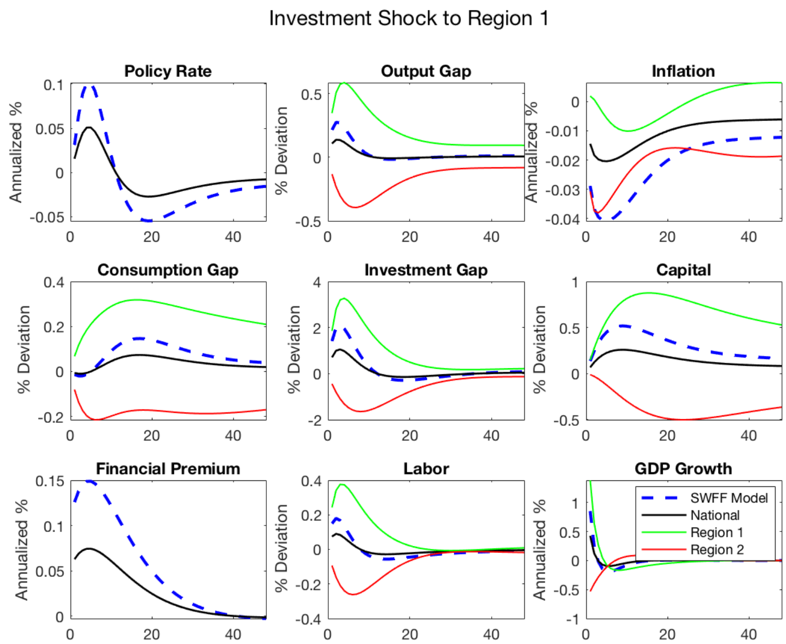
Figure 1: IRFs of Homogeneous Regions



that has similar dynamics to the economic boom in the SWFF model. However, in region 2 we see an economic decline in output, investment and consumption. This is because of two factors. First, because the national output gap is positive, the monetary authority raises the policy rate. This acts as a monetary contraction in region 2 that saw no exogenous economic shock. Second, because of the higher return on capital in region 1 and the higher national risk premium investment and financial capital flows into region 1 away from region 2. This creates a positive capital gap in region 1 and a negative capital gap in region 2. When the regions are aggregated, the regional investment shock causes a small increase in the national capital stock.

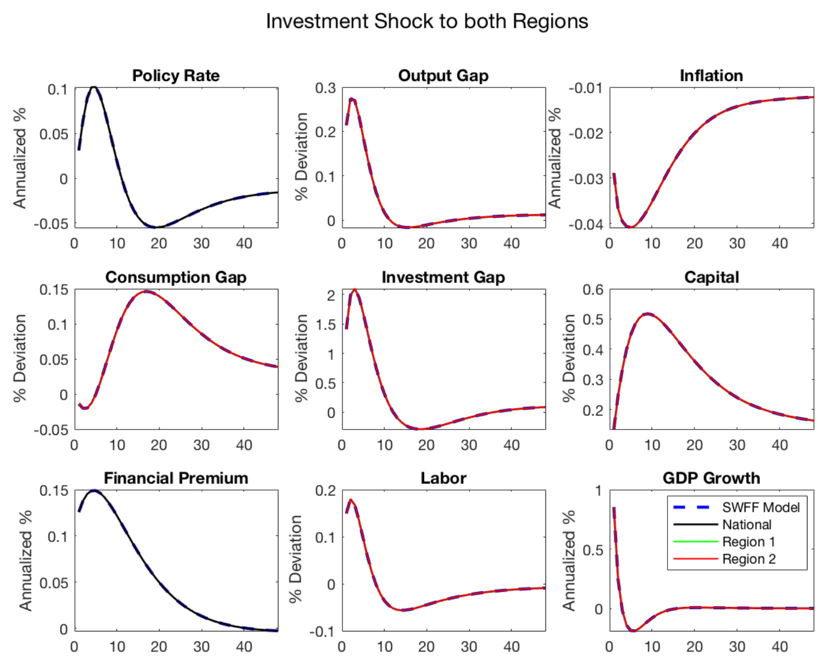
In all, the positive investment shock in region 1 acts as a negative policy and financial shock in region 2. Notice that the policy rate and financial premium is closer to their steady state values in the regional DSGE model when compared to the SWFF model. This is because the impact to the national output gap, national inflation rate and the national capital stock is smaller in the regional DSGE model, thus causing less of an endogenous response to the policy rate and the financial spread.

Figure 2: IRFs of Homogeneous Regions



If, however, both regions 1 and 2 encounter positive regional investment shocks, we see similar results to those in Figure 1 where the dynamics of the regional model are identical to the dynamics of the SWFF model as illustrated in Figure 3. If however, any heterogeneity exists in the regions' structural parameters, national shocks and identical regional shocks will cause the regions' dynamics to differ and the national dynamics to differ from the SWFF model. A circumstance that I demonstrate in detail in Section 4.

Figure 3: IRFs of Homogeneous Regions



3 Estimation and Data

To capture any regional heterogeneity that might exist, I estimate the regional model using specific data that matches particular states in the model. The state space representation of the solved model consists of a transition equation, which is calculated by solving the linearized system of the model for a given set of structural model parameters (θ):

$$S_t = G(\theta)S_{t-1} + H(\theta)v_t \quad \text{where } v_t \sim NID(0, I_m) \tag{15}$$

and the measurement equation:

$$X_t = \Lambda S_t + e_t \quad \text{where } e_t \sim NID(0, R) \tag{16}$$

Here X_t are the economic data sets, Λ is a matrix matching the observed data to the definitions of the model's state variables S_t and e_t is a vector that captures measurement error in the data.[5] The matrices $G(\theta)$ and $H(\theta)$ are functions of the model's structural parameters and v_t is a vector of the i.i.d. components of the model's exogenous processes $\hat{\varepsilon}_t$.

In order to estimate the regional model I must define what regional and national data I will use and how many regions (n) will exist in the model. I opt to estimate the regional model by aggregating state level data to the the four census regions of the United States. As a result $s = \{NE, S, MW, W\}$ and $n = 4$ in the equations of Section 2.[6]

For each region I choose to estimate the model using eight regional data series that are calculated by aggregating state level data to create a census region measure. These measures include an annualized and quarterly measure of per capita[7] GDP growth, an annualized and quarterly measure of the growth rate of the regional GDP deflator[8], an annualized growth rate of consumption and investment per capita[9], labor income share[10] and employment per

[5]For more detail on Bayesian DSGE-Reg estimation techniques please see An and Schorfheide (2007).

[6]A graph delineating the states in each census region can be found in Figure 20 of the appendix.

[7]Per capita variables are obtained by dividing regional variables by regionally aggregated state civilian non-institutionalized population provided by the BLS.

[8]Defined as $\frac{Nominal\, GDP_{region}\ in\ current\ dollars}{Real\, GDP_{region}\ in\ chained\ 2012\ dollars}$

[9]The BEA does not report a measure of expenditure investment for each state. I create a proxy dataset by taking each state's annual nominal GDP and subtracting each state's annual nominal personal consumption (reported by the BEA) and each state's industry nominal GDP for the Gov't sector. I aggregate this nominal measure to create a nominal census region investment expenditure level and I then deflate it by the calculated regional GDP deflator.

[10]Defined as the percentage of Total Wage income to Total Income for each region.

capita.[11] I opt to use a mixed frequency and missing value dataset because state level GDP does not begin until 2005, while an annual measure begins in 1997.[12] Further, state level measure of consumption (and as a result the proxy investment measure) are only reported at the annual frequency by the BEA.

In addition, to estimate the model I also use the eight national data measures used in the SWFF model estimation. These include real per capita GDP growth, quarterly GDP deflator growth, real consumption and investment growth per capita, real wage growth, the federal funds rate, the spread between BAA corporate bond rate and the 10-year treasury as well as aggregate hours worked.[13] The entire model is estimated over the time frame of 1998Q1 to 2019Q2. Since the estimation window includes time periods that the zero lower bound binds, I use Federal Fund Rate market expectations, as measured by OIS rates, following the approach described in Del Negro et al. (2013) as an identifier of the five anticipated monetary policy shock in the model. A complete summary of each regional data series and national data series is in included in Table 1.

Figure 4 plots the regional and national variation in each of the eight regional data series. We can see there is a clear trend amongst all four regions and the national data but still a significant amount of variation between them to help identify the regional structural parameters of the regional DSGE model.

[11] Since there is not a measures of aggregate hours worked in each state, I use state employment instead. As in Smets and Wouters (2003), I assume that in any given period only a constant fraction, ξ_e, of firms are able to adjust employment to its desired labour input. This translates to the following auxiliary equation for employment in the model:

$$\hat{E}_{t,s} = \beta \hat{E}_{t+1,s} + \frac{(1-\beta\xi_{e,s})(1-\xi_{e,s})}{\xi_{e,s}}(\hat{L}_{t,s} - \hat{E}_{t,s}) \tag{17}$$

where $E_{t,s}$ denotes the number of people employed in region s.

[12] Rondeau (2012) found that using long annual frequency data produces less bias estimates than short quarterly data.

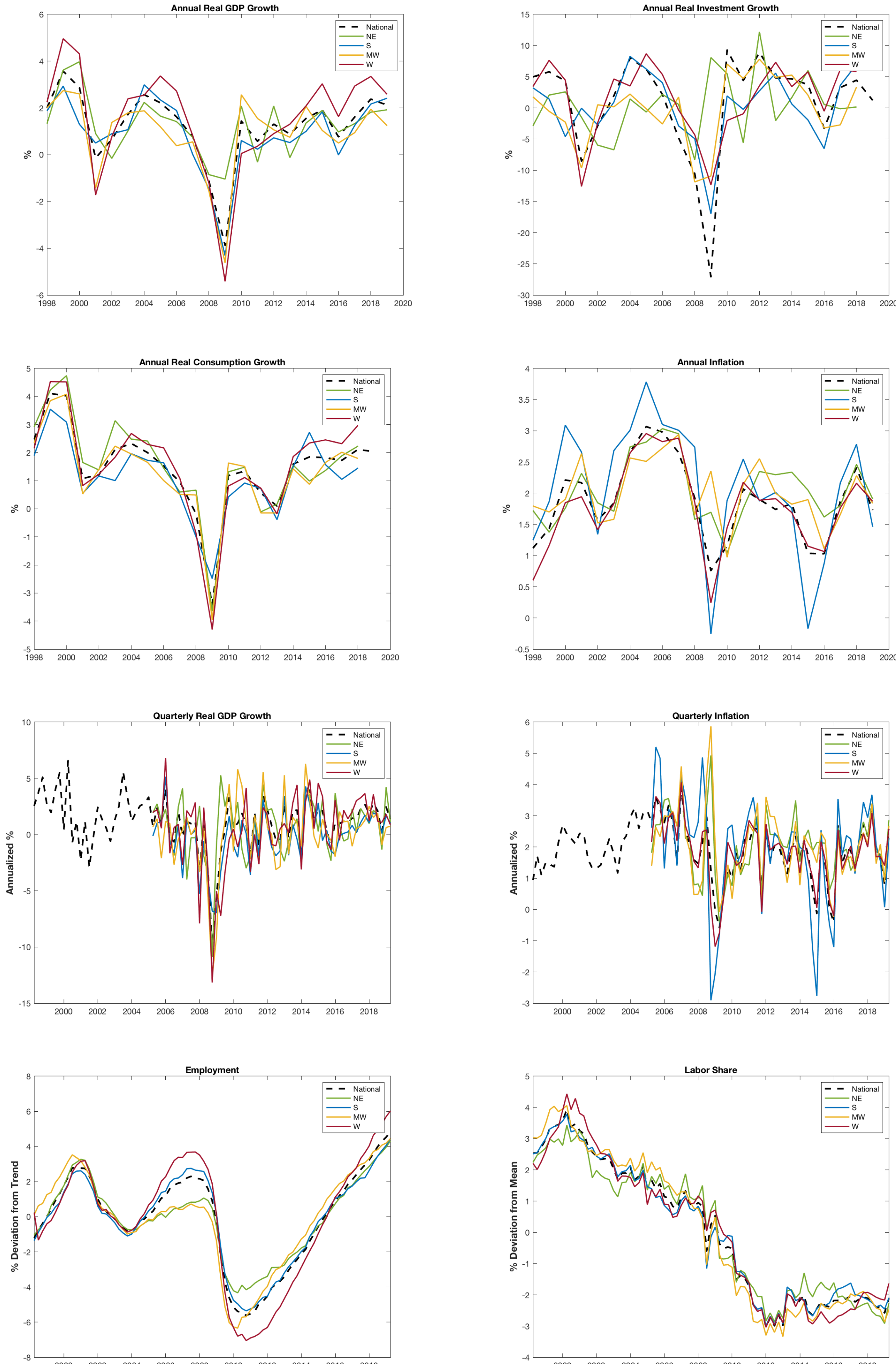
[13] All variables reported at the monthly frequency are averaged to create a quarterly observation.

Table 1: Data Series used in Estimation

Data Set	Transform	Dates	Freq	FRED Code
Regional Variables				
Annual Real GDP Growth	Demean	1998Q1-2019Q1	A	$AKRGSP$
Quarterly Real GDP Growth	Demean	2005Q1-2019Q2	Q	$AKRQGSP$
Annual Inflation	Demean	1998Q1-2019Q1	A	$AKNGSP/AKRGSP$
Quarterly Inflation	Demean	2005Q1-2019Q2	Q	$AKNQGSP/AKRQGSP$
Annual Real Consumption Growth	Demean	1998Q1-2018Q1	A	$AKPCE$
Annual Real Investment Growth	Demean	1998Q1-2018Q1	A	$AKNGSP-AKPCE-AKGOVNGSP$
Total Income Share to Wages	Demean	1998Q1-2019Q2	Q	$AKWTOT/AKOTOT$
Total Employment	Lin Detrend	1998Q1-2019Q2	M	$AKNA$
National Variables				
Quarterly Real GDP Growth	Demean	1998Q1-2019Q2	Q	$GDPC1$
Quarterly Inflation	Demean	1998Q1-2019Q2	Q	$A191RI1A225NBEA$
Quarterly Real Consumption Growth	Demean	1998Q1-2019Q2	Q	$PCEC96$
Quarterly Real Investment Growth	Demean	1998Q1-2019Q2	Q	$GPDIC1$
Federal Funds Rate	Calibrated	1998Q1-2019Q2	M	$EFFR$
Financial Spread	Calibrated	1998Q1-2019Q2	M	$BAA10Y$
Hours Worked	Lin Detrend	1998Q1-2019Q2	Q	$HOANBS$
Wage Inflation	Demean	1998Q1-2019Q2	Q	FRBATL Wage Tracker
Anticipated Monetary Policy				
Expectation of Fed Funds Rate +1Q	Calibrated	2008Q4-2019Q2	M	OIS Data
Expectation of Fed Funds Rate +2Q	Calibrated	2008Q4-2019Q2	M	OIS Data
Expectation of Fed Funds Rate +3Q	Calibrated	2008Q4-2019Q2	M	OIS Data
Expectation of Fed Funds Rate +4Q	Calibrated	2008Q4-2019Q2	M	OIS Data
Expectation of Fed Funds Rate +5Q	Calibrated	2008Q4-2019Q2	M	OIS Data

Note: The Table shows the FRED codes for Alaska only for brevity. In actuality, one would sum up all the state level statistics for the states in each region to create a census region level. All nominal variables are deflated using the regional or national GDP deflator. All variables are put in per capita terms by dividing by the civilian non-institutionalized population (CNP) provided by the BLS under the data code *ststdsadata*.

Figure 4: Regional Data Series and their National Level Counterpart



In all there are eight regional data series for each of the four regions (32 series total), eight national series and five anticipated monetary policy series. The individual measurement equations that relate to the model variables that appear in equation 16 are listed below.

$$\text{National GDP Growth} = 100(\hat{Y}_t - \hat{Y}_{t-1}) + e_t^{gdp} \tag{18}$$

$$\text{National Inflation} = 400(\hat{\pi}_t) + e_t^{inf} \tag{19}$$

$$\text{National Consumption Growth} = 100(\hat{C}_t - \hat{C}_{t-1}) \tag{20}$$

$$\text{National Investment Growth} = 100(\hat{I}_t - \hat{I}_{t-1}) \tag{21}$$

$$\text{Federal Funds Rate} = 400(R^* + \hat{R}_t) \tag{22}$$

$$\text{Spread} = 400(S^* + \hat{S}_t) \tag{23}$$

$$\text{Hours Worked} = 100(\hat{L}_t) + e_t^{hours} \tag{24}$$

$$\text{Wage Inflation} = 400(\hat{W}_t - \hat{W}_{t-1} + \hat{\pi}_t) + e_t^{wages} \tag{25}$$

$$\text{Annual GDP Growth}_s = 100(\hat{Y}_{t,s} - \hat{Y}_{t-4,s}) + e_t^{gds_s} \tag{26}$$

$$\text{Quarterly GDP Growth}_s = 100(\hat{Y}_{t,s} - \hat{Y}_{t-1,s}) \tag{27}$$

$$\text{Annual Inflation}_s = 100(\hat{\pi}_{t,s} + \hat{\pi}_{t-1,s} + \hat{\pi}_{t-2,s} + \hat{\pi}_{t-3,s}) + e_t^{inf_s} \tag{28}$$

$$\text{Quarterly Inflation}_s = 400(\hat{\pi}_{t,s}) \tag{29}$$

$$\text{Annual Consumption Growth}_s = 100(\hat{C}_{t,s} - \hat{C}_{t-4,s}) + e_t^{cons_s} \tag{30}$$

$$\text{Annual Investment Growth}_s = 100(\hat{I}_{t,s} - \hat{I}_{t-4,s}) + e_t^{inv_s} \tag{31}$$

$$\text{Labor Share of Income}_s = 100(\hat{L}_{t,s} + \hat{W}_{t,s} - \hat{Y}_{t,s}) \tag{32}$$

$$\text{Employment}_s = 100(\hat{E}_{t,s}) \tag{33}$$

where s refers to region and is equal to $s = \{NE, S, MW, W\}$. All data variables are measured in percent and are transformed according to Table 1. In order to identify the anticipated monetary policy shocks, I follow Del Negro and Schorfheide (2013) and augment the measurement equations with the following expectations for the Policy Rate R_t

$$\text{Federal Funds Rate}^{Exp}_{t,t+1} = 400R^* + \Lambda_R G(\theta)^1 S_t \tag{34}$$

$$\vdots \tag{35}$$

$$\text{Federal Funds Rate}^{Exp}_{t,t+5} = 400R^* + \Lambda_R G(\theta)^5 S_t \tag{36}$$

where Federal Funds $\text{Rate}^{Exp}_{t,t+k}$ is the market's time t expectations for the policy rate k quarters ahead and Λ_R is the row of Λ corresponding to the policy rate.

