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To: Research Directors

From: Matthew M. Luecke

Subject: Supporting Documents for DSGE Models Update

The attached documents support the update on the projections of the DSGE models.

System DSGE Project: Research Directors Drafts

March 9, 2015

The Current Outlook in EDO: March FOMC Meeting (Class II – Restricted FR)

Manuel Gonzalez-Astudillo*

March 4, 2015

1 The EDO Forecast from 2015 to 2017

Given recent data (including expectations for the federal funds rate), the EDO model projects real GDP growth slightly higher on average than its trend of 2.7 percent in 2015. Subsequently, real GDP growth declines to an average 2½ percent through the end of the forecast period. The unemployment rate rises to 5¾ percent by the end of 2015 and continues rising to reach 6¼ percent by the end of 2017. (Figures 1 and 3).[1] Inflation runs below the Committees 2 percent objective, averaging around 1½ percent over the next three years.

The lackluster growth of GDP in 2016 and 2017 is the product of two offsetting forces. First, the combination of weak growth in consumption along with relatively high real short-term interest rates has led the model to estimate a relatively elevated aggregate risk premium, the models main cyclical driver. All else equal, GDP growth would rise above trend as this risk premium converges to its historical average. However, the model also interprets the market-expected path of the federal funds rate as unusually accommodative, given the expected state of the economy and the estimated monetary policy reaction function. Although these lower-than-expected interest rates boost the current level of real GDP, these effects vanish over the medium term, lowering GDP growth. In the current forecast, these two forces are balanced, leading to roughly trend GDP growth. In the near-term, the model has interpreted the decline in oil prices as a short-lived price markup shock, boosting GDP growth over the second and third quarters of 2015.

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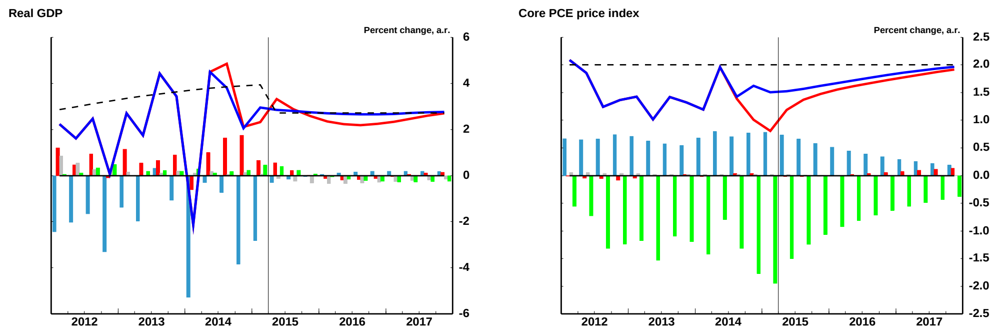
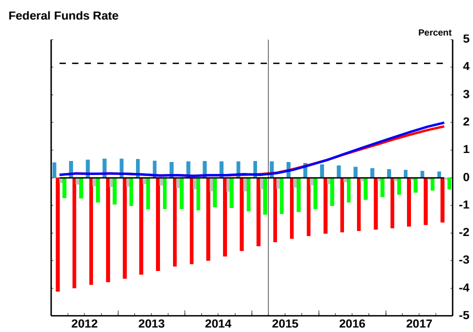
[1] The baseline forecast for EDO is conditioned on the staff's preliminary January 2015 Tealbook projection through 2015:Q1 and market expectations that the federal funds rate will remain at its effective lower bound through the second quarter of 2015 (as indicated by OIS market prices). We do not impose an unemployment or inflation threshold on the monetary policy rule.
The model's static structural parameters have been re-estimated using data through 2014:Q3. In particular, the new estimates incorporate the latest comprehensive revision to NIPA data. For estimation, the observable corresponding to the model's concept of investment excludes spending on intellectual property products.

Figure 1: Recent History and Forecasts

EDO Projection Summary





	2015 Q4/Q4	2016 Q4/Q4	2017 Q4/Q4
Real GDP (a)	2.8	2.3	2.6
Credible set (c)	.3-5.5	.5-4.0	.5-4.4
Core PCE Price index (a)	1.2	1.6	1.9
Credible set (c)	.8-1.5	.9-2.2	1.1-2.4
Federal Funds Rate (b)	0.5	1.2	1.9
Credible set (c)	.0-1.6	.0-3.2	.3-3.7

(a) Q4/Q4 percent change, (b) Q4 level, (c) 68 percent

Red, solid line -- Data (through 2015:Q1) and projections; Blue, solid line -- Previous projection (December, 2014, as of 2014:Q4); Black, dashed line -- Steady-state or trend values
Contributions (bars): Red -- Financial; Blue -- Technology; Silver -- Monetary policy; Green -- Other

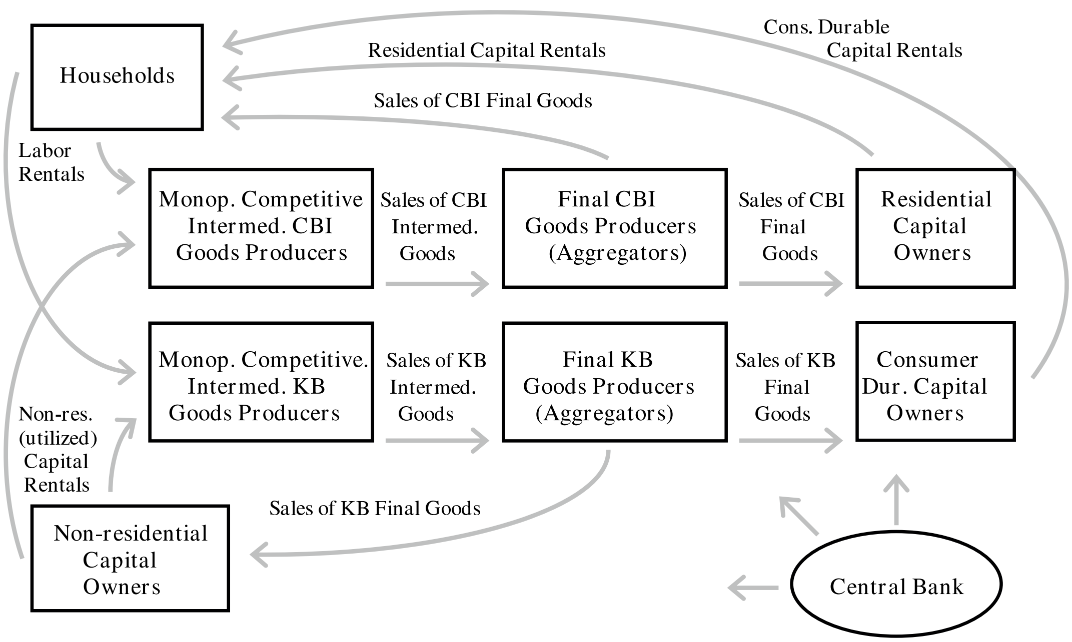
The gradual increase in projected inflation over the forecast horizon is driven by the rebound of wages following negative markup shocks and a slow return of household labor supply preferences to long-run levels. Even so, inflation is held below target by a combination of weak aggregate demand and muted pressure on wages in the labor market. Indeed, the unemployment rate rises through early 2015, driven largely by the weak demand conditions. By the end of the forecast, however, a substantial portion of the elevated unemployment rate is accounted for by the stickiness in wages and prices in EDO, which prevents the real wage from falling sufficiently to bring down unemployment; indeed, EDO estimates that the real wage must decline notably to clear the labor market.[2]

[2] As discussed below, unemployment enters the EDO model through a new-Keynesian wage Phillips curve, without much specificity regarding structural labor-market features. As such, the primary role of unemployment is as a gauge of the degree to which real-wage adjustment impedes labor market clearing, and anomalously persistent and elevated rates of unemployment lead EDO to detect a decline in the real wage needed to clear the labor market. While most of the runup in unemployment since 2007 is driven by weak demand (in EDO), the model identifies a component of the increase in unemployment as due to a decline in the market-clearing real wage. Finally, as noted in the model description below, such a decline is implemented in the model by a shift in labor supply.

2 An Overview of Key Model Features

Figure 2 provides a graphical overview of the model. While similar to most related models, EDO has a more detailed description of production and expenditure than most other models.[3]

Figure 2: Model Overview



Specifically, the model possesses two final good sectors in order to capture key long-run growth facts and to differentiate between the cyclical properties of different categories of durable expenditure (e.g., housing, consumer durables, and nonresidential investment). For example, technological progress has been faster in the production of business capital and consumer durables (such as computers and electronics).

The disaggregation of production (aggregate supply) leads naturally to some disaggregation of expenditures (aggregate demand). We move beyond the typical model with just two categories of (private domestic) demand (consumption and investment) and distinguish between four categories of private demand: consumer non-durable goods and non-housing services, consumer durable goods, residential investment, and non-residential investment. The boxes surrounding the producers in the

[3]Chung, Kiley, and Laforte (2011) provide much more detail regarding the model specification, estimated parameters, and model propeties.

figure illustrate how we structure the sources of each demand category. Consumer non-durable goods and services are sold directly to households; consumer durable goods, residential capital goods, and non-residential capital goods are intermediated through capital-goods intermediaries (owned by the households), who then rent these capital stocks to households. Consumer non-durable goods and services and residential capital goods are purchased (by households and residential capital goods owners, respectively) from the first of economy's two final goods producing sectors, while consumer durable goods and non-residential capital goods are purchased (by consumer durable and residential capital goods owners, respectively) from the second sector. In addition to consuming the non-durable goods and services that they purchase, households supply labor to the intermediate goods-producing firms in both sectors of the economy.

The remainder of this section provides an overview of the key properties of the model. In particular, the model has five key features:

- A new-Keynesian structure for price and wage dynamics. Unemployment measures the difference between the amount workers are willing to be employed and firms' employment demand. As a result, unemployment is an indicator of wage, and hence price, pressures as in Gali (2010).
- Production of goods and services occurs in two sectors, with differential rates of technological progress across sectors. In particular, productivity growth in the investment and consumer durable goods sector exceeds that in the production of other goods and services, helping the model match facts regarding long-run growth and relative price movements.
- A disaggregated specification of household preferences and firm production processes that leads to separate modeling of nondurables and services consumption, durables consumption, residential investment, and business investment.
- Risk premia associated with different investment decisions play a central role in the model. These include, first, an aggregate risk-premium, or natural rate of interest, shock driving a wedge between the short-term policy rate and the interest rate faced by private decisionmakers (as in Smets and Wouters (2007)) and, second, fluctuations in the discount factor/risk premia faced by the intermediaries financing household (residential and consumer durable) and business investment.

2.1 Two-sector production structure

It is well known (e.g., Edge, Kiley, and Laforte (2008)) that real outlays for business investment and consumer durables have substantially outpaced those on other goods and services, while the prices of these goods (relative to others) has fallen. For example, real outlays on consumer durables have far outpaced those on other consumption, while prices for consumer durables have been flat and those for other consumption have risen substantially; as a result, the ratio of nominal outlays in the two categories has been much more stable, although consumer durable outlays plummeted in the Great Recession. Many models fail to account for this fact.

EDO accounts for this development by assuming that business investment and consumer durables are produced in one sector and other goods and services in another sector. Specifically, production by firm j in each sector s (where s equals kb for the sector producing business investment and consumer durables sector and cbi for the sector producing other goods and services) is governed by a Cobb-Douglas production function with sector-specific technologies:

$$X_t^s(j) = \left(Z_t^m Z_t^s L_t^s(j)\right)^{1-\alpha} \left(K_t^{u,nr,s}(j)\right)^{\alpha}, \text{ for } s = cbi, kb. \tag{1}$$

In 1, Z^m represents (labor-augmenting) aggregate technology, while Z^s represents (labor-augmenting) sector-specific technology; we assume that sector-specific technological change affects the business investment and consumer durables sector only; L^s is labor input and $K^{u,nr,s}$ is capital input (that is, utilized *non-residential business* capital (and hence the nr and u terms in the superscript). Growth in this sector-specific technology accounts for the long-run trends, while high-frequency fluctuations allow the possibility that investment-specific technological change is a source of business cycle fluctuations, as in Fisher (2006).

2.2 The structure of demand

EDO differentiates between several categories of expenditure. Specifically, business investment spending determines non-residential capital used in production, and households value consumer nondurables goods and services, consumer durable goods, and residential capital (e.g., housing). Differentiation across these categories is important, as fluctuations in these categories of expenditure can differ notably, with the cycles in housing and business investment, for example, occurring at different points over the last three decades.

Valuations of these goods and services, in terms of household utility, is given by the following utility function:

$$\mathcal{E}_0 \sum_{t=0}^{\infty} \beta^t \Big\{ \varsigma^{cnn} \ln(E_t^{cnn}(i) - h E_{t-1}^{cnn}(i)) + \varsigma^{cd} \ln(K_t^{cd}(i)) + \varsigma^{r} \ln(K_t^{r}(i)) - \varsigma^{l} \frac{(L_t^{cbi}(i) + L_t^{kb}(i))^{1+\nu}}{1+\nu} \Big\}, \tag{2}$$

where E^{cnn} represents expenditures on consumption of nondurable goods and services, K^{cd} and K^r represent the stocks of consumer durables and residential capital (housing), $L^{cbi} + L^{kb}$ represents the sum of labor supplied to each productive sector (with hours worked causing disutility), and the remaining terms represent parameters (such as the discount factor, relative value in utility of each service flow, and the elasticity of labor supply).

By modeling preferences over these disaggregated categories of expenditure, EDO attempts to account for the disparate forces driving consumption of nondurables and durables, residential investment, and business investment – thereby speaking to issues such as the surge in business investment in the second half of the 1990s or the housing cycle in the early 2000s recession and the most recent downturn. Many other models do not distinguish between developments across these categories of spending.

2.3 Risk premia, financial shocks, and economic fluctuations

The structure of the EDO model implies that households value durable stocks according to their expected returns, including any expected service flows, and according to their risk characteristics, with a premium on assets which have high expected returns in adverse states of the world. However, the behaviour of models such as EDO is conventionally characterized under the assumption that this second component is negligible. In the absence of risk adjustment, the model would then imply that households adjust their portfolios until expected returns on all assets are equal.

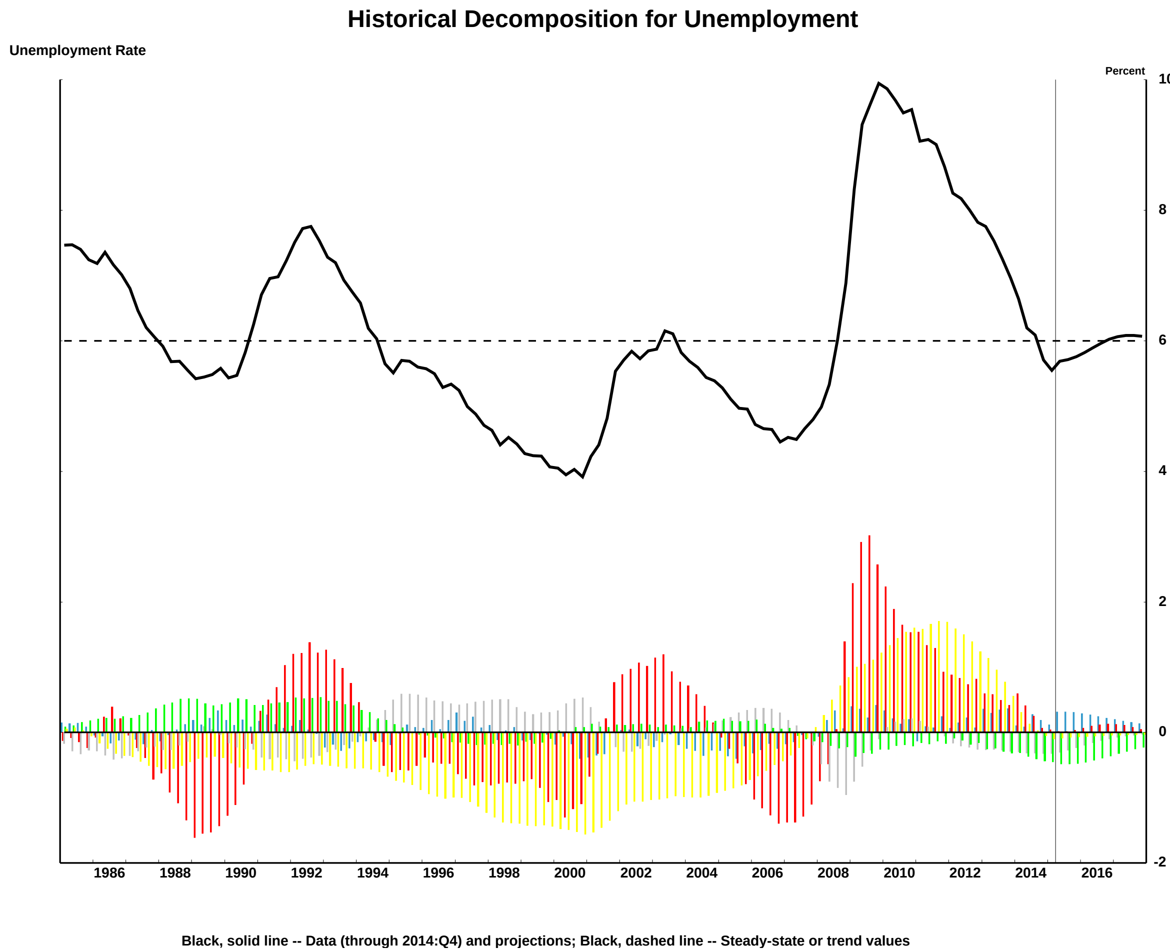
Empirically, however, this risk adjustment may not be negligible and, moreover, there may be a variety of factors, not explicitly modelled in EDO, which limit the ability of households to arbitrage away expected return differentials across different assets. To account for this possibility, EDO features several exogenous shocks to the rates of return required by the household to hold the assets in question. Following such a shock – an increase in the premium on a given asset, for example– households will wish to alter their portfolio composition to favor the affected asset, leading to changes in the prices of all assets and, ultimately, to changes in the expected path of production underlying these claims.

The "sector-specific" risk shocks affect the composition of spending more than the path of GDP itself. This occurs because a shock to these premia leads to sizable substitution across residential, consumer durable, and business investment; for example, an increase in the risk premia on residential investment leads households to shift away from residential investment and towards other types of productive investment. Consequently, it is intuitive that a large fraction of the non-cyclical, or idiosyncratic, component of investment flows to physical stocks will be accounted for by movements in the associated premia.

Shocks to the required rate of return on the nominal risk-free asset play an especially large role in EDO. Following an increase in the premium, in the absence of nominal rigidities, the households' desire for higher real holdings of the risk-free asset would be satisfied entirely by a fall in prices, i.e., the premium is a shock to the natural rate of interest. Given nominal rigidities, however, the desire for higher risk-free savings must be off-set, in part, through a fall in real income, a decline which is distributed across all spending components. Because this response is capable of generating comovement across spending categories, the model naturally exploits such shocks to explain the business cycle. Reflecting this role, we denote this shock as the "aggregate risk-premium".

Movements in financial markets and economic activity in recent years have made clear the role that frictions in financial markets play in economic fluctuations. This role was apparent much earlier, motivating a large body of research (e.g.,Bernanke, Gertler, and Gilchrist (1999)). While the range of frameworks used to incorporate such frictions has varied across researchers studying different questions, a common theme is that imperfections in financial markets – for example, related to imperfect information on the outlook for investment projects or earnings of borrowers – drives a wedge between the cost of riskless funds and the cost of funds facing households and firms. Much of the literature on financial frictions has worked to develop frameworks in which risk premia fluctuate for endogenous reasons (e.g., because of movements in the net worth of borrowers). Because the risk-premium shocks induces a wedge between the short-term nominal risk-free rate and the rate of return on the affected risky rates, these shocks may thus also be interpreted as a reflection of financial frictions not explicitly modelled in EDO. The sector-specific risk premia in EDO enter the model in much the same way as does the exogenous component of risk premia in models with some endogenous mechanism (such as the financial accelerator framework used Boivin, Kiley, and Mishkin (2010)), and the exogenous component is quantitatively the most significant one in that research.[4]

Figure 3: Unemployment Fluctuations in the EDO model



2.4 Unemployment Fluctuations in the EDO model

This version of the EDO model assumes that labor input consists of both employment and hours per worker. Workers differ in the disutility they associate with employment. Moreover, the labor market is characterized by monopolistic competition. As a result, unemployment arises in equilibrium – some

[4]Specifically, the risk premia enter EDO to a first-order (log)linear approximation in the same way as in the cited research if the parameter on net worth in the equation determining the borrowers cost of funds is set to zero; in practice, this parameter is often fairly small in financial accelerator models.

workers are willing to be employed at the prevailing wage rate, but cannot find employment because firms are unwilling to hire additonal workers at the prevailing wage.

As emphasized by Gali (2010), this framework for unemployment is simple and implies that the unemployment rate reflects wage pressures: When the unemployment rate is unusually high, the prevailing wage rate exceeds the marginal rate of subsitution between leisure and consumption, implying that workers would prefer to work more.

In addition, in our environment, nominal wage adjustment is sticky, and this slow adjustment of wages implies that the economy can experience sizable swings in unemployment with only slow wage adjustment. Our specific implementation of the wage adjustment process yields a relatively standard New-Keynesian wage Phillips curve. The presence of both price and wage rigidities implies that stabilization of inflation is not, in general, the best possible policy objective (although a primary role for price stability in policy objectives remains).

While the specific model on unemployment is suitable for discussions of the links between unemployment and wage/price inflation, it leaves out many features of labor market dynamics. Most notably, it does not consider separations, hires, and vacancies, and is hence not amenable to analysis of issues related to the Beveridge curve.

As emphasized above, the rise in unemployment during the Great Recession primarily reflected, according to the EDO model, the weak demand that arose from elevated risk premiums that depressed spending, as illustrated by the red bars in figure 3.

Indeed, these demand factors explain the overwhelming share of cyclical movements in unemployment over the past two-and-a-half decades, as is also apparent in figure 3. Other factors are important for some other periods. For example, monetary policymakers lowered the federal funds rate rapidly over the course of 2008, somewhat in advance of the rise in unemployment and decline in inflation that followed. As illustrated by the silver bars in figure 3, these policy moves mitigated the rise in unemployment somewhat over 2009; however, monetary policy efforts provided less stimulus, according to EDO, over 2010 and 2011 – when the federal funds rate was constrained from falling further. (As in many other DSGE models, EDO does not include economic mechanisms through which quantitative easing provides stimulus to aggregate demand).

The contribution of supply shocks – most notably labor supply shocks – is also estimated to contribute importantly to the low-frequency movements in unemployment, as shown by the yellow bars in figure 3. Specifically, favorable supply developments in the labor market are estimated to have placed downward pressure on unemployment during the second half of the 1990s; these developments have reversed, and some of the currently elevated rate of unemployment is, according to EDO, attributable to adverse labor market supply developments. As discussed previously, these developments are simply exogenous within EDO and are not informed by data on a range of labor market developments (such as gross worker flows and vacancies).

2.5 New-Keynesian Price and Wage Phillips Curves

As in most of the related literature, nominal prices and wages are both "sticky" in EDO. This friction implies that nominal disturbances – that is, changes in monetary policy – have effects on real economic activity. In addition, the presence of both price and wage rigidities implies that stabilization of inflation is not, in general, the best possible policy objective (although a primary role for price stability in policy objectives remains).

Given the widespread use of the New-Keynesian Phillips curve, it is perhaps easiest to consider the form of the price and wage Phillips curves in EDO at the estimated parameters. The price Phillips curve (governing price adjustment in both productive sectors) has the form:

$$\pi_t^{p,s} = 0.22\pi_{t-1}^{p,s} + 0.76E_t\pi_{t+1}^{p,s} + .017mc_t^s + \theta_t^s \tag{3}$$

where mc is marginal cost and θ is a markup shock. As the parameters indicate, inflation is primarily forward-looking in EDO.

The wage (w) Phillips curve for each sector has the form:

$$\triangle w_t^s = 0.01\triangle w_{t-1}^s + 0.95E_t\triangle w_{t+1}^s + .012\left(mrs_t^{c,l} - w_t^s\right) + \theta_t^w + adj.\,costs. \tag{4}$$

where mrs represents the marginal rate of substitution between consumption and leisure. Wages are primarily forward looking and relatively insensitive to the gap between households' valuation of time spent working and the wage.

The middle panel of figure 1 presents the decomposition of inflation fluctuations into the exogenous disturbances that enter the EDO model. As can be seen, aggregate demand fluctuations, including aggregate risk premiums and monetary policy surprises, contribute little to the fluctuations in inflation according to the model. This is not surprising: In modern DSGE models, transitory demand disturbances do not lead to an unmooring of inflation (so long as monetary policy responds systematically to inflation and remains committed to price stability). In the short run, inflation fluctuations primarily reflect transitory price and wage shocks, or markup shocks in the language of EDO. Technological developments can also exert persistent pressure on costs, most notably during and following the strong productivity performance of the second half of the 1990s which is estimated to have lowered marginal costs and inflation through the early 2000s. More recently, disappointing labor productivity readings over the course of 2011 have led the model to infer sizeable negative technology shocks in both sectors, contributing noticeably to inflationary pressure over that period (as illustrated by the blue bars in figure 1),

2.6 Monetary Authority and A Long-term Interest Rate

We now turn to the last agent in our model, the monetary authority. It sets monetary policy in accordance with an Taylor-type interest-rate feedback rule. Policymakers smoothly adjust the actual interest rate R_t to its target level $\bar{R}_t$

$$R_t = (R_{t-1})^{\rho^r}\left(\bar{R}_t\right)^{1-\rho^r}\exp\left[\epsilon_t^r\right], \tag{5}$$

where the parameter ρ^r reflects the degree of interest rate smoothing, while ϵ_t^r represents a monetary policy shock. The central bank's target nominal interest rate, $\bar{R}_t$ depends the deviation of output from the level consistent with current technologies and "normal" (steady-state) utilization of capital and labor ($\tilde{X}^{pf}$, the "production function" output gap) Consumer price inflation also enters the target. The target equation is:

$$\bar{R}_t = \left(\tilde{X}_t^{pf}\right)^{r^y} \left(\frac{\Pi_t^c}{\Pi_*^c}\right)^{r^\pi} R_*. \tag{6}$$

In equation (6), R_* denotes the economy's steady-state nominal interest rate, and ϕ^y and ϕ^π denote the weights in the feedback rule. Consumer price inflation, Π_t^c, is the weighted average of inflation in the nominal prices of the goods produced in each sector, $\Pi_t^{p,cbi}$ and $\Pi_t^{p,kb}$:

$$\Pi_t^c = (\Pi_t^{p,cbi})^{1-w_{cd}} (\Pi_t^{p,kb})^{w_{cd}}. \tag{7}$$

The parameter w^{cd} is the share of the durable goods in nominal consumption expenditures.

The model also includes a long-term interest rate (RL_t), which is governed by the expectations hypothesis subject to an exogenous term premia shock:

$$RL_t = \mathcal{E}_t \left[\Pi_{\tau=0}^N R_\tau\right] \cdot \Upsilon_t. \tag{8}$$

where Υ is the exogenous term premium, governed by

$$Ln\left(\Upsilon_t\right) = \left(1-\rho^\Upsilon\right) Ln\left(\Upsilon_*\right) + \rho^\Upsilon Ln\left(\Upsilon_{t-1}\right) + \epsilon_t^\Upsilon. \tag{9}$$

In this version of EDO, the long-term interest rate plays no allocative role; nonetheless, the term structure contains information on economic developments useful for forecasting (e.g., Edge, Kiley, and Laforte (2010)) and hence RL is included in the model and its estimation.

2.7 Summary of Model Specification

Our brief presentation of the model highlights several points. First, although our model considers production and expenditure decisions in a bit more detail, it shares many similar features with other DSGE models in the literature, such as imperfect competition, nominal price and wage rigidities, and real frictions like adjustment costs and habit-persistence. The rich specification of structural shocks (to aggregate and investment-specific productivity, aggregate and sector-specific risk premiums, and mark-ups) and adjustment costs allows our model to be brought to the data with some chance of finding empirical validation.

Within EDO, fluctuations in all economic variables are driven by thirteen structural shocks. It is most convenient to summarize these shocks into five broad categories:

- Permanent technology shocks: This category consists of shocks to aggregate and investment-specific (or fast-growing sector) technology.

- A labor supply shock: This shock affects the willingness to supply labor. As was apparent in our earlier description of the unemployment rate and in the presentation of the structural drivers below, this shock captures very persistent movements in unemployment that the model judges are not indicative of wage pressures. While EDO labels such movements labor supply shocks, an alternative interpretation would descrbie these as movements in unemployment that reflect persistent strucutral features not otherwise captured by the model.
- Financial, or intertemporal, shocks: This category consists of shocks to risk premia. In EDO, variation in risk premia – both the premium households' receive relative to the federal funds rate on nominal bond holdings and the additional variation in discount rates applied to the investment decisions of capital intermediaries – are purely exogenous. Nonetheless, the specification captures aspects of related models with more explicit financial sectors (e.g., Bernanke, Gertler, and Gilchrist (1999)), as we discuss in our presentation of the model's properties below.
- Markup shocks: This category includes the price and wage markup shocks.
- Other demand shocks: This category includes the shock to autonomous demand and a monetary policy shock.

3 Estimation: Data and Properties

3.1 Data

The empirical implementation of the model takes a log-linear approximation to the first-order conditions and constraints that describe the economy's equilibrium, casts this resulting system in its state-space representation for the set of (in our case 13) observable variables, uses the Kalman filter to evaluate the likelihood of the observed variables, and forms the posterior distribution of the parameters of interest by combining the likelihood function with a joint density characterizing some prior beliefs. Since we do not have a closed-form solution of the posterior, we rely on Markov-Chain Monte Carlo (MCMC) methods.

The model is estimated using 13 data series over the sample period from 1984:Q4 to 2011:Q4. The series are:

1. The civilian unemployment rate (U);
2. The growth rate of real gross domestic product (ΔGDP);
3. The growth rate of real consumption expenditure on non-durables and services (ΔC);
4. The growth rate of real consumption expenditure on durables (ΔCD);
5. The growth rate of real residential investment expenditure (ΔRes);
6. The growth rate of real business investment expenditure (ΔI);
7. Consumer price inflation, as measured by the growth rate of the Personal Consumption Expenditure (PCE) price index ($\Delta P_{C,total}$);
8. Consumer price inflation, as measured by the growth rate of the PCE price index excluding food and energy prices ($\Delta P_{C,core}$);

9. Inflation for consumer durable goods, as measured by the growth rate of the PCE price index for durable goods (ΔP_{cd});
10. Hours, which equals hours of all persons in the non-farm business sector from the Bureau of Labor Statistics (H);[5]
11. The growth rate of real wages, as given by compensation per hour in the non-farm business sector from the Bureau of Labor Statistics divided by the GDP price index (ΔRW);
12. The federal funds rate (R).
13. The yield on the 2-yr. U.S. Treasury security (RL).

Our implementation adds measurement error processes to the likelihood implied by the model for all of the observed series used in estimation except the short-term nominal interest rate series.

3.2 Variance Decompositions and impulse responses

We provide detailed variance decompositions and impulse response in Chung, Kiley, and Laforte (2011), and only highlight the key results here.

Volatility in aggregate GDP growth is accounted for primarily by the technology shocks in each sector, although the economy-wide risk premium shock contributes non-negligibly at short horizons.

Volatility in the unemployment rate is accounted for primarily by the economy-wide risk premium and business investment risk premium shocks at horizons between one and sixteen quarters. Technology shocks in each sector contribute very little, while the labor supply shock contributes quite a bit at low frequencies. The large role for risk premia shocks in the forecast error decomposition at business cycle horizons illustrates the importance of this type of "demand" shock for volatility in the labor market. This result is notable, as the unemployment rate is the series most like a "gap" variable in the model – that is, the unemployment rate shows persistent cyclical fluctuations about its long-run value.

Volatility in core inflation is accounted for primarily by the markup shocks.

Volatility in the federal funds rate is accounted for primarily by the economywide risk premium (except in the very near term, when the monetary policy shock is important).

