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Investment Shocks and Business Cycles

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ABSTRACT. Shocks to the marginal efficiency of investment are the most important drivers of business cycle fluctuations in US output and hours. Moreover, these disturbances drive prices higher in expansions, like a textbook demand shock. We reach these conclusions by estimating a DSGE model with several shocks and frictions. We also find that neutral technology shocks are not negligible, but their share in the variance of output is only around 25 percent, and even lower for hours. Labor supply shocks explain a large fraction of the variation of hours at very low frequencies, but not over the business cycle. Finally, we show that imperfect competition and, to a lesser extent, technological frictions are the key to the transmission of investment shocks in the model.

1. INTRODUCTION

What is the source of economic fluctuations? This is one of the defining questions of modern dynamic macroeconomics, at least since Sims (1980) and Kydland and Prescott (1982). Yet, the literature is far from a consensus on the answer. On the one hand, the work that approaches this question from the perspective of general equilibrium models tends to attribute a dominant role in business cycles to neutral technology shocks (see King and Rebelo (1999) for a comprehensive assessment). On the other hand, the structural VAR literature usually points to other disturbances as the main sources of business cycles, and rarely finds that technology shocks explain more than one quarter of output fluctuations (Shapiro and Watson (1988), King, Plosser, Stock, and Watson (1991), Cochrane (1994), Gali (1999), Christiano, Eichenbaum, and Vigfusson (2004) and Fisher (2006)).

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This paper confirms the SVAR evidence, but it does so from the perspective of a fully articulated dynamic stochastic general equilibrium (DSGE) model. Our main finding is that shocks to the marginal efficiency of investment are the key drivers of macroeconomic fluctuations. These shocks affect the yield of a foregone unit of consumption in terms of tomorrow's capital input. The literature often refers to them as investment specific technology shocks, since they are equivalent to productivity shocks specific to the capital goods producing sector in a simple two-sector economy (Greenwood, Hercowitz, and Krusell (1997)). For simplicity, we call them *investment shocks*.

Our findings are based on the Bayesian estimation of a New Neoclassical Synthesis model of the US economy (Goodfriend and King (1997)). The model includes a rich set of nominal and real frictions, along the lines of Christiano, Eichenbaum, and Evans (2005), and is buffeted by several shocks, as in Smets and Wouters (2007). Among them, a shock to total factor productivity, or neutral technology shock, as in the RBC literature, an investment shock, as in Greenwood, Hercowitz, and Huffman (1988) and Greenwood, Hercowitz, and Krusell (2000), and a shock to labor supply, as in Hall (1997).

According to our estimates, *investment shocks* account for between 50 and 60 percent of the variance of output and hours at business cycle frequencies and for more than 80 percent of that of investment. The contribution of the *neutral technology shock* is also non-negligible. It explains about a quarter of the movements in output and consumption, although only about 10 percent of those in hours. Moreover, this shock generates comovement between consumption and output, a feature of business cycles that the investment shock has some trouble replicating.

In this respect, the investment and neutral technology shocks play a complementary role in our model. The former is mainly responsible for generating the overall volatility and comovement of output, investment and hours, while the latter contributes a significant share of the comovement between output and consumption. Another aspect of this complementarity is that the two disturbances can be characterized as an aggregate demand and aggregate supply shock respectively. In fact, investment shocks generate a positive comovement between prices and quantities, while technology shocks move the two in opposite directions.

As for the labor supply shock, we show that it is the dominant source of fluctuations in hours at very low frequencies, but not over the business cycle. This is a key contribution of this paper, especially in light of the emphasis placed by the literature on the role of this

shock in business cycles (see, for example, Hall (1997) and Smets and Wouters (2007)). This role has also been interpreted as a weakness of estimated DSGE models (Chari, Kehoe, and McGrattan (2008)).

Investment shocks are unlikely candidates to generate business cycles in standard neoclassical environments. In this framework, a positive shock to the marginal efficiency of investment increases the rate of return on capital, which induces households to consume less, but also to work harder. Moreover, with capital fixed in the short run, labor productivity falls and so does the competitive real wage. This is not a recognizable business cycle. In fact, in neoclassical models, only neutral technology shocks can easily generate the observed comovement among all these variables. This is because the equality of the marginal rate of substitution between consumption and leisure and the marginal product of labor imposes tight restrictions on the relative movements of consumption and hours, as first pointed out by Barro and King (1984).