3.1 Structural and Steady-State Parameter Priors

The structural parameter marginal priors are in accordance to the Del Negro and Schrofheide (2013) priors. Some structural parameters are fixed including the national discount rate, national depreciation rate, and the steady state share of consumption, investment and government to total regional output. The latter parameters being calibrated to the average proportion of regional consumption and national government purchases of annual regional GDP over the sample period. The discount rate is fixed to a level that corresponds to an annualized R^* of 3%.

The model's steady state default rate is set to .0075 which corresponds to Bernanke, Gertler, Gilchrist (1999) annualized default rate of 3%. The quarterly survival rate of entrepreneurs is fixed at .99 which corresponds to an average entrepreneur life of 68 quarters or 17 years. The steady state spread is calibrated to 230 basis points which is roughly the sample median spread between the BAA corporate bond yield and 10 year Treasury bond yield.

All estimated structural parameters are assumed to be equal across the four regions and are similar to those used in estimation by Gelfer (2019) and Del Negro and Schrofheide (2013) in the SWFF model. One parameter prior of note is the economic size/weight of each census region (ω_s). It is assumed to be centered around the yearly mean share of regional CNP population to national CNP population. Its prior is uniformly distributed with bounds set equal to +/- one standard deviation of the sample regional to national CNP ratio.[14] Finally,

[14] ω_s is estimated for three of the four census regions and the fourth is assumed to be equal to $1 - \sum_{s=1}^{3} \omega_s$.

all measurement error is calibrated so that e_t^{data} has a variance equal to 10% of its sample variance for each respective data set. A complete list of calibrated structural parameters as well as the prior mean, standard deviation and description of the estimated structural parameters can be found in Table 5 and Table 6 of the appendix.

3.2 Estimation Technique

The estimated model has a large number of structural parameters and a likelihood function with many peaks and cliffs. Therefore, it is difficult to search for a posterior mode and a proposal distribution around that mode. As a result I employ a random walk Metropolis Hastings with a log adaptive proposals algorithm [Shaby and Wells (2010)] to ensure the posterior mode is found and searched around. The adaptive Metropolis algorithm used follows the following steps:

1. Specify Initial values of $\theta^{(0)}$, $\bar{c}$ and Σ
2. Repeat for g=1...G

   2.1 Solve the DSGE model numerically and obtain $G(\theta^{(g-1)})$ and $H(\theta^{(g-1)})$

   2.2 Propose $\theta^* = \theta^{(g-1)} + \bar{c}\,\varepsilon_\ell$ where $\varepsilon_\ell \sim NID(0, \Sigma)$

   2.3 Calculate $P(X_{1:T}|\theta^*)$ using the Missing Value Kalman Filter

   2.4 Calculate the acceptance probability ω

$$\omega = min\left\{\frac{P(X_{1:T}|\theta^*)P(\theta^*)}{P(X_{1:T}|\theta^{(g-1)})P(\theta^{(g-1)})}, 1\right\}$$

   2.5 $\theta^{(g)} = \theta^*$ with probability ω and $\theta^{(g)} = \theta^{(g-1)}$ with probability $(1-\omega)$

   2.6 Every k draws of g, adapt proposal distribution Σ and jump size $\bar{c}$

      2.6.1 Calculate the acceptance probability in last k draws (r_t)

      2.6.2 Calculate $\hat{\Sigma} = \frac{1}{k-1}(\Theta_{(:,g-k+1:g)} - \bar{\Theta})(\Theta_{(:,g-k+1:g)} - \bar{\Theta})'$

      2.6.3 Calculate $\gamma_1 = \frac{1}{g^{c_1}}$ and $\gamma_2 = c_0\gamma_1$

As a result the implied prior on the fourth census region is larger than the other three.

2.6.4 Set new jump size $log(\bar{c}^2_{(t+1)}) = log(\bar{c}^2_{(t)}) + \gamma_2(r_t - r_{optimal})$

2.6.5 New jump size equals $\bar{c} = exp(log(\bar{c}^2_{(t+1)})^{0.5}$

2.6.6 Set New proposal distribution $\Sigma_{(t+1)} = \Sigma_{(t)} + \gamma_1(\hat{\Sigma} - \Sigma_{(t)})$

2.6.7 New proposal distribution equals $\Sigma = \Sigma_{(t+1)}$

3. Return $\Theta = \{\theta^{(g)}\}_{g=1}^{G}$

The intuition behind the adaptive part of the algorithm is as follows: it calculates the acceptance rate for the last k draws. If it accepts too often, it increases $\bar{c}$, if it accepts too rarely, it decreases $\bar{c}$. It then computes the sample covariance matrix for the last k samples, and makes the the proposal covariance matrix Σ look more like the sample covariance matrix. As g gets larger and larger γ_1 and γ_2 gets smaller and smaller and thus the adjustments to $\bar{c}$ and Σ become smaller and smaller. Andrieu and Thoms (2008) and Shaby and Wells (2010) found that an adaptive proposal algorithm like the one above converges to the stationary posterior distribution quicker and more accurately than a MH algorithm with a stationary proposal distribution. This result was magnified when the number of parameters in θ is large as is the case in this paper.

To initialize the proposal distribution (Σ) and parameter values ($\theta^{(0)}$), I first search for each region's structural parameters that maximize the SWFF model as if it were the only region in the nation. I then use these regional structural parameters and the average of the"national" structural parameters as the initial parameter estimates and an initial proposal matrix whose diagonal elements are equal to the prior variance of each estimated parameter of the Regional DSGE model.

The calibrations regarding the adaptive proposal steps include the acceptance target rate which is set at 23.5%, an initial $\bar{c}$ which is set to .1 and an adjustment rate k which is set at 100. The adjustment rate k determines how many iterations take place between changing $\bar{c}$ and Σ as described in step 2.6. Further, as in Shaby and Wells (2010), C_0 is set at 10 and C_1 at 0.5. The posterior estimates of this paper are based on 400,000 draws, 2 parallel chains of 250,000 draws discarding the initial burn-in period of 50,000 iterations.

4 Estimation Results

In this section, the empirical results of the estimated regional model are presented and discussed. I find significant heterogeneity amongst the regional posterior estimates of the structural parameters as well as the estimated regional states of the model. The regional and national business cycle dynamics are discussed in this section with the aid of forecast error variance decomposition (FEVD) and national and regional impulse response functions (IRFs). Finally, I compare the estimated regional DSGE model of this paper to the estimated national SWFF model of Del Negro and Schorfhiede (2013), which is nested in the regional DSGE model.

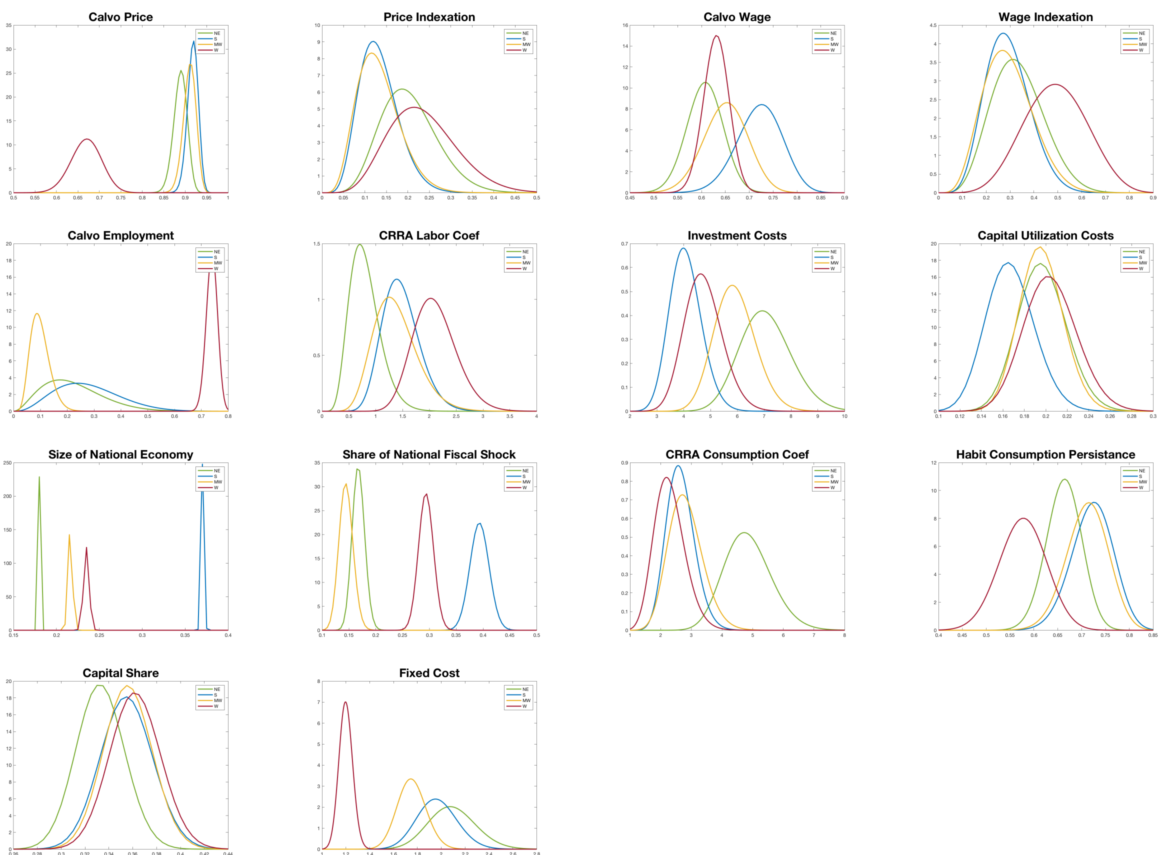
4.1 Structural Parameters and Estimated State Variables

We can examine some characteristics and trends across the region's parameter estimates by examining Figure 5. This figure plots the posterior distributions when fitted to a beta or gamma distribution for a select number of structural parameters of the regional DSGE model. A few observations emerge. First, the regional Calvo price estimates (ξ_p) are similar and high (0.89-.92) across three of the four regions, while the West region is estimated to be significantly lower at 0.62. Further, Calvo wage (ξ_w) and wage indexation (ι_w) estimates are estimated with some but not significant heterogeneity across the regions. However, employment rigidities (ξ_e) are estimated to be significantly small in three of the four regions (0.1-0.28) but quite large in the West region (0.74).

Investment costs (S'') are estimated with significant heterogeneity, with the Northeast having the largest and the South having the smallest adjustment costs. Capital share (α) and capital utilization costs (ψ) for the four regions are estimated with little to no heterogeneity but remain in traditional ranges for country-wide estimated DSGE models. With respect to the utility functions coefficient's across the four regions, I see large estimates of all four regions' consumption CRRA coefficient (σ_c) when compared to other country wide model estimates. While the CRRA coefficient on labor (ν_l) is estimated in the standard range of other models with some heterogeneity existing between the Northeast and the South. The habit consumption parameter (h), is estimated around the typical 0.7 value for three of the four regions and 0.6 for the West region.

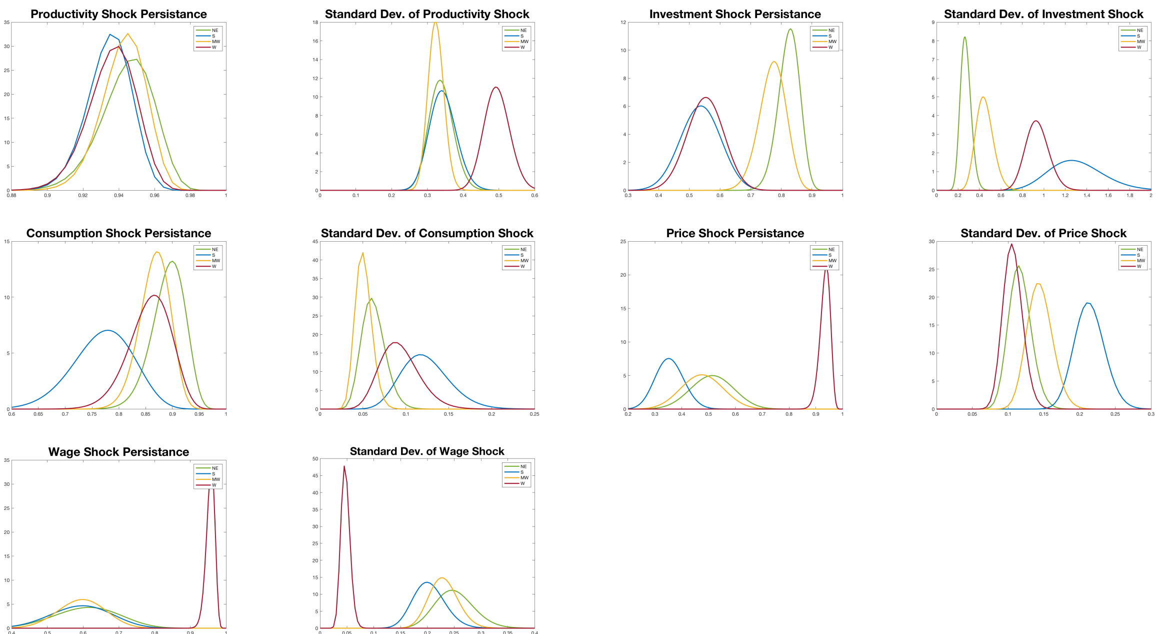
National Parameter estimates of the Taylor Rule policy parameters are found in line with estimates of other SWFF models, with interest rate policy inertia (ρ) estimated to be around 0.9 and response to contemporaneous inflation (r_{π_1}) and the output gap (r_{y_1}) estimated to be 1.44 and 0.06 respectively. The dynamics around the national financial accelerator are similar with the estimates of Del Negro et al. (2013), with the spread elasticity (χ) estimated at 0.061 and the finance shock (ρ_F) estimated to be very persistence and posses a similar distributional magnitude (σ_F). All posterior estimates for the structural parameters of the model are tabulated in Table 7.

Figure 5: Regional Structural Parameters



Turning to the exogenous shock estimates which are reported in Table 8 and plotted by type and region in Figure 6, I again find significant heterogeneity across the four regions. Most notably, price and wage shock persistence is estimated to be significantly higher in the West region, while shock persistence in investment and consumption shocks are estimated to be much higher in the Northeast and Midwest regions. While, the exogenous shock parameters with regard to productivity shocks show little to no heterogeneity across the four regions.

Figure 6: Regional Exogenous Shock Parameters

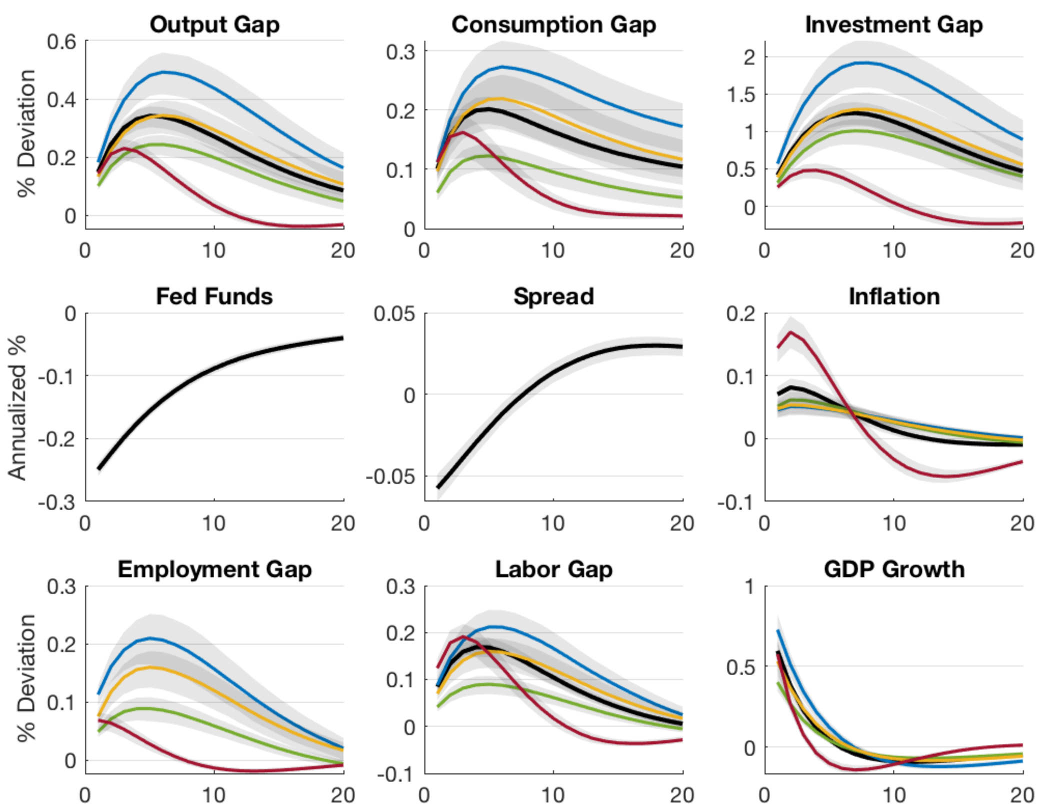


4.2 Internal Dynamics of the Model

In this subsection, I illustrate some of the key economic dynamics at work inside the model. I do so with the help of impulse response functions and variance decompositions of the shocks hitting the regional and national economies. Let's first look at the three national shocks that unite the regions under a central monetary authority, fiscal authority and national financial/banking system.