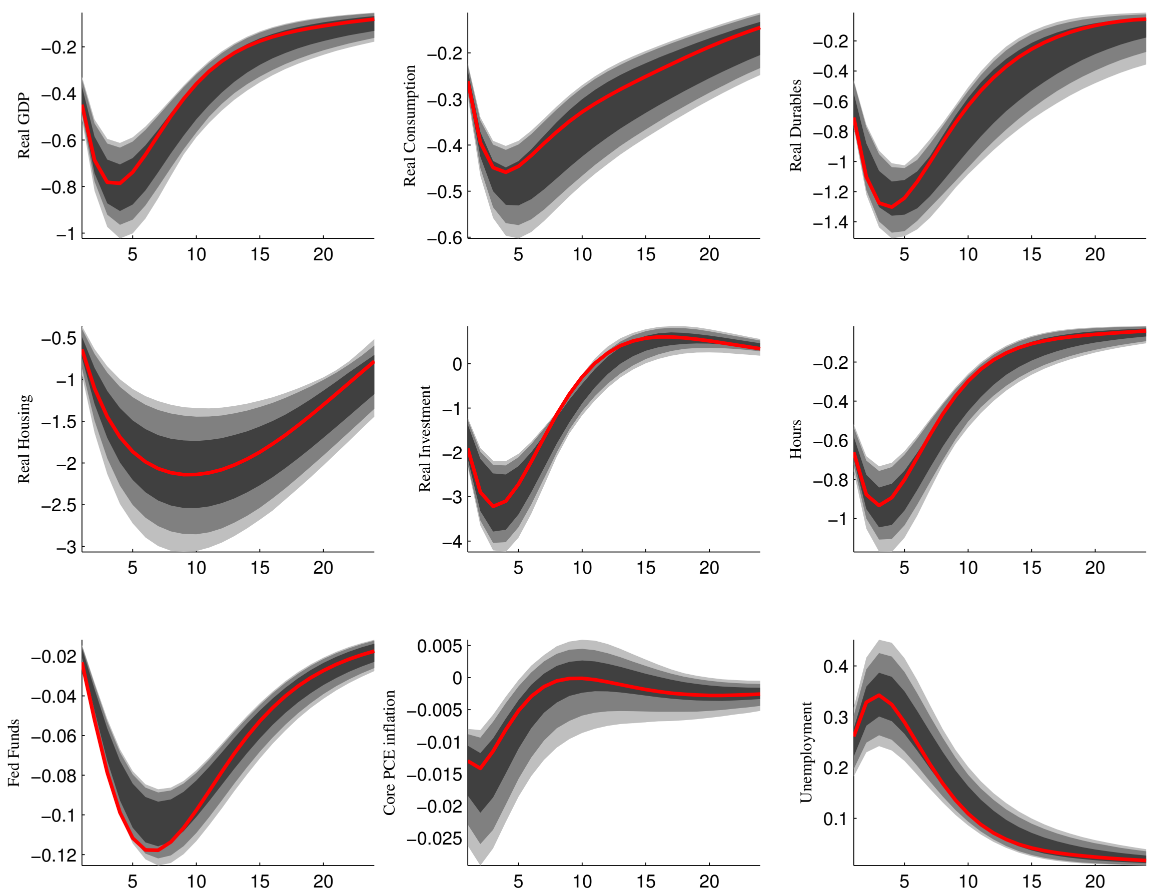
Volatility in expenditures on consumer non-durables and non-housing services is, in the near horizon, accounted for predominantly by economy-wide risk-premia shocks. In the far horizon, volatility is accounted for primarily by capital-specific and economy-wide technology shocks.

Volatilities in expenditures on consumer durables, residential investment, and non-residential investment are, in the near horizon, accounted for predominantly by their own sector specific risk-premium shocks. At farther horizons, their volatilities are accounted for by technology shocks.

With regard to impulse responses, we highlight the responses to the most important shock, the aggregate risk premium, in figure 4. As we noted, this shock looks like a traditional demand shock,

[5] We remove a low-frequency trend from hours. We first pad the historical series by appending 40 quarterly observations which approach the most recent 40-quarter moving average of the data at a rate of 0.05 percent per quarter. We then extract a trend from this padded series via the Hodrick-Prescott filter with a smoothing parameter of 6400; our model is not designed to capture low frequency trends in population growth or labor force participation.

Figure 4: Impulse Response to a One Standard Deviation Shock to the Aggregate Risk Premium.



with an increase in the risk premium lowering real GDP, hours worked, and inflation; monetary policy offsets these negative effects somewhat by becoming more accommodative. As for responses to other disturbances, the impulse responses to a monetary policy innovation captures the conventional wisdom regarding the effects of such shocks. In particular, both household and business expenditures on durables (consumer durables, residential investment, and nonresidential investment) respond strongly (and with a hump-shape) to a contractionary policy shock, with more muted responses by nondurables and services consumption; each measure of inflation responds gradually, albeit more quickly than in some analyses based on vector autoregressions (VARs).[6]

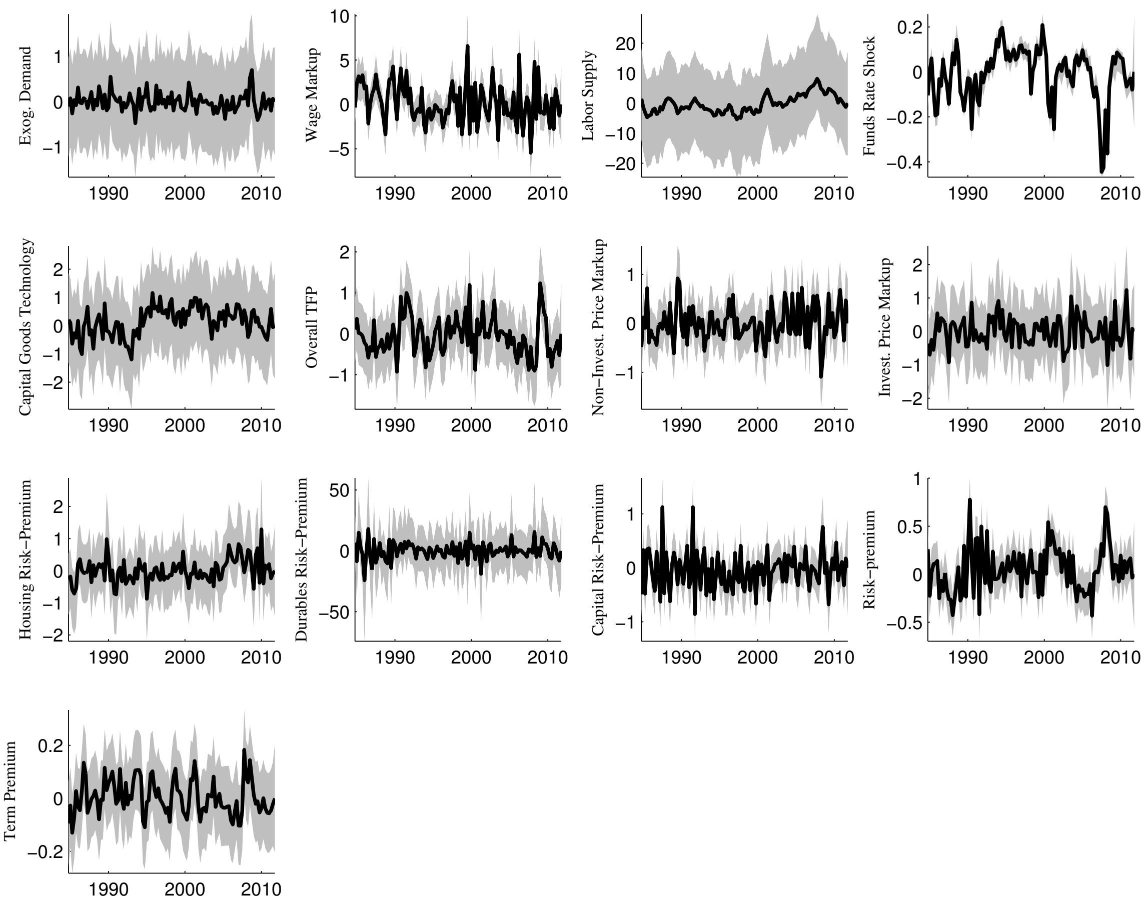
Shocks to sectoral risk premia principally depress spending in the associated category of expenditure (e.g., an increase in the residential risk premium lowers residential investment), with offsetting

[6]This difference between VAR-based and DSGE-model based impulse responses has been highlighted elsewhere – for example, in the survey of Boivin, Kiley, and Mishkin (2010).

positive effects on other spending (which is "crowded in").

Following an economy-wide technology shock, output rises gradually to its long-run level; hours respond relatively little to the shock (in comparison to, for example, output), reflecting both the influence of stick prices and wages and the offsetting income and substitution effects of such a shock on households willingness to supply labor.

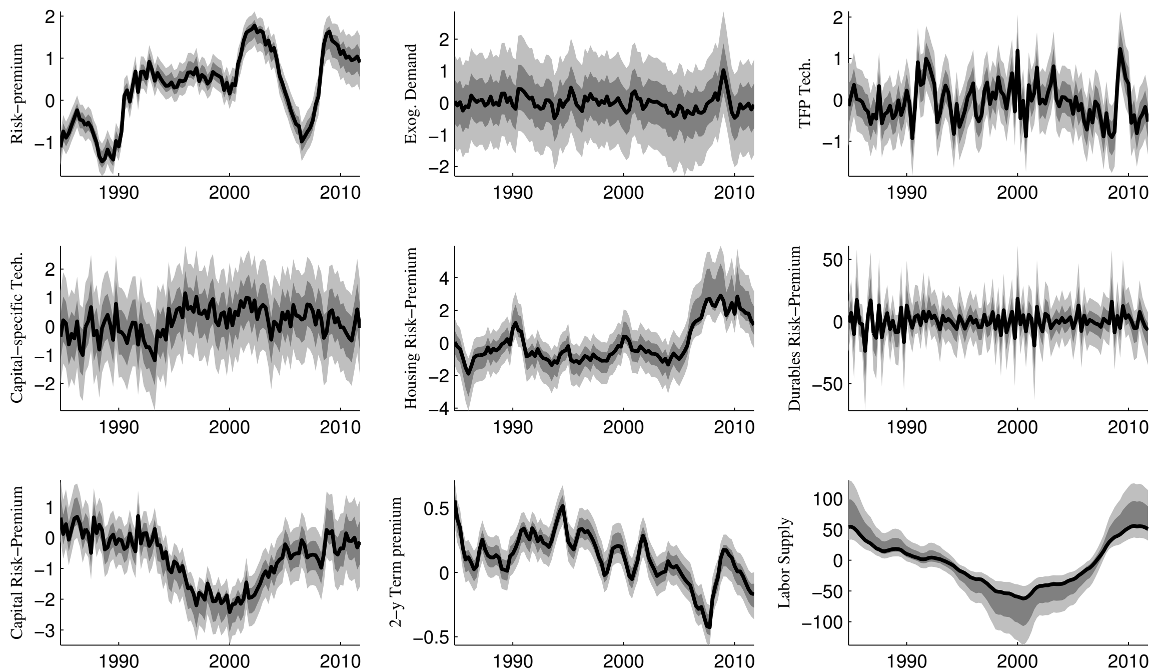
Figure 5: Innovations to Exogenous Processes



3.3 Estimates of Latent Variable Paths

Figures 5 and 6 report modal estimates of the model's structural shocks and the persistent exogenous fundamentals (i.e., risk premia and autonomous demand). These series have recognizable patterns for those familiar with U.S. economic fluctuations. For example, the risk premia jump at the end of the sample, reflecting the financial crisis and the model's identification of risk premia, both

Figure 6: Exogenous Drivers



economy-wide and for housing, as key drivers.

Of course, these stories from a glance at the exogenous drivers yield applications for alternative versions of the EDO model and future model enhancements. For example, the exogenous risk premia can easily be made to have an endogenous component following the approach of Bernanke, Gertler, and Gilchrist (1999) (and indeed we have considered models of that type). At this point we view incorporation of such mechanisms in our baseline approach as premature, pending ongoing research on financial frictions, banking, and intermediation in dynamic general equilibrium models. Nonetheless, the EDO model captured the key financial disturbances during the last several years in its current specification, and examining the endogenous factors that explain these developments will be a topic of further study.

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FRBNY DSGE Model: Research Directors Draft

March 9, 2015

Summary of the Forecasts

The FRBNY model forecasts are obtained using a new version of the FRBNY DSGE model, which builds on the New Keynesian model with financial frictions used in Del Negro et al. (2015). This model has been shown to provide a reasonable explanation for the behavior of inflation in the aftermath of the Great Recession, and relatively accurate forecasts of output growth and inflation throughout recent history (see Del Negro et al. (2014) and Del Negro and Schorfheide (2012)). Relative to the previous FRBNY model, the set of observable indicators is augmented with data on consumption and investment growth, survey-based long-run inflation expectations, which provide information on the publics perception of the central banks inflation objective, and the 10-year Treasury yield, in order to incorporate information about long-term rates. In addition, the model is estimated using two distinct measures of inflation: the GDP deflator and core PCE inflation. Finally, the model allows for persistent shocks to both the level and the growth rate of productivity, in an attempt to allow for the possibility of secular stagnation, and uses John Fernald's estimate of the growth rate of productivity as an observable. The model produces estimates and forecasts of the so-called natural level of output and rate of interest – which we define as output and interest rate obtained in the absence of nominal rigidities, markup shocks, and financial frictions. These quantities, which are not directly observable, inform us about the stance of monetary policy. The attached Model Documentation provides more details on the model.

The FRBNY model forecasts are obtained using data released through 2014Q4, augmented for 2015Q1 with the FRBNY staff forecasts for real GDP growth, core PCE inflation, and growth in total hours, and with values of the federal funds rate and the spread between Baa corporate bonds and 10-year Treasury yields based on 2015Q1 observations. The expected federal funds rate is constrained to equal market expectations, as measured by OIS rates, through 2015Q2. This constraint is implemented via anticipated policy shocks. The 2015Q1 staff projections, OIS rates and spreads are those that were available on February 27.

The FRBNY DSGE forecast for output growth is slightly stronger than it was in December. The model projects the economy to grow 2.4 percent in 2015 and 2.3 percent in 2016 and 2017. The headwinds that slowed down the economy in the aftermath of the financial crisis are finally abating, resulting in an increase of the natural rate of interest toward positive ranges and a gradual closing of the output gap – the difference between output and natural output. The gap is closing only slowly, however. Moreover, the models estimate of firms marginal costs suggests that these have not recovered much over the last few years, due to the weakness in real wage growth. As a consequence, inflation projections are weak: core PCE inflation is expected to remain below 1.5 percent until the end of 2017. Note that increases in future real wages and marginal costs, far from being a warning sign of impending inflationary pressures, are actually a necessary condition for this (albeit slow) convergence of inflation towards the FOMC long-run objective. In the absence of accelerating wages, inflation projections would be even weaker.

The change in inflation forecasts relative to December reflects both weak inflation data since December and the switch to the new version of the model. In terms of inflation forecasts, the new model differs from the old one in two dimensions. First, it features more persistence in inflation, which is largely endogenous and due to the fact that the output gap closes very gradually. Second, it features more persistent mark-up shocks. This is because mark-up shocks no longer have to capture the substantial high frequency noise in quarterly core inflation, given that inflation is measured as the common factor between core PCE inflation and the GDP deflator. In terms of the current forecast, this implies that mark-up shocks, which capture declines in oil prices and have recently been large, have a relatively prolonged effect on inflation.

The model projects the federal funds rate to reach 2.4 percent by the end of 2017, well below its steady state value. This relatively shallow path after lift-off is mostly driven by the endogenous response of policy to weak inflation, according to the historical reaction function estimated by the model. However, past forward guidance on interest rates, which is estimated to have provided consistent support to GDP growth and inflation over the last several years, also contributes to maintaining a lower expected future federal funds rates than is implied by the historical reaction function. The estimated natural real rate of interest has been well below the actual real rate during and after the crisis, indicating that the zero lower bound imposed a constraint on interest-rate policy. Currently, the natural rate is close to, but still below, the actual real rate, suggesting that policy is still not particularly accommodative.

Uncertainty around the forecasts is significant, particularly for GDP growth. The width of the 68 percent probability interval for GDP growth is 3.8 percentage points in 2015, ranging from -0.1 to 3.7 percent, and widens to 5.2 percentage points in 2017 – from -0.3 to 4.9 percent. The 68 percent probability intervals for inflation remain relatively tight, ranging from 0.4 to 1.4 percent in 2015 and from 0.5 to 2.2 percent in 2017.

1 The Model and Its Transmission Mechanism

General Features of the Model

The FRBNY DSGE model is a medium scale, one-sector dynamic stochastic general equilibrium model which is based on the New Keynesian model with financial frictions used in Del Negro et al. (2015). The core of the model is based on the work of Smets and Wouters (2007) and Christiano et al. (2005): It builds on the neo-classical growth model by adding nominal wage and price rigidities, variable capital utilization, costs of adjusting investment, and habit formation in consumption. The model also includes credit frictions as in the *financial accelerator* model developed by Bernanke et al. (1999), where the actual implementation of the credit frictions follows closely Christiano et al. (2014), and a time-varying inflation target following Del Negro and Schorfheide (2012). In contrast to these papers, the model features both a deterministic and a stochastic trend in productivity. Finally, it accounts for forward guidance in monetary policy by including anticipated policy shocks as in Laseen and Svensson (2011).

In this section, we briefly describe the microfoundations of the model, including the optimization problem of the economic agents and the nature of the exogenous processes. The innovations to these processes, which we refer to as "shocks," are the drivers of macroeconomic fluctuations. The model identifies these shocks by matching the model dynamics with numerous quarterly data series: real GDP growth, real consumption growth, real investment growth, real wage growth, hours worked, inflation in the personal consumption expenditures deflator and inflation in the GDP deflator, the federal funds rate (FFR), the 10-year nominal Treasury bond yield, 10-year survey-based inflation expectations, credit spreads (Baa - 10-year Treasury bond yield), and data on total factor productivity. In addition, since 2008, we use market expectations of future federal funds rates. Model parameters are estimated from 1960Q1 to the present using Bayesian methods.

The economic units in the model are households, firms, banks, entrepreneurs, and the government. (Figure 1 describes the interactions among the various agents, the frictions and the shocks that affect the dynamics of this economy.)

Households derive utility from leisure, supply labor services to firms, and set wages in a monopolistically competitive fashion. The labor market is subject to frictions because of nominal wage rigidities. In addition, we allow for exogenous disturbances to wage mark-ups, labeled "wage mark-up" shocks, which capture exogenous changes in the degree of competitiveness in the labor market, or other exogenous movements in the labor supply.

Households, who discount future utility streams, also have to choose how much to consume and save. Their savings take the form of deposits to banks and purchases of government bills. Household preferences feature habit persistence, a characteristic that affects their consumption smoothing decisions. In addition, "discount factor" shocks drive an exogenous wedge between the change in the marginal utility of consumption and the riskless real return. These shocks possibly capture phenomena like deleveraging, or increased risk aversion.

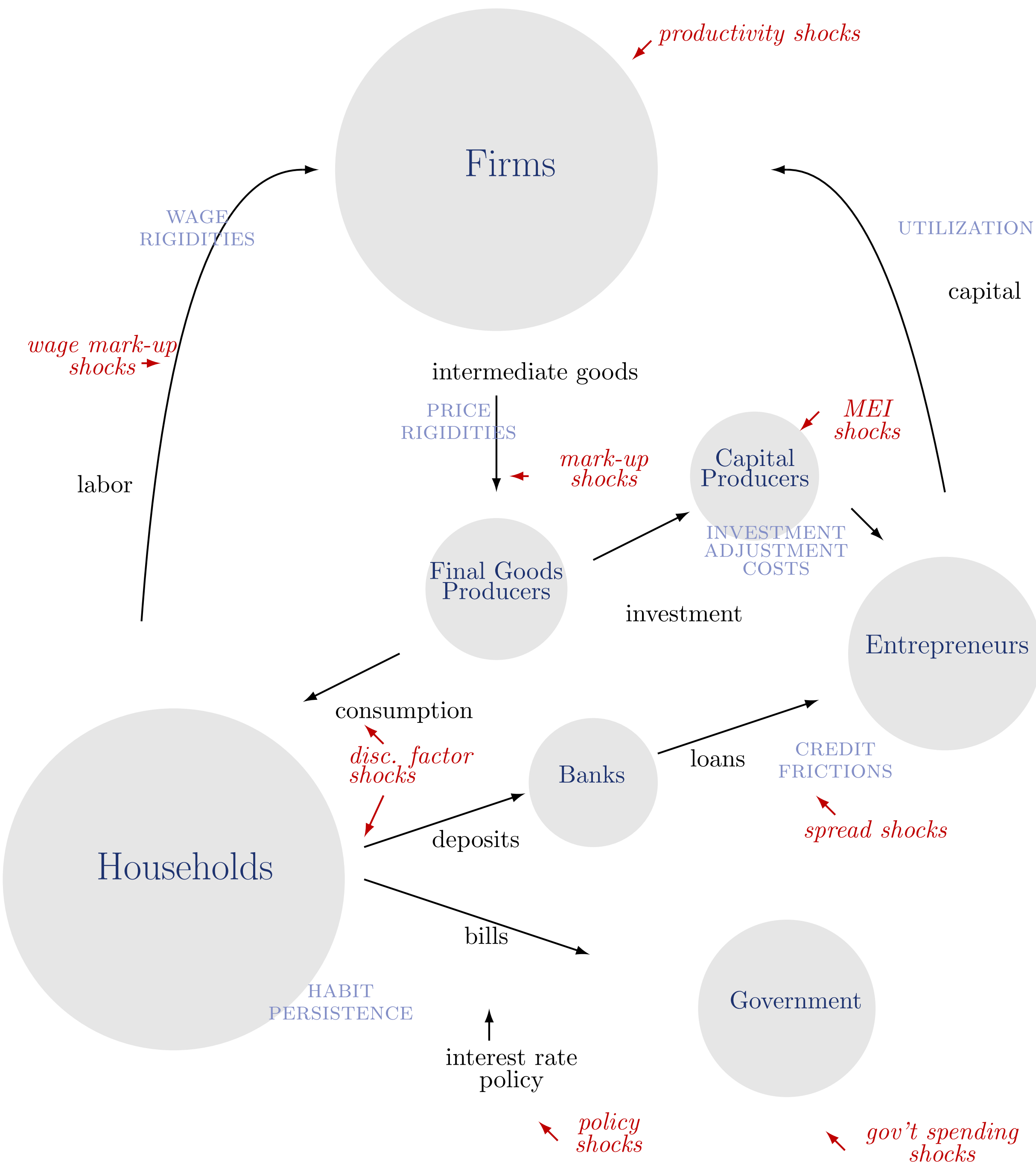
Monopolistically competitive firms produce intermediate goods, which a competitive firm aggregates into the single final good that is used for both consumption and investment. The production function of intermediate producers is subject to "total factor productivity" (TFP) shocks, which affect both the temporary and the permanent component of the level of total factor productivity. Intermediate goods markets are subject to price rigidities. Together with wage rigidities, this friction is quite important in allowing demand shocks to be a source of business cycle fluctuations, as countercyclical mark-ups induce firms to produce less when demand is low. Inflation evolves in the model according to a standard, forward-looking New Keynesian Phillips curve with indexing, which determines inflation as a function of marginal costs, expected future inflation, past inflation, and "price mark-up" shocks. Mark-up shocks capture exogenous changes in the degree of competitiveness in the intermediate goods market. In practice, these shocks capture unmodeled inflation pressures, such as those arising from fluctuations in commodity prices.

Financial intermediation involves two actors, *banks* and *entrepreneurs*, whose interaction captures imperfections in financial markets. These actors should not be interpreted in a literal sense, but rather as a device for modeling credit frictions. Banks take deposits from households and lend to entrepreneurs. Entrepreneurs use their own wealth and the loans from banks to acquire capital. They then choose the utilization level of capital and rent the capital to intermediate good producers. Entrepreneurs are subject to idiosyncratic disturbances in their ability to manage the capital. Consequently, entrepreneurs' revenue may not be enough to repay their loans, in which case they default. Banks protect against default risk by pooling loans to all entrepreneurs and charging a spread over the deposit rate. Such spreads vary endogenously as a function of the entrepreneurs' leverage, but also exogenously depending on the entrepreneurs' riskiness. Specifically, mean-preserving changes in the volatility of entrepreneurs' idiosyncratic shocks lead to variations in the spread (to compensate banks for changes in expected losses from individual defaults). We refer to these exogenous movements as "spread" shocks. Spread shocks capture financial intermediation disturbances that affect entrepreneurs' borrowing costs. Faced with higher borrowing costs, entrepreneurs reduce their demand for capital, and investment drops. With lower aggregate demand, there is a contraction in hours worked and real wages. Wage rigidities imply that hours worked fall even more (because nominal wages do not fall enough). Price rigidities mitigate price contraction, further depressing aggregate demand.

Capital producers transform general output into capital goods, which they sell to the entrepreneurs. Their production function is subject to investment adjustment costs: producing capital goods is more costly in periods of rapid investment growth. It is also subject to exogenous changes in the "marginal efficiency of investment" (MEI). These MEI shocks capture exogenous movements in the productivity of new investments in generating new capital. A positive MEI shock implies that fewer resources are needed to build new capital, leading to higher real activity and inflation, with an effect that persists over time. Such MEI shocks reflect both changes in the relative price of investment versus that of consumption goods (although the literature has shown the effect of these relative price changes to be small), and most importantly financial market imperfections that are not reflected in movements of the spread.

Finally, the *government* sector comprises a monetary authority that sets short-term interest rates according to a Taylor-type rule and a fiscal authority that sets public spending and collects lump-sum taxes to balance the budget. Exogenous changes in government spending are called "government" shocks; more generally, these shocks capture exogenous movements in aggregate demand. All exogenous processes are assumed to follow independent AR(1) processes with different degrees of persistence, except for mark-up shocks which have also a moving-average component, disturbances to government spending which are allowed to be correlated with total factor productivity disturbances, and exogenous disturbances to the monetary policy rule, or "policy" shocks, which are assumed to be i.i.d.

Figure 1: Model Structure



The Model's Transmission Mechanism

In this section, we illustrate some of the key economic mechanisms at work in the model's equilibrium. We do so with the aid of the impulse response functions to the main shocks hitting the economy, which we report in Figures 10 to 15.

We start with the shocks most closely associated with the Great Recession and the severe financial crisis that characterized it: the discount factor shock and the spread shock. The discount factor shock reflects the sudden desire by households to cut down on their consumption and save more. This may capture the fact that households want to reduce their debt level, or their increased pessimism about future economic conditions. Figure 10 shows the impulse responses of the variables used in the estimation to a one-standard-deviation innovation in the spread shock. Such a shock results in a decline in consumption (fourth panel in left column), and hence in aggregate demand, which leads to a decrease in output growth (top left panel), hours worked (top right panel), and real wage growth. The implied reduction in marginal costs induces measures of inflation to fall (see inflation of GDP and PCE deflators, in second and third rows). In addition, the discount factor shock implies an increase in credit spread (fifth panel in left row) which causes investment growth to contract. Monetary policy typically attempts to mitigate the decline in activity and inflation by lowering the FFR, but is unable to fully offset the shock.

The other key shock, the spread shock, stems from an increase in the perceived riskiness of borrowers, which induces banks to charge higher interest rates for loans, thereby widening credit spreads. As a result of this increase in the expected cost of capital, entrepreneurs' borrowing falls, hindering their ability to channel resources to the productive sector via capital accumulation. The model identifies this shock by matching the behavior of the ratio of the Baa corporate bond rate to the 10-year Treasury yield, and the spread's comovement with output growth, inflation, and the other observables. Figure 11 shows the impulse responses to a one-standard-deviation innovation in the spread shock. An innovation of this size increases the observed spread by roughly 25 basis points (fifth panel in left column). This leads to a reduction in investment and consequently to a reduction in output growth (top left panel) and hours worked (top right panel). The fall in the level of hours is fairly sharp in the first year and persists for many quarters afterwards, leaving the labor input barely higher than at the trough four years after the impulse. Of course, the effects of this same shock on GDP growth, which roughly mirrors the change in the level of hours, are much more short-lived. Output growth returns to its steady state level less than three years after the shock hits, but it barely moves above it after that, implying no catch up of the level of GDP towards its previous trend (bottom left panel). The persistent drop in the level of economic activity due to the spread shock also leads to a prolonged decline in real marginal costs, and, via the New Keynesian Phillips curve, in inflation. Finally, policymakers endogenously respond to the change in the inflation and real activity outlook by cutting the federal funds rate (right panel on the third row).

Similar considerations hold for the MEI shock, which represents a direct hit to the 'technological' ability of entrepreneurs to transform investment goods into productive capital, rather than an increase in their funding cost. The impulse responses to MEI shocks, shown in Figure 12, also feature a decrease in investment, output and hours worked, as well as in real wages, although these are less persistent than in the case of spread shocks. Inflation responds little however, as marginal costs are expected revert back to steady state relatively quickly. One key difference between the responses to spread and MEI shocks which allows us to tell them apart empirically, is that the MEI shock leaves spreads virtually unchanged (bottom right panel).

Another shock that plays an important role in the model is the stationary TFP shock (the model features shocks to both the level and the growth rate of productivity – we discuss here the former). As shown in Figure 13, a positive TFP shock has a large and persistent effect on output growth, even if the response of hours is muted in the first few quarters (and slightly negative on impact). This muted response of hours is due to the presence of nominal rigidities, which prevent an expansion of aggregate demand sufficient to absorb the increased ability of the economy to supply output. With higher productivity, marginal costs and thus the labor share fall, leading to lower inflation. The policy rule specification implies that this negative correlation between inflation and real activity, which is typical of supply shocks, produces offsetting forces on the interest rate, which as a result moves little. These dynamics make the TFP shock particularly suitable to account for the first phase of the recovery, in which GDP growth was above trend, but hours and inflation remained weak.

The last shock that plays a relevant role in the current economic environment is the price mark-up shock, whose impulse response is depicted in Figure 14. This shock is an exogenous source of inflationary pressures, stemming from changes in the market power of intermediate goods producers. As such, it leads to higher inflation and lower real activity, as producers reduce supply to increase their desired markup. Compared to those of the other prominent supply shock in the model, the TFP shock, the effects of markup-shocks feature significantly less persistence. GDP growth falls on impact after mark-ups increase, but returns above average after about one year, and the effect on the level of output is absorbed in a little over four years. Inflation is sharply higher, but only for a couple of quarters, leading to a temporary spike in the nominal interest rate, as monetary policy tries to limit the pass-through of the shock to inflation. Unlike in the case of TFP shocks, however, hours fall immediately, mirroring the behavior of output.

Forecasts

	Unconditional Forecast							
	2015 (Q4/Q4)		2016 (Q4/Q4)		2017 (Q4/Q4)		2018 (Q4/Q4)	
	March	December	March	December	March	December	March	December
Core PCE	0.9	1.1	1.1	1.5	1.4	1.8	1.6	2.0
Inflation	(0.4,1.4)	(0.4,1.6)	(0.3,1.8)	(0.7,2.2)	(0.5,2.2)	(1.0,2.6)	(0.7,2.4)	(1.2,2.8)
Real GDP	2.4	2.6	2.3	2.0	2.3	1.9	2.3	2.0
Growth	(-0.0,3.9)	(-0.2,4.8)	(-0.6,4.6)	(-1.2,5.0)	(-0.3,4.8)	(-1.4,5.2)	(-0.3,5.1)	(-1.2,5.4)

	Conditional Forecast*							
	2015 (Q4/Q4)		2016 (Q4/Q4)		2017 (Q4/Q4)		2018 (Q4/Q4)	
	March	December	March	December	March	December	March	December
Core PCE	0.9	1.2	1.1	1.5	1.4	1.8	1.6	2.0
Inflation	(0.4,1.4)	(0.6,1.8)	(0.3,1.9)	(0.8,2.2)	(0.5,2.2)	(1.0,2.6)	(0.7,2.4)	(1.2,2.8)
Real GDP	2.4	2.0	2.3	1.9	2.3	1.9	2.3	2.1
Growth	(-0.1,3.7)	(-0.9,4.1)	(-0.6,4.6)	(-1.4,4.9)	(-0.3,4.9)	(-1.4,5.2)	(-0.3,5.1)	(-1.2,5.5)

*The unconditional forecasts use data up to 2014Q4, the quarter for which we have the most recent GDP release, as well as the federal funds rate and spreads data for 2015Q1. In the conditional forecasts, we further include the 2015Q1 FRBNY projections for GDP growth, core PCE inflation, and growth in total hours worked as additional data points. Numbers in parentheses indicate 68 percent probability intervals.

We detail the forecast of three main variables over the horizon 2014-2017: real GDP growth, core PCE inflation and the federal funds rate. To obtain the forecast we set federal funds rate expectations equal to market expectations for the federal funds rate (as measured by OIS rates) through 2015Q2. We capture policy anticipation by adding anticipated monetary policy shocks to the central bank's reaction function starting in 2008Q4, the beginning of the zero bound period, as in Laseen and Svensson (2011). We estimate the standard deviation of the anticipated shocks as in Campbell et al. (2012), but use only post-2008Q4 data.