Figure 7 plots the model's implied IRFs of major macroeconomic variables for each region as well as the national level from an unanticipated, negative 25 basis points monetary shock. The dynamics are those familiar from other DSGE studies. The fall in the policy rate, leads to an expansion in the real economy (output, consumption and investment) for all four regions and nationally. However, its impact is greatest for states in the Southern census region and smallest for states in the Western census region. Growth in National GDP remains above trend for up to a year after the shock with hours working increasing in a humped shaped fashion nationally and for all four regions. Employment gains for the shock are smallest in the West and Northeast regions. National inflation increases by roughly 10 basis points. Regional inflation also increases by a similar margin for all regions except the West region. Instead, inflation in the West region increases by roughly 15 basis points and remains above all other regions for nearly 6 quarters. This is due to the relatively lower estimated price rigidities in the West region. Anticipated monetary shocks have similar dynamics except they are delayed by the anticipation period.

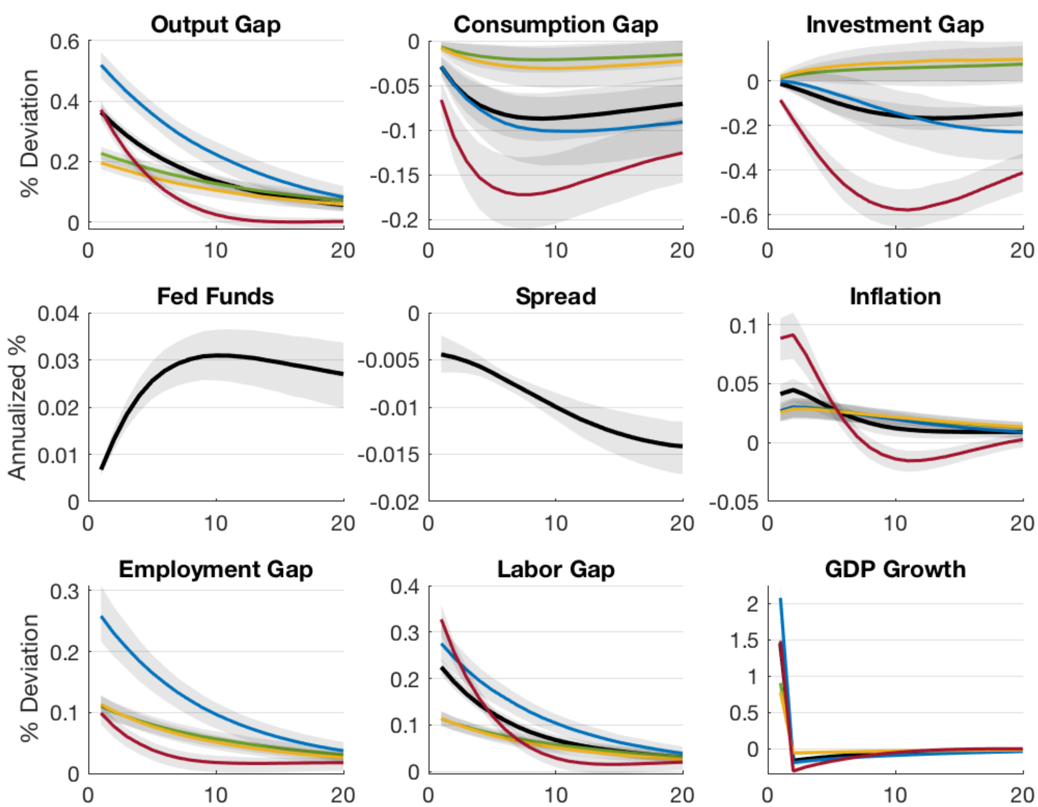
Figure 7: Responses to Monetary Policy Shock (-25 basis points)



Note: The figure plots the median impulse response estimates of the % deviation from steady state of output, consumption, investment, labor and employment for the four regions and the National level. Further, the annualized % deviations from steady state for the policy rate, financial spread, inflation and GDP growth are also plotted. The Northeast region is in green, the South region is in blue, the Midwest in yellow, the West in red and the black line is the national variable. The shaded areas represent the 70% credible interval for each series.

Figure 8 reports the IRFs of the national government spending shock, in terms of dynamics, the shock boosts GDP growth, employment and hours in the very short run for all regions. The shock generates a small amount of national inflationary pressure and little to no movement in the national interest rates. There is also the traditional crowding out of private consumption and investment at the national levels. However, this crowding out mostly takes place in the Western and Southern census regions and is negligible in the Northeast and Midwest regions. Further, the positive fiscal shock increases total output the most in the Southern and Western regions.

Figure 8: Responses to Fiscal Policy Shock



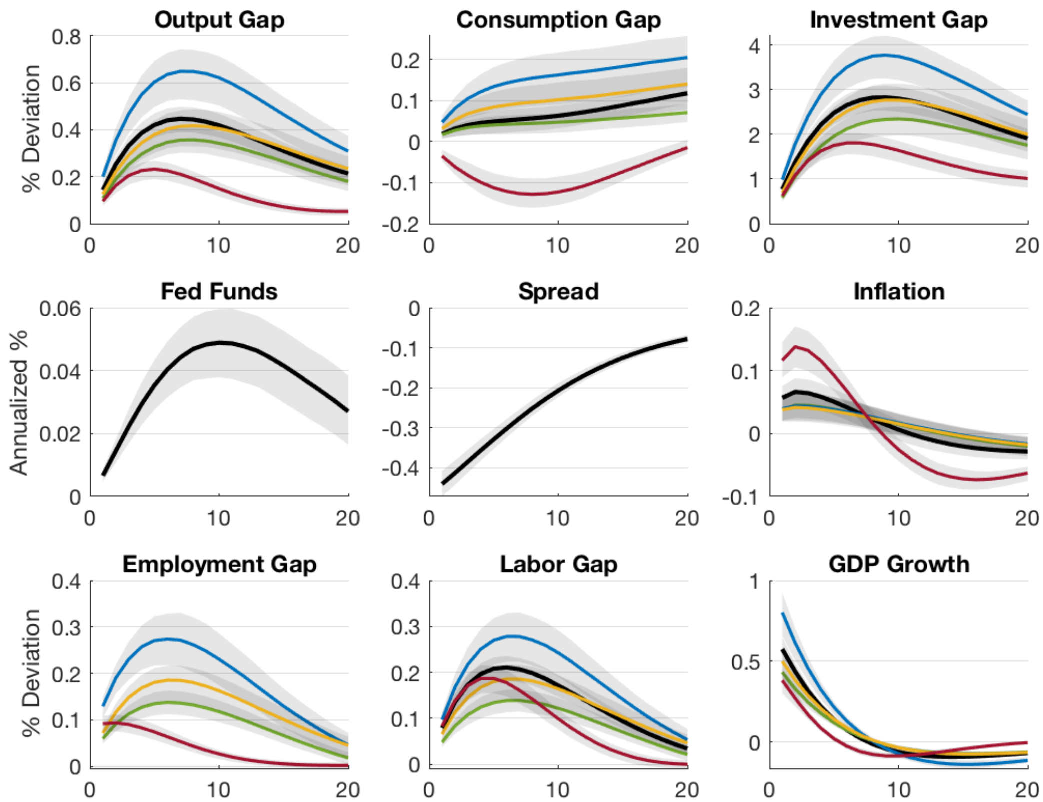
Note: The figure plots the median impulse response estimates of the % deviation from steady state of output, consumption, investment, labor and employment for the four regions and the National level. Further, the annualized % deviations from steady state for the policy rate, financial spread, inflation and GDP growth are also plotted. The Northeast region is in green, the South region is in blue, the Midwest in yellow, the West in red and the black line is the national variable. The shaded areas represent the 70% credible interval for each series.

Figure 9 examines the shock most closely associated with the Great Recession, the financial spread shock. The shock stems from an increase in the perceived riskiness of borrowing national entrepreneurs. This widens credit spreads and results in less national capital accumulation. This will have a heterogeneous effect across the regions, as different regions have different capital utilization and investment adjustment costs and a different share of capital in the production sector.

A negative one standard deviation risk shock decreases the spread by roughly 40 basis points and keeps it deflated for several quarters afterward. The prolonged decrease in spreads leads to an increase in investment and output nationally and for all four regions. Once again the model estimates that financial shocks will relatively effect real output the most in the South region and the least in the West region. Investment and consumption will both increase in three of the four regions but the West region sees an investment-consumption tradeoff due to the relatively higher regional inflation rate. GDP growth in all four regions will remain elevated above trend for up to two years after the shock.

The level of hours and employment will remain above trend for a similar period of time nationally and for all four regions. There are positive inflationary pressures in all four regions due to the shock, this and the previously discussed positive output gap cause the policy rate to increase by a small amount.

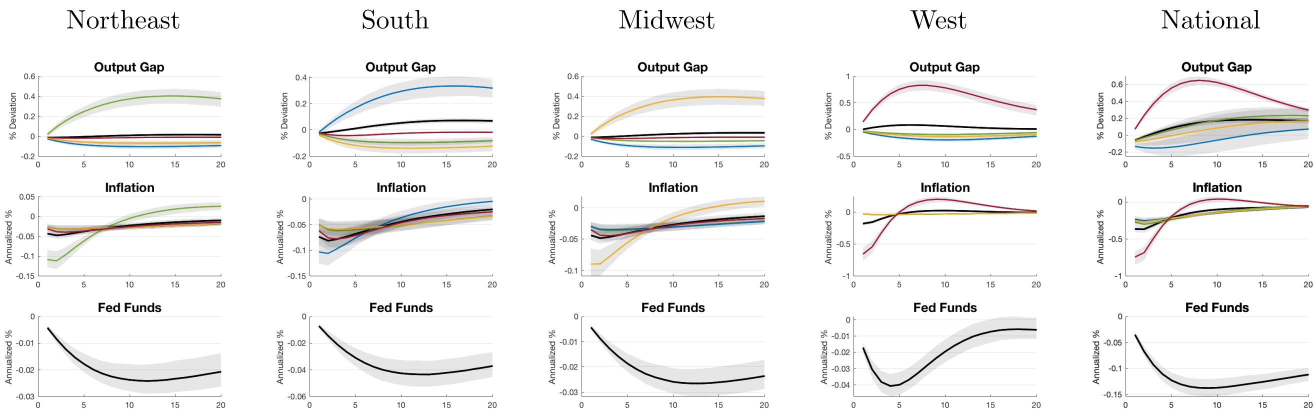
Figure 9: Responses to Financial Risk Shock



Note: The figure plots the median impulse response estimates of the % deviation from steady state of output, consumption, investment, labor and employment for the four regions and the National level. Further, the annualized % deviations from steady state for the policy rate, financial spread, inflation and GDP growth are also plotted. The Northeast region is in green, the South region is in blue, the Midwest in yellow, the West in red and the black line is the national variable. The shaded areas represent the 70% credible interval for each series.

Figures 10 to 14 plot the dynamics of output, inflation and the federal funds rate nationally and for each region for all five regional shocks. Each labeled column corresponds to the region/area where the shock originated. Let's start with a positive productivity shock. We see in Figure 10 that output and inflation respond in the traditional way for each region in which the shock was originated. The disinflationary pressure associated with a productivity shock decrease regional inflation by about 10 basis points for three of the four regions but a productivity shock originating in the West decreases Western inflation by over 50 basis points. Further, the national change in inflation and output do the regional productivity shock is small. As a result, regional productivity shocks have little to no effect on the policy rate. The national productivity shocks initially raises output in the west but eventually raises output at the aggregate national level. In addition the national shock has a greater effect in national inflation and thus the fed funds rate compared to the regional productivity shocks.

Figure 10: Responses to Regional Productivity shock

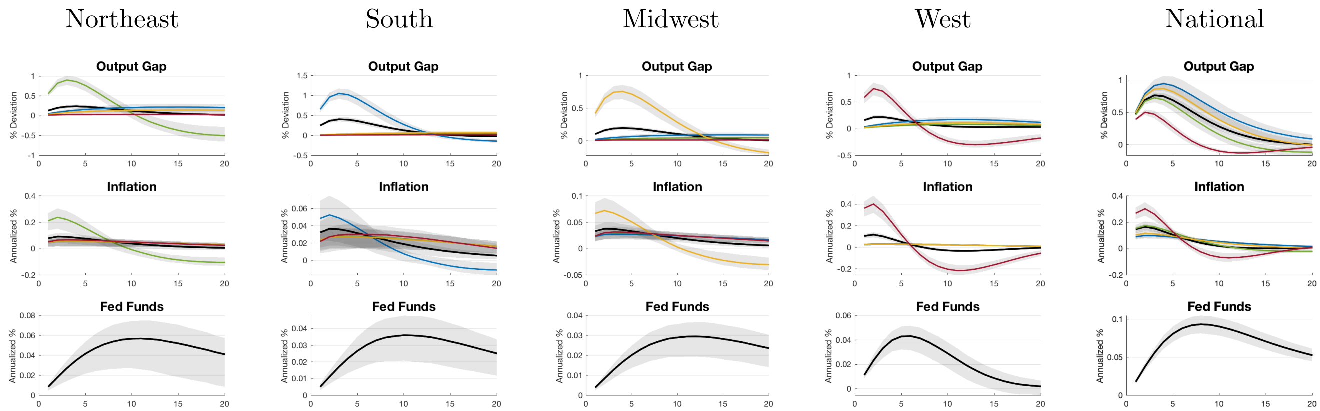


Note: The figure plots the median impulse response estimates of the % deviation from steady state of output and the annualized % deviations from steady state for the policy rate and inflation resulting from a regional shock. Each labeled column corresponds to where the shock originated. The Northeast region is in green, the South region is in blue, the Midwest in yellow, the West in red and the black line is the national variable. The shaded areas represent the 70% credible interval for each series.

Figures 11 and 12 plot the response of two types of regional demand shocks, consumption and investment respectively. With respect to the positive regional consumption shock we see that regional output increases immediately in the originating region and peaks about three to four quarters after the shock. The positive output gap in the originating region is large enough to create a positive national output gap. I also see the traditional demand-pull inflation in both the originating shock region as well as at the national level. However, the positive national output gap and the small increase in national inflation only marginally increases the policy rate. Similar, dynamics are realized by the national consumption shock but at a larger scale.

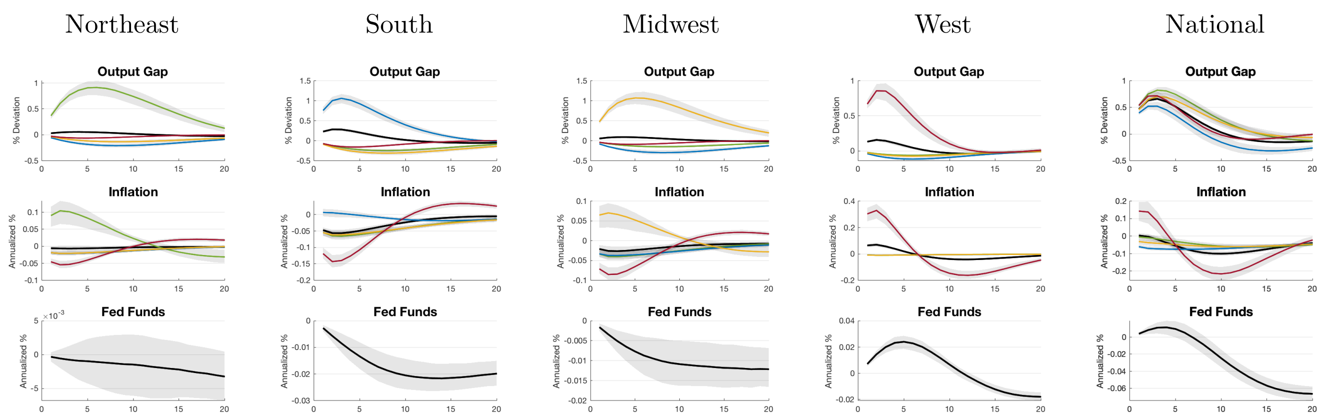
I see similar output dynamics when looking at the response to a positive regional investment shock. One difference of note, is that the other three regions where the investment shock did not originate, actually see a negative output gap. This is contrary to the positive consumption shock where a positive regional output gap resulted when the consumption shock occurred from outside their own region. As a result the national output gap remains flat after a regional investment shock. Further, national demand-pull inflation after an investment shock occurs only in investment shocks originating in the West census region.

Figure 11: Responses to Regional Consumption shock



Note: The figure plots the median impulse response estimates of the % deviation from steady state of output and the annualized % deviations from steady state for the policy rate and inflation resulting from a regional shock. Each labeled column corresponds to where the shock originated. The Northeast region is in green, the South region is in blue, the Midwest in yellow, the West in red and the black line is the national variable. The shaded areas represent the 70% credible interval for each series.

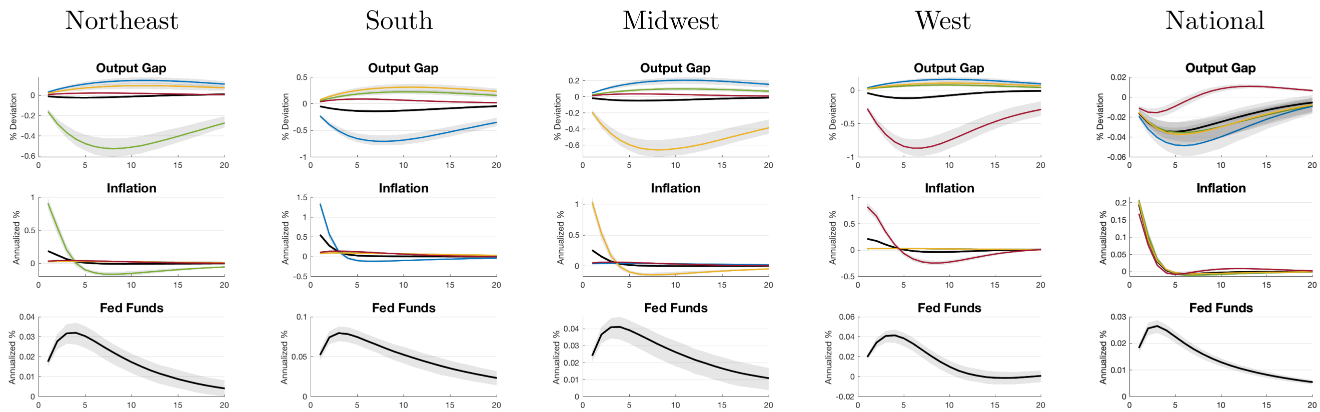
Figure 12: Responses to Regional Investment shock



Note: The figure plots the median impulse response estimates of the % deviation from steady state of output and the annualized % deviations from steady state for the policy rate and inflation resulting from a regional shock. Each labeled column corresponds to where the shock originated. The Northeast region is in green, the South region is in blue, the Midwest in yellow, the West in red and the black line is the national variable. The shaded areas represent the 70% credible interval for each series.

The last type of regional structural shock is the price and wage mark-up shocks, whose impulse response is plotted in Figures 13 and 14. This shock is an exogenous source of inflationary pressure on prices or wages. The price mark-up shock leads to significant increase (ranging from 90 to 140 basis points) in the originating regional inflation level as well as the national inflation level (ranging from 20 to 50 basis points). Elevated regional inflation stays above steady state for about four quarters after a regional price shock occurs. Regional inflation in the other three regions where the shock did not originate are unaffected. The price shock leads to lower real activity in the originating region but the other three regions actually see a positive output gap as a result of the shock. This is due to a lower relative real interest rate on capital in the three regions where the price shock did not originate. As a result the national output gap is mostly unaffected by a regional price shock. The flat national output gap and the increase in national inflation lead to an increase in the nominal federal funds rate.

Figure 13: Responses to Regional Price shock

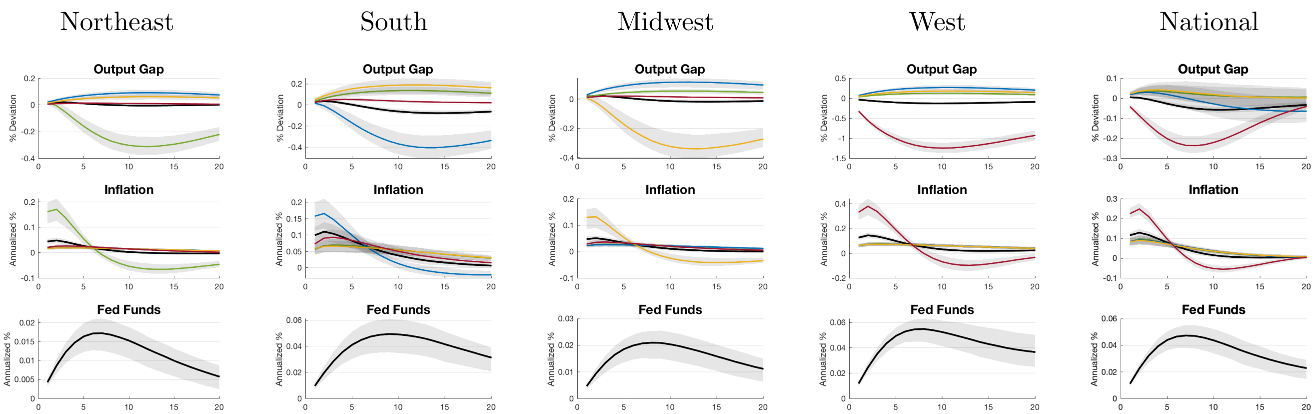


Note: The figure plots the median impulse response estimates of the % deviation from steady state of output and the annualized % deviations from steady state for the policy rate and inflation resulting from a regional shock. Each labeled column corresponds to where the shock originated. The Northeast region is in green, the South region is in blue, the Midwest in yellow, the West in red and the black line is the national variable. The shaded areas represent the 70% credible interval for each series.

Regional wage mark-up shocks exhibit similar response dynamics to regional price mark-up shocks. However, the increase in originating regional inflation and the national inflation level is much smaller. Regional inflation increases by only 15-40 basis points in the region in which the shock originates from. The decline in the output gap in the originating shock region also is relatively less compared to the decline from a price shock. As a result the federal funds rate also increases by a lesser amount from a regional wage shock compared to a regional price shock.

Tables 10 and 11 report the FEVD of the select macroeconomic variables by type of shock for the short-run and long-run (unconditional). These tables show that variance in the West region's economy is much more attributed to supply-shocks, while variance in the other three regions is mostly attributed to demand shocks. The unconditional FEVD of national output is mostly driven by monetary policy shocks (42%) and financial shocks (26%) while the unconditional FEVD of national inflation is mostly attributed to regional mark-up shocks (55%). Further, regional output and employment variance in the South and Midwest regions

Figure 14: Responses to Regional Wage shock



Note: The figure plots the median impulse response estimates of the % deviation from steady state of output and the annualized % deviations from steady state for the policy rate and inflation resulting from a regional shock. Each labeled column corresponds to where the shock originated. The Northeast region is in green, the South region is in blue, the Midwest in yellow, the West in red and the black line is the national variable. The shaded areas represent the 70% credible interval for each series.

caused by monetary and financial shocks is significantly higher compared to the variance they cause in Northeast and West regional output and employment.

4.3 Comparing the Regional to the Nested National SWFF Model

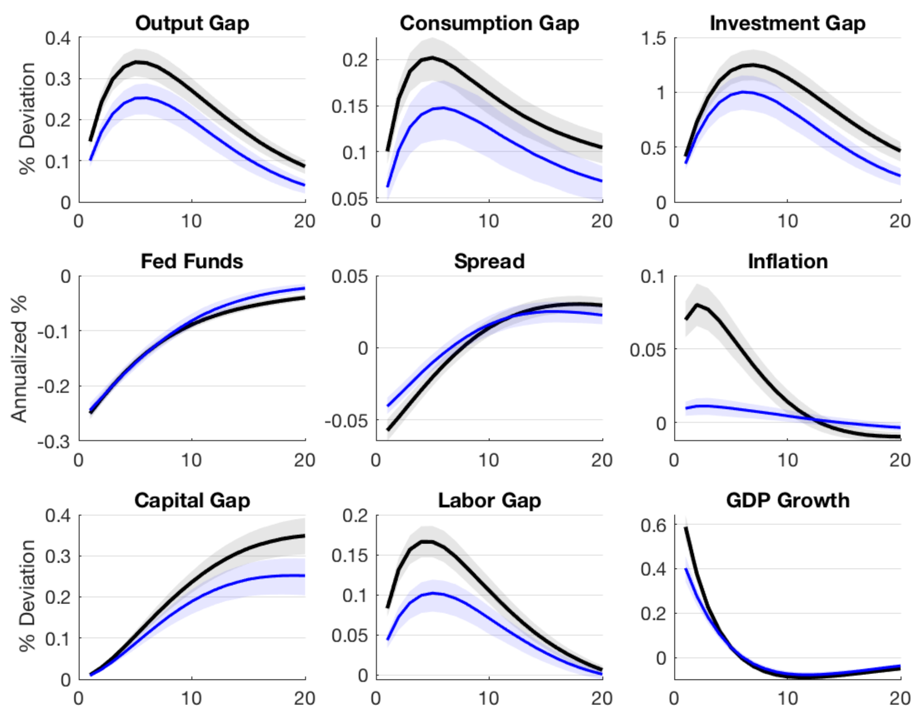
One of the advantages of the regional model's set up is its ability to nest the National SWFF model of Del Negro and Schrofheide (2013, 2015)[15]. I estimate the nested national SWFF model using only national data and anticipated federal funds data. The estimates of the structural parameters for the National SWFF model are reported in Table 9. I find that wages, prices and employment rigidity parameters to be much greater in the national SWFF model compared to all four regions in the regional model. This implies changes to wages, prices and employment to be more flexible when regional data is incorporated. A finding that is in line with other regional and firm-level analysis [Beraja, Hurst and Ospina (2019)]. There is also a significant increase in estimated capital share and investment adjustment costs when regional data and modeling is used to estimate the SWFF model.

As a result of the different parameter estimates between the regional and national models, the business cycle causes and dynamics implied by each model also differ. Figure 15 plots the responses to a 25 basis points decline in both models. The blue line represents the

[15]The regional model is equivalent to the national model when $\zeta = 1$, $\sigma_{i,s} = 0$ for all i and s and when all the structural parameters in region j are equal to each other in all regions s.

national SWFF model and the black line represents the aggregate variable in the regional model. We can see that inflation, output, consumption, investment, labor and capital are all more responsive to a monetary policy shock in the estimated regional model compared to the estimated national model. Inflation in the national model barely responds, mostly due to the high estimate of price rigidity needed in order to fit the national inflation data in the national model.

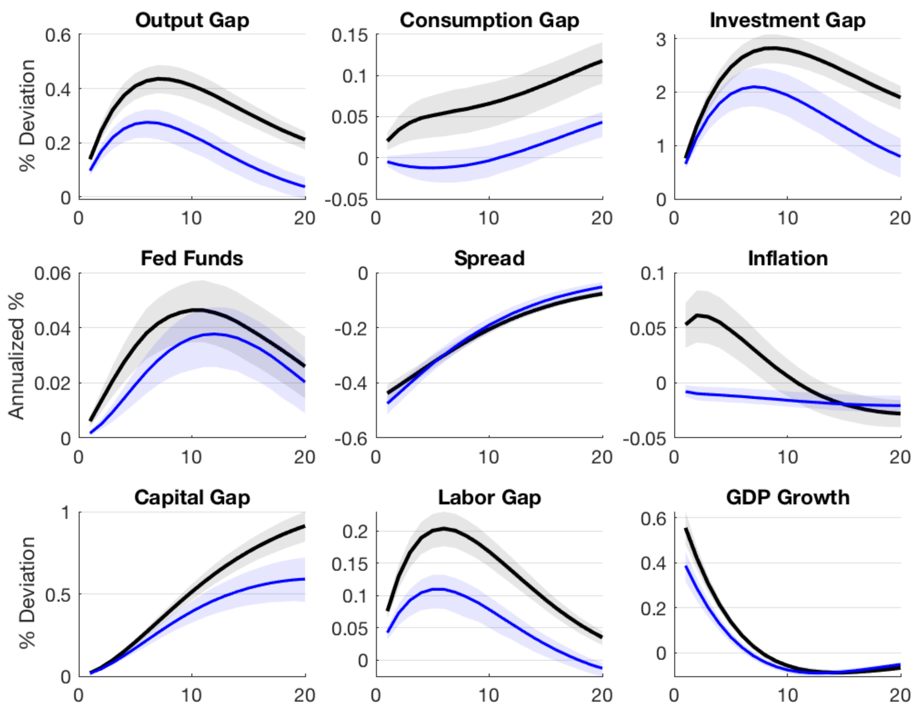
Figure 15: Responses to Monetary Policy Shock (-25 basis points)



Note: The figure plots the median impulse response estimates of the % deviation from steady state of output, consumption, investment, capital, and labor for the Aggregate level of the Regional Model and National Model. Further, the annualized % deviations from steady state for the policy rate, financial spread, inflation and GDP growth are also plotted. The Regional model is in black and the National model is in blue. The shaded areas represent the 70% credible interval for each series.

Figure 16 plots the responses of both models to a standardized decline to the financial spread. The financial risk shock is associated with a significantly bigger impact on output, investment and labor in the regional model compared to the national model. The estimated financial premium parameters are estimated to be remarkably similar between the two models. This suggests that the difference in impact to the real variable across the two models results from the difference in other structural parameters where the distinction in regional variation is exploited.

Figure 16: Responses to Financial Risk Shock



Note: The figure plots the median impulse response estimates of the % deviation from steady state of output, consumption, investment, capital, and labor for the Aggregate level of the Regional Model and National Model. Further, the annualized % deviations from steady state for the policy rate, financial spread, inflation and GDP growth are also plotted. The Regional model is in black and the National model is in blue. The shaded areas represent the 70% credible interval for each series.

Further, we can examine and compare the FEVD of the national model to the regional model to understand the difference in business cycles regional variation may imply. Table 12 reports the short-run and long-run FEVD indicated by the estimated national model. If I compare it to Tables 10 and 11, I see that monetary and financial shocks are less important to the variation to aggregate output in the national model compared to the regional model in the short-run (19% compared to 44%) and long-run (32% compared to 66%). The same is true for the cause of inflation variation. In the national model there is a larger cause of consumption and investment shocks causing national variation compared to the regional model. In particular, the variation in national investment caused by financial shocks in the long run is estimated to be 61% in the regional model and only 23% in the national model.

On the supply side we see a larger attribution of mark-up shocks and productivity shocks in the business cycle for the national SWFF model. Variation in wage growth is almost exclusively driven by wage shocks for the short-run and long-run in the national model while the regional model attributes a bigger role to monetary and financial shocks. I also see that long-run variation in the policy rate attributed to policy shocks declines from 69% to 35% between the regional model and the national model. The national model imparts a much bigger emphasis on mark-up shocks explaining variation in the policy rate than does the regional model.

4.4 Comparing the Sample-fit of the Regional and National Model

As we can see from Tables 7-9 the regional and national model offer significantly different estimates for many structural parameters inside the model and thus create different internal dynamics as seen in Figures 15 and 16. However, the question remains if the internal dynamics of one model creates a better fit of the national data that is used in both models. In other words, does the inclusion of the regional data and modeling approach help explain the dynamics of national macroeconomic variables better. To answer such a question I calculate the relative in-sample accuracy of point and density forecasts (individual and joint) for data that is used in both the regional and national model estimation. The in-sample accuracy is evaluated with the root mean squared error (RMSE) and the average log predictive scores (LPS).

In all there are eight national data sets which are used in both models. These include Quarterly GDP, consumption, and investment growth, inflation measured by the GDP deflator, wage inflation, total hours worked, the federal funds rate and the interest rate spread between BAA Corporate bonds and treasuries. I draw from the estimated posterior distribution of the structural parameters of each model and generate forecast distribution for various horizons for each time t of the estimated sample. For each time t, I calculate the first two moments of the predictive density $p(Y^f_{t+h}|t, model)$ where p($Y^f_{t+h}|t, model$) is a Gaussian distribution based upon $5,000$ random draws and simulations from the posterior distribution of each respected model.

I then calculate the RMSE of each of the eight variables in both models by calculating the point forecast as the mean of the first moment of $p(Y^f_{t+h}|t, model)$ and comparing it to the actual realization of Y_{t+h} in the data using the standard RMSE calculation equation. I then calculate the predictive density score by calculating the pdf of $p(Y^f_{t+h}|t, model)$ given the actual realization of Y_{t+h} for all eight datasets individually, jointly for GDP growth and inflation and jointly for all eight datasets The average RMSE and average LPS results for different horizons h are reported in Tables 2 and 3.

Table 2: RMSE and Average LPS scores for both the National and Regional Model

	RMSE				Average LPS			
	h=1	h=2	h=4	h=8	h=1	h=2	h=4	h=8
GDP Growth								
National Model	0.67	0.83	0.87	0.69	-1.015	-1.236	-1.299	-1.069
Regional Model	0.66	**0.76**	**0.76**	0.62	-1.002	**-1.141**	**-1.139**	**-0.991**
Inflation								
National Model	1.03	1.31	1.35	1.03	-1.456	-1.713	-1.721	-1.536
Regional Model	**0.84**	**0.95**	**1.00**	0.99	**-1.256**	**-1.374**	**-1.428**	**-1.438**
Policy Rate								
National Model	0.46	0.85	1.52	2.21	-0.640	-1.369	-2.273	-2.779
Regional Model	0.45	0.80	**1.36**	**1.99**	-0.627	**-1.226**	**-1.957**	**-2.600**
Consumption Growth								
National Model	0.57	0.65	0.70	0.61	-0.855	-0.993	-1.066	-0.956
Regional Model	0.55	0.63	0.66	0.58	-0.830	-0.968	**-1.014**	**-0.871**
Investment Growth								
National Model	2.98	3.27	3.33	3.12	**-2.514**	-2.605	-2.622	-2.565
Regional Model	2.76	**2.94**	**3.07**	3.05	-2.591	-2.595	-2.609	-2.579
Total Hours								
National Model	1.72	2.17	2.95	3.74	**-4.217**	**-3.749**	**-3.830**	**-3.882**
Regional Model	1.58	2.03	2.88	3.88	-4.527	-4.269	-4.165	-4.385
Wage Inflation								
National Model	**1.04**	**1.18**	**1.29**	1.29	**-1.794**	**-1.847**	**-1.959**	**-1.944**
Regional Model	1.36	1.40	1.40	1.32	-2.528	-2.769	-2.498	-2.658
Spread								
National Model	0.39	0.60	0.83	0.98	-0.544	-0.933	-1.240	-1.453
Regional Model	0.39	0.60	0.83	1.03	**-0.516**	-0.923	-1.239	-1.448

Note: Bold entries under the RMSE columns denote the 5% significance level of the Diebold-Mariano test, where the long-run variance is calculated with the Newey-West method, while bold entries under the LPS columns denote the 5% significance level for the Amisano and Giacomini (2007) test.