The table above presents Q4/Q4 forecasts for real GDP growth and inflation for 2014-2017, with 68 percent probability intervals. We include two sets of forecasts. The *unconditional* forecasts use data up to 2014Q4, the quarter for which we have the most recent GDP release, as well as the federal funds rate and spreads data for 2015Q1 (we use the average realizations for the quarter up to the forecast date). In the *conditional* forecasts, we further include the 2015Q1 FRBNY staff projections for GDP growth, core PCE inflation, and hours worked as additional data points (as of February 27, quaterly annualized projections for 2015Q1 are 2.5 percent for output growth and 0.9 percent for core PCE inflation). Treating the 2015Q1 staff forecasts as data allows us to incorporate information about the current quarter into the DSGE forecasts for the subsequent quarters. In addition to providing the current forecasts, the table reports the forecasts included in the DSGE memo forwarded to the FOMC in advance of its December 2014 meeting.

Figure 2 presents quarterly forecasts, both unconditional (left panels) and conditional (right panels). In the graphs, the black line represents data, the red line indicates the mean forecast, and the shaded areas mark the uncertainty associated with our forecast as 50, 60, 70, 80 and 90 percent probability intervals. Output growth and inflation are expressed in terms of percent annualized rates, quarter to quarter. The interest rate is the annualized quarterly average of the daily series. The bands reflect both parameter and shock uncertainty. Figure 3 compares the current forecasts with the December forecasts. Our discussion will mainly focus on the conditional forecasts, which are those reported in the memo to the FOMC.

The FRBNY DSGE forecast changed substantially since December, especially for inflation, as shown in Figure 3. The trajectory of output is a bit stronger in 2016 and 2017, while inflation is weaker throughout the forecast horizon. Relative to December, the GDP growth forecast for 2015 (Q4/Q4) increased from 2.0 to 2.4, and the forecasts for 2016 and 2017 (Q4/Q4) are both at around 2.3 percent. For inflation, the mean core PCE inflation for 2015 is projected to be 0.9 percent, lower than the 1.2 percent projected in December. Inflation returns closer to the long term objective of 2 percent over the forecast horizon, but more gradually than in December. The point forecasts are 1.1 for 2016 and 1.4 for 2017, below the December point forecasts.

The change in the forecasts is mainly due to the change in the model as opposed to the new data. Figure 4 shows in fact the change in the forecast that are due to the data only, as it uses the "old" model for both forecasts. The differences are very small, and largely affect only core PCE inflation projections in the short run. Figure 5 repeats the same exercise using the "new" model, and reaches the same conclusions. Note however that changes in the core inflation forecast in the new model are more persistent than under the old model – a point we will return to later. Finally, Figure 6 shows the comparison between forecasts obtained with the old and the new version of the FRBNY model, where both model use the most recent data. The comparison reinforces the point that projections for inflation are weaker under the new version. In regard to inflation forecasts, the new model differs from the old one in two dimensions. First, it features more persistence in inflation, which is largely endogenous and due to the fact that the output gap closes very gradually. Second, it features more persistent mark-up shocks. This is because mark-up shocks no longer have to capture the substantial high frequency noise in quarterly core inflation, given that inflation is measured as the common factor between core PCE inflation and the GDP deflator. In terms of the current forecast, this implies that mark-up shocks, which capture declines in oil prices and have recently been large, have a relatively prolonged effect on inflation, as discussed in the next section.

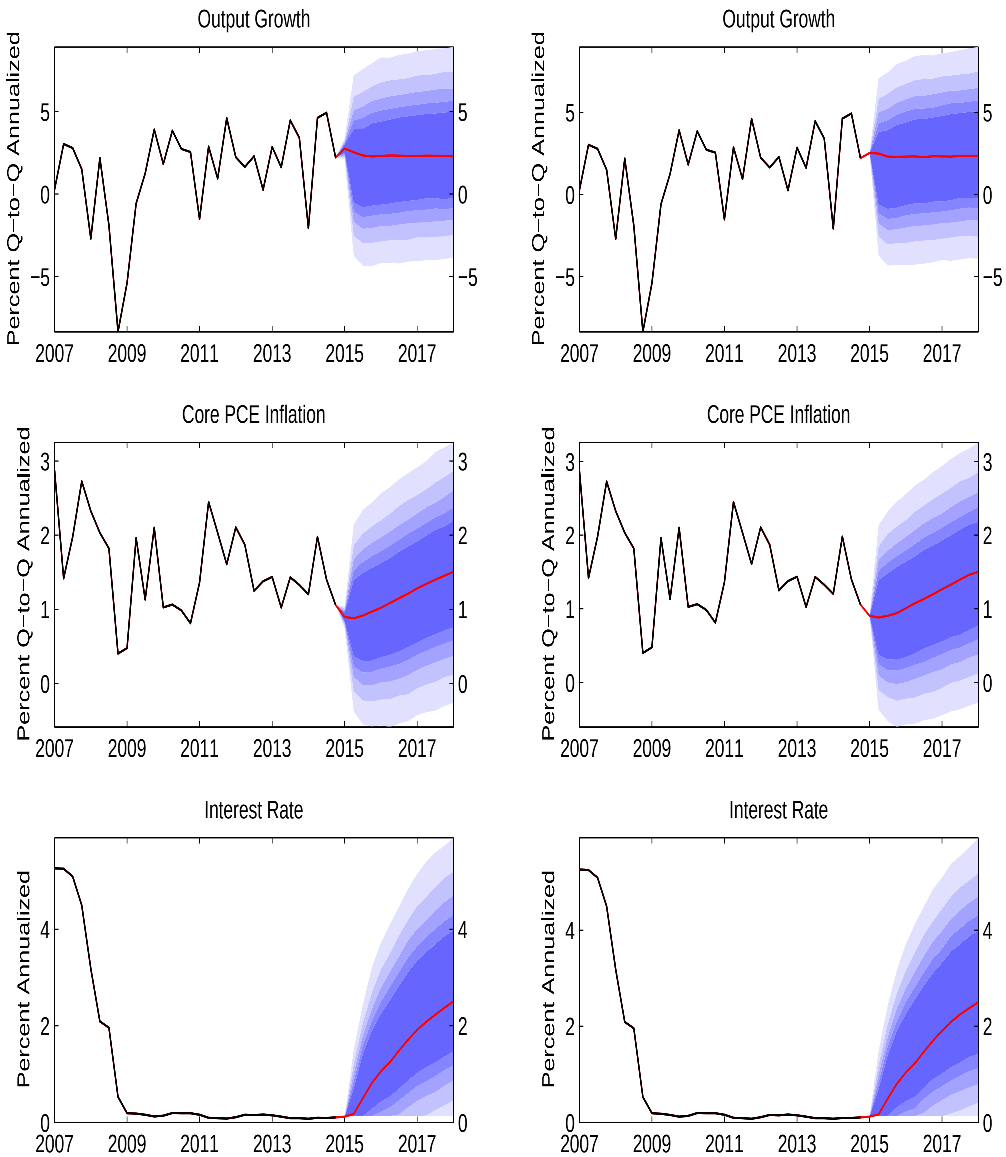
Uncertainty around the real GDP growth, as measured by the 68 percent bands, has diminished somewhat for output and is roughly unchanged for inflation. For GDP growth, the 68 percent bands cover the intervals -0.1 to 3.7 percent in 2015, -0.6 to 4.6 in 2016, and -0.3 to 4.9 in 2017. For inflation, the 68 percent probability bands range from 0.5 to 2.2 percent throughout 2017.

As mentioned above, we constrain the federal funds rate expectations through 2015Q2 to be equal to the expected federal fund rate as measured by the OIS rates on February 27; after that the federal funds rate rises gradually and is forecasted to be around 1 3/4 percent at the end of 2016 and around 2.4 percent by the end of 2017.

Finally, note that the March conditional and unconditional forecasts are very close to one another, indicating that the nowcast for 2015Q1 is in line with the DSGE model predictions.

Figure 2: Forecasts

Unconditional **Conditional**

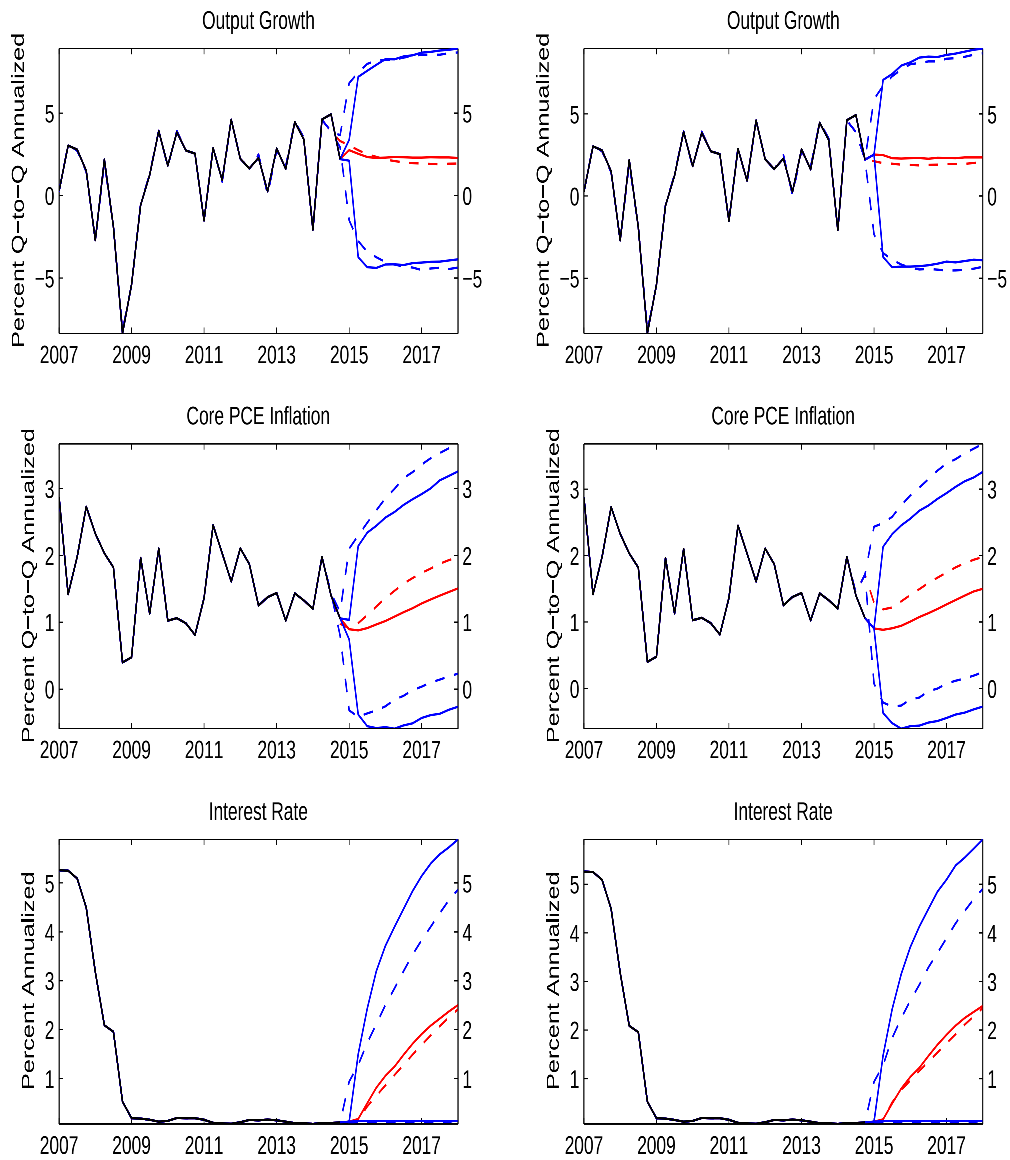


Black lines indicate data, red lines indicate mean forecasts, and shaded areas mark the uncertainty associated with our forecast as 50, 60, 70, 80, and 90 percent probability intervals.

Figure 3: Change in Forecasts

Unconditional

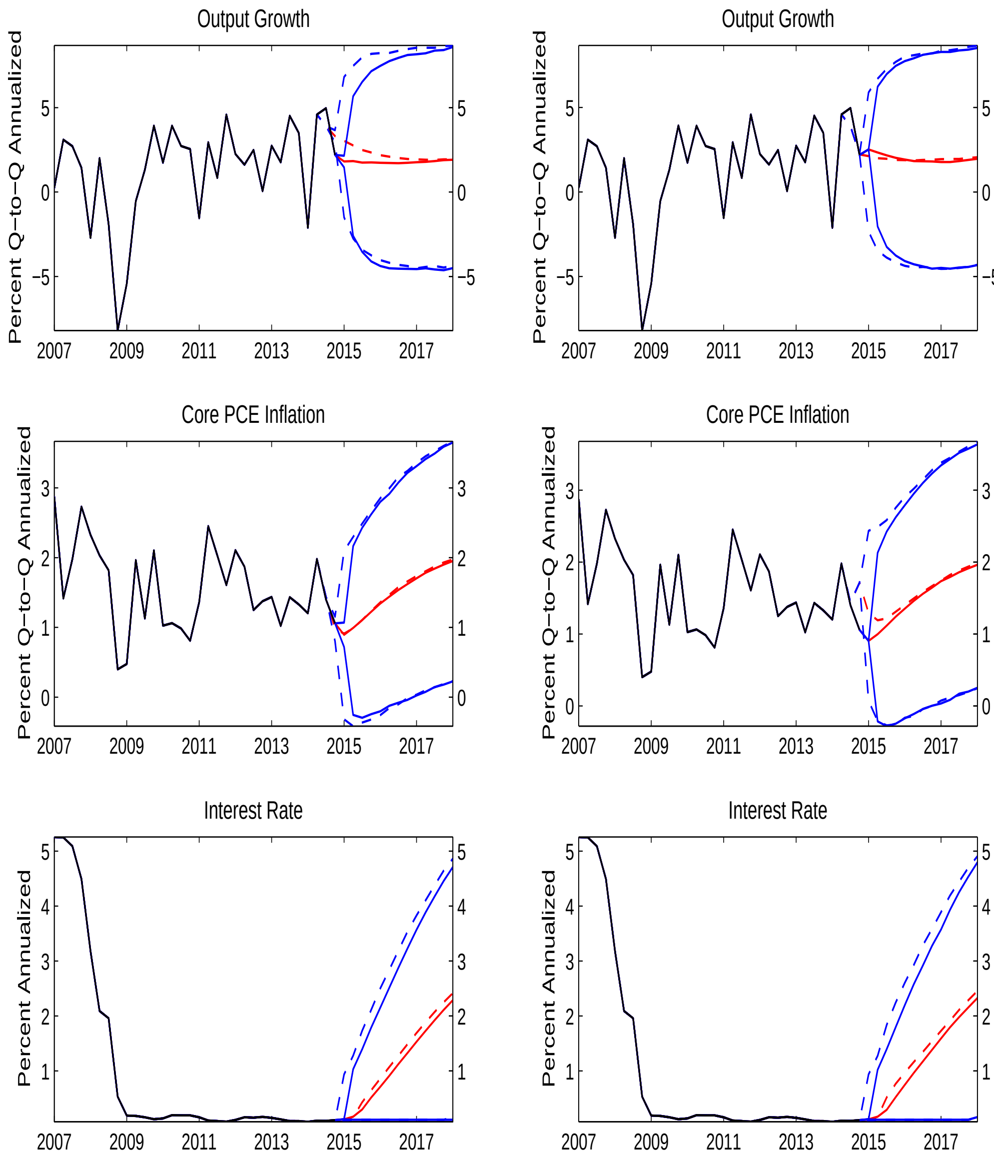
Conditional



Solid (dashed) red and blue lines represent the mean and the 90 percent probability intervals of the current (previous) forecast.

Figure 4: Change in Forecasts: Old Model, March 2015 vs. December 2014 Data

Unconditional **Conditional**



Solid (dashed) red and blue lines represent the mean and the 90 percent probability intervals of the current (previous) forecast.

Figure 5: Change in Forecasts, New Model, March 2015 vs. December 2014 Data

Unconditional **Conditional**

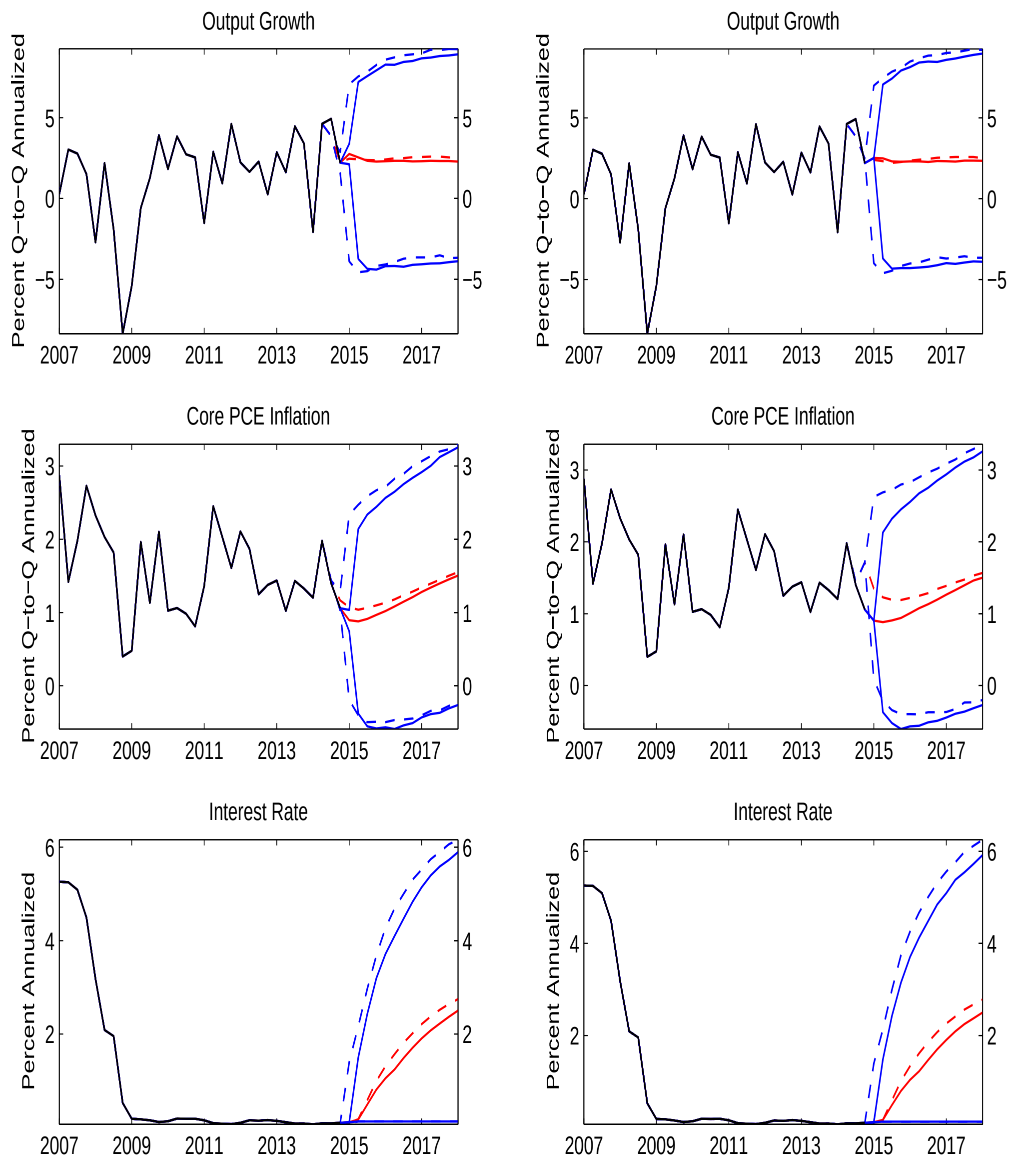
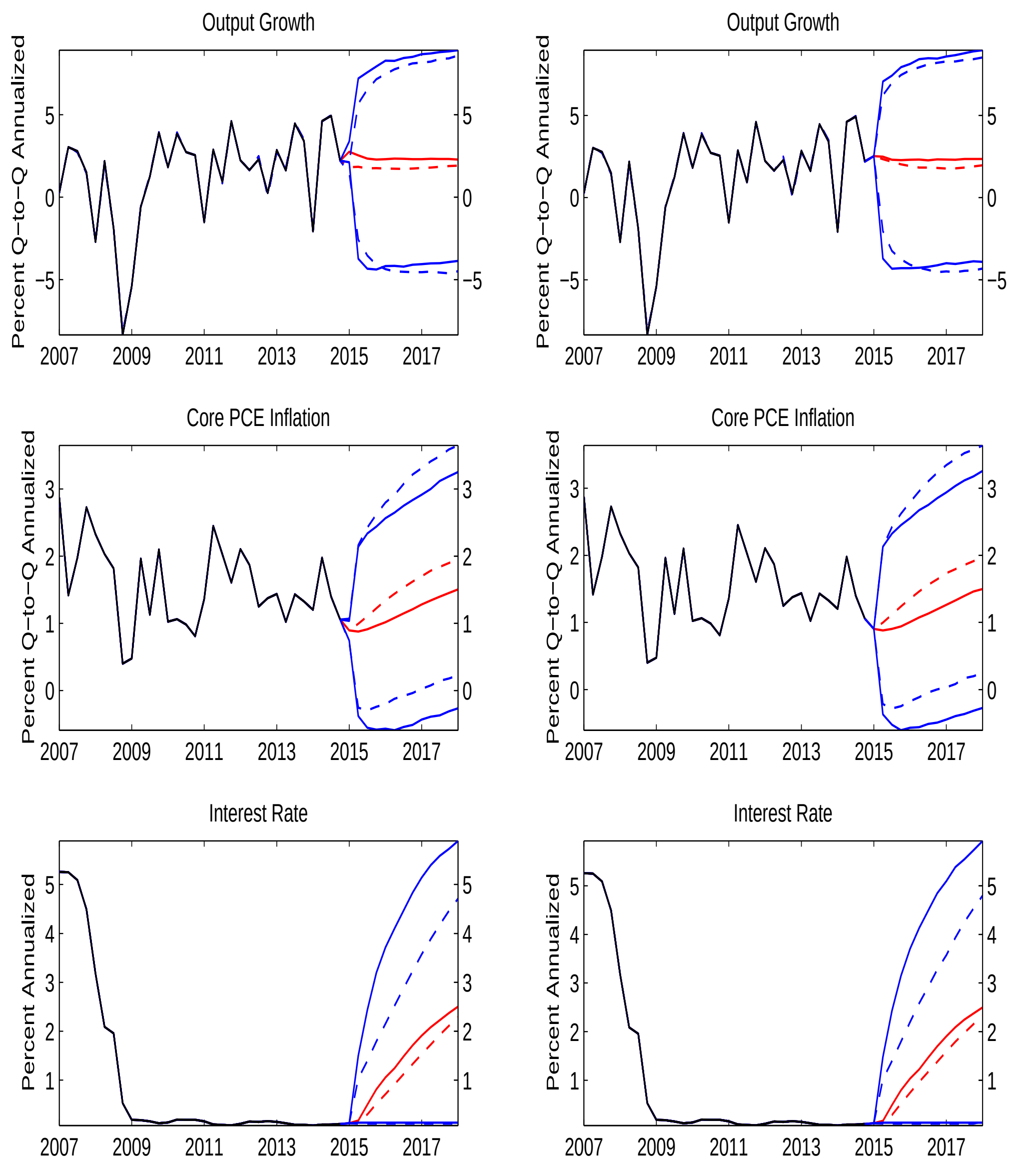


Figure 6: New vs. Old Model Forecasts, March 2015 Data

Unconditional Conditional



Solid (dashed) red and blue lines represent the mean and the 90 percent probability intervals of the current (previous) forecast.

Interpreting the Forecasts

We use the shock decomposition shown in Figure 7 to interpret the forecasts. This figure quantifies the importance of the most important shocks for output growth, core PCE inflation, and the federal funds rate (FFR) from 2007 on, by showing the extent to which each of the disturbances contributes to keeping the variables from reaching their long-run values. Specifically, in each of the three panels the solid line (black for realized data, red for mean forecast) shows the variable in deviation from its steady state (for output, the numbers are per capita, as the model takes population growth as exogenous; for both output and inflation, the numbers are quarter-to-quarter annualized). The bars represent the contribution of each shock to the deviation of the variable from steady state, that is, the counterfactual values of output growth, inflation, and the federal funds rate (in deviations from the mean) obtained by setting all other shocks to zero. We should note that the impact of some shocks have been aggregated. For example, the "financial" shock (purple) captures both shocks to the spread as well as shocks to the discount factor.

The dynamics behind the FRBNY DSGE forecast can be described as follows. The headwinds from the financial crisis, which are captured in the model by the contribution of the financial (purple) and MEI (azure) shocks, are finally waning, implying that both shocks have a positive contribution on output growth. Figure 8 shows the output gap – the difference between output and its "natural" level (the counterfactual level of output in absence of nominal rigidities, mark-up shocks, and financial frictions) – and the corresponding "natural" rate of interest through history. The natural interest rate remains below zero, but has risen recently consistently with the waning of the headwinds from the financial crisis.

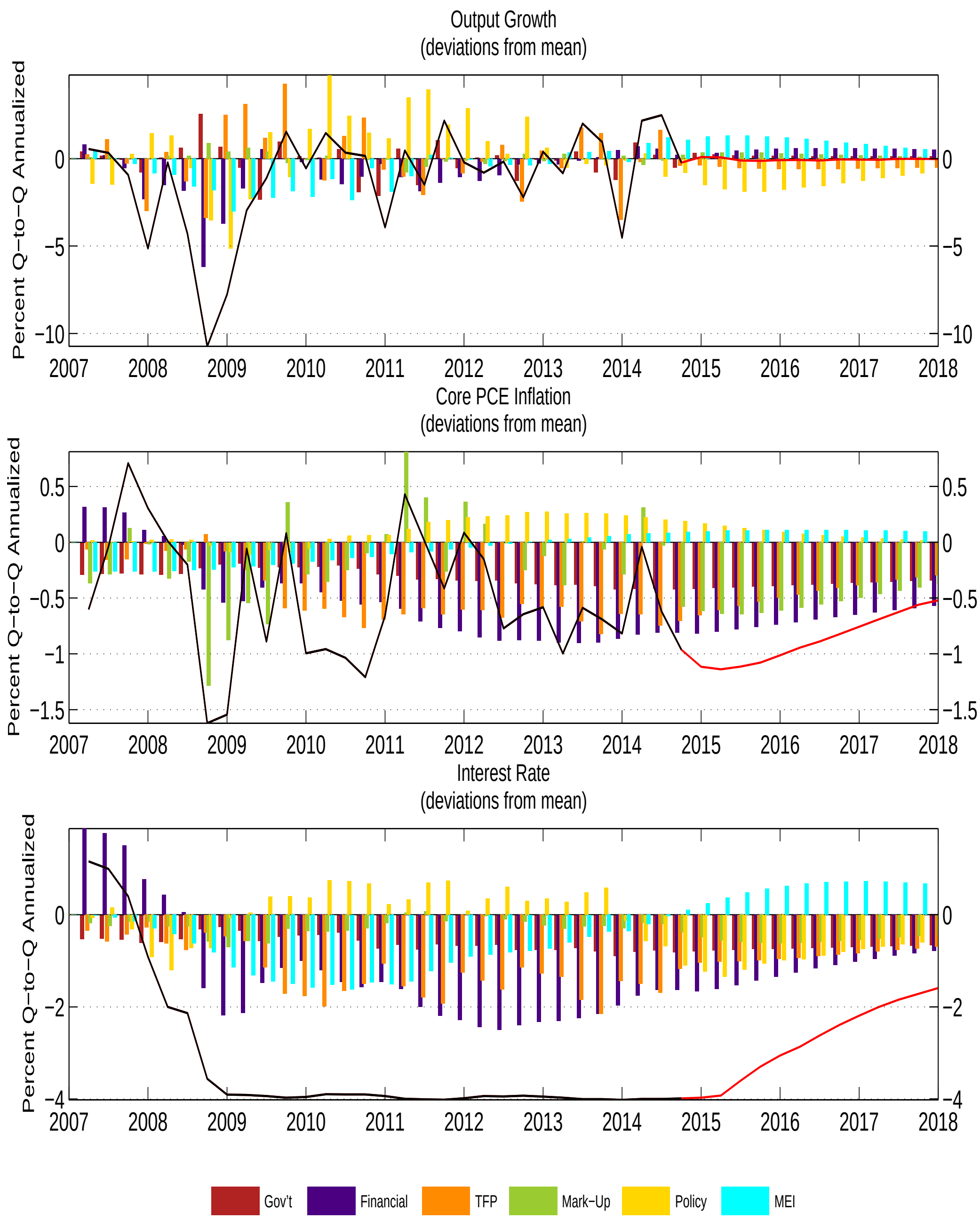
The impact of financial shocks on the level of output is still negative throughout the forecast horizon, however, as can be inferred from their negative contribution to inflation. In fact, Figure 7 shows that financial shocks are mostly responsible for the slow return of inflation to the 2 percent target, and for the interest rate being below its steady state value. The output gap, which is shown in Figure 8, remains negative and closes only gradually. Financial shocks are mostly responsible for that.

While total factor productivity shocks contributed negatively to economic activity in late 2007 and 2008, these shocks have instead pushed GDP up significantly in 2009 and 2010. In addition, over the past several years, the negative impact of the headwinds mentioned above has been partly compensated by expansionary monetary policy. In particular, forward-guidance about the future path of the federal funds rate (captured here by anticipated policy shocks) has played an important role in counteracting these headwinds, lifting both output and inflation. However, the positive effect of this policy accommodation on the level of output has been negligible over the most recent quarters. Since monetary policy is neutral in the long run in this model, the impact of policy accommodation on the level of output will wane eventually, and has already begun to do so by the end of 2014, implying a negative effect on growth. As a consequence of forward guidance the renormalization path is somewhat slower than that implied by the estimated rule, as indicated by the yellow bars in the shock decomposition for interest rates. The comparison between the estimated natural real rate of interest and the actual real rate of interest, shown in Figure 8, is also revealing in regard to the stance of policy. The natural rate of interest has been well below the actual real rate during and after the crisis, indicating that the zero lower bound imposed a constraint on interest-rate policy. Currently, the natural rate is close to, but still below, the actual real rate, suggesting that policy is still not particularly accommodative.

The shock decomposition for inflation also shows that mark-up shocks (green bars), which capture the effect of exogenous changes in marginal costs such as those connected with fluctuations in commodity prices, play an important role. As explained above, these shocks tend to have a fairly persistent impact on inflation. Recent negative mark-up shocks, likely reflecting declines in oil prices, contribute to push inflation down relative to target by at least half of a percentage point during the current year and the next one. Moreover, the positive productivity shocks registered in the immediate aftermath of the Great Recession, have had a negative and persistent impact on inflation.

Finally, Figure 9 shows unconditional (left panels) and conditional (right panels) forecasts that do not incorporate federal funds rate expectations (dashed lines) as well as our baseline forecasts (solid lines), which do. The figure shows that the impact of incorporating these expectations is very small.

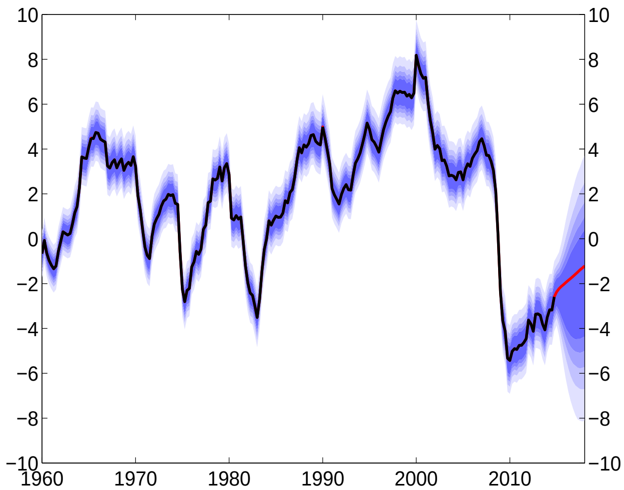
Figure 7: Shock Decomposition



The shock decomposition is presented for the conditional forecast. The solid lines (black for realized data, red for mean forecast) show each variable in deviation from its steady state. The bars represent the shock contributions; specifically, the bars for each shock represent the counterfactual values for the observables (in deviations from the mean) obtained by setting all other shocks to zero.