We can see that the average RMSE for six of the eight variables is lower in-sample for the regional model for all horizons h. The RMSE is significantly lower for the point forecasts of national inflation in the regional model. This suggests that regional data in a regional structural model can play a significant role in lowering the forecast error in national inflation. When we look at the univariate density forecasts of the two models, we see a similar result, with the log predictive scores of GDP growth, inflation, the policy rate and consumption growth all higher in the regional model than the national model. The only area in which the regional model does not do a better job than the national model is the labor market where both the point forecasts and log predictive score for total hours and wage inflation is more accurate when the forecast comes from the national model.

Table 3: Multivariate Average LPS scores for both the National and Regional Model

	Average LPS			
	h=1	h=2	h=4	h=8
GDP Growth and Inflation				
National Model	-2.464	-2.941	-3.011	-2.603
Regional Model	**-2.280**	**-2.549**	**-2.585**	**-2.417**
All National Variables				
National Model	-6.604	-8.288	-9.569	-9.661
Regional Model	-6.587	**-8.233**	**-9.480**	-9.670

Note: Bold entries denote the 5% significance level for the Amisano and Giacomini (2007) test, where the long-run variance is calculated with the Newey-West method.

When I compare the average LPS's for the multivariate forecasts, which take into account the covariances of the variables, I see that the regional model has significantly higher LPS for the joint forecasts of GDP growth and inflation for all horizons and significantly higher LPS for all national variables of horizon 2 to six. We can interpret these results as confirming our conclusions formulated from the univariate forecasts, i.e. that the regional DSGE model with regional data signifcantly helps in explaining the movement and co-movement of key macroeconomic variables. In particular, the key variables to policy makers of GDP and Inflation.

5 Monetary Policy and Central Bank Loss Functions

In this section, I assess the importance of regional information by simulating the estimated regional model and comparing central bank loss functions under three different monetary policy rules. The central bank clearly has the objective of keeping inflation low and stable, economic activity as close to potential and doing so in an environment with low short-run variance around its policy rate. The relative importance/preferences of these goals may differ through time and be unknown to society. Such preferences are generally represented by a weighted loss function that the central bank seeks to minimize.

Many central bank loss functions used in this paper appear in the literature [Taylor and Wieland (2012) and Adolfson et al. (2014)]. The evaluation methodology is similar to Benchimol and Fourcans (2019) and intends to account for all possible relative preferences that could exist in the central bank's loss function. For various sets of central bank preference weights, I compute loss function calculations by sampling from the posterior distribution of the estimated parameters of the DSGE model.

The central bank loss function, $\mathcal{L}_t$, is defined as:[16]

$$\mathcal{L}_t = Var[\pi_t] + \lambda_y Var[Y_t] + \lambda_r Var[(R_t - R_{t-1})] \tag{37}$$

where π_t and Y_t are national measures of inflation and output gap and λ_y and λ_r are the relative preference weights a central bank has on the national output gap and nominal interest rate differential variances. The three Taylor Rule specifications I use to calculate the central bank loss function are as follows:

- Taylor Rule that only endogenously changes due to national output and national inflation. This is the same rule as equation 11, I denote this monetary policy rule as TR_{Nat}

- Taylor Rule that responds to regional inflation and regional output gaps. I denote this monetary policy rule as TR_{Region} and it has the following form:

$$\begin{aligned} \hat{R}_t = \rho\hat{R}_{t-1} + (1-\rho)[r_{\pi_1}(\hat{\pi}_{t,NE} + \hat{\pi}_{t,S} + \hat{\pi}_{t,MW} + \hat{\pi}_{t,W}) \\ + r_{y_1}(\hat{Y}_{t,NE} + \hat{Y}_{t,S} + \hat{Y}_{t,MW} + \hat{Y}_{t,W})] + \hat{\varepsilon}^r_t + \sum_{k=1}^{5} \hat{\varepsilon}^r_{k,t-k} \end{aligned}$$

- Taylor Rule that responds to regional inflation and regional output gaps by considering relative regional price rigidities. This is a Taylor rule that follows Benigno (2004), who

[16]The loss function used in this paper is identical to Rudebusch and Svensson (1999).

found that such a national rule is nearly optimal in a currency union. I denote this monetary policy rule as $TR_{\xi_{p,region}}$ and it has the following form:

$$\begin{aligned}\hat{R}_t = \rho\hat{R}_{t-1} + (1-\rho)[r_{\pi_1}(ss_{NE}\hat{\pi}_{t,NE} + ss_S\hat{\pi}_{t,S} + ss_{MW}\hat{\pi}_{t,MW} + ss_W\hat{\pi}_{t,W})\\ + \ r_{y_1}(ss_{NE}\hat{Y}_{t,NE} + ss_S\hat{Y}_{t,S} + ss_{MW}\hat{Y}_{t,MW} + ss_W\hat{Y}_{t,W})]\\ + \hat{\varepsilon}^r_t + \sum_{k=1}^{5}\hat{\varepsilon}^r_{k,t-k}\end{aligned}$$

where $ss_s = \frac{(1-\xi_{p,NE})(1-\xi_{p,NE})(1-\xi_{p,NE})(1-\xi_{p,NE})\omega_s}{(1-\xi_{p,s})}$ for region $s = \{NE, S, MW, W\}$.

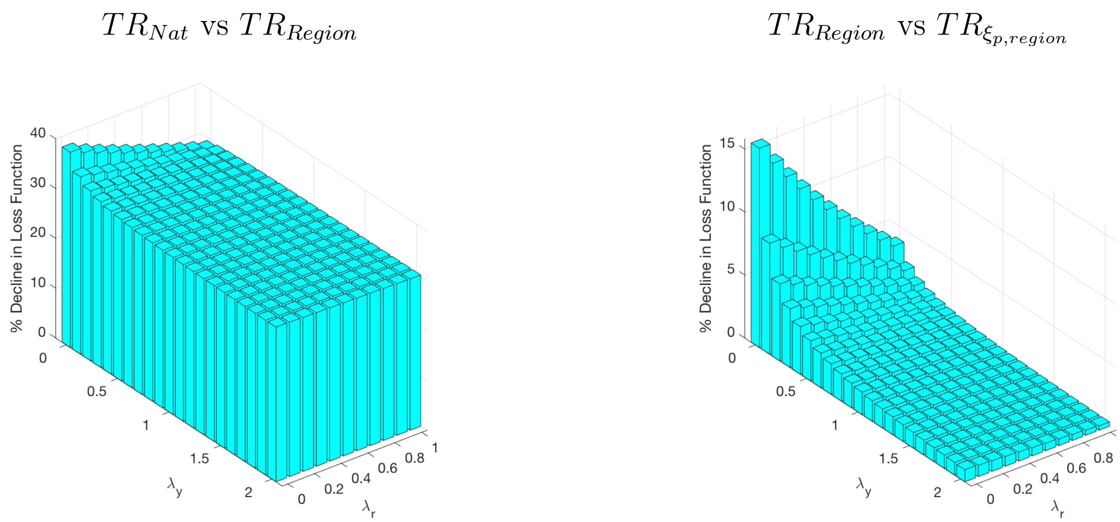
In order to account for parameter uncertainty, I sample the parameter posterior distribution 10000 times and simulate the regional model under the three different Taylor rule specifications for a total of 400 periods. I use the last 200 periods of each simulation and calculate the central bank's loss function using equation 37 for each of three monetary policy rules and parameter samples.

5.1 What Can be Gained with Regional Economic Information

Three important questions are answered in this subsection. First, Are there welfare gains (Loss function declines) under TR_{Region} policy and if so are they large enough to conclude that including regional economic information is important when conducting monetary policy? To answer this question, I compare the simulated mean loss function values of the TR_{Nat} and TR_{Region} policy rule specifications for a wide subset of potential policy preference parameters. These results are plotted and summarized in Figure 17 and Table 4. I find significant declines in the central bank's loss function under the TR_{Region} policy rule, which reacts to regional disturbances in inflation and output regardless of policy preference parameters. Overall national loss function declines range from 39% if the central bank only cares about inflation stabilization and 30% once a central bank puts output variation and interest rate change on equal footing with inflation stabilization.

These national loss function declines remain significantly large (30%+) even as central bank disdain for output variation (λ_y) gets quite large. The loss reduction is directly related to the reductions of the unconditional variances of inflation and the output gap. The average variance reduction is 39 percent for inflation and 30 percent for the output gap. The central bank does see its loss function increase due to an increase in interest rate change variance of 17 percent. I conduct one-tailed tests on the entire sample of simulations, which incorporates parameter uncertainty. The tests allow for rejection of the null hypothesis of equal value between loss functions for all combinations of preference parameters, suggesting that the results in Figure 17 are robust to parameter uncertainty.

Figure 17: Central Bank Loss Reduction in including Regional Information



Note: The figure on the left reports the percentage reduction in the value of the loss function attained under the incorporation of regional economic information into the Taylor rule (TR_{Region}) relative to the national information based rule (TR_{Nat}). The figure on the right reports the percentage reduction in the value of the loss function attained under the incorporation of regional economic information and price rigidities ($TR_{\xi_{p,region}}$) into the Taylor rule relative to the regional information based rule (TR_{Region}). The parameters λ_y and λ_r reflect the weight attached by the policymaker to the output gap and the interest rate variability in its loss function.

Table 4: National and Regional Loss Reduction between the Three Rule Specifications

	TR_{Nat} **vs** TR_{Region}			TR_{Region} **vs** $TR_{\xi_{p,region}}$		
			National			
	$\lambda_r = 0$	$\lambda_r = 0.5$	$\lambda_r = 1$	$\lambda_r = 0$	$\lambda_r = 0.5$	$\lambda_r = 1$
$\lambda_y = 0$	39.2	33.8	29.4	15.8	8.9	4.0
$\lambda_y = 0.2$	34.1	31.9	29.9	6.1	3.8	*1.8*
$\lambda_y = 0.5$	32.4	31.3	30.2	*3.2*	*2.1*	*1.0*
$\lambda_y = 1$	31.6	30.9	30.3	*1.8*	*1.2*	*0.6*
$\lambda_y = 10$	30.6	30.5	30.4	*0.2*	*0.2*	*0.1*
			Northeast			
	$\lambda_r = 0$	$\lambda_r = 0.5$	$\lambda_r = 1$	$\lambda_r = 0$	$\lambda_r = 0.5$	$\lambda_r = 1$
$\lambda_y = 0$	15.9	14.2	12.7	6.9	4.7	*2.8*
$\lambda_y = 0.2$	12.5	12.0	11.5	*3.1*	*2.4*	*1.8*
$\lambda_y = 0.5$	11.7	11.5	11.3	*2.2*	*1.9*	*1.6*
$\lambda_y = 1$	11.4	11.2	11.1	*1.8*	*1.6*	*1.5*
$\lambda_y = 10$	11.0	11.0	11.0	*1.4*	*1.4*	*1.4*
			South			
	$\lambda_r = 0$	$\lambda_r = 0.5$	$\lambda_r = 1$	$\lambda_r = 0$	$\lambda_r = 0.5$	$\lambda_r = 1$
$\lambda_y = 0$	12.8	11.3	9.9	4.7	*2.7*	*1.0*
$\lambda_y = 0.2$	10.7	10.3	10.0	5.2	4.7	4.2
$\lambda_y = 0.5$	10.3	10.1	10.0	5.3	5.1	4.9
$\lambda_y = 1$	10.2	10.1	10.0	5.4	5.2	5.1
$\lambda_y = 10$	10.0	10.0	10.0	5.4	5.4	5.4
			Midwest			
	$\lambda_r = 0$	$\lambda_r = 0.5$	$\lambda_r = 1$	$\lambda_r = 0$	$\lambda_r = 0.5$	$\lambda_r = 1$
$\lambda_y = 0$	18.1	16.0	14.1	*2.2*	*-0.1*	*-2.0*
$\lambda_y = 0.2$	18.9	18.3	17.7	*-2.0*	*-2.5*	*-3.0*
$\lambda_y = 0.5$	19.0	18.7	18.5	*-2.7*	*-3.0*	*-3.2*
$\lambda_y = 1$	19.1	18.9	18.8	*-3.1*	*-3.2*	*-3.3*
$\lambda_y = 10$	19.1	19.1	19.1	*-3.4*	*-3.4*	*-3.4*
			West			
	$\lambda_r = 0$	$\lambda_r = 0.5$	$\lambda_r = 1$	$\lambda_r = 0$	$\lambda_r = 0.5$	$\lambda_r = 1$
$\lambda_y = 0$	26.0	24.9	23.9	6.5	5.2	4.1
$\lambda_y = 0.2$	11.4	11.1	10.8	*1.9*	*1.6*	*1.2*
$\lambda_y = 0.5$	6.7	6.5	6.4	*0.8*	*0.6*	*0.4*
$\lambda_y = 1$	4.3	4.3	4.2	*0.2*	*0.1*	*0.0*
$\lambda_y = 10$	*1.7*	*1.7*	*1.7*	*-0.4*	*-0.4*	*-0.4*

Note: The left panel reports the percentage reduction in the value of the national and regional loss functions attained under the incorporation of regional economic information into the Taylor rule (TR_{Region}) relative to the national information based rule (TR_{Nat}). The right panel reports the percentage reduction in the value of the national and regional loss functions attained under the incorporation of regional economic information and price rigidities ($TR_{\xi_{p,region}}$) into the Taylor rule relative to the regional information based rule (TR_{Region}). The parameters λ_y and λ_r reflect the weight attached by the policymaker to the output gap and the interest rate variability in its loss function. Non-significant reductions at the 5% level are in italics.

The second question I examine is: What regional macroeconomic effects are experienced by the four regions of the model if monetary policy is conducted under the (TR_{Region}) rule. To do this I define region (s)'s loss function as:

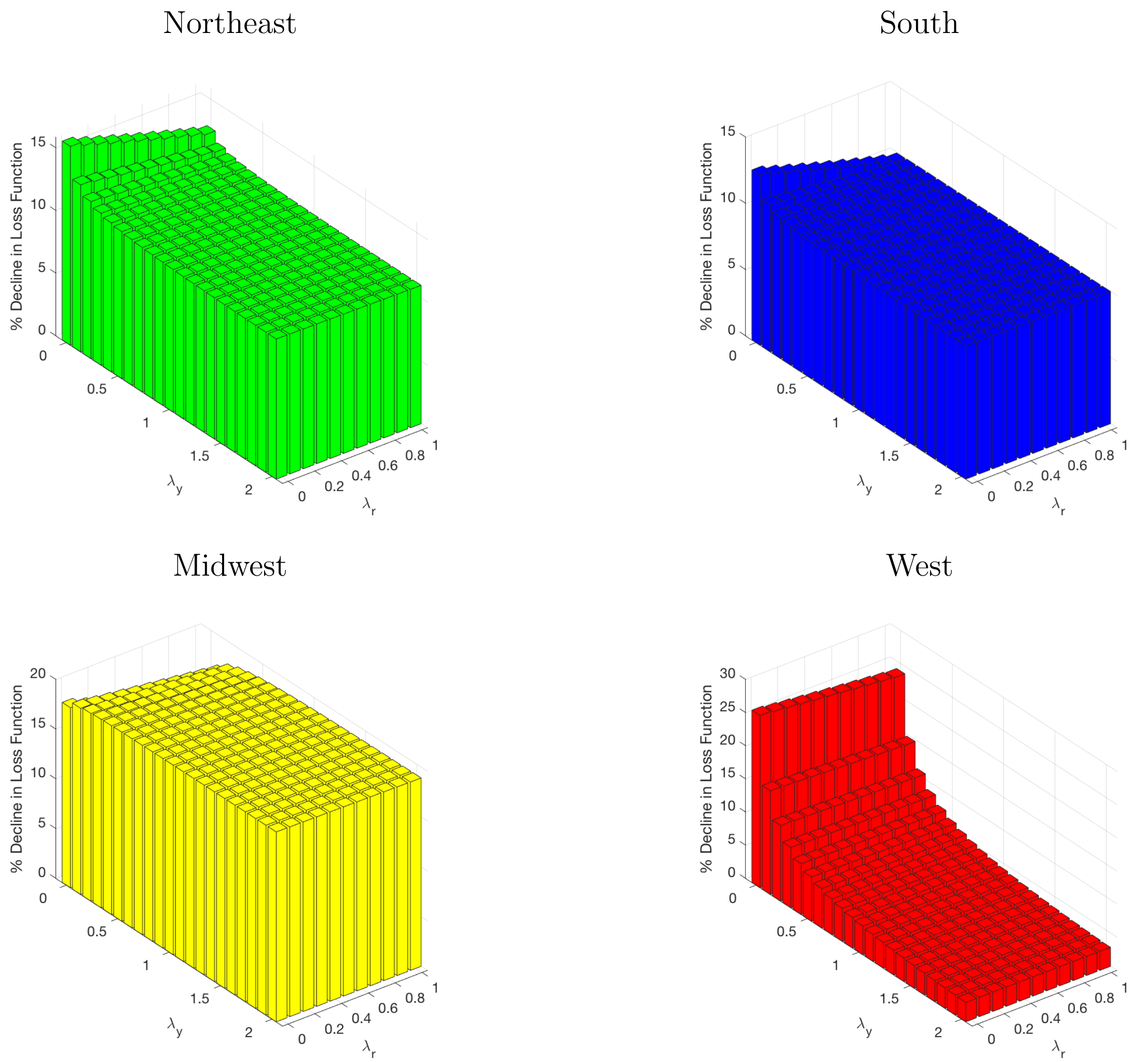
$$\mathcal{L}_{t,s} = Var[\pi_{t,s}] + \lambda_y Var[Y_{t,s}] + \lambda_r Var[(R_t - R_{t-1})] \tag{38}$$

where $\pi_{t,s}$ and $Y_{t,s}$ are measures of regional inflation and regional output gap in region s. These results are plotted and summarized in Figure 18 and Table 4. I see that for most preference parameters the reduction in the regional loss function is significant for all four regions. This suggest that (TR_{Region}) rule would likely be a Pareto improvement for all four regions. The reduction in the loss function becomes inconclusive for the Western region as the central bank's relative disdain preference for the output gap (λ_y) becomes very large. This is because the (TR_{Region}) rule lowers the unconditional variance in West regional inflation by about 25% but only lowers the variance on the regional output gap out West by 1%. The region that benefits the most in terms of reduction in variance in regional output and inflation is the Midwest.

The third question I analyze is: What can be gained if a central bank reacts to regional information while also accounting for regional price rigidities? Benigno (2004) showed that a central bank operating under a currency union that weighted its policy response to regional inflation by relative regional price rigidities and regional economic size was nearly optimal. The rule $(TR_{\xi_{p,region}})$ does just this and I compare the national and regional loss functions for such a rule to a central bank that did not incorporate relative regional price rigidities in its rule but still reacted to regional economic information (TR_{Region}). This comparison is plotted and summarized on the right sides of Figure 17 and Table 4 as well as Figure 21.

I find that the inclusion of relative price rigidity weighting does slightly decrease the unconditional variance in national and regional inflation. However, it does not decrease the variance on the national output gap, this coupled with the significant increase in interest rate change variation reduces the loss function reduction when a $(TR_{\xi_{p,region}})$ rule is used for policy. Further, The Midwest and Western regions actually see a slight welfare loss (loss function gain) as λ_y becomes larger. Further, the only significant regional or national loss

Figure 18: Regional Loss Reduction when Central Bank includes Regional Information



Note: The figure plots the percentage reduction in the value of the regional loss function attained under the incorporation of regional economic information into the Taylor rule (TR_{Region}) relative to the national information based rule (TR_{Nat}). The parameters λ_y and λ_r reflect the weight attached by the policymaker to the output gap and the interest rate variability in its loss function.

reduction of using the ($TR_{\xi_{p,region}}$) rule instead of the (TR_{Region}) rule, occurs at the national level when a central bank is only primarily concerned about national inflation variation.

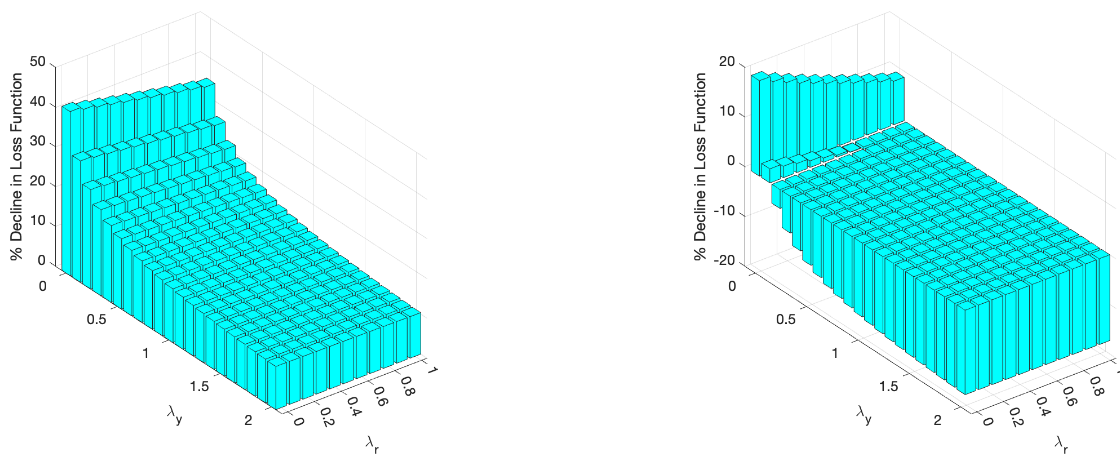
Benigno and Woodward (2012) showed that when a model has both sticky prices and wages, wage inflation must also be included in a central bank's loss function to be optimal. Further, if the true utility function for households was non-separable between consumption and labor [as in King, Plosser and Rebelo (1988)], optimal policy would require attention to labor related variables by the central bank. I add wage inflation ($\lambda_w(\Delta w_t)$) to equations

(37) and (38) and recalculate the national and regional loss functions. I find the results and conclusions do not change for values of λ_w between zero and one.

Finally, one might be wondering how much of the heterogeneous regional volatility is driving the findings that optimal monetary policy should take into effect regional information when conducting policy and how much is related to heterogeneity in the regional structural parameters. For example, one might suspect that the majority of productivity, consumption and investment shocks and supply shocks are truly national with little to no regional variation and policy should not consider regional information if it is only the regional shock volatility that lowers the loss function. To address such a question, I set all of the regional exogenous disturbances standard deviations to zero, i.e. ($\sigma_{i,s} = 0$ for all i and s). From equation 14 all regional exogenous shocks would then be equal to the national exogenous shock for all disturbances in the model. What we see from Figure 19 is that the decline in the loss function with regional information in the Taylor Rule is smaller but still positively significant compared to just national information in the Taylor Rule. Further, the Pareto improvement of all 4 regions remains with the TR_{Region} policy rule. Interestingly, the loss function of $TR_{\xi_{p,region}}$ compared to TR_{Region} actually increases when regional shocks are turned off and the policy maker has some care of output volatility.

Figure 19: Central Bank Loss Reduction in including Regional Information with no Regional Shocks

TR_{Nat} vs TR_{Region} $\qquad$ TR_{Region} vs $TR_{\xi_{p,region}}$



Note: The figure on the left reports the percentage reduction in the value of the loss function attained under the incorporation of regional economic information into the Taylor rule (TR_{Region}) relative to the national information based rule (TR_{Nat}). The figure on the right reports the percentage reduction in the value of the loss function attained under the incorporation of regional economic information and price rigidities ($TR_{\xi_{p,region}}$) into the Taylor rule relative to the regional information based rule (TR_{Region}). The parameters λ_y and λ_r reflect the weight attached by the policymaker to the output gap and the interest rate variability in its loss function. In all simulations, regional shocks are turned off, i.e. $\sigma_{i,s} = 0$ for all i and s.

These results suggest that regardless of the existence of regional shock variation, including regional information in the Taylor Rule can significantly lower the loss function of the central bank regardless of their inflation and output volatility preferences.

6 Conclusion

The purpose of this paper is to shed light on the regional and national dynamics of monetary policy and financial shocks inside the United States. To conduct this analysis I expand the FRBNY DSGE model (Del Negro et al. 2013) to a model that includes n regional economies connected together by a central monetary and fiscal authority as well as a national financial and banking system. I then estimate the regional DGSE model under the four census regions of the United States by using aggregated state level data for output, consumption, investment, employment, inflation and wages.

I find significant heterogeneity amongst the regional structural parameters of the model. I also find that monetary and financial shocks have a greater economic impact on output and investment in the Southern and Midwestern census regions. When I compare the in-sample forecasts of national variables in both the regional and national model, I find that the regional model significantly out performs the national model in both point and density prediction.

After estimating the model and examining its dynamics, I then simulate the regional DSGE model under three different monetary policy rules and evaluate a standard central bank loss function at the national and regional level for each policy rule. The monetary policy rules include a central bank that only reacts to national inflation and the national output gap, a central bank that incorporates regional economic information by incorporating regional inflation and regional output gaps into is interest rate rule and a central bank that incorporates regional economic information as well as regional price rigidities in its rule. The third rule introduces price rigidities by weighting the response to regional inflation by the monetary policy authority by relative Calvo pricing estimates. This type of rule was found to be near optimal for a currency union in Benigno (2004).

I find that a central bank that incorporates regional economic information in its policy rule can significantly reduce its national loss function regardless of relative preferences on inflation, output gap or interest rate change variation. Further, such a rule is Pareto improving as all estimated regions in the United States would also see significant reductions in their regional loss functions. However, if a central bank also incorporated relative regional price rigidities the reduction in its loss function is only significant when national inflation stabilization is the main objective of a central bank. Such a rule is also not Pareto improving as the Midwest and Western census regions see their regional loss functions increase from such a policy rule.

This paper addresses an important question for the design of monetary policy in the United States: What can be gained by incorporating regional information in the decision-making process of monetary policy? All together the results of this paper imply that national monetary policy has a significantly different effect across the geographic regions of the United States. As a result, conducting national monetary policy that incorporates regional economic information can create significant welfare gains at the national level and regional levels.

References

Adao, R., Arkolakis, C. and Esposito, F. (2019), Spatial linkages, global shocks, and local labor markets: Theory and evidence, Technical report, National Bureau of Economic Research.

Adolfson, M., Laséen, S., Lindé, J. and Svensson, L. E. (2014), 'Monetary policy trade-offs in an estimated open-economy dsge model', *Journal of Economic Dynamics and Control* **42**, 33–49.

An, S. and Schorfheide, F. (2007), 'Bayesian Analysis of DSGE Models', *Econometric Reviews* **26**(2-4), 113–172.

Andrieu, C. and Thoms, J. (2008), 'A tutorial on adaptive mcmc', *Statistics and computing* **18**(4), 343–373.

Angelini, P., Del Giovane, P., Siviero, S. and Terlizzese, D. (2008), 'Monetary policy in a monetary union: What role for regional information?', *International Journal of Central Banking* .

Benchimol, J. and Fourçans, A. (2019), 'Central bank losses and monetary policy rules: a dsge investigation', *International Review of Economics & Finance* **61**, 289–303.

Benigno, P. (2004), 'Optimal monetary policy in a currency area', *Journal of international economics* **63**(2), 293–320.

Benigno, P. and Woodford, M. (2012), 'Linear-quadratic approximation of optimal policy problems', *Journal of Economic Theory* **147**(1), 1–42.

Beraja, M., Fuster, A., Hurst, E. and Vavra, J. (2019), 'Regional heterogeneity and the refinancing channel of monetary policy', *The Quarterly Journal of Economics* **134**(1), 109–183.

Beraja, M., Hurst, E. and Ospina, J. (2019), 'The aggregate implications of regional business cycles', *Econometrica* **87**(6), 1789–1833.

Bernanke, B. S., Gertler, M. and Gilchrist, S. (1999), 'The financial accelerator in a quantitative business cycle framework', *Handbook of macroeconomics* **1**, 1341–1393.

Bragoli, D., Rigon, M. and Zanetti, F. (2016), 'Optimal inflation weights in the euro area', *Bank of Italy Temi di Discussione (Working Paper) No* **1045**.

Calvo, G. A. (1983), 'Staggered prices in a utility-maximizing framework', *Journal of monetary Economics* **12**(3), 383–398.

Carlino, G. and DeFina, R. (1998), 'The differential regional effects of monetary policy', *Review of economics and statistics* **80**(4), 572–587.

Carlino, G. and DeFina, R. (1999), 'The differential regional effects of monetary policy: Evidence from the us states', *Journal of Regional science* **39**(2), 339–358.

Del Negro, M., Eusepi, S., Giannoni, M., Sbordone, A., Tambalotti, A., Cocci, M., Hasegawa, R. and Linder, M. H. (2013), The FRBNY DSGE model, Staff Reports 647, Federal Reserve Bank of New York.

Del Negro, M., Giannoni, M. P. and Schorfheide, F. (2015), 'Inflation in the great recession and new keynesian models', *American Economic Journal: Macroeconomics* **7**(1), 168–96.

Del Negro, M. and Otrok, C. (2007), '99 luftballons: Monetary policy and the house price boom across us states', *Journal of Monetary Economics* **54**(7), 1962–1985.

Del Negro, M. and Schorfheide, F. (2013), Dsge model-based forecasting, *in* 'Handbook of economic forecasting', Vol. 2, Elsevier, pp. 57–140.

Dominguez-Torres, H. and Hierro, L. A. (2019), 'The regional effects of monetary policy: A survey of the empirical literature', *Journal of Economic Surveys* **33**(2), 604–638.

Erceg, C. J., Lindé, J. et al. (2010), *Asymmetric shocks in a currency union with monetary and fiscal handcuffs*, Board of Governors of the Federal Reserve System.

Gali, J. and Monacelli, T. (2008), 'Optimal monetary and fiscal policy in a currency union', *Journal of international economics* **76**(1), 116–132.

Gelfer, S. (2019), 'Data-rich dsge model forecasts of the great recession and its recovery', *Review of Economic Dynamics* **32**, 18–41.

Gilchrist, S., Schoenle, R., Sim, J. and Zakrajsek, E. (2018), 'Financial heterogeneity and monetary union'.

Jones, C., Midrigan, V. and Philippon, T. (2018), Household leverage and the recession, Technical report, National Bureau of Economic Research.

King, R. G., Plosser, C. I. and Rebelo, S. T. (1988), 'Production, growth and business cycles', *Journal of monetary Economics* **21**(2/3), 196–232.

Kolasa, M. and Lombardo, G. (2014), 'Financial frictions and optimal monetary policy in an open economy', *International Journal of Central Banking* .

Lombardo, G. (2006), 'Inflation targeting rules and welfare in an asymmetric currency area', *Journal of International Economics* **68**(2), 424–442.

Mian, A. and Sufi, A. (2014), 'What explains the 2007–2009 drop in employment?', *Econometrica* **82**(6), 2197–2223.

Nakamura, E. and Steinsson, J. (2014), 'Fiscal stimulus in a monetary union: Evidence from us regions', *American Economic Review* **104**(3), 753–92.

Owyang, M. T., Piger, J. and Wall, H. J. (2005), 'Business cycle phases in us states', *Review of Economics and Statistics* **87**(4), 604–616.

Owyang, M. T. and Wall, H. J. (2009), 'Regional vars and the channels of monetary policy', *Applied Economics Letters* **16**(12), 1191–1194.

Rondeau, S. (2012), Sources of fluctuations in emerging markets: DSGE estimation with mixed frequency data, PhD thesis, Columbia University.

Rudebusch, G. and Svensson, L. E. (1999), Policy rules for inflation targeting, *in* 'Monetary policy rules', University of Chicago Press, pp. 203–262.

Shaby, B. and Wells, M. T. (2010), ‘Exploring an adaptive metropolis algorithm’, *Duke University Working Paper* .

Silva, J. S. and Tenreyro, S. (2010), ‘Currency unions in prospect and retrospect’, *Annual Review Economics* **2**(1), 51–74.

Smets, F. and Wouters, R. (2003), ‘An Estimated Dynamic Stochastic General Equilibrium Model of the Euro Area’, *Journal of the European Economic Association* **1**(5), 1123–1175.

Smets, F. and Wouters, R. (2007), ‘Shocks and Frictions in US Business Cycles: A Bayesian DSGE Approach’, *American Economic Review* **97**(3), 586–606.

Taylor, J. B. and Wieland, V. (2012), ‘Surprising comparative properties of monetary models: results from a new model database’, *Review of Economics and Statistics* **94**(3), 800–816.

A Tables and FIgures

Table 5: Calibrated Parameters

	Description	Value
β	Discount rate	0.99255
R^*	S.S. Policy Rate (Annual %)	3
τ	Depreciation rate	0.025
$C_{y,NE}$	S.S. Consumption proportion of output in NE	0.678
$C_{y,S}$	S.S. Consumption proportion of output in S	0.675
$C_{y,MW}$	S.S. Consumption proportion of output in MW	0.694
$C_{y,W}$	S.S. Consumption proportion of output in W	0.657
$g_{y,s}$	S.S. government proportion of output in region s	0.18
$\lambda_{w,s}$	Degree of wage markup in region s	0.3
γ	Survival rate of entrepreneur	0.99
F^*	Loan default rate	0.0075
S^*	S.S. Spread (Annual %)	2.3

Table 6: Priors for DSGE Models' Parameters

	Description	Distribution	Mean	Std
Regional Structural Parameters				
ψ_s	Capital utilization costs	Beta	0.2	0.08
α_s	Capital Share	Beta	0.3	0.02
$\iota_{p,s}$	Degree of indexation on prices	Beta	0.5	0.15
$\iota_{w,s}$	Degree of indexation on wages	Beta	0.5	0.15
$\xi_{p,s}$	Calvo price stickiness	Beta	0.7	0.05
$\xi_{w,s}$	Calvo wage stickiness	Beta	0.7	0.05
$\xi_{e,s}$	Calvo Employment stickiness	Beta	0.5	0.15
$\nu_{l,s}$	CRRA coef. on labor	Gamma	1.4	0.45
$\sigma_{c,s}$	CRRA coef. on consumption	Gamma	1.2	0.45
h_s	Habit consumption	Beta	0.7	0.1
ϕ_s	Fixed cost of production	Gamma	1.5	0.2
$S_s^{''}$	Capital adjustment cost	Gamma	5	1
g_s^*	Regional Share of Fiscal Shock	Beta	0.25	0.1
National Parameters				
r_{π_1}	Taylor Rule coef. on inflation	Gamma	2	0.25
r_{y_1}	Taylor Rule coef. on output gap	Gamma	0.2	0.05
ρ	Lagged interest rate in Taylor Rule	Beta	0.7	0.1
$\chi*$	Spread Elasticity	Beta	0.05	0.005
ρ_F	AR(1) coef. on finance shock	Beta	0.7	0.1
σ_F	Std. of finance shock	Inv. Gamma	0.1	2*
ρ_G	AR(1) coef. on gov't spending shock	Beta	0.7	0.1
σ_G	Std. of gov't spending shock	Inv. Gamma	0.1	2*
σ_r	Std. of monetary policy shock	Inv. Gamma	0.1	2*
Regional Economic Share				
ω_{NE}	Share of NE to National Economy	Uniform	0.185	0.007
ω_S	Share of S to National Economy	Uniform	0.365	0.007
ω_{MW}	Share of MW to National Economy	Uniform	0.22	0.007
Regional Exogenous Processes Parameters				
$\rho_{a,s}$	AR(1) coef. on productivity shock	Beta	0.7	0.1
$\rho_{b,s}$	AR(1) coef. on preference shock	Beta	0.7	0.1
$\rho_{I,s}$	AR(1) coef. on investment shock	Beta	0.7	0.1
$\rho_{w,s}$	AR(1) coef. on wage mark-up shock	Beta	0.5	0.1
$\rho_{p,s}$	AR(1) coef. on price mark-up shock	Beta	0.5	0.1
$\sigma_{a,s}$	Std. of productivity shock	Inv. Gamma	0.1	2*
$\sigma_{b,s}$	Std. of preference shock	Inv. Gamma	0.1	2*
$\sigma_{I,s}$	Std. of investment shock	Inv. Gamma	0.1	2*
$\sigma_{p,s}$	Std. of price mark-up shock	Inv. Gamma	0.1	2*
$\sigma_{w,s}$	Std. of wage mark-up shock	Inv. Gamma	0.1	2*

Note: The parameter χ is estimated with $\chi^* = .0225 + .0825\chi$

Note: The parameter g_s is estimated with $g_s^*/(\sum_{s=1}^{4} g_s^*)$

Note: All inverse gamma distributions list degrees of freedom instead of std.