Figure 8: Output Gap and the Natural Interest Rate

Output Gap



Natural Rate & Ex-Ante Real Rate

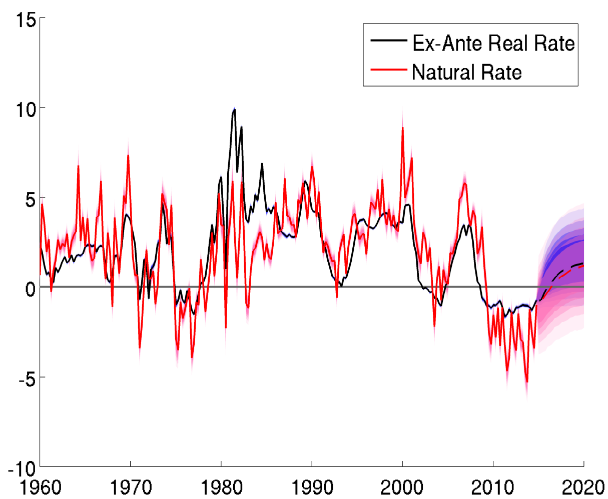
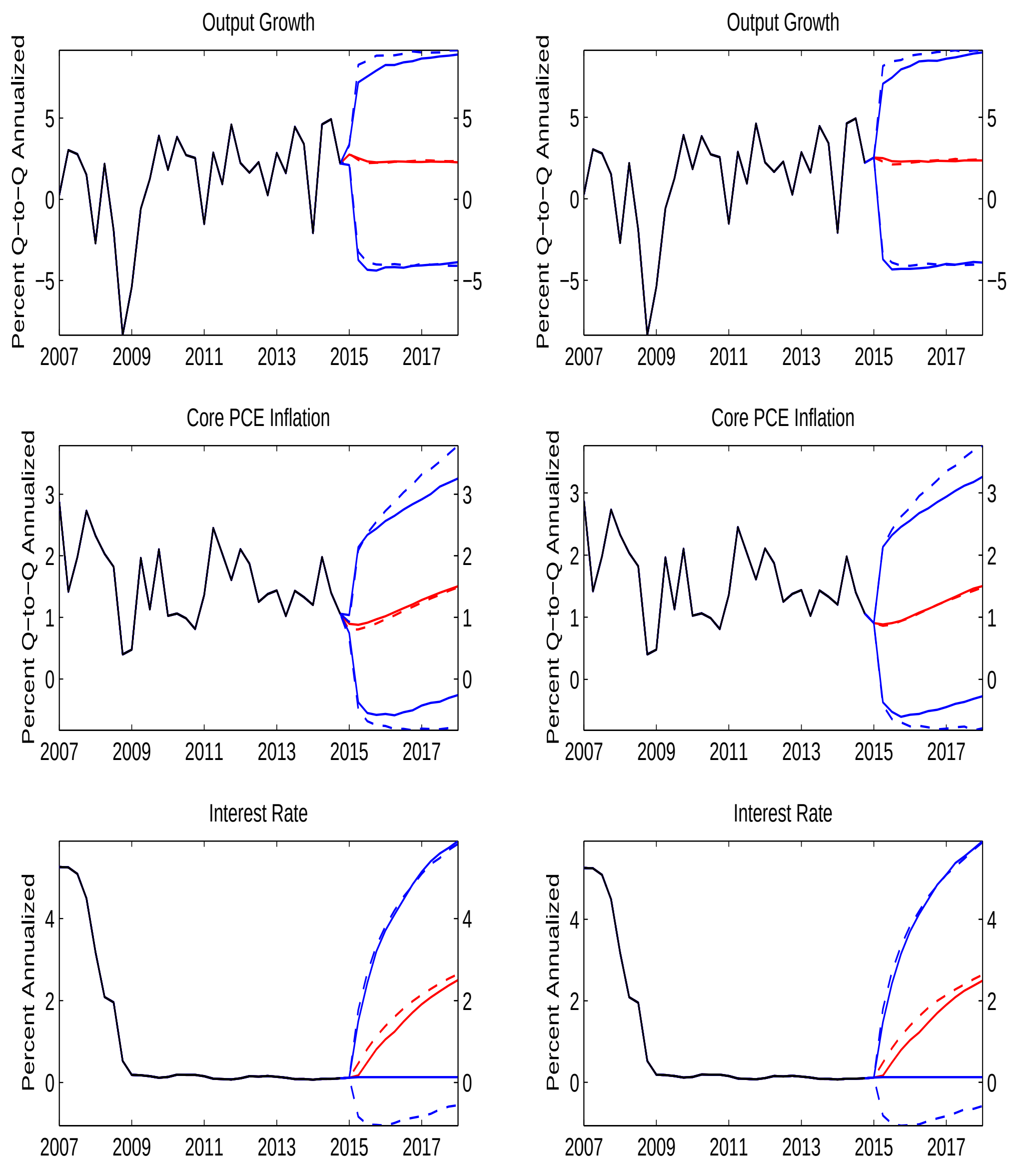


Figure 9: Effect of Incorporating FFR Expectations

Unconditional **Conditional**



Solid (dashed) red lines represent the mean for the forecast that does (does not) incorporate FFR expectations. Solid and dashed blue lines represent the associated 90 percent probability intervals.

Figure 10: Responses to a Discount Factor Shock

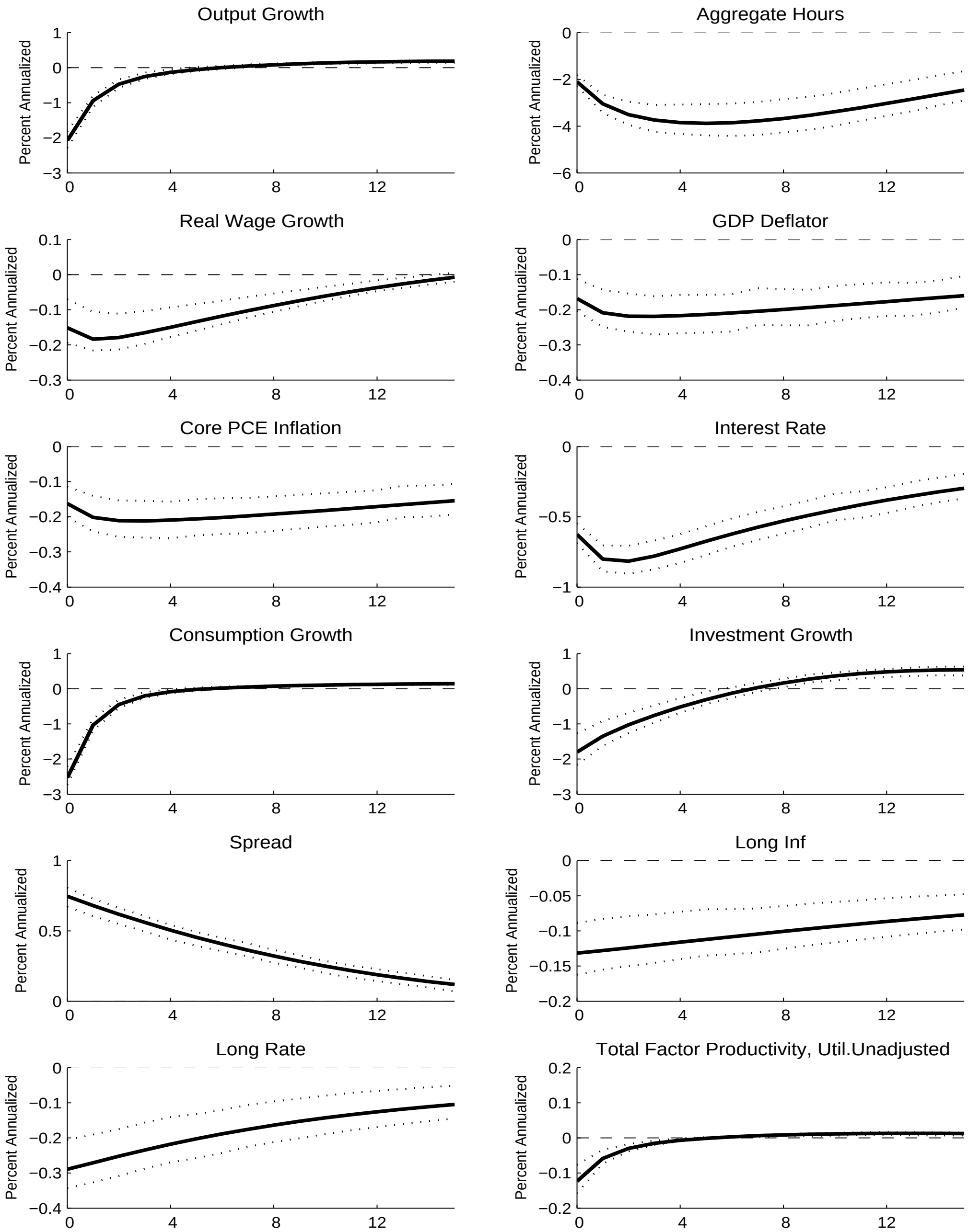


Figure 11: Responses to a Spread Shock

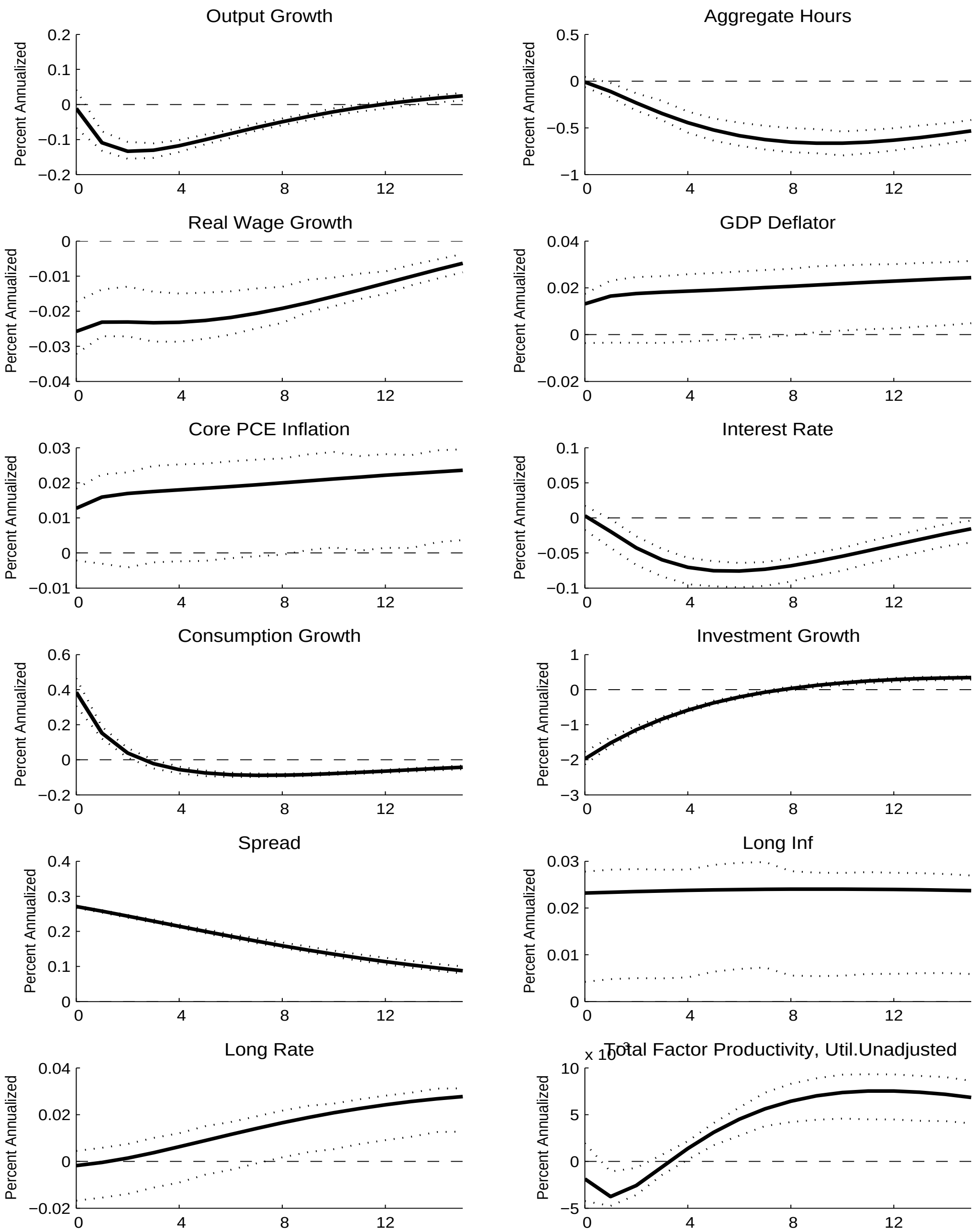


Figure 12: Responses to an MEI Shock

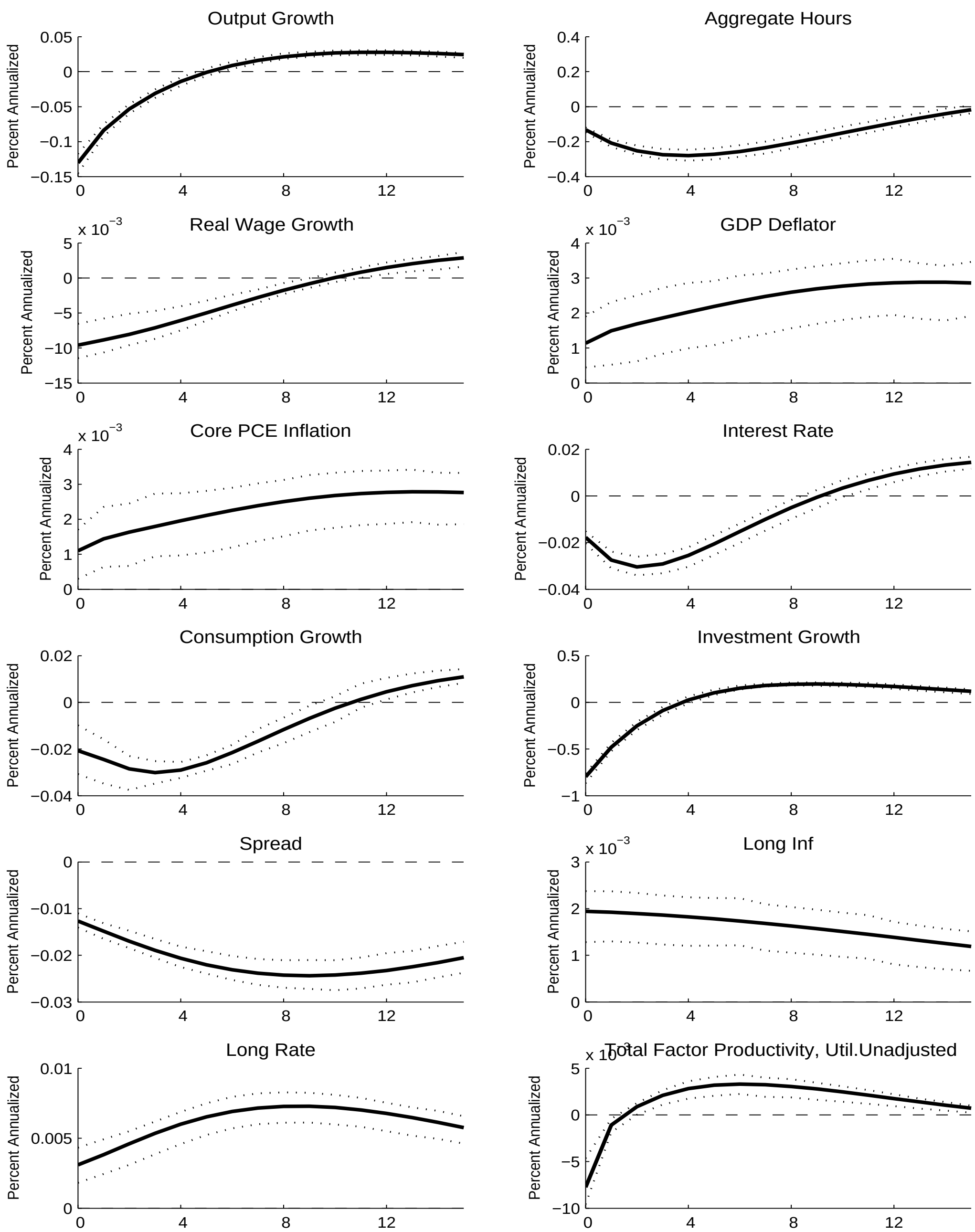


Figure 13: Responses to a TFP Shock

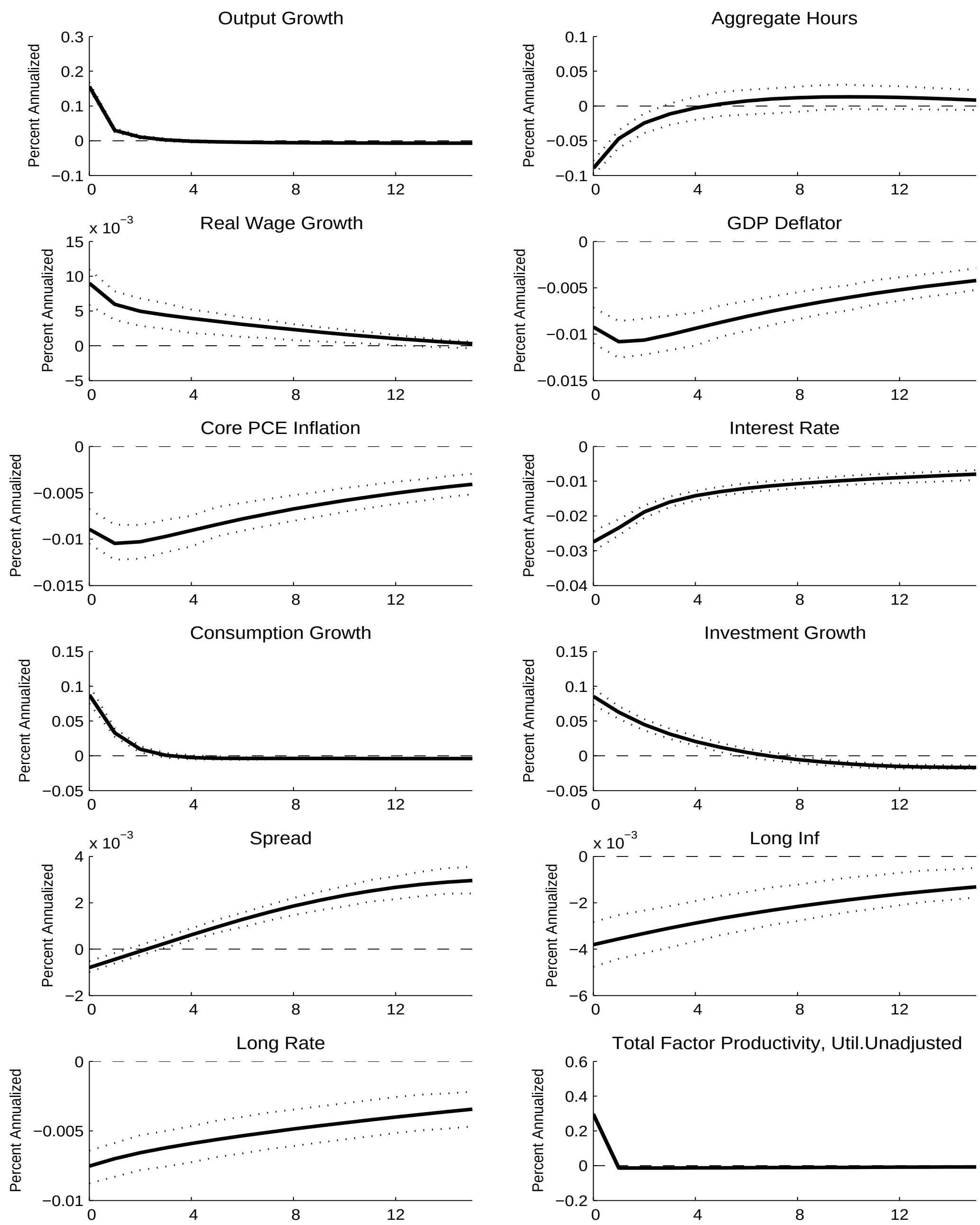


Figure 14: Responses to a Price Mark-up Shock

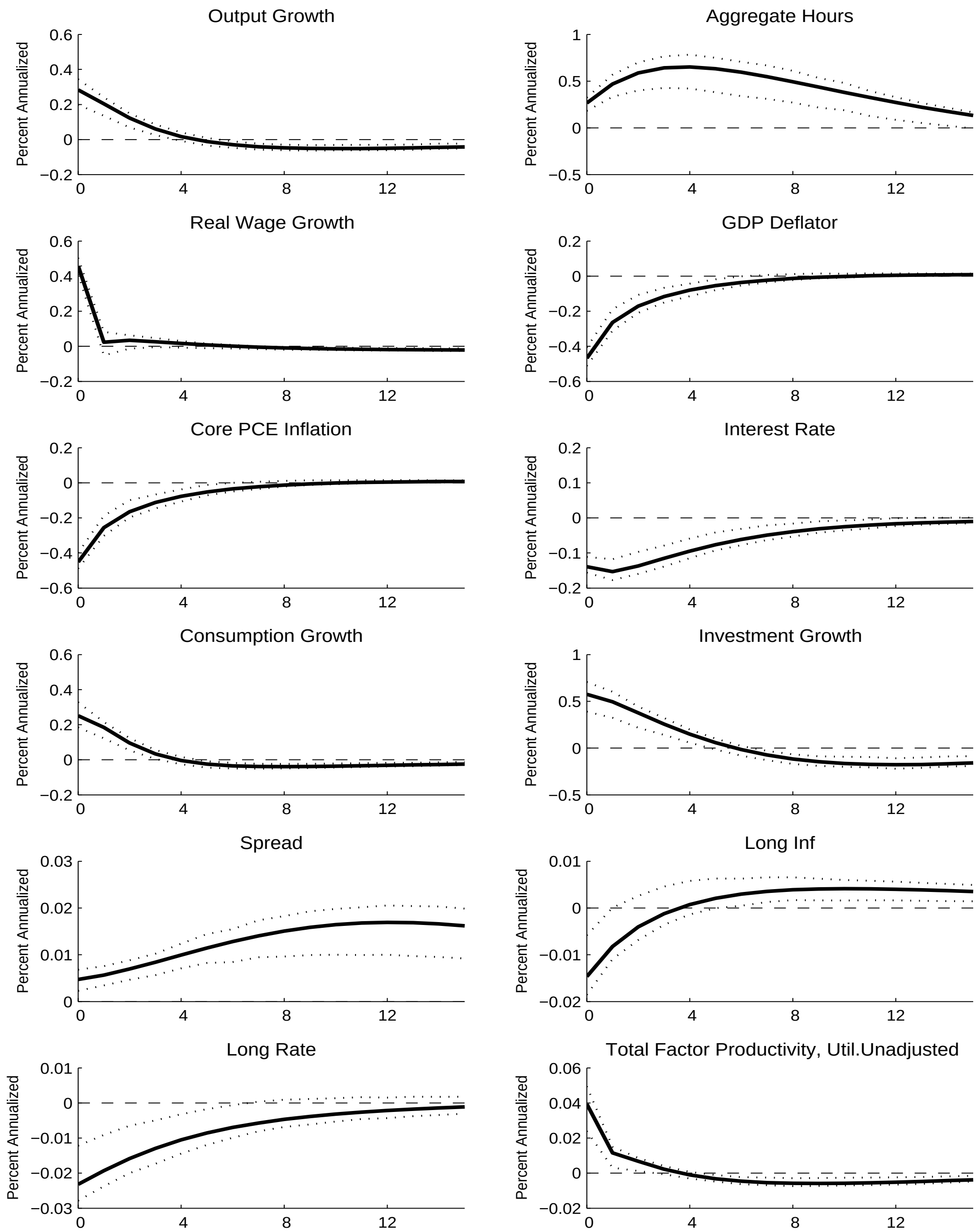


Figure 15: Responses to a Monetary Policy Shock

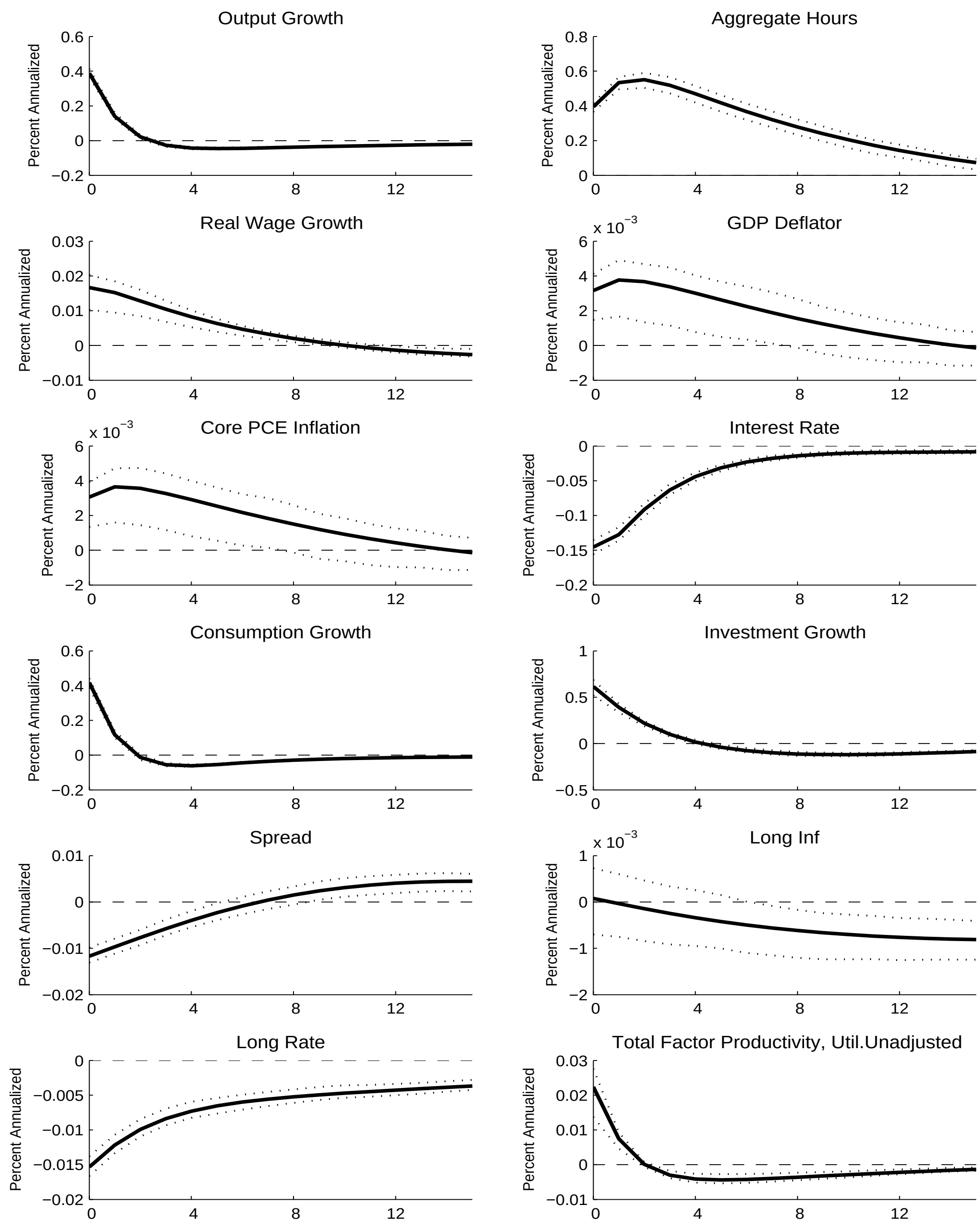


Figure 16: Shock Histories

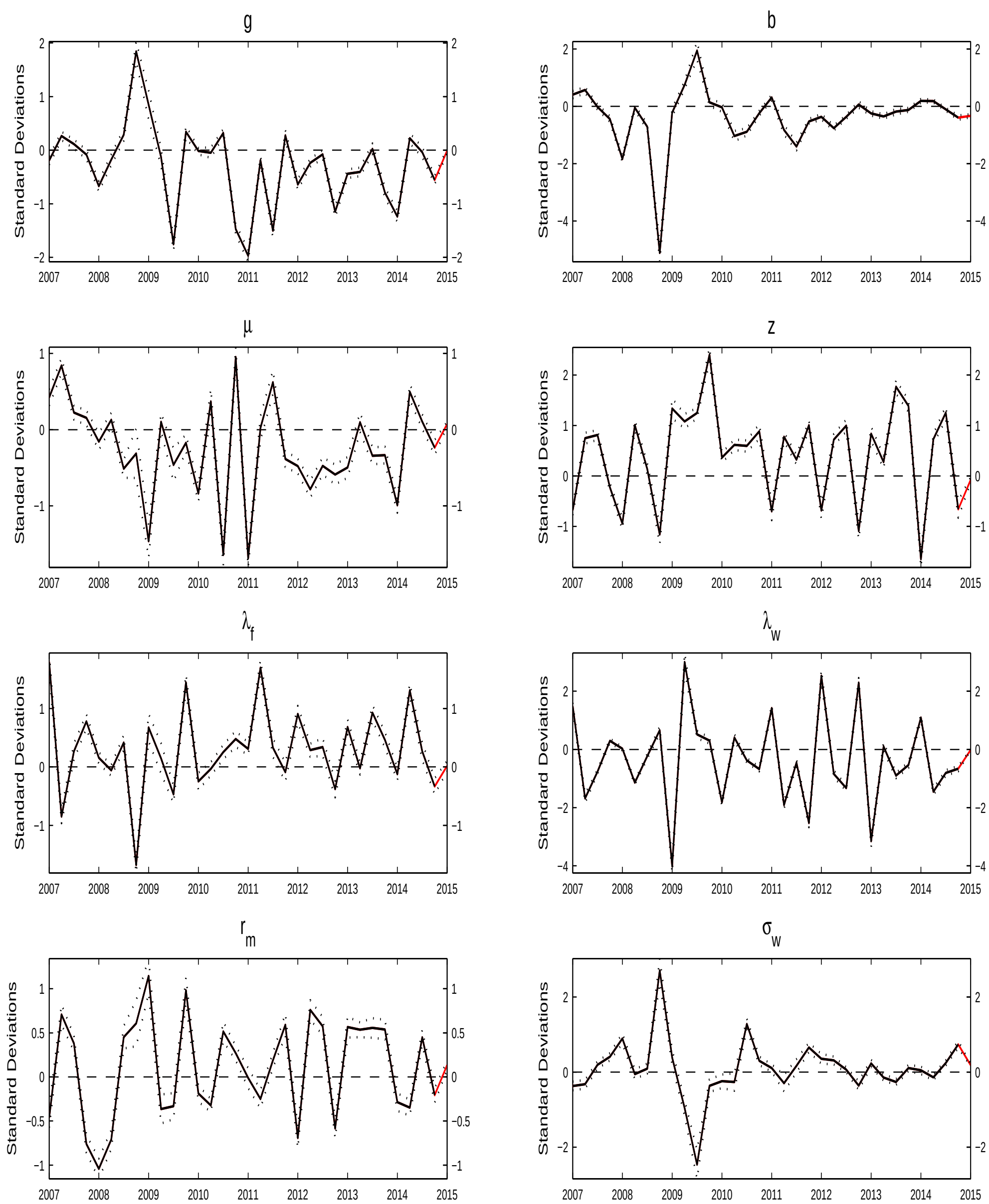
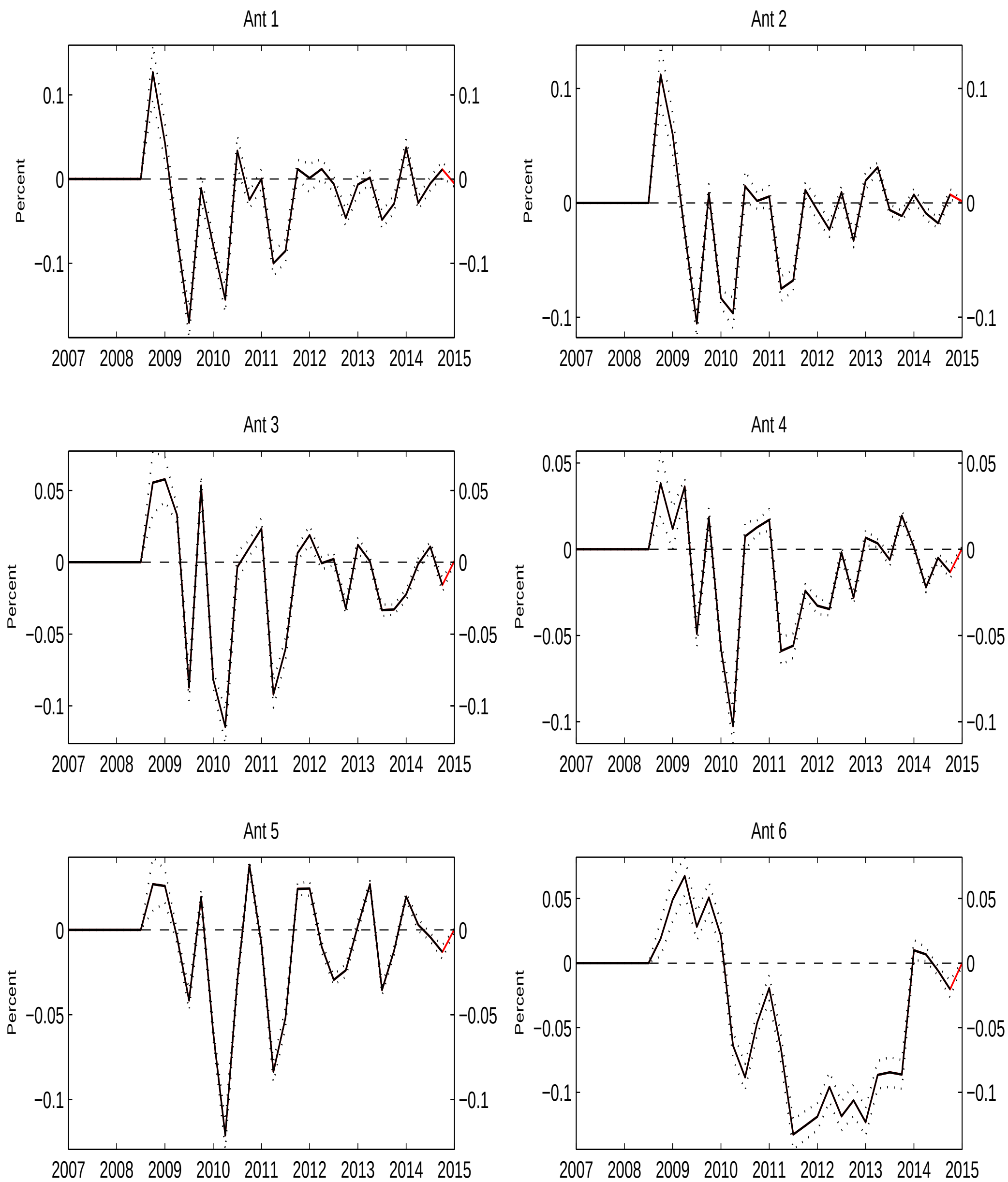


Figure 17: Anticipated Shock Histories



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FRBNY DSGE Model Documentation

DSGE Group, Research and Statistics, FRBNY, March 9, 2015

1 General Structure

The FRBNY DSGE model is a medium scale, one-sector dynamic stochastic general equilibrium model which is based on the New Keynesian model with financial frictions used in Del Negro et al. (2015). The core of the model is based on the work of Smets and Wouters (2007) (henceforth SW) and Christiano et al. (2005): It builds on the neo-classical growth model by adding nominal wage and price rigidities, variable capital utilization, costs of adjusting investment, habit formation in consumption. The model also includes credit frictions as in the *financial accelerator* model developed by Bernanke et al. (1999b), where the actual implementation of the credit frictions follows closely Christiano et al. (2014), and a time-varying inflation target following Del Negro and Schorfheide (2012). In contrast to these papers, the model features both a deterministic and a stochastic trend in productivity. Finally, it accounts for forward guidance in monetary policy by including anticipated policy shocks as in Laseen and Svensson (2011).