Note: All uniform distributions list +/- Bounds instead of std.

Table 7: Posterior Estimates for DSGE Structural Parameters

	Mean	5%	95%		Mean	5%	95%
Calvo Prices				**Price Indexation**			
$\xi_{p,NE}$	0.89	0.86	0.91	$\iota_{p,NE}$	0.20	0.10	0.31
$\xi_{p,S}$	0.92	0.90	0.94	$\iota_{p,S}$	0.13	0.07	0.21
$\xi_{p,MW}$	0.91	0.89	0.93	$\iota_{p,MW}$	0.13	0.06	0.22
$\xi_{p,W}$	0.67	0.62	0.73	$\iota_{p,W}$	0.23	0.12	0.38
Calvo Wages				**Wage Indexation**			
$\xi_{w,NE}$	0.61	0.55	0.67	$\iota_{w,NE}$	0.33	0.17	0.52
$\xi_{w,S}$	0.72	0.64	0.80	$\iota_{w,S}$	0.29	0.15	0.45
$\xi_{w,MW}$	0.65	0.57	0.72	$\iota_{w,MW}$	0.29	0.14	0.48
$\xi_{w,W}$	0.63	0.59	0.67	$\iota_{w,W}$	0.49	0.28	0.70
Calvo Employment				**CRRA Labor**			
$\xi_{e,NE}$	0.22	0.09	0.46	$\nu_{l,NE}$	0.80	0.42	1.33
$\xi_{e,S}$	0.28	0.11	0.50	$\nu_{l,S}$	1.47	0.94	2.07
$\xi_{e,MW}$	0.10	0.04	0.16	$\nu_{l,MW}$	1.37	0.74	2.02
$\xi_{e,W}$	0.74	0.70	0.77	$\nu_{l,W}$	2.1	1.47	2.79
Inv. Adjustment Costs				**Capital Utilization Costs**			
S''_{NE}	7.06	5.57	8.69	ψ_{NE}	0.20	0.16	0.23
S''_{S}	4.07	3.11	5.03	ψ_{S}	0.20	0.13	0.20
S''_{MW}	5.91	4.71	7.19	ψ_{MW}	0.17	0.16	0.23
S''_{W}	4.74	3.64	5.92	ψ_{W}	0.20	0.16	0.24
Share of National Economy				**Share of Fiscal Policy**			
ω_{NE}	0.179	0.178	0.181	g_{NE}	0.17	0.15	0.19
ω_{S}	0.370	0.367	0.372	g_{S}	0.39	0.36	0.42
ω_{MW}	0.216	0.213	0.221	g_{MW}	0.14	0.12	0.17
ω_{W}	0.235	0.229	0.240	g_{W}	0.29	0.27	0.32
CRRA Consumption				**Habit Consumption**			
$\sigma_{c,NE}$	4.85	3.57	6.04	h_{NE}	0.66	0.61	0.72
$\sigma_{c,S}$	2.65	1.92	3.40	h_{S}	0.72	0.65	0.79
$\sigma_{c,MW}$	2.82	1.97	3.84	h_{MW}	0.71	0.64	0.78
$\sigma_{c,W}$	2.30	1.56	3.18	h_{W}	0.58	0.49	0.66
Capital Share				**Fixed Cost of Production**			
α_{NE}	0.33	0.30	0.37	ϕ_{NE}	2.09	1.77	2.42
α_{S}	0.35	0.32	0.39	ϕ_{S}	1.97	1.72	2.28
α_{MW}	0.36	0.32	0.39	ϕ_{MW}	1.75	1.57	1.96
α_{W}	0.36	0.33	0.40	ϕ_{W}	1.20	1.11	1.73
Taylor Rule Parameters				**Spread Elasicity**			
ρ	0.93	0.92	0.94	χ	0.061	0.055	0.067
r_{π_1}	1.44	1.27	1.61				
r_{y_1}	0.06	0.04	0.08				

Table 8: Posterior Estimates for DSGE Exogenous Shock Parameters

	Mean	5%	95%		Mean	5%	95%
Regional Productivity Shock							
$\rho_{a,NE}$	0.94	0.92	0.97	$\sigma_{a,NE}$	0.34	0.29	0.40
$\rho_{a,S}$	0.94	0.91	0.95	$\sigma_{a,S}$	0.34	0.29	0.43
$\rho_{a,MW}$	0.93	0.92	0.96	$\sigma_{a,MW}$	0.32	0.29	0.36
$\rho_{a,W}$	0.94	0.91	0.96	$\sigma_{a,W}$	0.49	0.44	0.55
Regional Investment Shock							
$\rho_{I,NE}$	0.82	0.77	0.88	$\sigma_{I,NE}$	0.27	0.20	0.36
$\rho_{I,S}$	0.54	0.43	0.64	$\sigma_{I,S}$	1.31	0.96	1.70
$\rho_{I,MW}$	0.77	0.70	0.84	$\sigma_{I,MW}$	0.45	0.32	0.58
$\rho_{I,W}$	0.55	0.46	0.65	$\sigma_{I,W}$	0.94	0.76	1.11
Regional Consumption Shock							
$\rho_{b,NE}$	0.77	0.67	0.85	$\sigma_{b,NE}$	0.06	0.04	0.09
$\rho_{b,S}$	0.87	0.82	0.91	$\sigma_{b,S}$	0.12	0.08	0.17
$\rho_{b,MW}$	0.86	0.78	0.92	$\sigma_{b,MW}$	0.05	0.04	0.07
$\rho_{b,W}$	0.51	0.39	0.65	$\sigma_{b,W}$	0.09	0.06	0.13
Regional Price Shock							
$\rho_{p,NE}$	0.51	0.39	0.65	$\sigma_{p,NE}$	0.12	0.09	0.14
$\rho_{p,S}$	0.35	0.27	0.44	$\sigma_{p,S}$	0.21	0.18	0.25
$\rho_{p,MW}$	0.48	0.35	0.60	$\sigma_{p,MW}$	0.14	0.12	0.18
$\rho_{p,W}$	0.93	0.90	0.96	$\sigma_{p,W}$	0.11	0.09	0.13
Regional Wage Shock							
$\rho_{w,NE}$	0.61	0.47	0.77	$\sigma_{w,NE}$	0.25	0.19	0.31
$\rho_{w,S}$	0.59	0.45	0.73	$\sigma_{w,S}$	0.20	0.16	0.25
$\rho_{w,MW}$	0.59	0.48	0.70	$\sigma_{w,MW}$	0.23	0.19	0.28
$\rho_{w,W}$	0.96	0.93	0.97	$\sigma_{w,W}$	0.05	0.03	0.06
National Shocks							
ρ_F	0.98	0.98	0.99	σ_F	0.09	0.08	0.10
ρ_G	0.94	0.91	0.97	σ_G	1.23	1.12	1.34
				σ_r	0.13	0.12	0.14

Table 9: Posterior Estimates for National DSGE (SWFF) Structural Parameters

	Mean	5%	95%		Mean	5%	95%
Structural Parameters							
ξ_p	0.94	0.92	0.95	ι_p	0.17	0.08	0.29
ξ_w	0.74	0.67	0.80	ι_w	0.46	0.23	0.72
ξ_e	0.36	0.16	0.53	ν_l	1.63	0.95	2.41
S''	4.37	3.19	5.81	ψ	0.21	0.17	0.26
σ_c	2.60	1.71	3.65	h	0.76	0.68	0.83
α	0.25	0.21	0.28	ϕ	1.46	1.06	1.96
ρ	0.93	0.92	0.95	χ	0.062	0.056	0.069
r_{π_1}	1.91	1.62	2.22				
r_{y_1}	0.11	0.07	0.16				
Exogenous Shock Parameters							
ρ_a	0.94	0.91	0.96	σ_a	0.43	0.35	0.52
ρ_I	0.67	0.59	0.75	σ_I	0.81	0.67	0.96
ρ_b	0.82	0.74	0.88	σ_b	0.07	0.05	0.09
ρ_p	0.37	0.26	0.48	σ_p	0.12	0.09	0.15
ρ_w	0.79	0.71	0.85	σ_w	0.12	0.08	0.16
ρ_F	0.97	0.94	0.98	σ_F	0.10	0.09	0.12
ρ_G	0.89	0.76	0.96	σ_G	0.23	0.18	0.28
				σ_r	0.11	0.10	0.12

Table 10: Variance Decomposition by Types of Shocks (h=4)

	Prod	Cons	Inv	Price	Wage	Mont	Ant Mont	Finance	Govt
NE Output	1.5	41.7	32.9	7.5	1.0	7.9	1.7	3.1	2.7
S Output	0.8	29.0	33.3	6.8	1.0	14.3	3.1	5.3	6.4
MW Output	1.6	25.3	41.2	9.9	1.5	12.5	2.7	3.6	1.7
W Output	9.6	18.5	27.3	13.3	19.2	6.5	1.2	1.3	3.2
National Output	0.3	29.0	13.5	2.0	0.7	28.7	6.1	9.3	10.5
National GDP Growth	0.6	26.1	16.4	1.4	0.7	21.5	4.5	6.8	22.0
NE Inflation	4.7	11.6	3.4	67.5	8.4	2.9	0.8	0.5	0.2
S Inflation	2.7	1.3	0.4	87.4	5.8	1.5	0.5	0.3	0.2
MW Inflation	3.8	2.3	2.1	81.3	7.0	2.4	0.7	0.4	0.2
W Inflation	22.2	11.7	9.8	28.9	15.2	8.1	2.0	1.6	0.6
National Inflation	11.3	7.2	2.4	53.5	14.8	7.1	1.9	1.4	0.6
NE Consumption	1.5	91.9	1.5	1.6	0.6	2.3	0.5	0.1	0.0
S Consumption	1.2	81.9	2.0	3.4	1.6	7.6	1.7	0.5	0.2
MW Consumption	3.0	71.6	5.6	6.0	2.3	9.2	2.0	0.3	0.0
W Consumption	6.7	65.4	0.4	4.3	16.8	4.3	0.9	0.3	0.8
National Consumption	0.8	75.2	0.3	1.0	1.3	16.9	3.7	0.2	0.5
NE Investment	1.3	7.1	69.2	5.9	1.9	6.5	1.4	6.7	0.0
S Investment	0.5	0.6	72.8	3.9	1.0	10.4	2.2	8.7	0.0
MW Investment	0.8	0.9	76.6	5.3	1.5	7.0	1.5	6.5	0.0
W Investment	6.7	7.3	63.8	6.6	6.9	2.4	0.4	5.7	0.2
National Investment	0.1	0.2	45.6	0.6	0.0	24.0	4.9	24.5	0.0
NE Employment	24.6	16.4	26.1	2.5	18.3	5.5	1.1	2.8	2.7
S Employment	10.0	23.7	25.7	2.6	13.2	12.0	2.6	4.6	5.5
MW Employment	11.9	19.5	31.7	3.8	17.3	9.5	2.0	2.8	1.6
W Employment	1.1	1.3	4.3	10.8	79.1	1.5	0.3	1.0	0.7
National Hours Worked	12.4	21.7	11.8	1.2	9.3	22.0	4.5	6.9	10.2
NE Wage Growth	0.4	29.5	3.0	8.6	55.9	1.8	0.4	0.3	0.0
S Wage Growth	0.1	2.7	1.4	13.3	79.2	2.0	0.5	0.7	0.1
MW Wage Growth	0.2	4.6	4.5	12.5	74.7	2.3	0.6	0.5	0.1
W Wage Growth	22.3	3.4	3.3	60.4	9.4	0.9	0.2	0.1	0.1
National Wage Growth	0.8	8.1	0.5	10.2	72.4	5.3	1.3	1.3	0.2
Policy Rate	1.1	1.0	0.2	4.4	1.4	86.2	5.5	0.2	0.1
Financial Spread	0.2	0.1	9.2	0.4	0.3	4.1	0.4	85.1	0.0

Note: The FEVD is calculated using the posterior means of all estimated parameters of the regional DSGE model. Total FEVD may not add up to 100 because of rounding.

Table 11: Unconditional Variance Decomposition by Types of Shocks (h=1000)

	Prod	Cons	Inv	Price	Wage	Mont	Ant Mont	Finance	Govt
NE Output	12.1	25.3	27.6	13.8	5.9	6.6	1.6	5.8	1.4
S Output	6.8	15.0	16.8	14.4	8.7	18.6	4.6	12.3	2.7
MW Output	11.2	12.1	28.8	18.1	8.3	10.4	2.6	7.8	0.7
W Output	15.3	5.0	6.3	13.0	56.4	1.6	0.3	1.5	0.6
National Output	1.9	15.2	5.9	2.8	3.5	32.7	7.9	25.2	4.9
National GDP Growth	0.7	26.8	17.2	1.6	1.0	21.6	4.6	6.9	19.6
NE Inflation	7.3	18.7	6.3	48.3	11.4	3.8	1.0	2.7	0.5
S Inflation	5.3	3.4	1.8	73.3	9.5	3.0	0.8	2.4	0.3
MW Inflation	6.9	4.9	5.1	63.1	11.6	3.8	1.0	3.0	0.5
W Inflation	20.0	14.5	11.4	25.6	13.8	8.7	2.2	3.4	0.5
National Inflation	12.7	8.4	4.4	40.3	16.2	8.9	2.4	6.0	0.8
NE Consumption	10.3	60.7	12.1	6.5	3.7	2.7	0.7	3.3	0.0
S Consumption	8.3	26.7	14.6	11.4	10.0	13.3	3.3	11.9	0.6
MW Consumption	12.7	22.1	26.0	14.3	8.4	7.0	1.8	7.7	0.1
W Consumption	12.3	17.1	5.1	6.5	54.4	0.9	0.2	2.0	1.4
National Consumption	3.0	30.1	4.4	2.0	4.5	23.0	5.7	25.5	1.7
NE Investment	8.6	37.4	27.1	8.6	4.8	3.0	0.6	9.8	0.0
S Investment	5.6	5.7	26.9	11.1	8.2	14.5	3.4	24.5	0.1
MW Investment	7.7	7.9	41.0	13.3	7.3	6.2	1.4	15.2	0.0
W Investment	12.9	13.3	12.6	8.4	41.2	0.7	0.2	10.1	0.7
National Investment	0.4	0.8	9.7	0.6	0.5	21.8	4.7	61.4	0.2
NE Employment	12.1	25.0	31.1	8.6	11.0	4.3	1.0	5.5	1.3
S Employment	6.3	15.5	17.5	8.3	20.0	16.4	4.0	8.2	3.7
MW Employment	6.1	12.8	30.3	12.5	19.0	10.8	2.6	4.8	1.0
W Employment	1.3	1.1	1.7	5.8	88.9	0.5	0.1	0.4	0.3
National Hours Worked	6.8	12.7	7.0	2.0	27.1	21.9	5.2	11.7	5.7
NE Wage Growth	9.7	35.1	11.9	12.2	23.1	3.5	0.9	3.6	0.1
S Wage Growth	4.3	5.9	5.8	17.3	46.2	9.9	2.5	7.8	0.3
MW Wage Growth	7.4	8.0	15.8	20.3	34.3	6.8	1.7	5.6	0.2
W Wage Growth	27.3	3.7	3.7	50.9	11.1	0.3	0.1	2.6	0.2
National Wage Growth	1.5	8.6	1.0	8.7	41.4	16.6	4.2	17.7	0.3
Policy Rate	5.8	5.9	2.1	4.7	7.1	59.2	10.0	3.8	1.4
Financial Spread	1.0	1.7	16.3	1.4	1.5	4.7	1.4	71.7	0.4

Note: The FEVD is calculated using the posterior means of all estimated parameters of the regional DSGE model. Total FEVD may not add up to 100 because of rounding.