The model economy is populated by eight classes of agents: 1) a continuum of households, who consume and supply differentiated labor; 2) competitive labor aggregators that combine labor supplied by individual households; 3) competitive final good-producing firms that aggregate the intermediate goods into a final product; 4) a continuum of monopolistically competitive intermediate good producing firms; 5) competitive capital producers that convert final goods into capital; 6) a continuum of entrepreneurs who purchase capital using both internal and borrowed funds and rent it to intermediate good producing firms; 7) a representative bank collecting deposits from the households and lending funds to the entrepreneurs; and finally 8) a government, composed of a monetary authority that sets short-term interest rates and a fiscal authority that sets public spending and collects taxes.

The data set as well as the prior distribution used for the estimation is discussed in Section **??**. Finally, Section **??** discusses how the DSGE model is solved to generate forecasts as of 2008Q4 and how it is solved to examine the 2009-2012 data in view of zero nominal interest rate and the forward guidance policy pursued by the Fed.

2 DSGE Model Specification

Since the derivation of the SW model is discussed in detail in Christiano et al. (2005), we will only present a summary of the log-linearized equilibrium conditions. We will first reproduce the equilibrium conditions for the SW model and then discuss the two extensions that underly the DSGE model used for our analysis.

1.1 The SW Model

All variables in the following equations are expressed in log deviations from their non-stochastic steady state. In SW this is defined as $Z_t = e^{\gamma t + \frac{1}{1-\alpha}\tilde{z}_t}$, where γ is the steady state growth rate of the economy, and $\tilde{z}_t$ be the linearly detrended log productivity process which follows the autoregressive law of motion

$$\tilde{z}_t = \rho_z \tilde{z}_{t-1} + \sigma_z \varepsilon_{z,t}. \tag{1}$$

The growth rate of Z_t in deviations from γ, denoted by z_t, follows the process:

$$z_t = \ln(Z_t/Z_{t-1}) - \gamma = \frac{1}{1-\alpha}(\rho_z - 1)\tilde{z}_{t-1} + \frac{1}{1-\alpha}\sigma_z \epsilon_{z,t}. \tag{2}$$

Steady state values are denoted by $*$-subscripts and steady state formulas are provided in the technical appendix of Del Negro and Schorfheide (2012), which is available online. The consumption Euler equation is given by:

$$\begin{aligned} c_t = &-\frac{(1-he^{-\gamma})}{\sigma_c(1+he^{-\gamma})}\left(R_t - I\!\!E_t[\pi_{t+1}] + b_t\right) + \frac{he^{-\gamma}}{(1+he^{-\gamma})}\left(c_{t-1} - z_t\right) \\ &+ \frac{1}{(1+he^{-\gamma})} I\!\!E_t\left[c_{t+1} + z_{t+1}\right] + \frac{(\sigma_c - 1)}{\sigma_c(1+he^{-\gamma})}\frac{w_* L_*}{c_*}\left(L_t - I\!\!E_t[L_{t+1}]\right), \end{aligned} \tag{3}$$

where c_t is consumption, L_t is labor supply, R_t is the nominal interest rate, and π_t is inflation. The exogenous process b_t drives a wedge between the intertemporal ratio of the marginal utility of consumption and the riskless real return $R_t - I\!\!E_t[\pi_{t+1}]$, and follows an AR(1) process with parameters ρ_b and σ_b. The parameters σ_c and h capture the degree of relative risk aversion and the degree of habit persistence in the utility function, respectively. The following condition expresses the relationship between the value of capital in terms of consumption q_t^k

and the level of investment i_t measured in terms of consumption goods:

$$q_t^k = S'' e^{2\gamma}(1+\bar{\beta})\Big(i_t - \frac{1}{1+\bar{\beta}}\left(i_{t-1} - z_t\right) - \frac{\bar{\beta}}{1+\bar{\beta}}\mathbb{E}_t\left[i_{t+1} + z_{t+1}\right] - \mu_t\Big), \tag{4}$$

which is affected by both investment adjustment cost (S'' is the second derivative of the adjustment cost function) and by μ_t, an exogenous process called the "marginal efficiency of investment" that affects the rate of transformation between consumption and installed capital (see Greenwood et al. (1998)). The exogenous process μ_t follows an AR(1) process with parameters ρ_μ and σ_μ. The parameter $\bar{\beta} = \beta e^{(1-\sigma_c)\gamma}$ depends on the intertemporal discount rate in the utility function of the households β, the degree of relative risk aversion σ_c, and the steady-state growth rate γ.

The capital stock, $\bar{k}_t$, evolves as

$$\bar{k}_t = \left(1 - \frac{i_*}{\bar{k}_*}\right)\left(\bar{k}_{t-1} - z_t\right) + \frac{i_*}{\bar{k}_*} i_t + \frac{i_*}{\bar{k}_*} S'' e^{2\gamma}(1+\bar{\beta})\mu_t, \tag{5}$$

where $i_*/\bar{k}_*$ is the steady state ratio of investment to capital. The arbitrage condition between the return to capital and the riskless rate is:

$$\frac{r_*^k}{r_*^k + (1-\delta)}\mathbb{E}_t[r_{t+1}^k] + \frac{1-\delta}{r_*^k + (1-\delta)}\mathbb{E}_t[q_{t+1}^k] - q_t^k = R_t + b_t - \mathbb{E}_t[\pi_{t+1}], \tag{6}$$

where r_t^k is the rental rate of capital, r_*^k its steady state value, and δ the depreciation rate. Given that capital is subject to variable capacity utilization u_t, the relationship between $\bar{k}_t$ and the amount of capital effectively rented out to firms k_t is

$$k_t \;=\; u_t - z_t + \bar{k}_{t-1}. \tag{7}$$

The optimality condition determining the rate of utilization is given by

$$\frac{1-\psi}{\psi} r_t^k = u_t, \tag{8}$$

where ψ captures the utilization costs in terms of foregone consumption. Real marginal costs for firms are given by

$$mc_t \;=\; w_t + \alpha L_t - \alpha k_t, \tag{9}$$

where w_t is the real wage and α is the income share of capital (after paying mark-ups and fixed costs) in the production function. From the optimality conditions of goods producers it follows that all firms have the same capital-labor ratio:

$$k_t \;=\; w_t - r_t^k + L_t. \tag{10}$$

The production function is:

$$y_t \;=\; \Phi_p\left(\alpha k_t + (1-\alpha)L_t\right) + \mathcal{I}\{\rho_z < 1\}(\Phi_p - 1)\frac{1}{1-\alpha}\tilde{z}_t, \tag{11}$$

if the log productivity is trend stationary. The last term $(\Phi_p - 1)\frac{1}{1-\alpha}\tilde{z}_t$ drops out if technology has a stochastic trend, because in this case one has to assume that the fixed costs are proportional to the trend. Similarly, the resource constraint is:

$$y_t = g_t + \frac{c_*}{y_*}c_t + \frac{i_*}{y_*}i_t + \frac{r_*^k k_*}{y_*}u_t - \mathcal{I}\{\rho_z < 1\}\frac{1}{1-\alpha}\tilde{z}_t, \tag{12}$$

where again the term $-\frac{1}{1-\alpha}\tilde{z}_t$ disappears if technology follows a unit root process. Government spending g_t is assumed to follow the exogenous process:

$$g_t = \rho_g g_{t-1} + \sigma_g \varepsilon_{g,t} + \eta_{gz}\sigma_z\varepsilon_{z,t}.$$

Finally, the price and wage Phillips curves are, respectively:

$$\pi_t = \kappa\, mc_t + \frac{\iota_p}{1+\iota_p\bar{\beta}}\pi_{t-1} + \frac{\bar{\beta}}{1+\iota_p\bar{\beta}}\mathbb{E}_t[\pi_{t+1}] + \lambda_{f,t}, \tag{13}$$

and

$$\begin{aligned} w_t = {} & \frac{(1-\zeta_w\bar{\beta})(1-\zeta_w)}{(1+\bar{\beta})\zeta_w((\lambda_w - 1)\epsilon_w + 1)}\left(w_t^h - w_t\right) - \frac{1+\iota_w\bar{\beta}}{1+\bar{\beta}}\pi_t + \frac{1}{1+\bar{\beta}}\left(w_{t-1} - z_t - \iota_w\pi_{t-1}\right) \\ & + \frac{\bar{\beta}}{1+\bar{\beta}}\mathbb{E}_t\left[w_{t+1} + z_{t+1} + \pi_{t+1}\right] + \lambda_{w,t}, \end{aligned} \tag{14}$$

where $\kappa = \frac{(1-\zeta_p\bar{\beta})(1-\zeta_p)}{(1+\iota_p\bar{\beta})\zeta_p((\Phi_p-1)\epsilon_p+1)}$, the parameters ζ_p, ι_p, and ϵ_p are the Calvo parameter, the degree of indexation, and the curvature parameter in the Kimball aggregator for prices, and ζ_w, ι_w, and ϵ_w are the corresponding parameters for wages. w_t^h measures the household's marginal rate of substitution between consumption and labor, and is given by:

$$w_t^h = \frac{1}{1 - he^{-\gamma}} \left(c_t - he^{-\gamma} c_{t-1} + he^{-\gamma} z_t\right) + \nu_l L_t, \tag{15}$$

where ν_l characterizes the curvature of the disutility of labor (and would equal the inverse of the Frisch elasticity in absence of wage rigidities). The mark-ups $\lambda_{f,t}$ and $\lambda_{w,t}$ follow exogenous ARMA(1,1) processes

$$\lambda_{f,t} = \rho_{\lambda_f} \lambda_{f,t-1} + \sigma_{\lambda_f} \varepsilon_{\lambda_f,t} + \eta_{\lambda_f} \sigma_{\lambda_f} \varepsilon_{\lambda_f,t-1}, \text{ and}$$

$$\lambda_{w,t} = \rho_{\lambda_w} \lambda_{w,t-1} + \sigma_{\lambda_w} \varepsilon_{\lambda_w,t} + \eta_{\lambda_w} \sigma_{\lambda_w} \varepsilon_{\lambda_w,t-1},$$

respectively. Finally, the monetary authority follows a generalized feedback rule:

$$\begin{aligned} R_t \;=\; & \rho_R R_{t-1} + (1 - \rho_R) \left(\psi_1 \pi_t + \psi_2 (y_t - y_t^f)\right) \\ & + \psi_3 \left((y_t - y_t^f) - (y_{t-1} - y_{t-1}^f)\right) + r_t^m, \end{aligned} \tag{16}$$

where the flexible price/wage output y_t^f is obtained from solving the version of the model without nominal rigidities (that is, Equations (3) through (12) and (15)), and the residual r_t^m follows an AR(1) process with parameters ρ_{r^m} and σ_{r^m}.

1.2 Time-Varying Target Inflation and Long-Run Inflation Expectations

In order to capture the rise and fall of inflation and interest rates in the estimation sample, we replace the constant target inflation rate by a time-varying target inflation. While time-varying target rates have been frequently used for the specification of monetary policy rules in DSGE model (e.g., Erceg and Levin (2003) and Smets and Wouters (2003), among others), we follow the approach of Aruoba and Schorfheide (2008) and Del Negro and Eusepi (2011) and include data on long-run inflation expectations as an observable into the estimation of the DSGE model. At each point in time, the long-run inflation expectations essentially determine the level of the target inflation rate. To the extent that long-run inflation expectations at the forecast origin contain information about the central bank's objective function, e.g. the desire to stabilize inflation at 2%, this information is automatically included in the forecast.

More specifically, for the SW model the interest-rate feedback rule of the central bank (16) is modified as follows:

$$\begin{aligned} R_t &= \rho_R R_{t-1} + (1-\rho_R)\Big(\psi_1(\pi_t - \pi_t^*) + \psi_2(y_t - y_t^f)\Big) \\ &\quad + \psi_3\Big((y_t - y_t^f) - (y_{t-1} - y_{t-1}^f)\Big) + r_t^m. \end{aligned} \tag{17}$$

The time-varying inflation target evolves according to:

$$\pi_t^* = \rho_{\pi^*}\pi_{t-1}^* + \sigma_{\pi^*}\epsilon_{\pi^*,t}, \tag{18}$$

where $0 < \rho_{\pi^*} < 1$ and $\epsilon_{\pi^*,t}$ is an iid shock. We model π_t^* as a stationary process, although our prior for ρ_{π^*} will force this process to be highly persistent. The assumption that the changes in the target inflation rate are exogenous is, to some extent, a short-cut. For instance, the learning models of Sargent (1999) or Primiceri (2006) imply that the rise in the target inflation rate in the 1970's and the subsequent drop is due to policy makers learning about the output-inflation trade-off and trying to set inflation optimally. We are abstracting from such a mechanism in our specification.

1.3 Financial Frictions

Building on the work of Bernanke et al. (1999a), Christiano et al. (2003), De Graeve (2008), and Christiano et al. (2014) we also add financial frictions to our DSGE model. We assume that banks collect deposits from households and lend to entrepreneurs who use these funds as well as their own wealth to acquire physical capital, which is rented to intermediate goods producers. Entrepreneurs are subject to idiosyncratic disturbances that affect their ability to manage capital. Their revenue may thus be too low to pay back the bank loans. Banks protect themselves against default risk by pooling all loans and charging a spread over the deposit rate. This spread may vary as a function of the entrepreneurs' leverage and their riskiness. Adding these frictions to the SW model amounts to replacing equation (6) with the following conditions:

$$E_t\left[\tilde{R}_{t+1}^k - R_t\right] = b_t + \zeta_{sp,b}\left(q_t^k + \bar{k}_t - n_t\right) + \tilde{\sigma}_{\omega,t} \tag{19}$$

and

$$\tilde{R}_t^k - \pi_t = \frac{r_*^k}{r_*^k + (1-\delta)} r_t^k + \frac{(1-\delta)}{r_*^k + (1-\delta)} q_t^k - q_{t-1}^k, \tag{20}$$

where $\tilde{R}_t^k$ is the gross nominal return on capital for entrepreneurs, n_t is entrepreneurial equity, and $\tilde{\sigma}_{\omega,t}$ captures mean-preserving changes in the cross-sectional dispersion of ability across entrepreneurs (see Christiano et al. (2014)) and follows an AR(1) process with parameters ρ_{σ_ω} and σ_{σ_ω}. The second condition defines the return on capital, while the first one determines the spread between the expected return on capital and the riskless rate. Note that if $\zeta_{sp,b} = 0$ and the financial friction shocks $\tilde{\sigma}_{\omega,t}$ are zero, (19) and (20) coincide with (6). The following condition describes the evolution of entrepreneurial net worth:

$$\begin{aligned} n_t \;=\; & \zeta_{n,\tilde{R}^k} \left(\tilde{R}_t^k - \pi_t \right) - \zeta_{n,R} \left(R_{t-1} - \pi_t \right) + \zeta_{n,qK} \left(q_{t-1}^k + \bar{k}_{t-1} \right) + \zeta_{n,n} n_{t-1} \\ & - \tfrac{\zeta_{n,\sigma_\omega}}{\zeta_{sp,\sigma_\omega}} \tilde{\sigma}_{\omega,t-1}. \end{aligned} \tag{21}$$

1.4 Adding Long Run Changes in Productivity Growth

We add long run changes in productivity and now define Z_t as

$$Z_t = e^{\frac{1}{1-\alpha}\tilde{z}_t} Z_t^p e^{\left(\gamma + \frac{\alpha}{1-\alpha}\log \Upsilon\right)t}, \tag{22}$$

where $\tilde{z}_t$ – the stationary component of productivity – evolves as in equation 2 while Z_t^p follows a non stationary process.[1] Specifically, $z_t^p = log(Z_t^p / Z_{t-1}^p)$ follows AR(1) processes:

$$z_t^p = \rho_{z^p} z_{t-1}^p + \sigma_{z^p} \epsilon_{z^p,t},\ \epsilon_{z^p,t} \sim N(0,1), \tag{23}$$

It follows that

$$z_t = log(Z_t/Z_{t-1}) - \gamma = \frac{1}{1-\alpha}(\rho_z - 1)\tilde{z}_{t-1} + \frac{1}{1-\alpha}\sigma_z \epsilon_{z,t} + z_t^p, \tag{24}$$

and

$$E_t[z_{t+1}] = \frac{1}{1-\alpha}(\rho_z - 1)\tilde{z}_t + \rho_{z^p} z_t^p. \tag{25}$$

Since there is a stochastic trend in growth, in equations 11 and 12 the term $\frac{1}{1-\alpha}\tilde{z}_t$ needs to be dropped.

[1] The production function is $Y_t(i) = \max\{e^{\tilde{z}_t} K_t(i)^\alpha \left(L_t(i) e^{\gamma t} Z_t^p\right)^{1-\alpha} - \Phi Z_t, 0\}$.

1.5 Anticipated Policy Shocks

This section describes the introduction of anticipated policy shocks in the model, which follows Laseen and Svensson (2011). We modify the exogenous component of the policy rule (17) so to incorporate anticipated policy shocks:

$$r_t^m = \rho_{r^m} r_{t-1}^m + +\epsilon_t^R + \sum_{k=1}^{K} \epsilon_{k,t-k}^R, \tag{26}$$

where $\epsilon_{R,t}$ is the usual contemporaneous policy shock, and $\epsilon_{k,t-k}^R$ is a policy shock that is known to agents at time $t-k$, but affects the policy rule k periods later, that is, at time t. We assume that $\epsilon_{k,t-k}^R \sim N(0, \sigma_{k,r}^2),\ i.i.d.$.

In order to solve the model we need to express the anticipated shocks in recursive form. For this purpose, we augment the state vector s_t with K additional states ν_t^R,...,ν_{t-K}^R whose law of motion is as follows:

$$\begin{aligned} \nu_{1,t}^R &= \nu_{2,t-1}^R + \epsilon_{1,t}^R \\ \nu_{2,t}^R &= \nu_{3,t-1}^R + \epsilon_{2,t}^R \\ &\vdots \\ \nu_{K,t}^R &= \epsilon_{K,t}^R \end{aligned}$$

and rewrite the policy rule (26) as[2]

$$r_t^m = \rho_{r^m} r_{t-1}^m + +\epsilon_t^R + \nu_{1,t-1}^R.$$

1.6 State Space Representation

We use the method in Sims (2002) to solve the system of log-linear approximate equilibrium conditions and obtain the transition equation:

$$s_t = \mathcal{T}(\theta) s_{t-1} + \mathcal{R}(\theta)\epsilon_t. \tag{27}$$

We collect all the DSGE model parameters in a vector θ and stack the structural shocks in a vector ϵ_t. The state-space representation for our vector of observables y_t, which we describe in the next section, is composed of the transition equation (27), which summarizes

[2] It is easy to verify that $\nu_{1,t-1}^R = \sum_{k=1}^K \epsilon_{k,t-k}^R$, that is, $\nu_{1,t-1}^R$ is a "bin" that collects all anticipated shocks that affect the policy rule in period t.

the evolution of the states s_t, and of a system of measurement equations:

$$y_t = \mathcal{D}(\theta) + \mathcal{Z}(\theta)s_t, \tag{28}$$

mapping the states into the observables, which we describe in detail in the section **??**. We assume that some of the variables are measured with "error", that is, the observed value equals the model implied value plus an exogenous process, which evolves as an AR(1). We add this exogenous process to the vector of states s_t.

3 Data

The estimation of the DSGE model is based on data on real output growth, consumption growth, investment growth, real wage growth, hours worked, inflation, interest rates, 10-year inflation expectations, and spreads. Measurement equations related the model variables that appeared in Section 2 to the observables:

$$\begin{array}{lcl}
\text{Output growth} & = & \gamma + 100\left(y_t - y_{t-1} + z_t\right) \\
\text{Consumption growth} & = & \gamma + 100\left(c_t - c_{t-1} + z_t\right) \\
\text{Investment growth} & = & \gamma + 100\left(i_t - i_{t-1} + z_t\right) \\
\text{Real Wage growth} & = & \gamma + 100\left(w_t - w_{t-1} + z_t\right) \\
\text{Hours} & = & \bar{l} + 100 l_t \\
\text{Core PCE Inflation} & = & \pi_* + 100\pi_t + e_{pce,t} \\
\text{GDP Deflator Inflation} & = & \pi_* + \lambda_{gdp} * 100\pi_t + e_{gdp,t} \\
\text{FFR} & = & R_* + 100 R_t \\
\text{10y Nominal Bond Yield} & = & R_* + 100\mathbb{E}_t\left[\frac{1}{40}\sum_{k=1}^{40} R_{t+k}\right] + e_{R,t} \\
\text{10y Infl. Expectations} & = & \pi_* + 100\mathbb{E}_t\left[\frac{1}{40}\sum_{k=1}^{40} \pi_{t+k}\right] \\
\text{Spread} & = & SP_* + 100\mathbb{E}_t\left[\tilde{R}^k_{t+1} - R_t\right] \\
\text{TFP growth} & = & \gamma + 100\left(z_t + u_t\right) + e_{z,t}
\end{array} . \tag{29}$$

where all variables are measured in percent. All the $e_{*,t}$ processes follow an exogenous AR(1) specification, and can be thought of either measurement error or some other unmodeled source of discrepancy between the model and the data (e.g., risk premia for the long term nominal rate). The terms π_* and R_* measure the steady state level of net inflation and short term nominal interest rates, respectively, and $\bar{l}$ captures the mean of hours (this variable is measured as an index). The first seven series are commonly used in the estimation of the SW model. The 10-year inflation expectations contain information about low-frequency inflation movements and are obtained from the Blue Chip Economic Indicators survey and the Survey of Professional Forecasters. As spread variable we use a Baa Corporate Bond Yield spread over the 10-Year Treasury Note Yield at constant maturity. Details on the construction of the data set are provided in Appendix A.

In order to estimate the importance of anticipated shocks and their effect on the variables of interest, we follow Del Negro and Schorfheide (2012) and augment the measurement equation (28) with the expectations for the policy rate:

$$\begin{aligned} FFR^e_{t,t+1} &= 100(\mathcal{Z}(\theta)_{R,\cdot}\mathcal{T}(\theta)^1 s_t + R^*), \\ &\vdots \\ FFR^e_{t,t+K} &= 100(\mathcal{Z}(\theta)_{R,\cdot}\mathcal{T}(\theta)^K s_t + R^*), \end{aligned} \tag{30}$$

where $FFR^e_{t,t+k}$ are the market's expectations for the FFR k quarters ahead, and $\mathcal{Z}(\theta)_{R,\cdot}$ is the row of $\mathcal{Z}(\theta)$ corresponding to the interest rate.

4 Inference, Prior and Posterior Parameter Estimates

We use Bayesian techniques in the subsequent empirical analysis, which require the specification of a prior distribution for the model parameters. For most of the parameters we use the same marginal prior distributions as Smets and Wouters (2007). There are two important exceptions. First, the original prior for the quarterly steady state inflation rate π_* used by Smets and Wouters (2007) is tightly centered around 0.62% (which is about 2.5% annualized) with a standard deviation of 0.1%. We favor a looser prior, one that has less influence on the model's forecasting performance, that is centered at 0.75% and has a standard deviation of 0.4%. Second, for the financial frictions mechanism we specify priors for the parameters SP_*, $\zeta_{sp,b}$, ρ_{σ_ω}, and σ_{σ_ω}. We fix the parameters corresponding to the steady state default probability and the survival rate of entrepreneurs, respectively. In turn, these parameters imply values for the parameters of (21).

Information on the the prior and posterior mean is provided in section B. Section C reports the impulse response functions of the observable variables to the various shocks.

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A Data Construction

Data on real GDP (GDPC), the GDP deflator (GDPDEF), core PCE inflation (PCEPILFE), nominal personal consumption expenditures (PCEC), and nominal fixed private investment (FPI) are produced at a quarterly frequency by the Bureau of Economic Analysis, and are included in the National Income and Product Accounts (NIPA). Average weekly hours of production and nonsupervisory employees for total private industries (AWHNONAG), civilian employment (CE16OV), and the civilian non-institutional population (LNSINDEX) are produced by the Bureau of Labor Statistics (BLS) at a monthly frequency. The first of these series is obtained from the Establishment Survey, and the remaining from the Household Survey. Both surveys are released in the BLS Employment Situation Summary. Since our models are estimated on quarterly data, we take averages of the monthly data. Compensation per hour for the non-farm business sector (COMPNFB) is obtained from the Labor Productvity and Costs release, and produced by the BLS at a quarterly frequency. All data are transformed following Smets and Wouters (2007). The federal funds rate is obtained from the Federal Reserve Board's H.15 release at a business day frequency. We take quarterly averages of the annualized daily data and divide by four. Let Δ denote the temporal difference operator. Then:

$$\begin{aligned}
\text{Output growth} &= 100 * \Delta LN((GDPC)/LNSINDEX) \\
\text{Consumption growth} &= 100 * \Delta LN((PCEC/GDPDEF)/LNSINDEX) \\
\text{Investment growth} &= 100 * \Delta LN((FPI/GDPDEF)/LNSINDEX) \\
\text{Real wage growth} &= 100 * \Delta LN(COMPNFB/GDPDEF) \\
\text{Hours worked} &= 100 * LN((AWHNONAG * CE16OV/100)/LNSINDEX) \\
\text{GDP Deflator Inflation} &= 100 * \Delta LN(GDPDEF) \\
\text{Core PCE Inflation} &= 100 * \Delta LN(PCEPILFE) \\
\text{FFR} &= (1/4) * FEDERAL\ FUNDS\ RATE
\end{aligned}$$

Long-run inflation expectations are obtained from the Blue Chip Economic Indicators survey and the Survey of Professional Forecasters available from the FRB Philadelphia's Real-Time Data Research Center. Long-run inflation expectations (average CPI inflation over the next 10 years) are available from 1991Q4 onward. Prior to 1991Q4, we use the 10-year expectations data from the Blue Chip survey to construct a long time series that begins in 1979Q4. Since the Blue Chip survey reports long-run inflation expectations only twice a year, we treat these expectations in the remaining quarters as missing observations and adjust the measurement equation of the Kalman filter accordingly. Long-run inflation expectations $\pi_t^{O,40}$ are therefore measured as

$$\text{10y Infl Exp} = (\text{10-YEAR AVERAGE CPI INFLATION FORECAST} - 0.50)/4.$$

where 0.50 is the average difference between CPI and GDP annualized inflation from the beginning of the sample to 1992. We divide by 4 to express the data in quarterly terms. Finally, we measure *Spread* as the annualized Moody's Seasoned Baa Corporate Bond Yield spread over the 10-Year Treasury Note Yield at Constant Maturity. Both series are available from the Federal Reserve Board's H.15 release. Like the federal funds rate, the spread data are also averaged over each quarter and measured at a quarterly frequency. This leads to:

$$\text{Spread} = (1/4) * (Baa\ Corporate\ -\ 10\ year\ Treasury).$$

Similarly,

$$\text{10y Bond yield} = (1/4) * (10\ year\ Treasury).$$

Last TFP growth is measured using John Fernald's TFP growth, unadjusted for changes in utilization and expressed in labor augmenting terms:

$$\text{TFP growth } = (1/4) * \text{Fernald's TFP growth, unadjusted }.$$

B Prior and Posterior Distributions

Parameter Estimates: Prior and Posterior Mean

Parameter	Prior Mean	Prior Stdd	Post Mean	90% Lower Band	90% Upper Band
α	0.300	0.050	0.167	0.143	0.191
ι_p	0.500	0.150	0.256	0.115	0.398
Υ	1.000	0.000	1.000	1.000	1.000
Φ	1.250	0.120	1.120	1.049	1.189
S''	4.000	1.500	2.940	1.941	3.874
h	0.700	0.100	0.440	0.353	0.530
psi	0.500	0.150	0.725	0.586	0.866
ι_w	0.500	0.150	0.526	0.314	0.738
β	0.250	0.100	0.132	0.055	0.202
σ_c	1.500	0.370	1.120	0.878	1.353
ρ	0.750	0.100	0.665	0.599	0.733
$F(\omega)$	0.030	0.000	0.030	0.030	0.030
spr_*	2.000	0.100	1.752	1.625	1.879
γ_*	0.990	0.000	0.990	0.990	0.990
γ	0.400	0.100	0.348	0.277	0.423
$Lmean$	-45.000	5.000	-47.469	-49.289	-45.633
σ_g	0.100	2.000	2.559	2.352	2.760
σ_b	0.100	2.000	0.029	0.025	0.034
σ_μ	0.100	2.000	0.468	0.403	0.533
σ_z	0.100	2.000	0.678	0.612	0.743
σ_{λ_f}	0.100	2.000	0.085	0.066	0.102
σ_{λ_w}	0.100	2.000	0.384	0.337	0.431
σ_{rm}	0.100	2.000	0.235	0.213	0.258
σ_{sigw}	0.050	4.000	0.043	0.034	0.051

Parameter Estimates: Prior and Posterior Mean

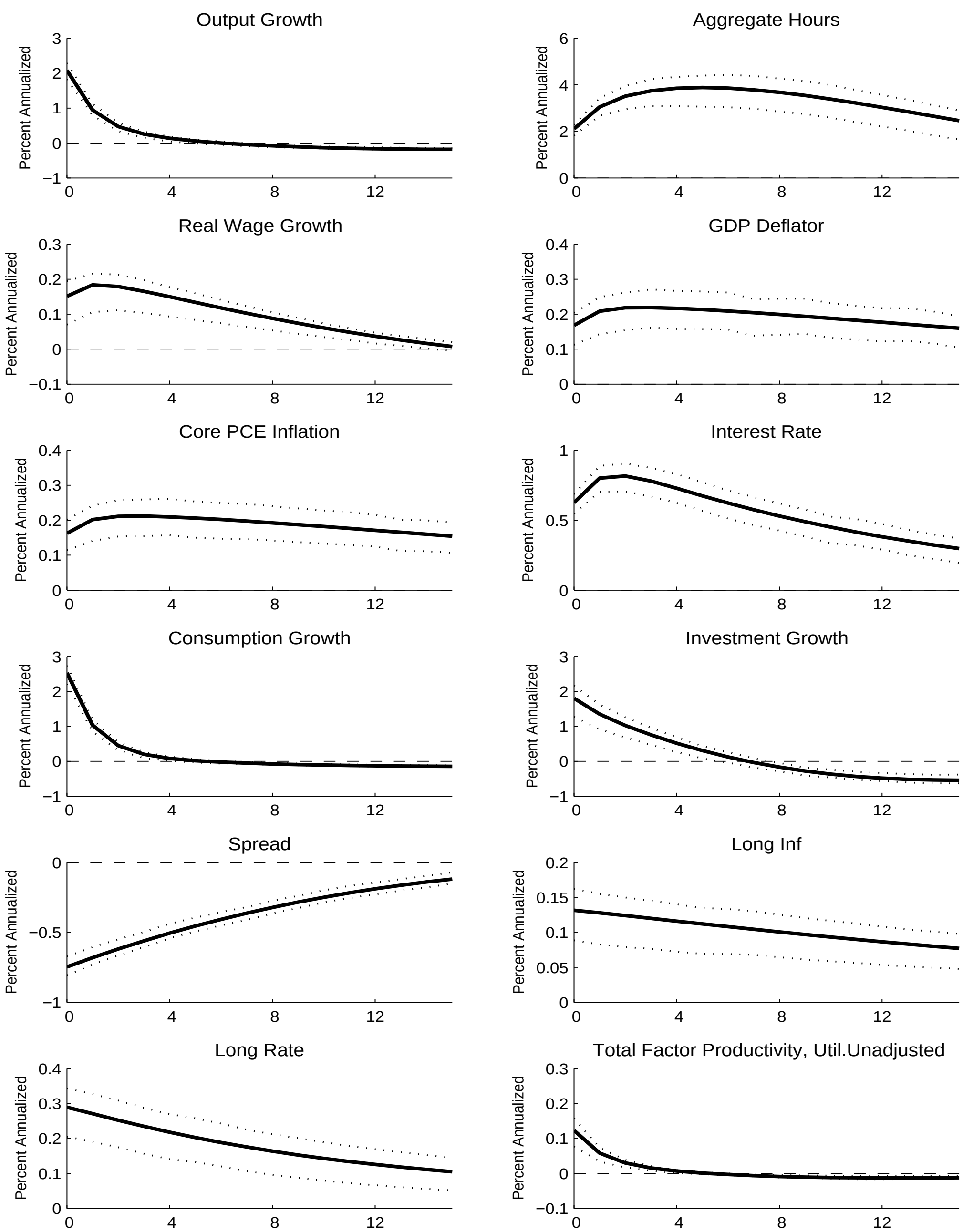
Parameter	Prior Mean	Prior Stdd	Post Mean	90% Lower Band	90% Upper Band
σ_{mue}	0.000	0.000	0.000	0.000	0.000
σ_{gamm}	0.000	0.000	0.000	0.000	0.000
σ_{lr}	0.750	2.000	0.184	0.149	0.219
σ_{z^p}	0.100	2.000	0.194	0.104	0.288
σ_{tfp}	0.100	2.000	0.828	0.755	0.899
σ_{gdpdef}	0.100	2.000	0.160	0.143	0.179
σ_{pce}	0.100	2.000	0.100	0.081	0.120
σ_{ant1}	0.200	4.000	0.100	0.076	0.122
σ_{ant2}	0.200	4.000	0.090	0.070	0.110
σ_{ant3}	0.200	4.000	0.090	0.069	0.110
σ_{ant4}	0.200	4.000	0.085	0.065	0.103
σ_{ant5}	0.200	4.000	0.086	0.066	0.105
σ_{ant6}	0.200	4.000	0.109	0.083	0.134
σ_{ant7}	0.200	4.000	0.258	0.105	0.400
σ_{ant8}	0.200	4.000	0.309	0.104	0.474
σ_{ant9}	0.200	4.000	0.251	0.106	0.399
σ_{ant10}	0.200	4.000	0.250	0.101	0.399
σ_{ant11}	0.200	4.000	0.234	0.112	0.362
σ_{ant12}	0.200	4.000	0.236	0.108	0.366
σ_{ant13}	0.000	0.000	0.000	0.000	0.000
σ_{ant14}	0.000	0.000	0.000	0.000	0.000
σ_{ant15}	0.000	0.000	0.000	0.000	0.000
σ_{ant16}	0.000	0.000	0.000	0.000	0.000
σ_{ant17}	0.000	0.000	0.000	0.000	0.000
σ_{ant18}	0.000	0.000	0.000	0.000	0.000

Parameter Estimates: Prior and Posterior Mean

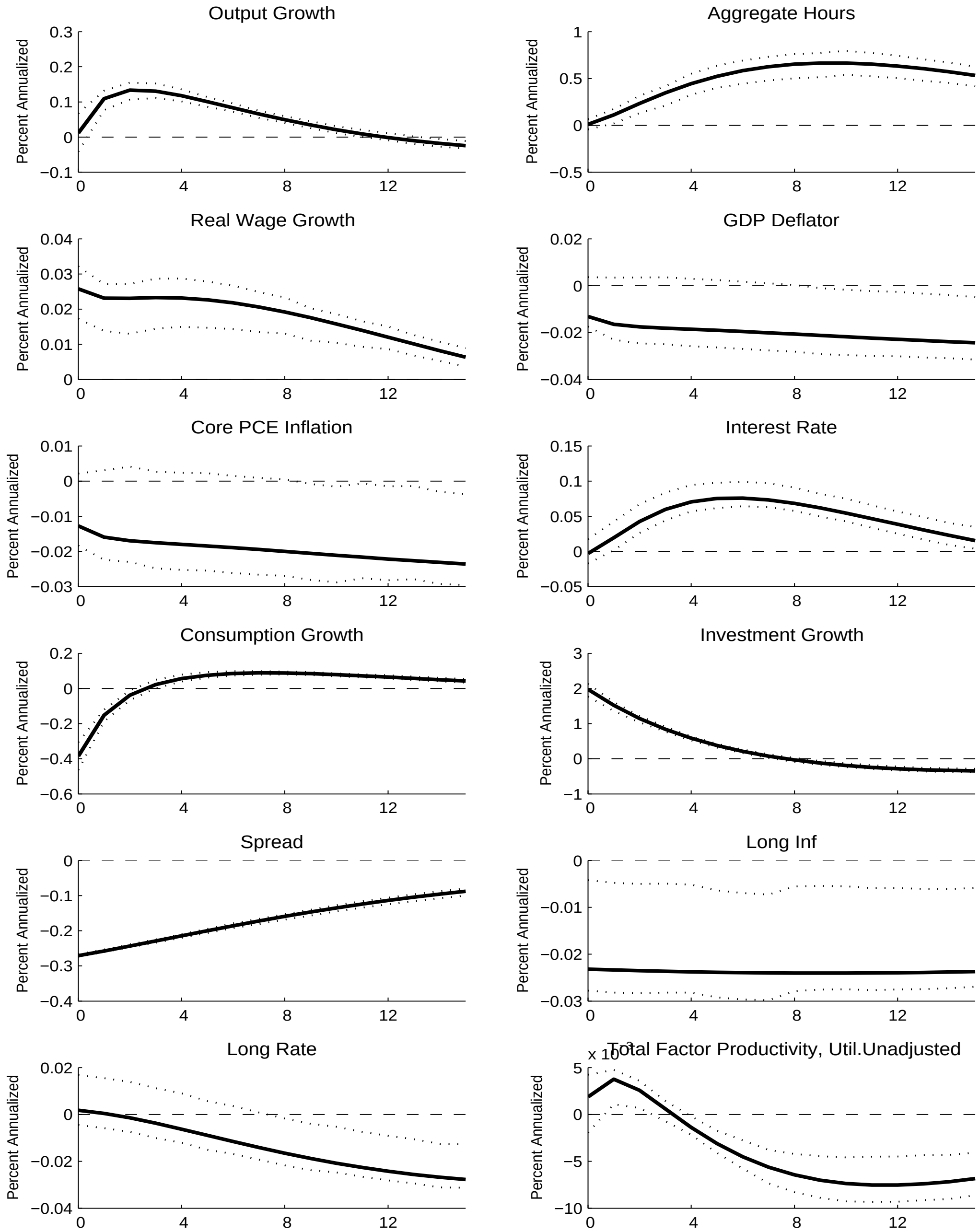
Parameter	Prior Mean	Prior Stdd	Post Mean	90% Lower Band	90% Upper Band
σ_{ant19}	0.000	0.000	0.000	0.000	0.000
σ_{ant20}	0.000	0.000	0.000	0.000	0.000
η_{gz}	0.500	0.200	0.768	0.580	0.962
η_{λ_f}	0.500	0.200	0.608	0.401	0.822
η_{λ_w}	0.500	0.200	0.432	0.184	0.683
i_{α}^{model}	0.000	0.000	0.000	0.000	0.000
Γ_{gdpdef}	1.000	2.000	1.033	0.951	1.118
δ_{gdpdef}	0.000	2.000	0.000	-0.053	0.054

C Impulse Response Functions

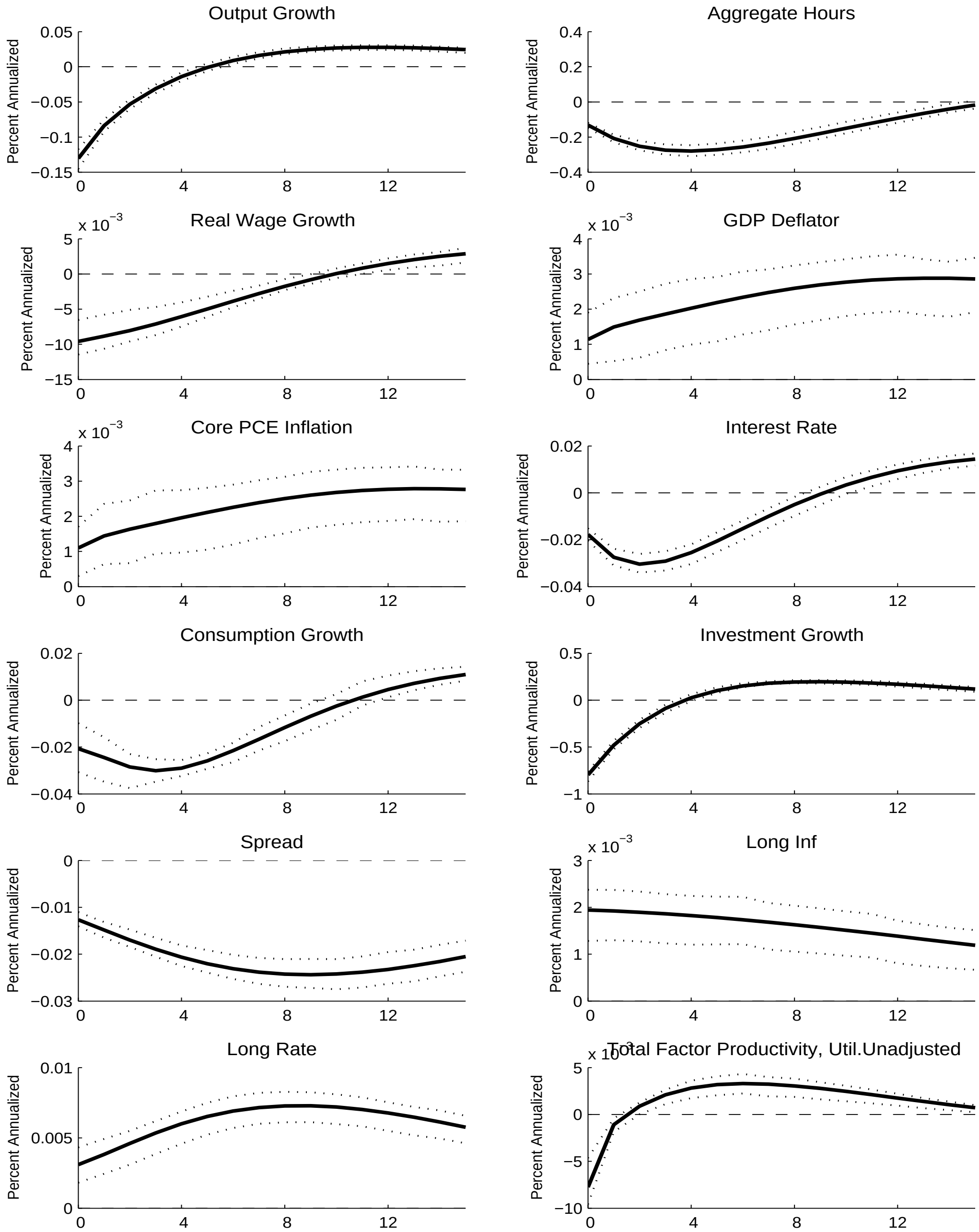
Responses to a Discount Rate (b) Shock



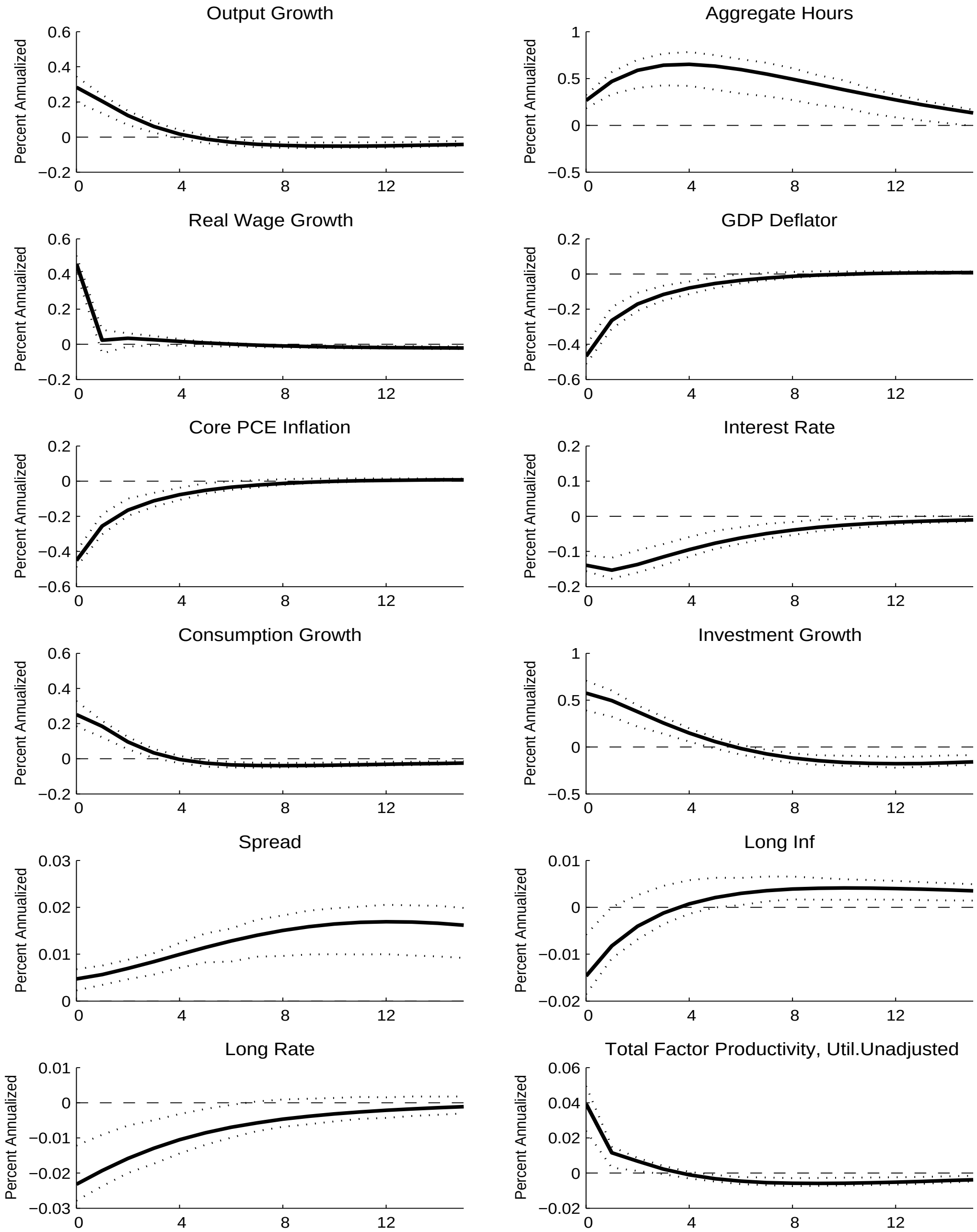
Responses to a Spread Shock



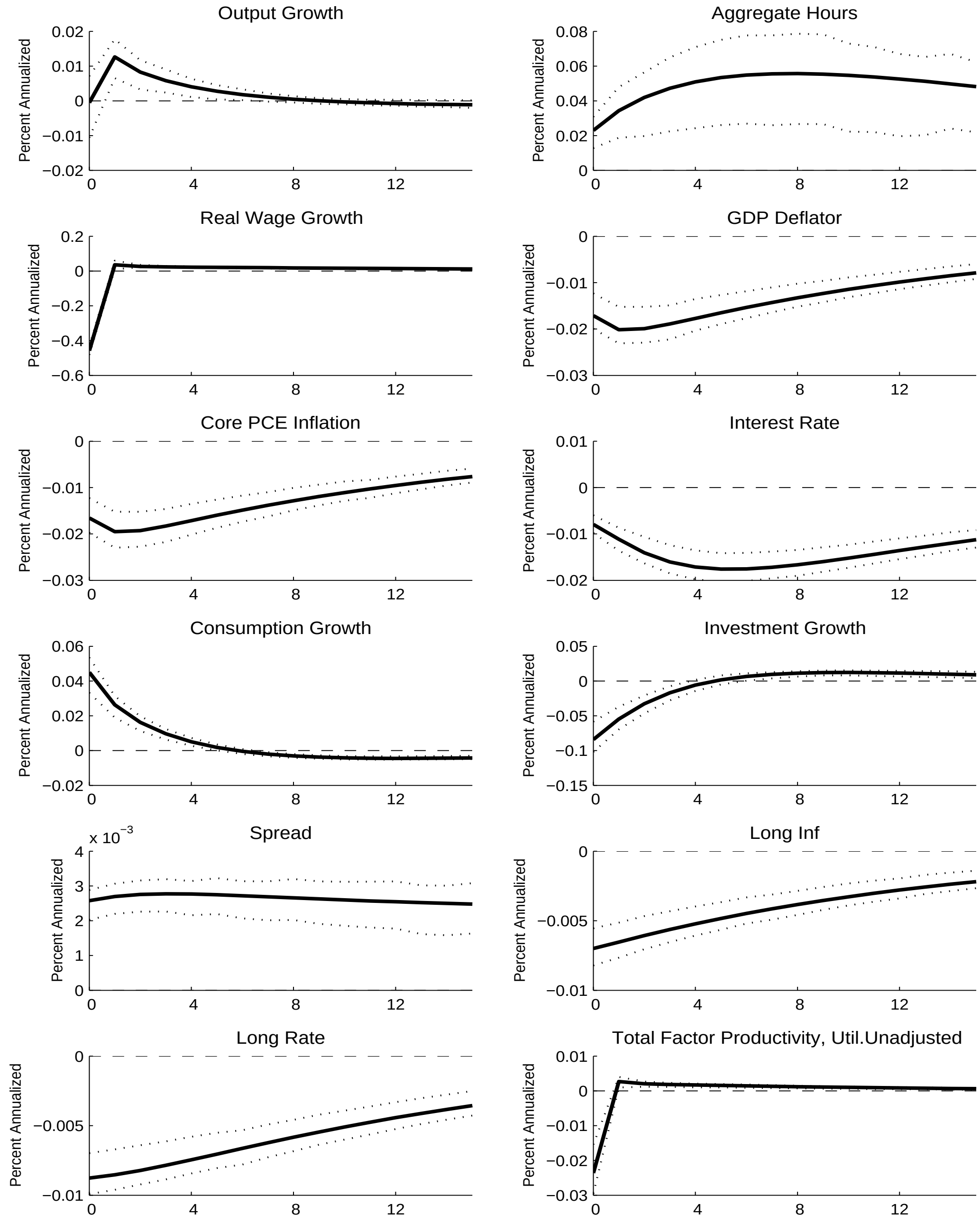
Responses to an MEI Shock



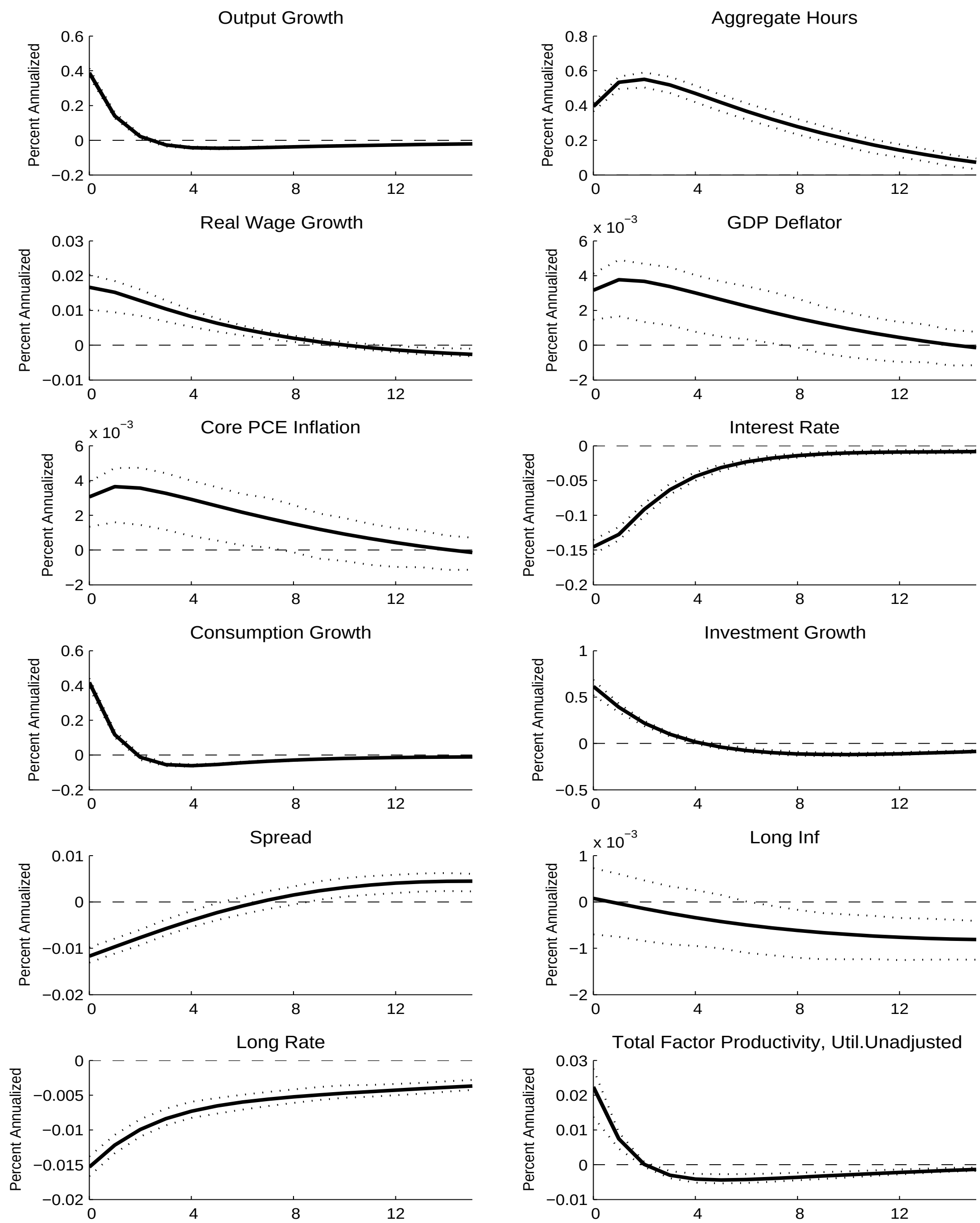
Responses to a Price Mark-up Shock



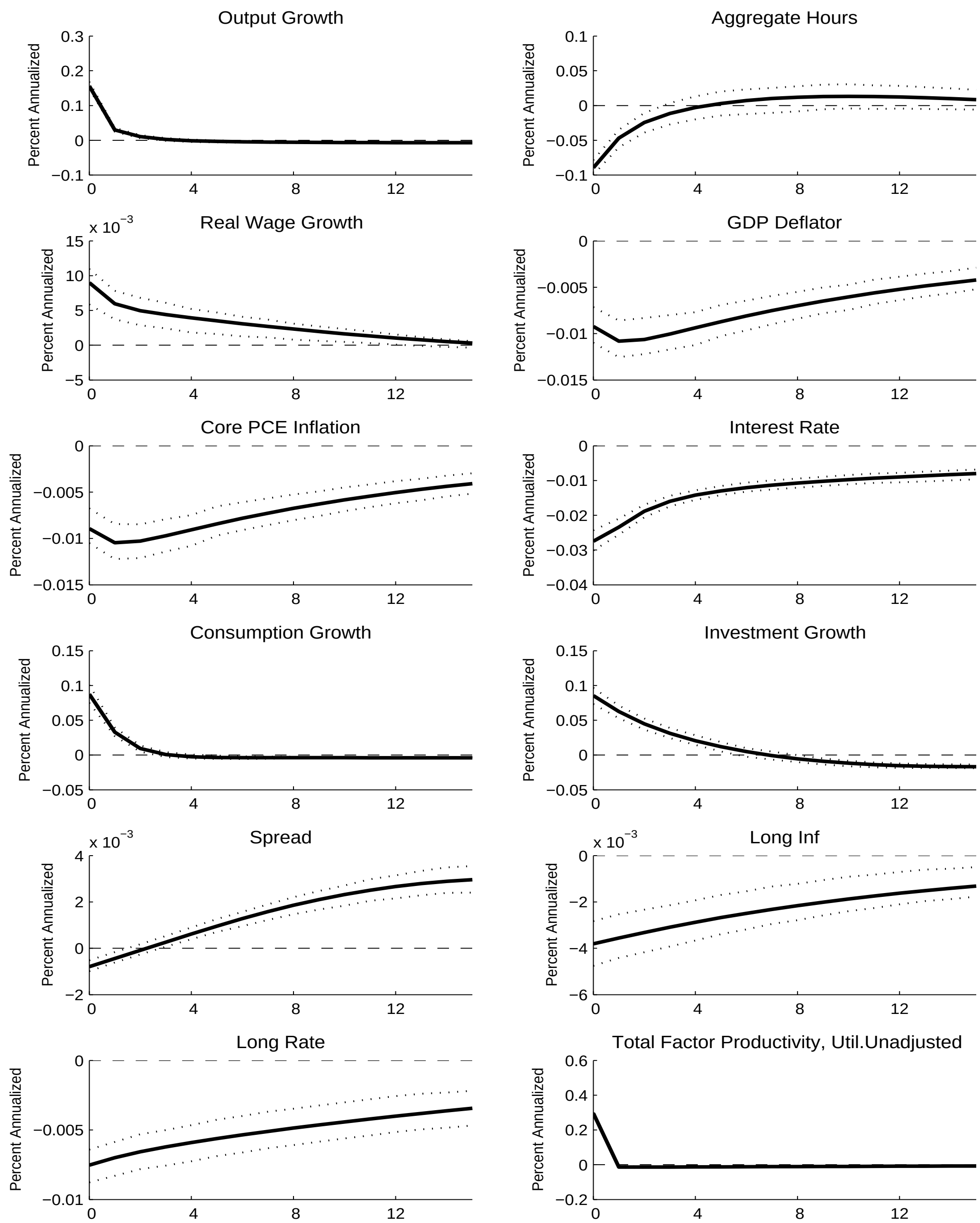
Responses to a Wage Mark-up Shock



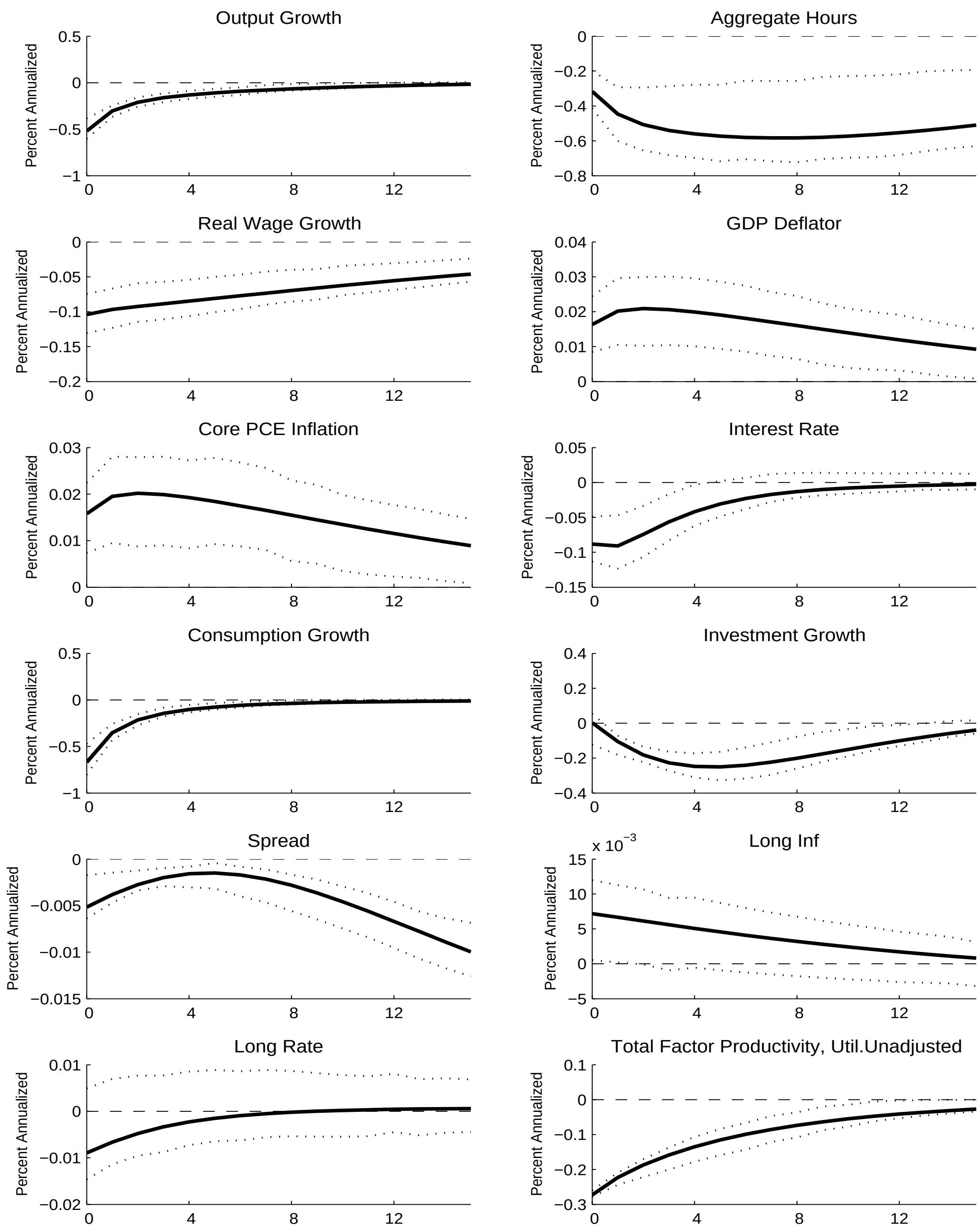
Responses to a Monetary Policy Shock



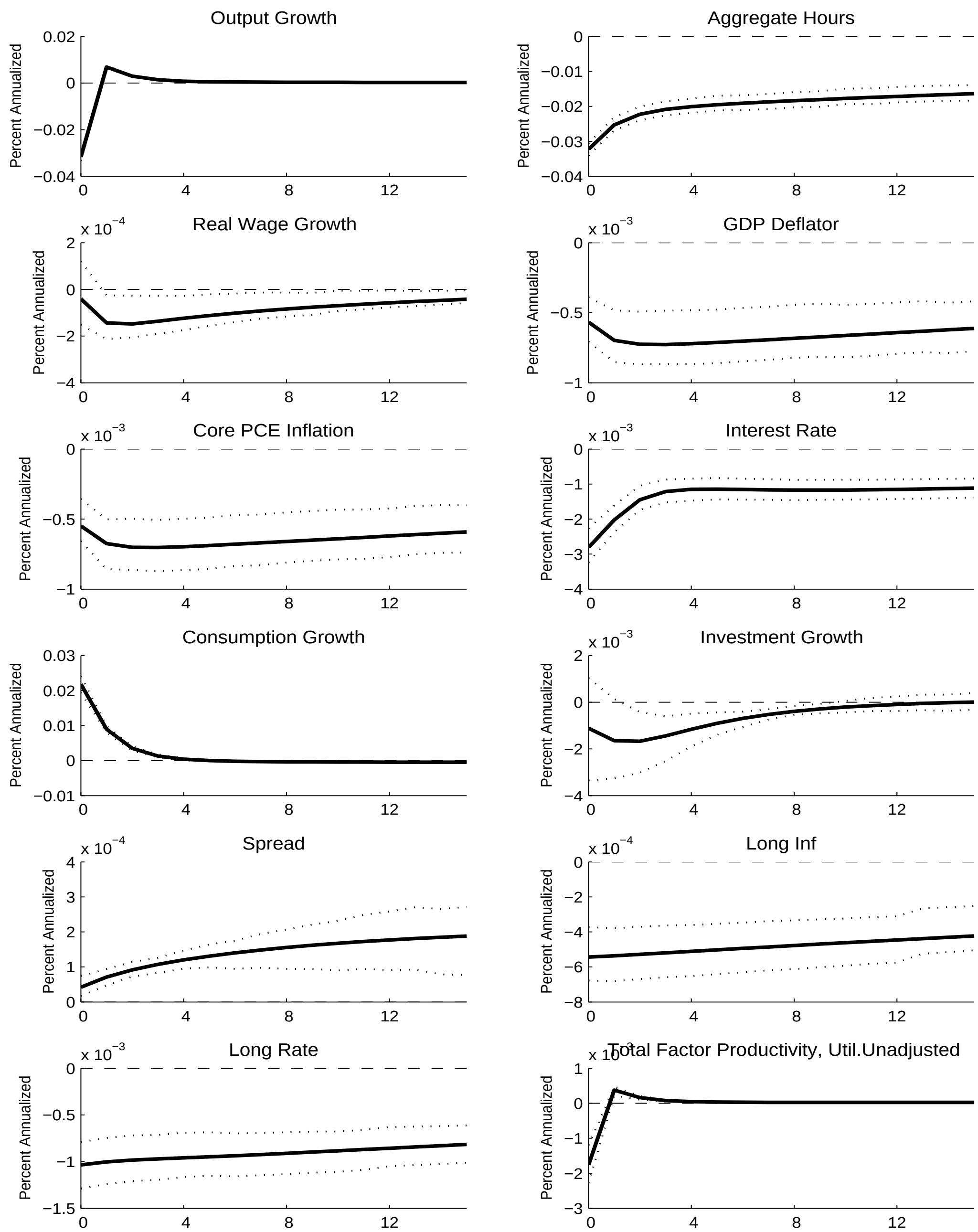
Responses to a Stationary Productivity Shock