Table 12: Variance Decomposition by Types of Shocks–National SWFF

hline	Prod	Cons	Inv	Price	Wage	Mont	Ant Mont	Finance	Govt
Horizon=4									
National Output	0.3	44.0	30.4	1.8	0.6	12.3	2.5	4.3	3.8
National GDP Growth	1.2	38.3	33.4	1.4	0.8	9.5	1.9	3.3	10.1
National Inflation	6.6	0.6	0.3	61.4	30.9	0.1	0.0	0.0	0.0
National Consumption	0.6	91.7	0.1	0.5	2.0	4.0	0.8	0.0	0.1
National Investment	0.0	1.7	76.8	0.6	0.0	8.5	1.7	10.5	0.1
National Hours Worked	46.4	19.5	13.1	0.2	10.8	5.3	1.1	1.9	1.9
National Wage Growth	0.2	0.9	0.1	2.5	95.9	0.3	0.1	0.1	0.0
Policy Rate	1.5	1.7	0.4	9.8	6.5	75.2	4.8	0.0	0.1
Financial Spread	0.2	0.0	19.7	0.3	0.8	1.2	0.1	77.7	0.0
Horizon=1000									
National Output	3.4	34.0	18.8	2.5	7.5	19.6	4.8	7.7	1.7
National GDP Growth	1.3	37.3	34.7	1.4	2.2	9.3	2.0	3.4	8.4
National Inflation	12.0	1.1	1.7	40.7	43.1	0.5	0.1	0.8	0.0
National Consumption	5.5	59.6	6.2	1.0	14.7	7.9	2.0	2.7	0.4
National Investment	1.0	8.2	43.1	0.9	4.2	15.6	3.3	23.4	0.3
National Hours Worked	29.8	13.9	9.3	0.4	34.4	6.7	1.6	3.1	0.8
National Wage Growth	0.4	1.1	0.1	1.2	96.1	0.8	0.2	0.1	0.0
Policy Rate	10.3	11.7	2.9	4.8	33.5	30.3	4.8	1.4	0.4
Financial Spread	1.6	3.8	33.6	0.9	7.2	1.6	0.6	50.6	0.1

Note: The FEVD is calculated using the posterior means of all estimated parameters for the National SWFF model. Total FEVD may not add up to 100 because of rounding.

Figure 20: Census Regions

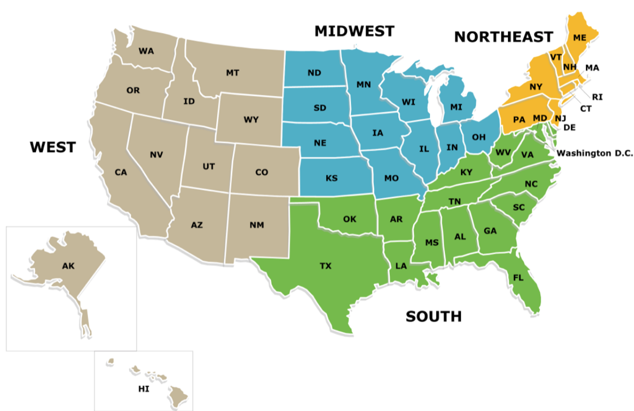
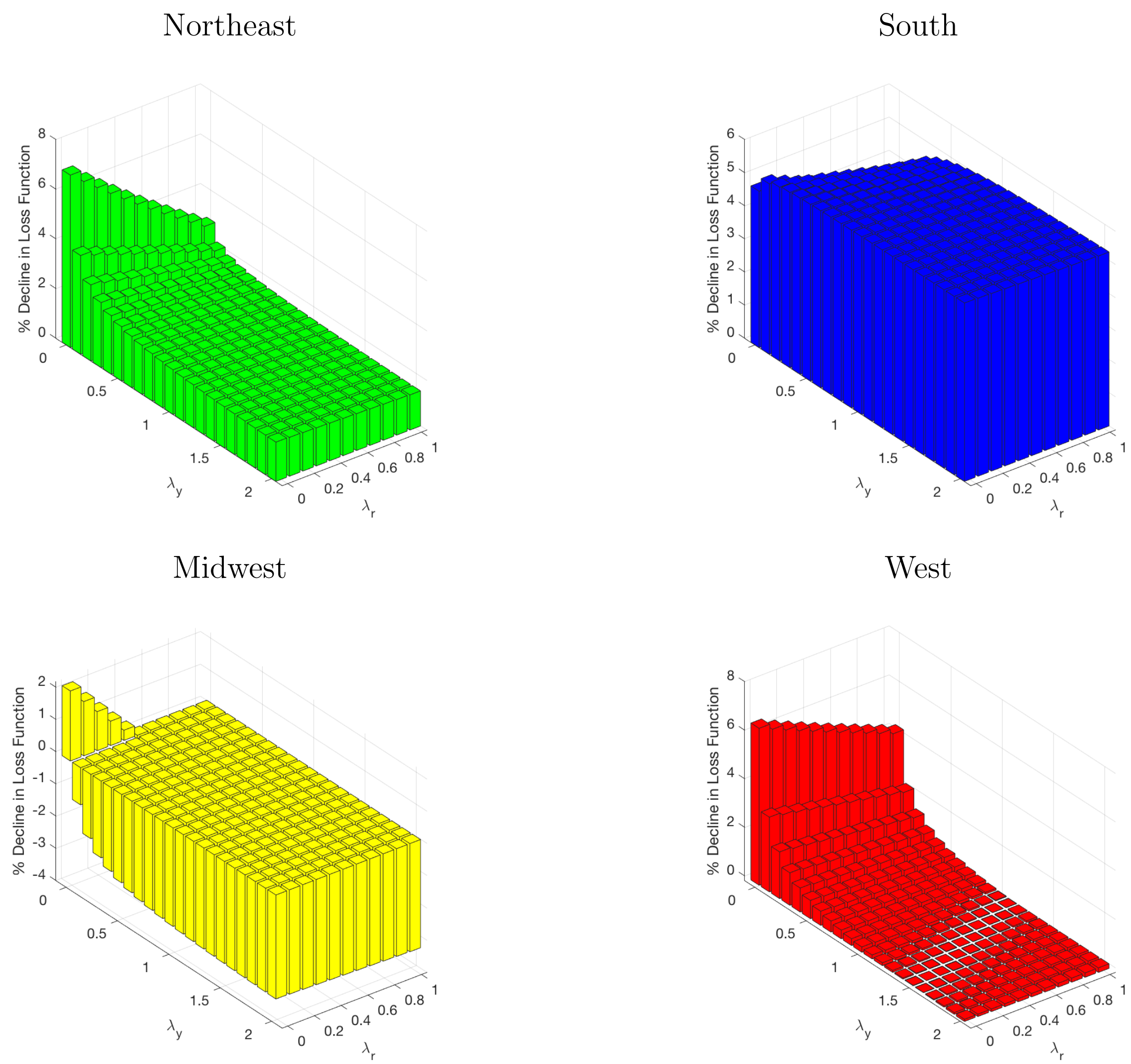


Figure 21: Regional Loss Reduction when central bank includes Regional Information and Price Rigidities

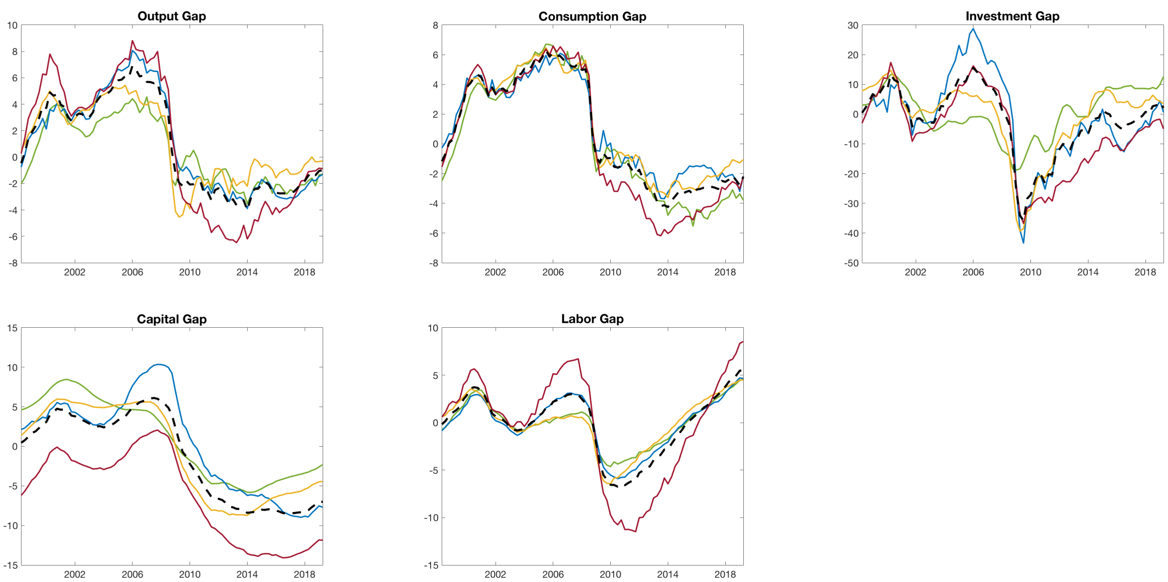


Note: The figure plots the percentage reduction in the value of the regional loss function attained under the incorporation of regional economic information and price rigidities ($TR_{\xi_{p,region}}$) into the Taylor rule relative to the regional information based rule (TR_{Region}).The parameters λ_y and λ_r reflect the weight attached by the policymaker to the output gap and the interest rate variability in its loss function.

B Evaluating the Estimated States of the Regional DSGE Model

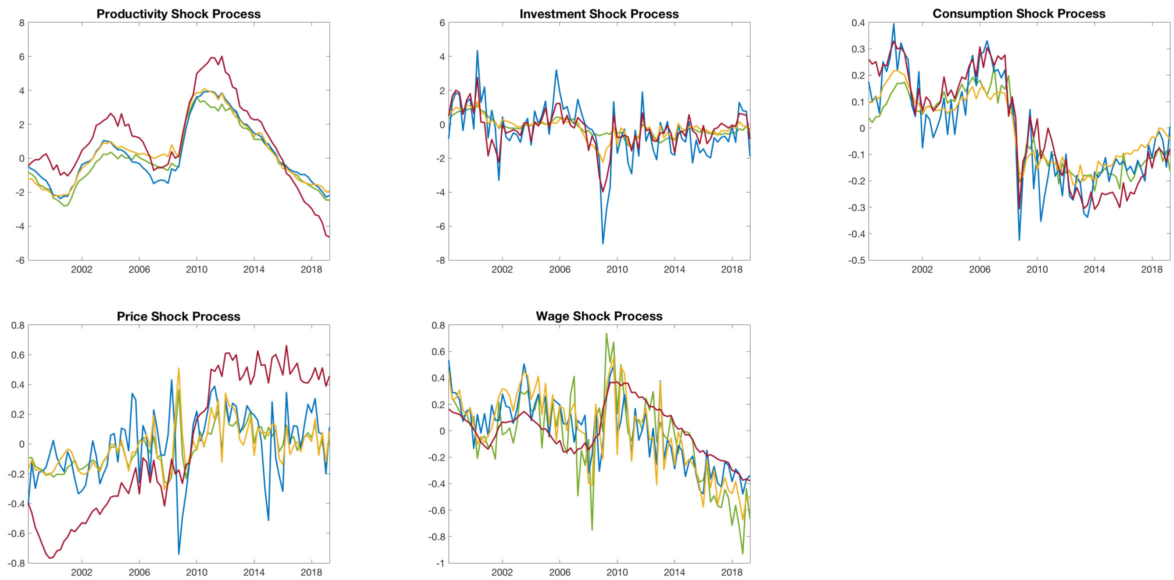
Using a Carter-Kohn smoothing algorithm, I calculate the estimates of the endogenous and exogenous variables of the model over the sample time period. The median estimates for a select few variables in the regional DSGE model are plotted in Figures 22 and 23. Three observations stand out. First, output (Y) and its major components (C and I) exhibit large swings and prolonged deviations from steady state at the national and regional level. Second, in accordance with the data, (seen in Figure 4) all regional variables are highly correlated with their aggregated national variable but still exhibit significant heterogeneity across the four regions. Third, there is no consistent ranking pattern of the four regions for most variables across the estimation sample. In most cases, a regional's endogenous and exogenous variable will change its ranking order multiple times throughout the estimation window of 1998 to 2019.

Figure 22: Select Estimated Endogenous Variables



Note: The figure plots the median estimate of the % deviation of Output, consumption, investment, capital and labor for the four regions and the National level. The Northeast region is in green, the South region is in blue, the Midwest in yellow, the West in red and the dashed black line is the national variable.

Figure 23: Estimated Regional Exogenous Processes

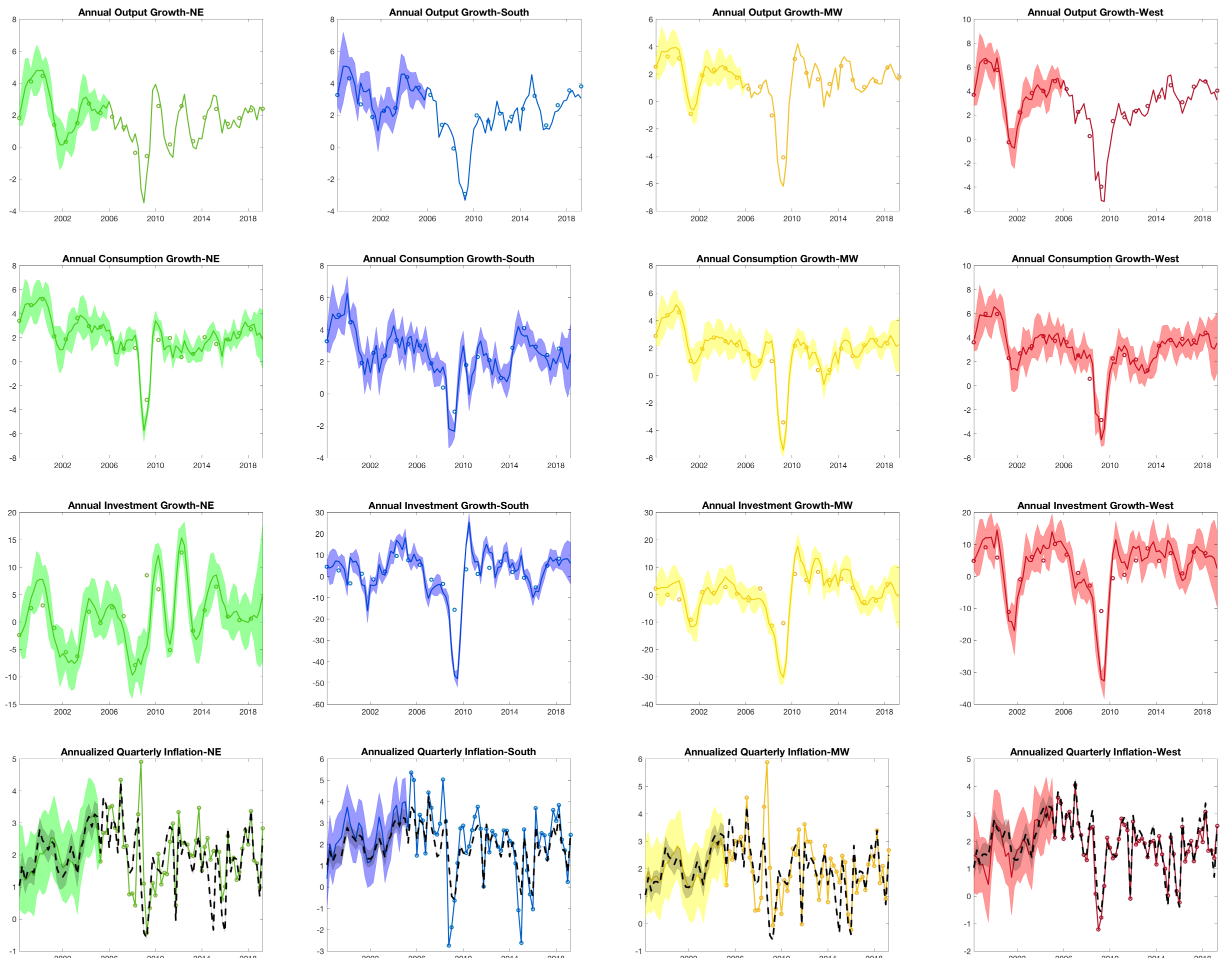


Note: The figure plots the median estimate of the % deviation of the five regional exogenous shock processes. The Northeast region is in green, the South region is in blue, the Midwest in yellow, and the West in red.

An additional contribution of this paper is that it provides estimates for quarterly and annualized regional growth rates for real GDP, consumption and investment growth as well as an estimate for regional quarterly inflation. These four estimates and their resulting 90% credible interval for each region are plotted in Figure 24. I see that each region's growth rates are a close fit to its respected data, with the lone exception being investment. Investment Growth is estimated to be much lower during the Great Recession (2008-2009) for all four regions. This is likely due to the fact that net exports increased during this time period causing the proxy for regional investment decline to be smaller than it actually was. However, the model is able to correct for this as it must match aggregated quarterly national investment growth.

When examining regional and national inflation, the West Region closely follows national inflation in both the short-run and long-run. While, regional inflation for the Northeast, South and Midwest regions show short periods of significant difference when compared to national inflation but a long-run trend that closely reflects national inflation. This is key to the policy loss function results of Section 5, as it suggests that disturbances in short-run regional inflation can suggest future disturbances in national inflation dynamics.

Figure 24: Estimated Regional Growth Rates



Note: The figure plots the estimates of the Annual growth rates of regional output, consumption, investment and annualized quarterly inflation. The Northeast region is in green, the South region is in blue, the Midwest in yellow, the West in red and the dashed black line is the national variable. The *o* is the data used in estimation of each variable and the shaded areas represent the 90% credible interval for each series.