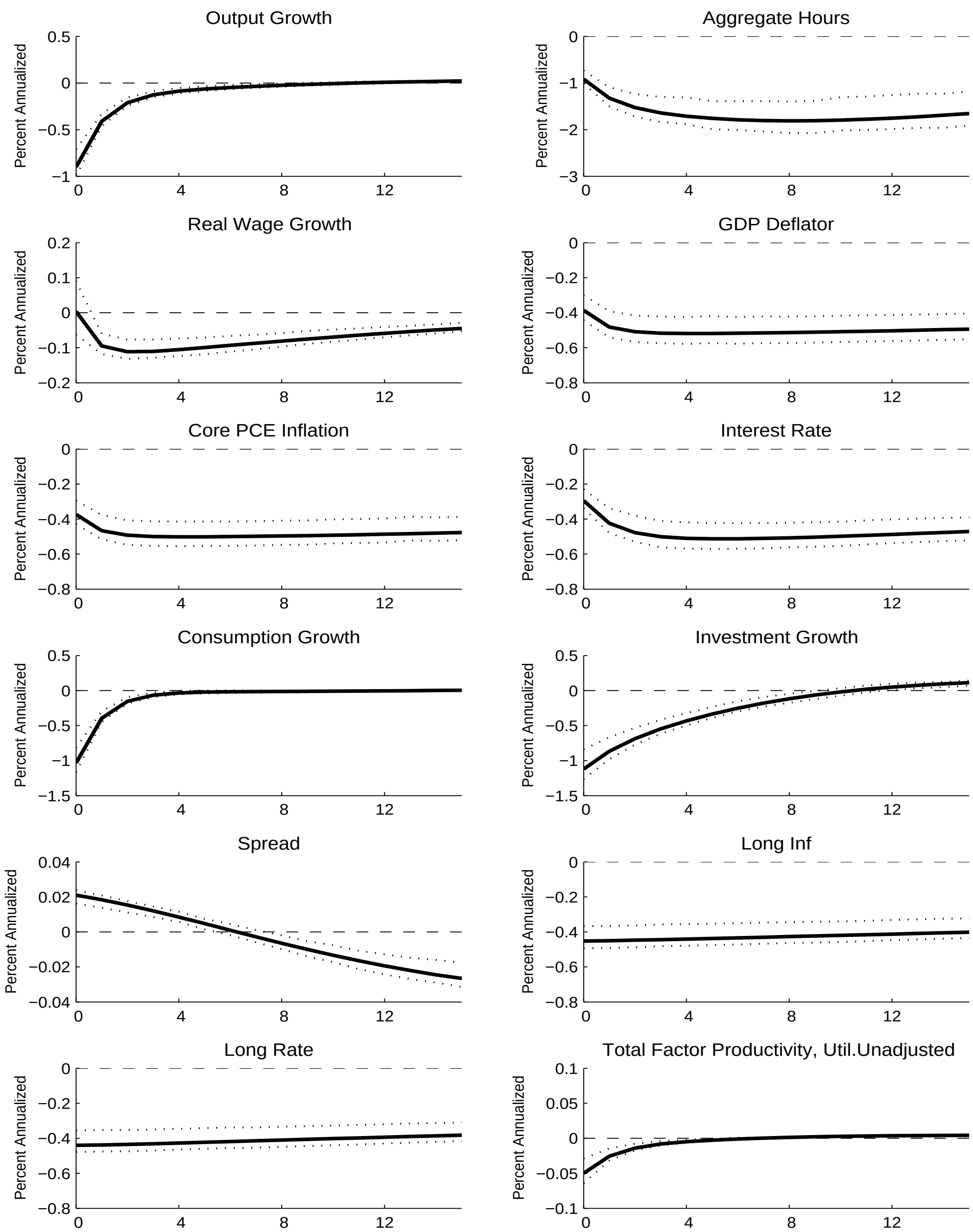
Responses to a Shock to the TFP Growth Rate



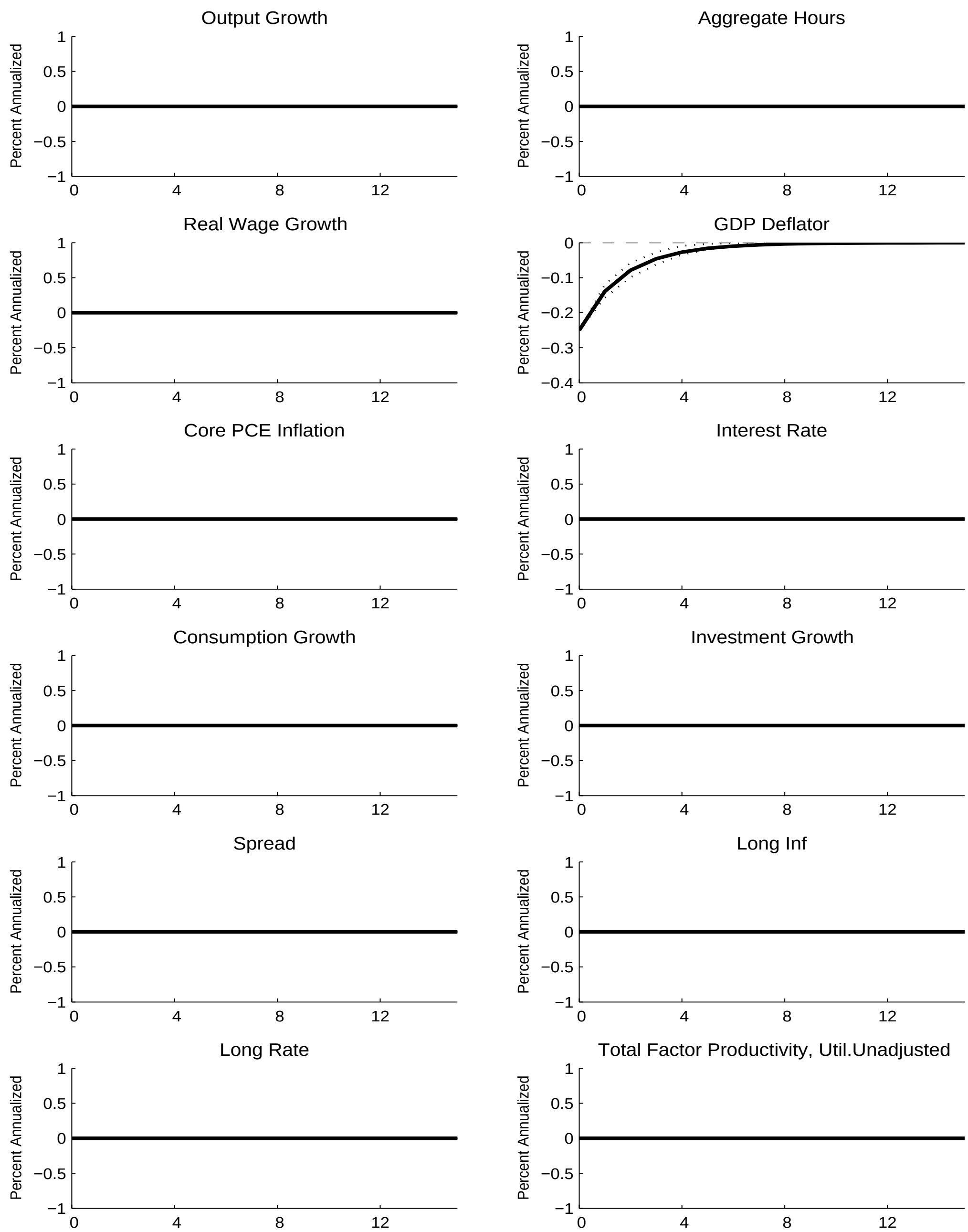
Responses to a Government Spending Shock



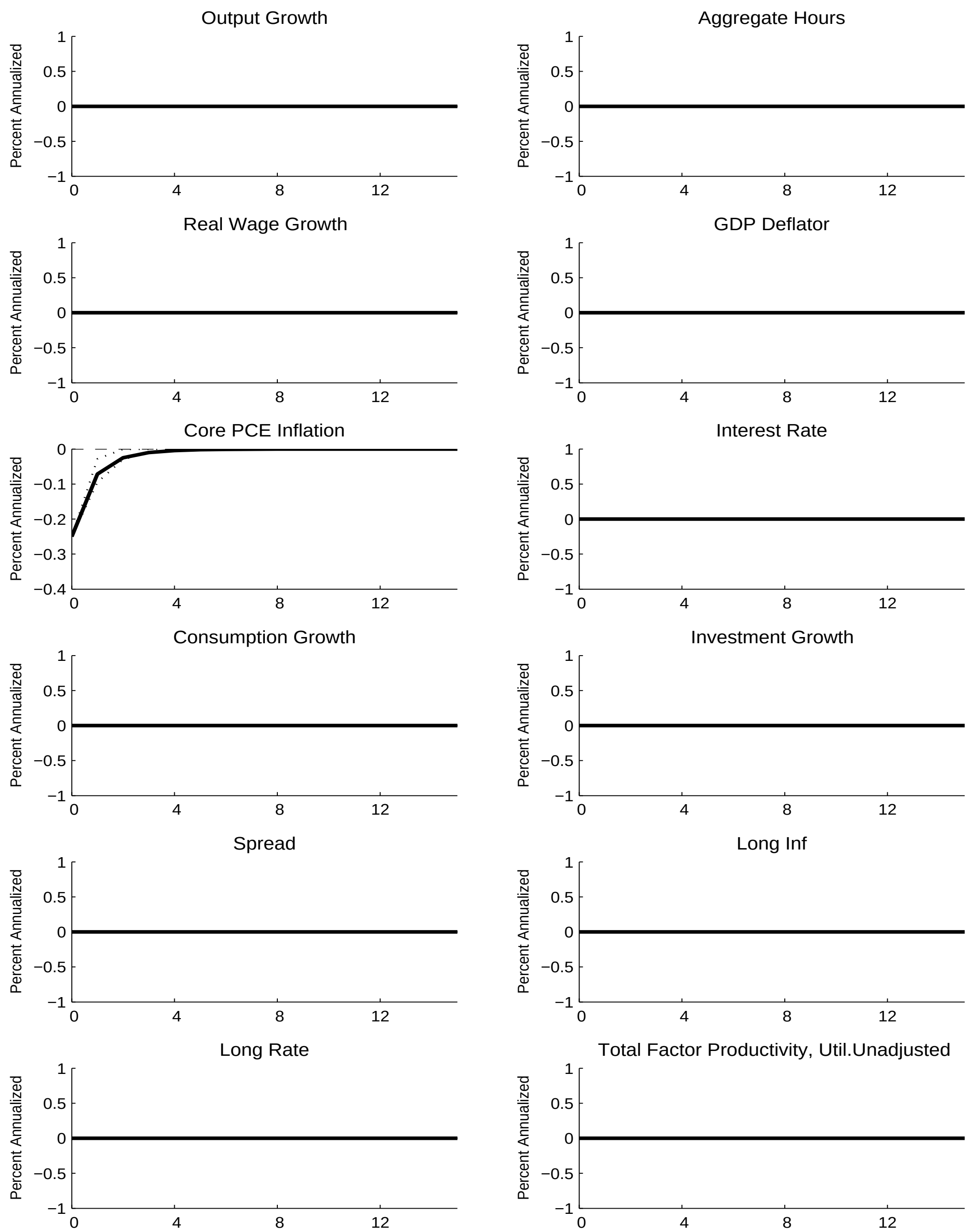
Responses to a π^* Shock



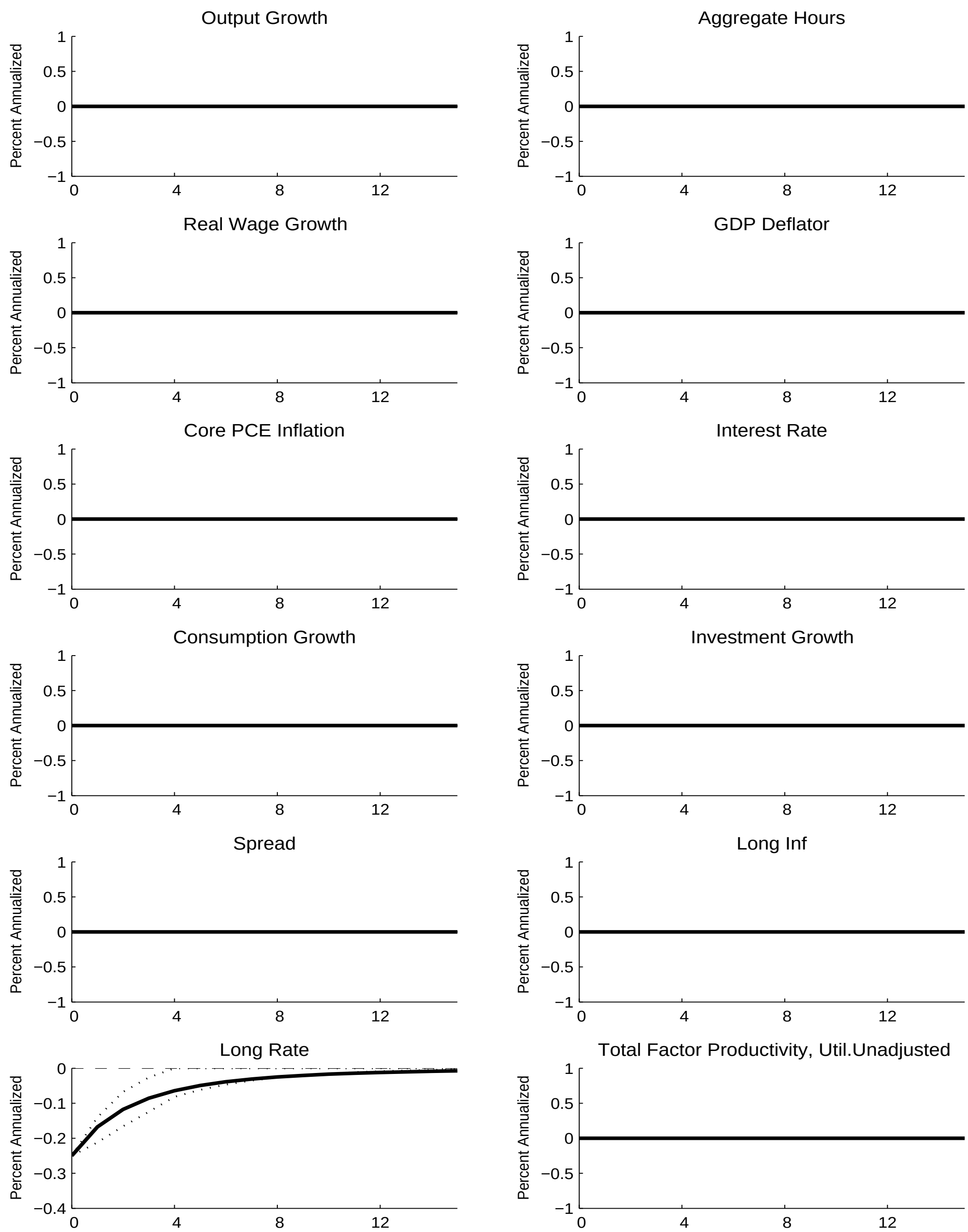
Responses to GDP Deflator Measurement Error



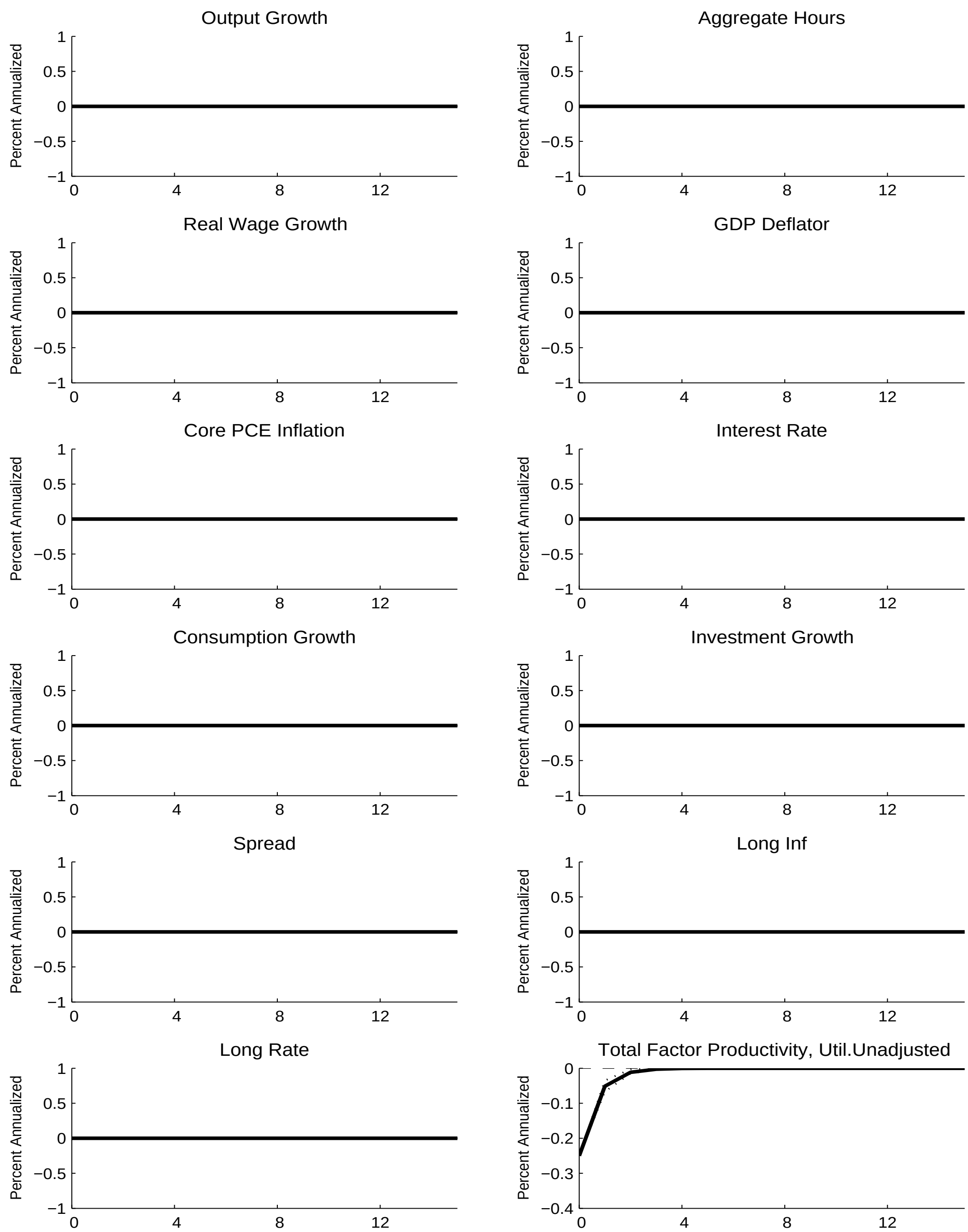
Responses to Core PCE Measurement Error



Responses to Long Rate Measurement Error



Responses to TFP Measurement Error



Detailed Philadelphia (PRISM) Forecast Overview

March 2015
Keith Sill

Forecast Summary

The FRB Philadelphia DSGE model denoted PRISM, projects that real GDP growth will run at a fairly strong pace over the forecast horizon with real output growth peaking at about 3.8 percent in the second half of 2016. Core PCE inflation is projected to be contained at below 2 percent through 2017. For this forecast round, we have implemented the assumption that the forecasted federal funds rate is pinned down by current futures market projections through mid-2015. The funds rate is unconstrained beginning in 2015Q3, and rises to about 1.1 percent in 2015Q4. Many of the model's variables continue to be well below their steady-state values. In particular, consumption, investment, and the capital stock are low relative to steady state, and absent any shocks, the model would predict a rapid recovery. These state variables have been below steady state since the end of the recession. The relatively slow pace of growth and low inflation that have characterized U.S. economic performance over the past few years require the presence of shocks to offset the strength of the model's internal propagation channels.

The Current Forecast and Shock Identification

The PRISM model is an estimated New Keynesian DSGE model with sticky wages, sticky prices, investment adjustment costs, and habit persistence. The model is similar to the Smets & Wouters 2007 model and is described more fully in Schorfheide, Sill, and Kryshko 2010. Unlike in that paper though, we estimate PRISM directly on core PCE inflation rather than projecting core inflation as a non-modeled variable. Details on the model and its estimation are available in a Technical Appendix that was distributed for the June 2011 FOMC meeting or is available on request.

The current forecasts for real GDP growth, core PCE inflation, and the federal funds rate are shown in Figures 1a-1c along with the 68 percent probability coverage intervals. The forecast uses data through 2014Q4 supplemented by a 2015Q1 nowcast based on the latest Macroeconomic Advisers forecast. For example, the model takes 2015Q1 output growth of 2.4 percent as given and the projection begins with 2015Q2. PRISM anticipates that growth accelerates to about 3.8 percent by 2016Q3. Output growth then holds eases down to about a 3.6 percent pace at the end of 2017. Overall, the output growth forecast for this round is a bit weaker compared with December projection. While output growth is fairly robust, core PCE inflation stays contained at below 2 percent through the forecast horizon. Based on the 68 percent coverage interval, the model sees a minimal chance of deflation or recession (measured as negative quarters of real GDP growth) over the next 3 years. The federal funds rate is constrained near the zero bound through mid-2015. Thereafter, the model dynamics take over and the funds rate rises gradually to 2.5 percent in 2016Q4 and 3.2 percent in 2017Q4. This path is similar to the December projection.

The key factors driving the projection are shown in the forecast shock decompositions (Figures 2a-2e) and the smoothed estimates of the model's primary shocks (shown in Figure 3, where they are normalized by standard deviation). The primary shocks driving above-trend real output growth over the next 3 years are labor supply shocks (labeled Labor), government spending shocks, and marginal efficiency of investment shocks (labeled MEI). The model attributes the weak reading on real GDP growth over the past two quarters to negative shocks to TFP and government spending (which includes net exports). Over the course of the recession and recovery PRISM estimated a sequence of large positive shocks to leisure (negative shocks to labor supply) that have a persistent effect on hours worked and so pushed hours well below steady state. As these shocks unwind hours worked rebounds strongly over the forecast horizon and so leads to higher output growth.

As seen in Figure 3, the model estimates a sequence of largely negative discount factor shocks since 2008. All else equal, these shocks push down current consumption and push up investment, with the effect being very persistent. Consequently, the de-trended level of consumption (nondurables + services) remains below the model's estimated steady state at this point. As these shocks unwind over the projection period, consumption growth gradually accelerates from about 2.3 percent at the beginning of 2015 to 3 percent at the end of 2017. The model attributes the recent strength in investment growth (gross private domestic + durable goods consumption) to the gradual unwinding of a history of negative MEI shocks since the start of the recession (see Figures 2e and 3). Consequently, the principal shocks driving strong investment growth over the forecast horizon are efficiency of investment shocks with an additional boost from labor shocks. Offsetting these factors to some extent are financial shocks: the unwinding of the discount factor shocks leads to a downward pull on investment growth over the next three years. Investment growth runs at about a 4 percent pace in 2015, rising to near 5 percent by the start of 2017.

The forecast for core PCE inflation is largely a story of upward pressure from the unwinding of negative labor supply shocks and MEI shocks being offset by downward pressure from the waning of discount factor shocks. Negative discount factor shocks have a strong and persistent negative effect on marginal cost and inflation in the estimated model. Compared, for example, to a negative MEI shock that lowers real output growth by 1 percent, a negative discount factor shock that lowers real output growth by 1 percent leads to a 3 times larger drop in inflation that is more persistent. The negative discount factor shock leads to capital deepening and higher labor productivity. Consequently, marginal cost and inflation fall. The negative effect of discount factor shocks on inflation is estimated to have been quite significant since the end of 2008. As these shocks unwind over the projection period there is a decreasing, but still substantial, downward effect on inflation over the next three years (these shocks have a very persistent effect on inflation).

Partly offsetting the downward pressure on inflation from discount factor shocks is the upward pressure coming from the unwinding of negative labor supply shocks. Labor supply shocks that push down aggregate hours also serve to put upward pressure on the real wage and hence marginal cost. The effect is persistent -- as the labor supply shocks unwind over the forecast horizon they exert a waning upward push to inflation. On balance the effect of these opposing forces is to keep inflation below 2 percent through the forecast horizon.

The federal funds rate is projected to rise fairly quickly once the constraint from market expectations is removed in 2015Q3. The model attributes the low level of the funds rate to a combination of monetary policy, discount factor and MEI shock dynamics. After 2015Q2, the positive contribution from labor supply shocks is more than offset by discount factor shock dynamics, keeping the funds rate below its steady state level through 2017.

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Schorfheide, Frank, Keith Sill, and Maxym Kryshko. 2010. "DSGE model-based forecasting of non-modelled variables." *International Journal of Forecasting,* 26(2): 348-373.

Smets, Frank, and Rafael Wouters. 2007. "Shocks and Frictions in U.S. Business Cycles: A Bayesian DSGE Approach." *American Economic Review,* 97(3): 586-606.

Figure 1a

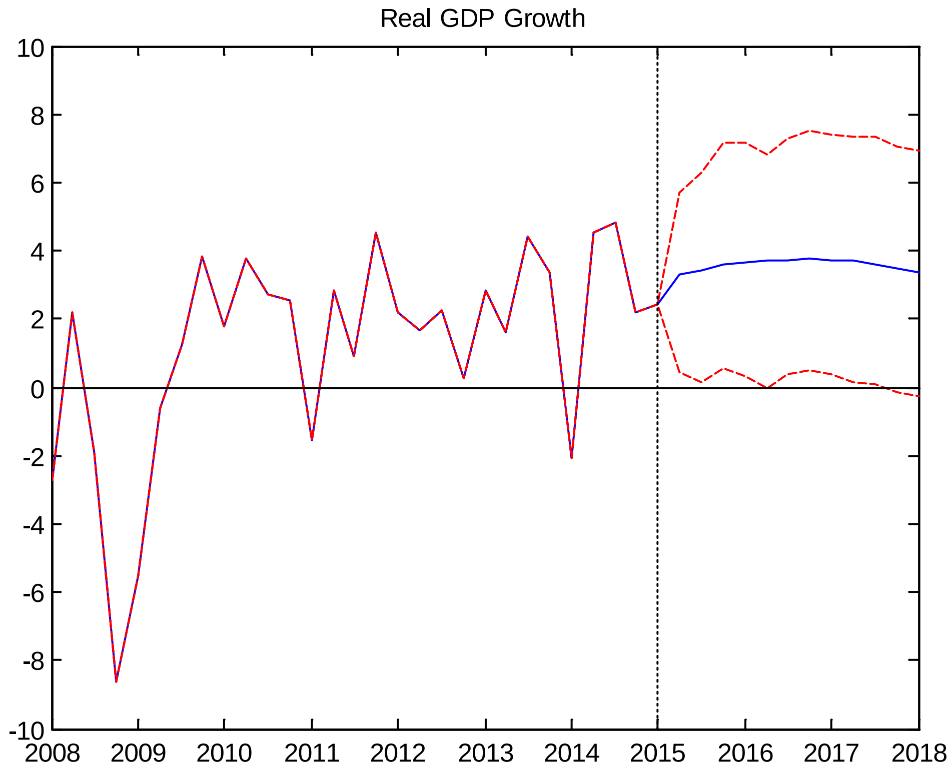

Real GDP Growth
10
8
6
4
2
0
-2
-4
-6
-8
-10
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018

Figure 1b

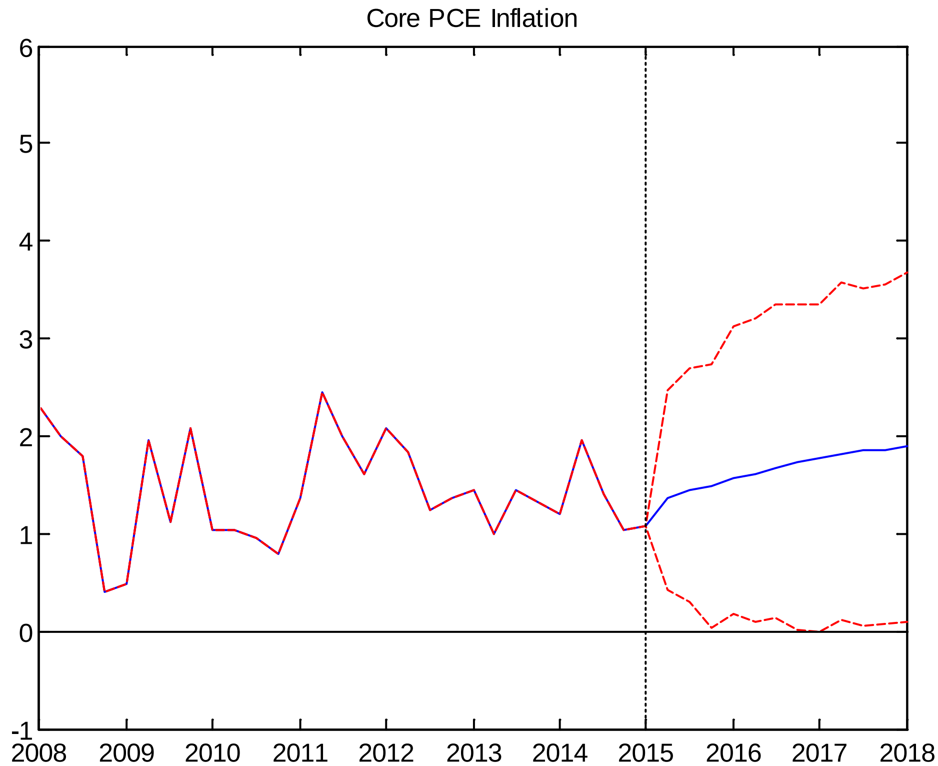

Core PCE Inflation
6
5
4
3
2
1
0
-1
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018

Figure 1c

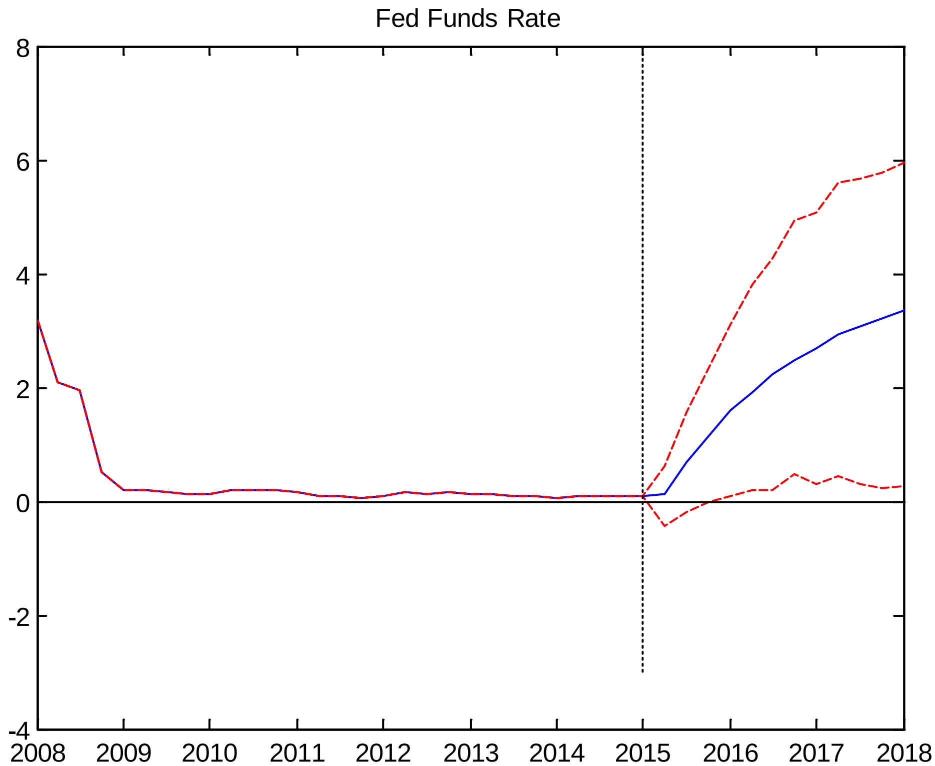
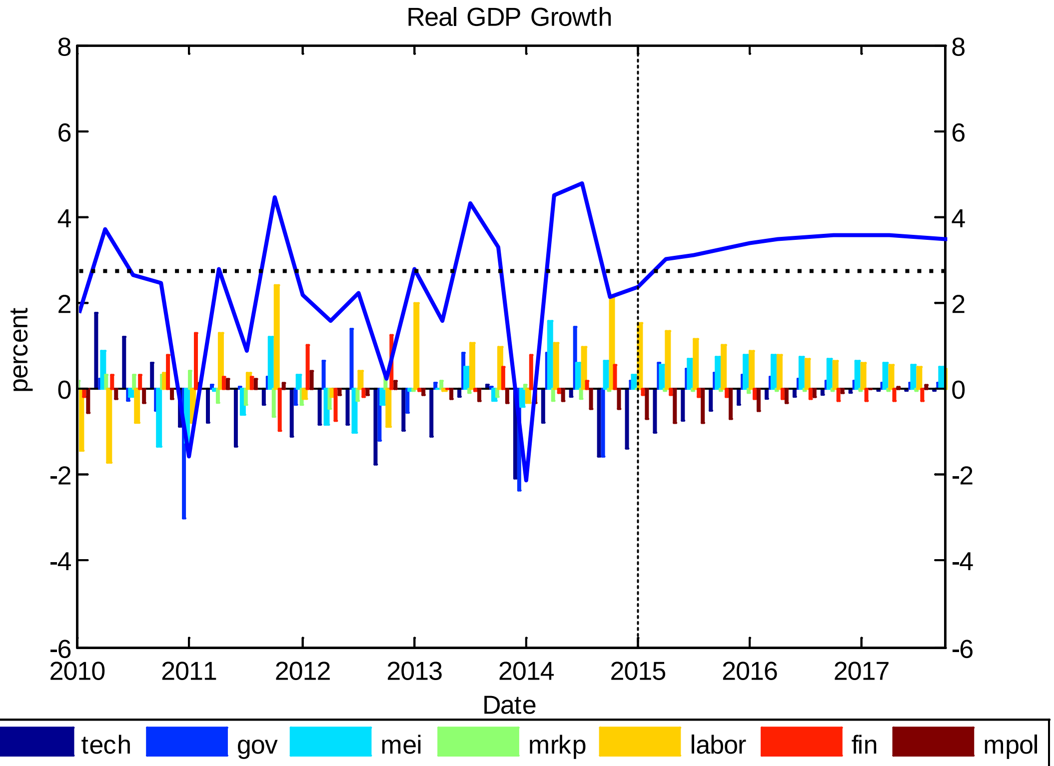

Fed Funds Rate
8
6
4
2
0
-2
-4
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018

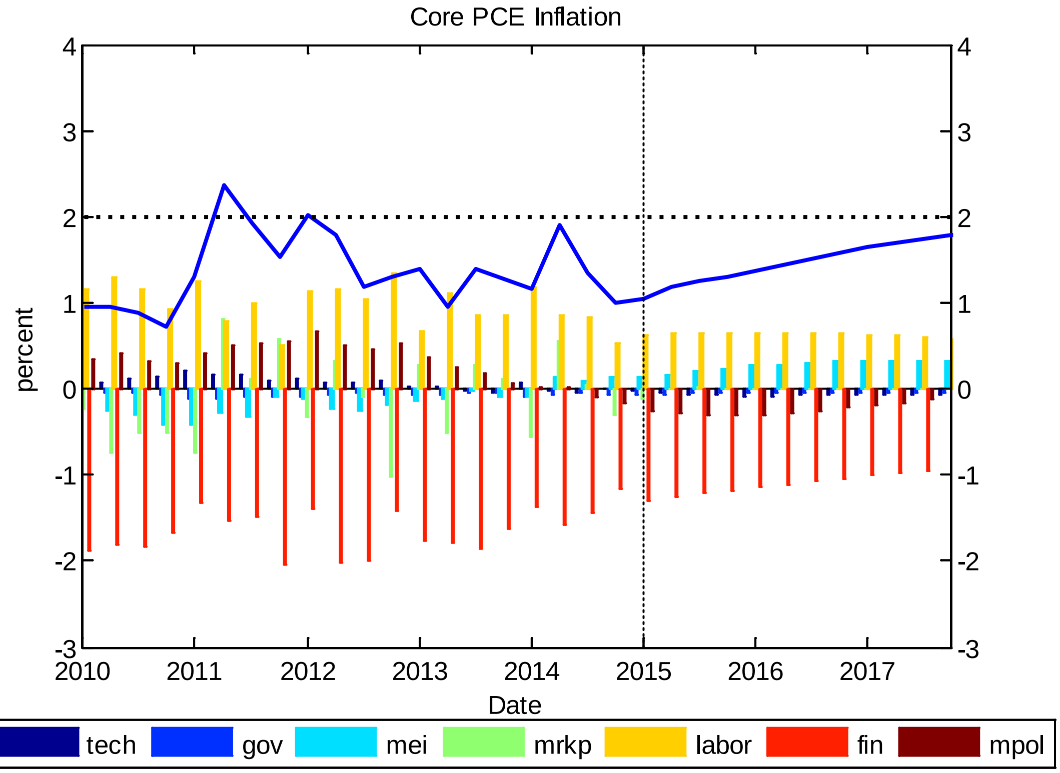
Figure 2a
Conditional Forecast



shocks:

TFP:	Total factor productivity growth shock
Gov:	Government spending shock
MEI:	Marginal efficiency of investment shock
MrkUp:	Price markup shock
Labor:	Labor supply shock
Fin:	Discount factor shock
Mpol:	Monetary policy shock

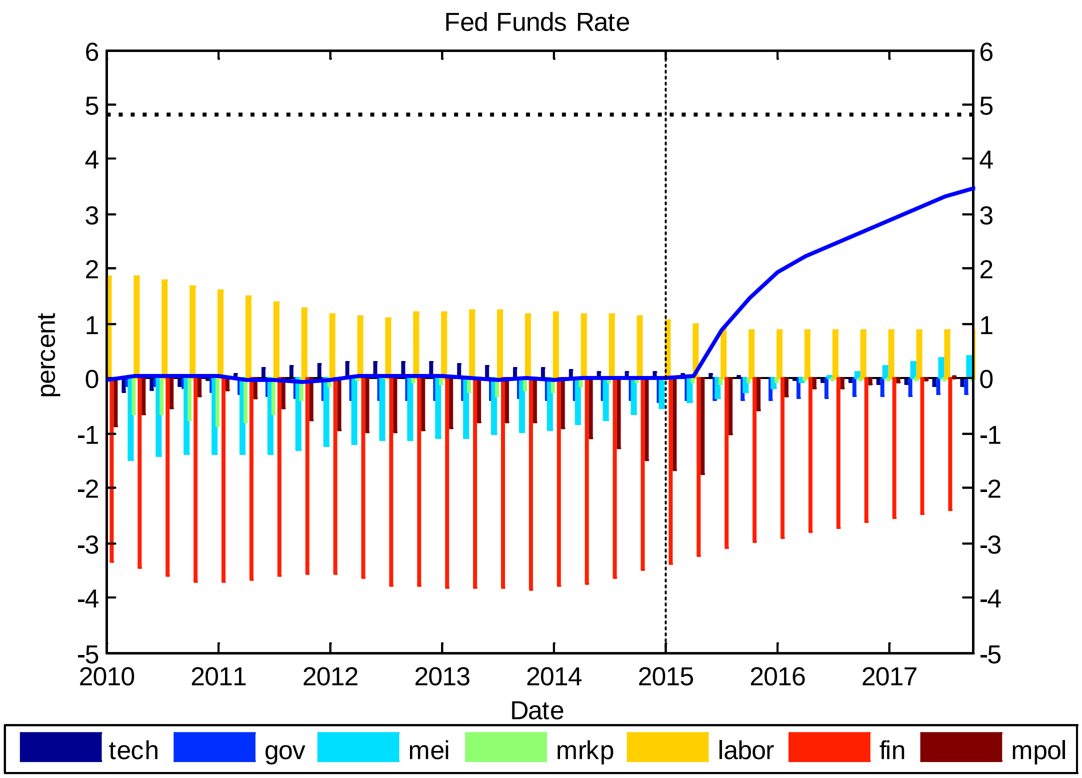
Figure 2b
Conditional Forecast



shocks:

TFP:	Total factor productivity growth shock
Gov:	Government spending shock
MEI:	Marginal efficiency of investment shock
MrkUp:	Price markup shock
Labor:	Labor supply shock
Fin:	Discount factor shock
Mpol:	Monetary policy shock

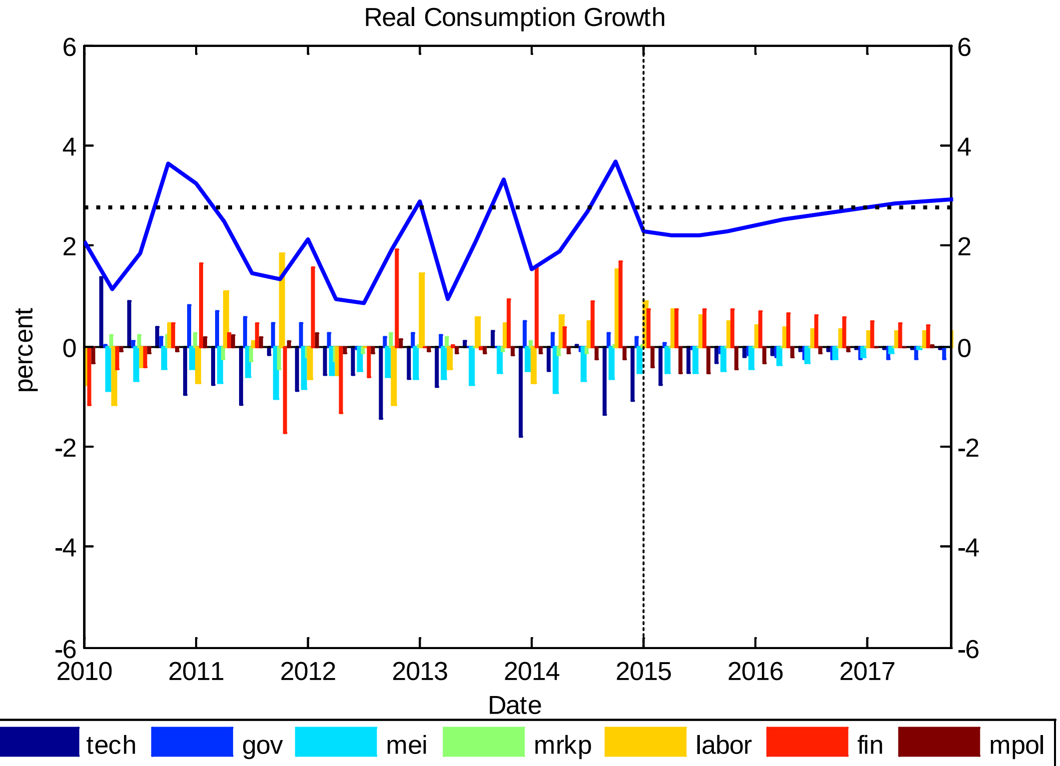
Figure 2c
Conditional Forecast



shocks:

TFP:	Total factor productivity growth shock
Gov:	Government spending shock
MEI:	Marginal efficiency of investment shock
MrkUp:	Price markup shock
Labor:	Labor supply shock
Fin:	Discount factor shock
Mpol:	Monetary policy shock

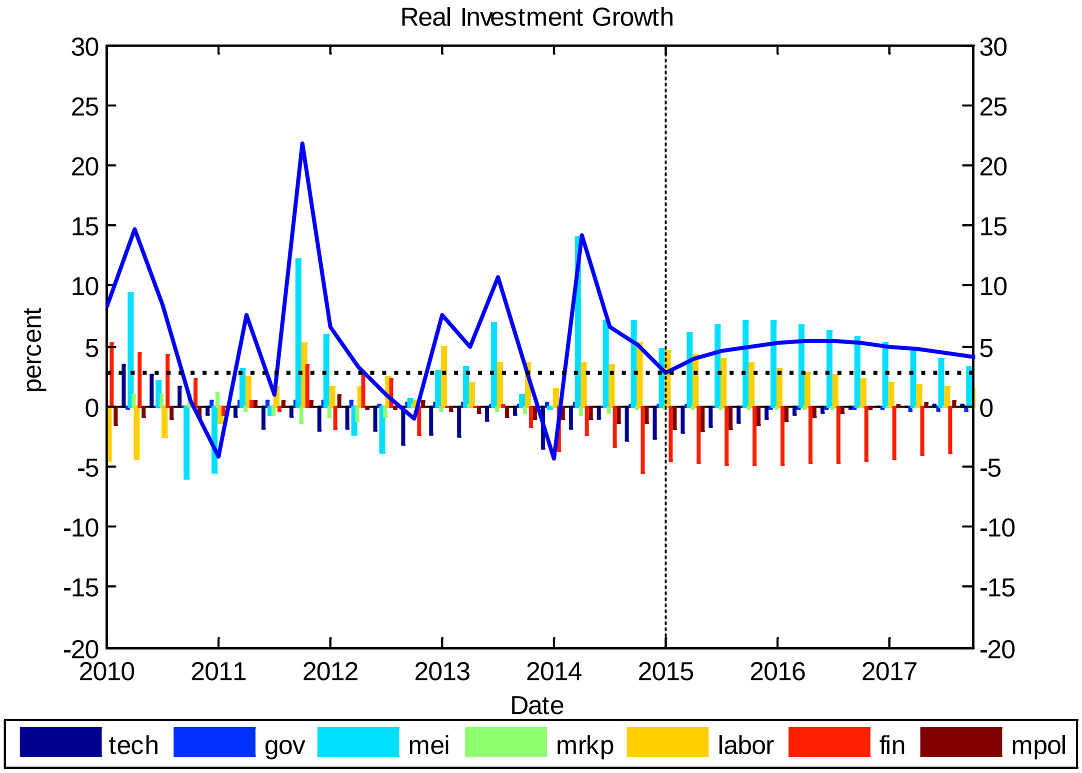
Figure 2d
Conditional Forecast



shocks:

TFP:	Total factor productivity growth shock
Gov:	Government spending shock
MEI:	Marginal efficiency of investment shock
MrkUp:	Price markup shock
Labor:	Labor supply shock
Fin:	Discount factor shock
Mpol:	Monetary policy shock

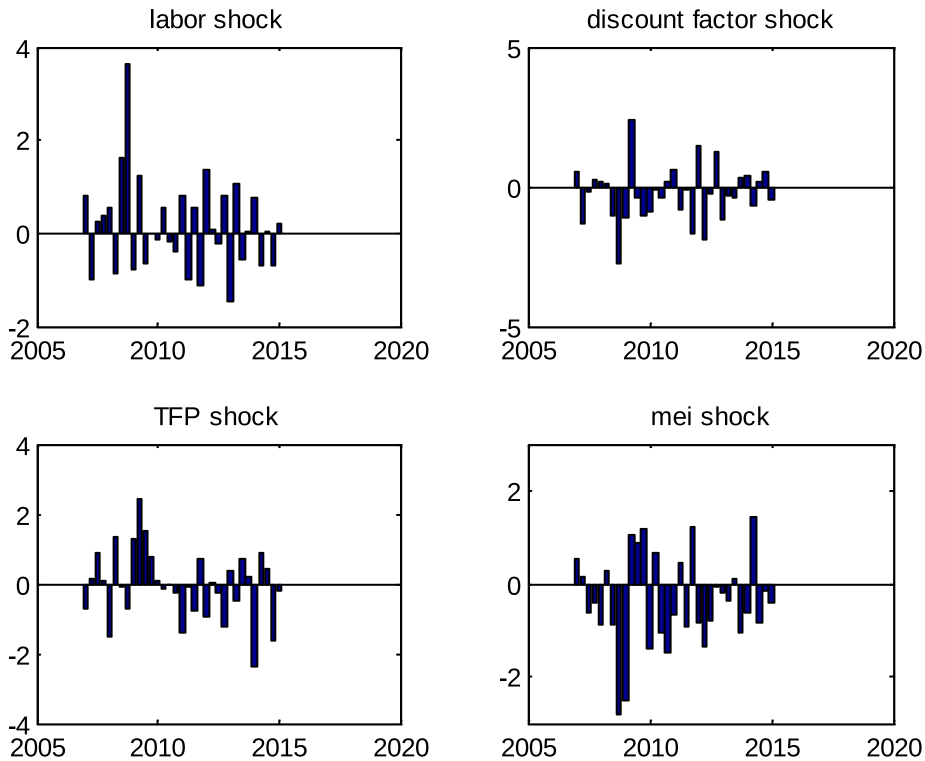
Figure 2e
Conditional Forecast



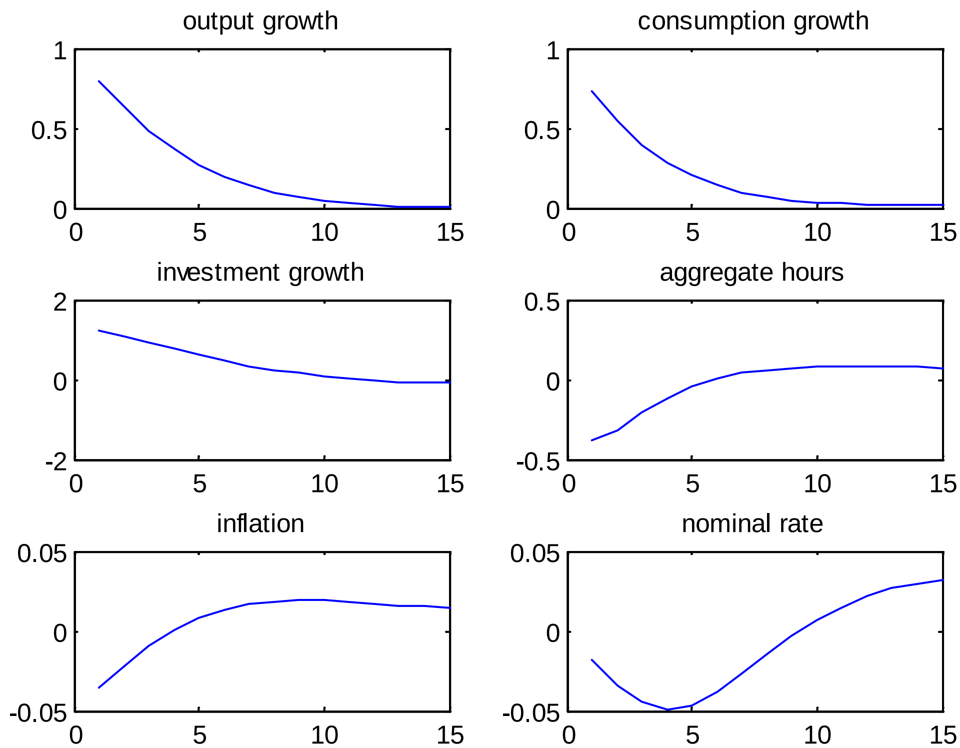
shocks:

TFP:	Total factor productivity growth shock
Gov:	Government spending shock
MEI:	Marginal efficiency of investment shock
MrkUp:	Price markup shock
Labor:	Labor supply shock
Fin:	Discount factor shock
Mpol:	Monetary policy shock

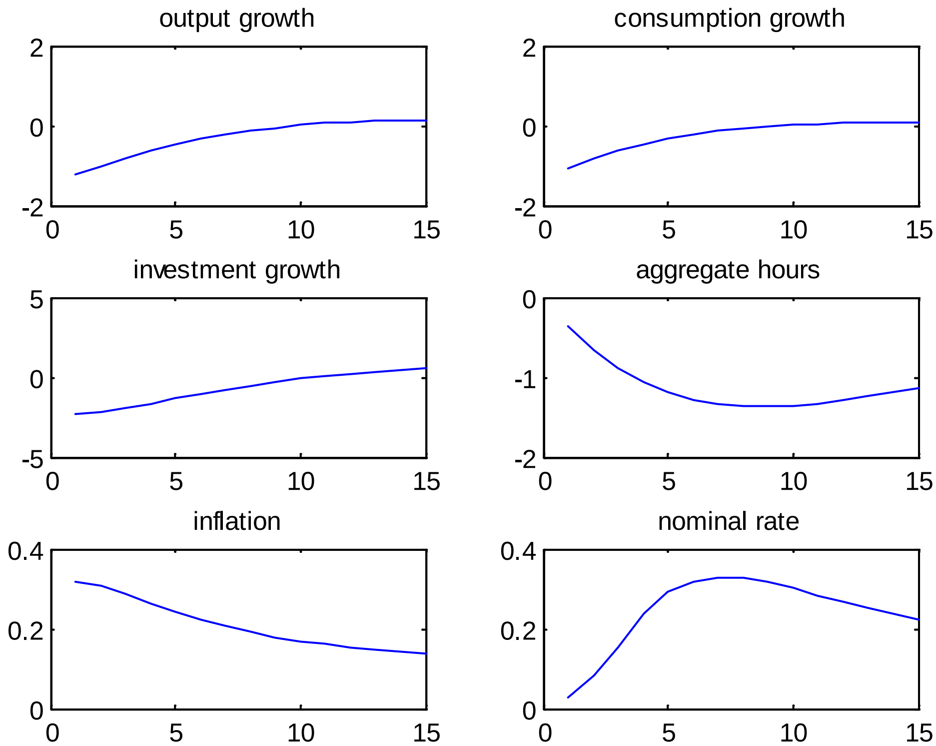
Figure 3
Smoothed Shock Estimates for Conditional Forecast Model
(normalized by standard deviation)



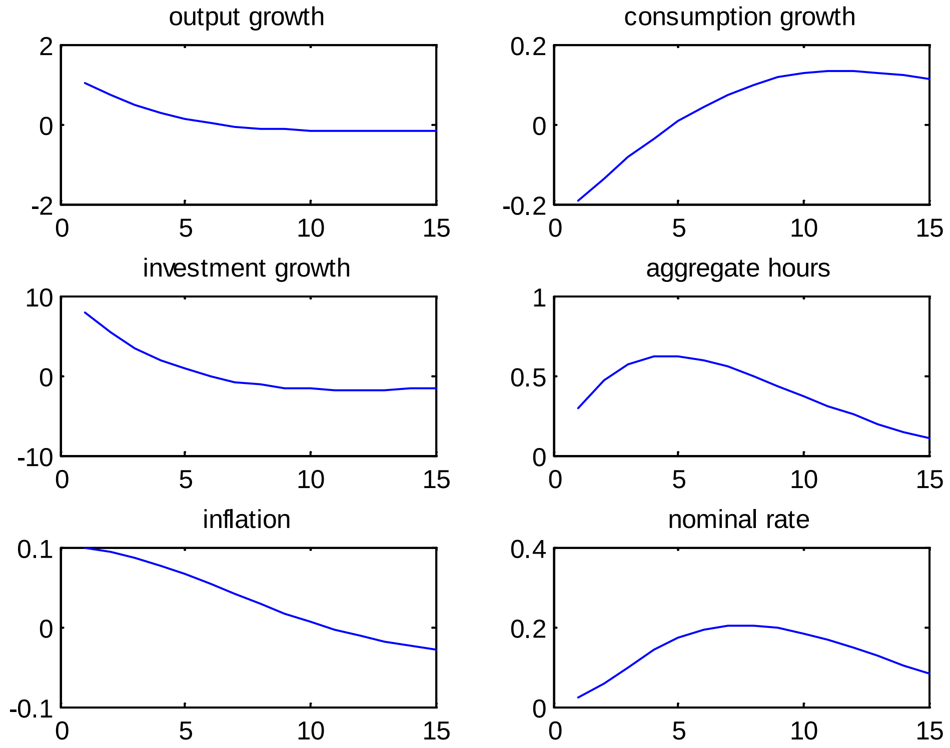
Impulse Responses to TFP shock



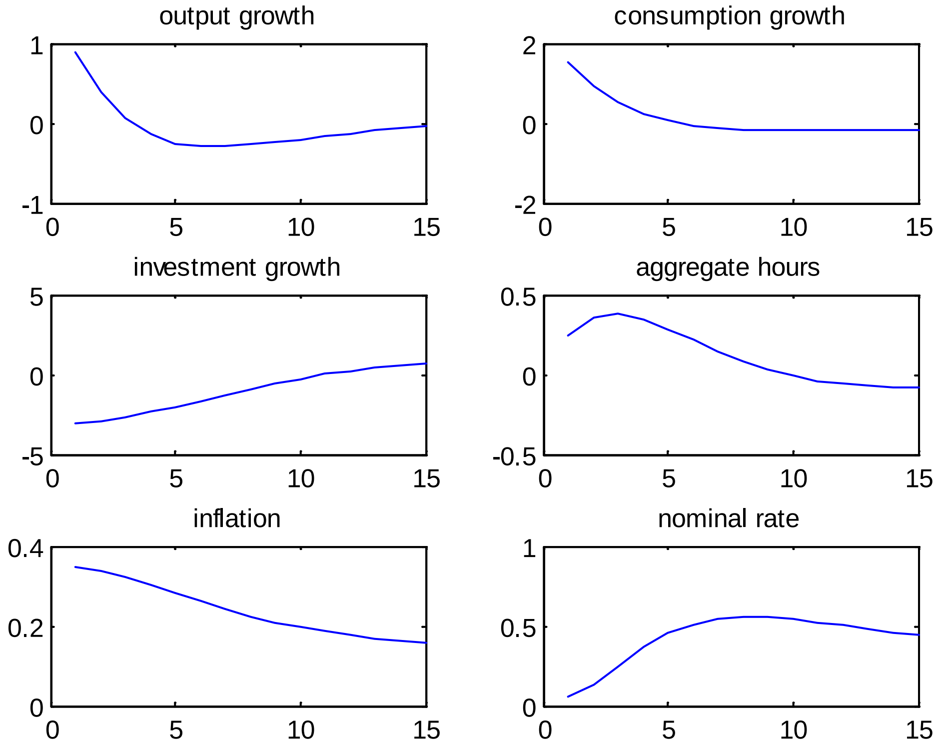
Impulse Response to Leisure Shock



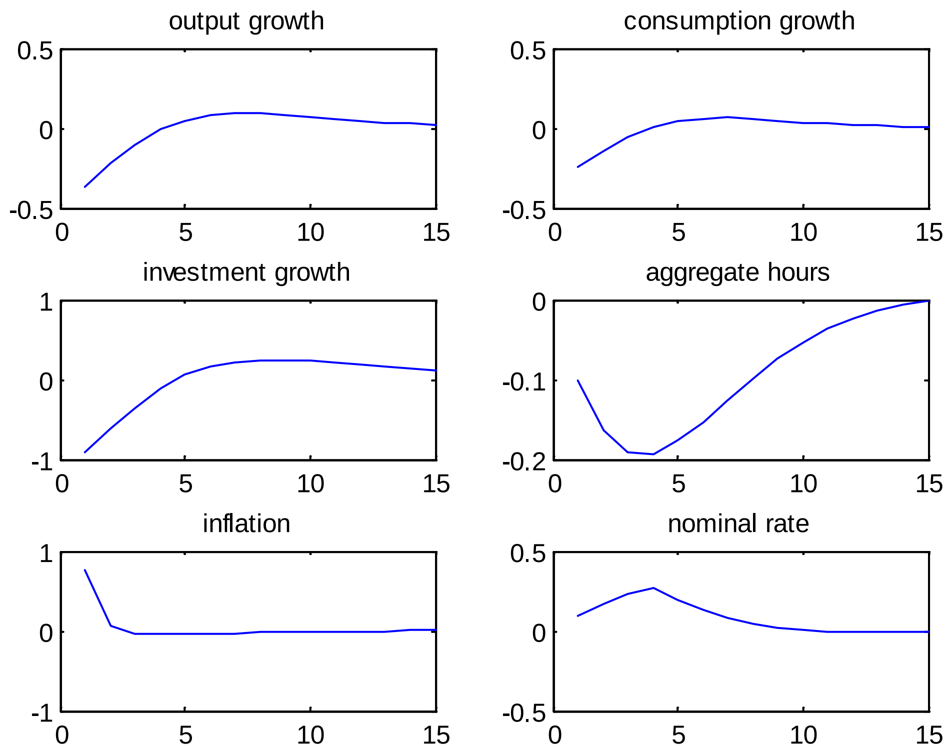
Impulse Responses to MEI Shock



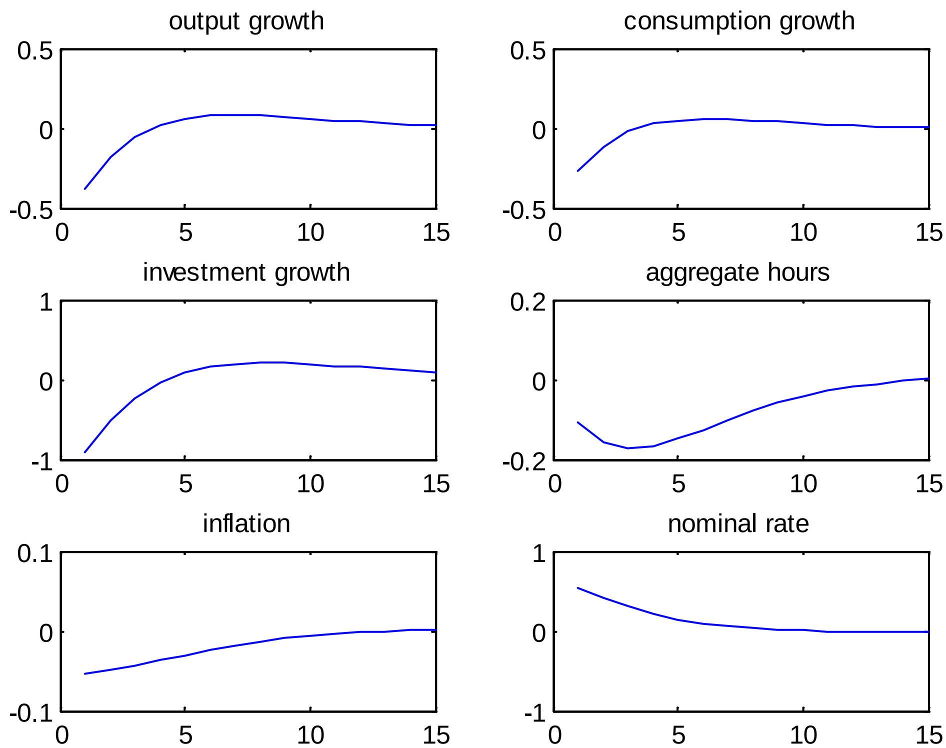
Impulse Responses to Financial Shock



Impulse Responses to Price Markup Shock



Impulse Responses to Unanticipated Monetary Policy Shock



Impulse Responses to Govt Spending Shock