Therefore, to give other shocks a fair chance to be plausible sources of fluctuations, our model adds to a neoclassical core a number of real and nominal frictions, such as habit formation in consumption, variable capital utilization, investment adjustment costs and imperfect competition with price stickiness in goods and labor markets. These frictions were originally proposed in the literature as a way to improve the empirical performance of monetary models (Christiano, Eichenbaum, and Evans (2005)). We show that they also play a crucial role in turning investment shocks into a viable source of business cycle fluctuations.

Among these frictions, we find that monopolistic competition with sticky prices and wages is the fundamental mechanism for the transmission of investment shocks. This friction breaks the intratemporal efficiency condition, by driving an endogenous wedge between the marginal product of labor and the marginal rate of substitution between leisure and consumption. As a result, the relative movements of consumption and hours are not as tightly linked as in a perfectly competitive economy. For example, in our estimated model price markups decrease in response to a positive investment shock, thus increasing labor demand at any given wage. As a result, consumption, hours, productivity and the competitive real wage can all be procyclical in response to investment shocks.

The prominent role of investment shocks in business cycles implied by our estimates is consistent with the SVAR evidence of Fisher (2006) and Canova, Lopez-Salido, and Michelacci (2006), and broadly in line with the general equilibrium analysis of Greenwood, Hercowitz, and Krusell (2000). Unlike these authors, however, we do not use direct observations on the relative price of investment as a measure of investment specific technological progress. Instead, we treat the investment shock as an unobservable process, and identify it through its dynamic effects on the variables included in the estimation, according to the restrictions implied by the DSGE model.¹ This empirical strategy might be better suited to capture sources of variation in the marginal efficiency of investment that are not fully reflected in the variability of the relative price of investment. This would be the case, for example, in an economy with sticky investment prices, or in which the process of capital accumulation were subject to more frictions than those we have modeled here, as in Bernanke, Gertler, and Gilchrist (1999) or Christiano, Motto, and Rostagno (2007).

This paper is also related to a recent literature on the estimation of medium scale DSGE models (Altig, Christiano, Eichenbaum, and Linde (2005), Del Negro, Schorfheide, Smets, and Wouters (2007), Gertler, Sala, and Trigari (2007), Justiniano and Primiceri (2007) and Smets and Wouters (2007)). We share with this literature the basic structure of the theoretical framework, but we differ from it in three important respects, which summarize our main contributions. First, we focus the analysis on the origins of business cycle fluctuations, which leads us to emphasize the key role of investment shocks. Second, we investigate how the departures of our model from the neoclassical benchmark contribute to this result. Finally, we de-emphasize the contribution of labor supply shocks, by demonstrating that they play a role only at very low frequencies, but not over the business cycle.

The rest of the paper is organized as follows. Section 2 provides the details of the theoretical model. Section 3 describes the approach to inference and discusses the fit of the estimated model. Sections 4 and 5 highlight the role of investment shocks in fluctuations and the effect of frictions on their transmission. Section 6 compares our results to those of Smets and Wouters (2007). Section 7 compares our estimates of the investment shock to the data on the relative price of investment. Section 8 conducts a series of robustness checks, including a detailed comparison with the results of Smets and Wouters (2007). Section 9 concludes.

¹ In this respect, our strategy is similar to that followed by Fisher (1997), who infers the properties of technological progress in the investment sector through a GMM strategy applied to macroeconomic quantities.

2. THE MODEL ECONOMY

This section outlines our baseline model of the U.S. business cycle. It is a medium scale DSGE model with a neoclassical growth core, which we augment with several departures from the standard assumptions on tastes, technology and market structure—“frictions” for short—now quite common in the literature. This is an ideal framework for the study of business cycles, for two reasons. First, the model fits the data well, as shown for example by Del Negro, Schorfheide, Smets, and Wouters (2007) and Smets and Wouters (2007). Second, it encompasses most of the views on the origins of business cycles proposed in the literature.

The model economy is populated by five classes of agents. Producers of a final good, which “assemble” a continuum of intermediate goods produced by monopolistic intermediate goods producers. Households, who consume the final good, accumulate capital, and supply differentiated labor services to competitive “employment agencies”. A Government. We present their optimization problems in turn.

2.1. Final goods producers. At every point in time t , perfectly competitive firms produce the final consumption good Y_t combining a continuum of intermediate goods $\{Y_t(i)\}_i$, $i \in [0, 1]$, according to the technology

$$Y_t = \left[\int_0^1 Y_t(i)^{\frac{1}{1+\lambda_{p,t}}} di \right]^{1+\lambda_{p,t}}.$$

We assume that $\lambda_{p,t}$ follows the exogenous stochastic process

$$\log \lambda_{p,t} = (1 - \rho_p) \log \lambda_p + \rho_p \log \lambda_{p,t-1} + \varepsilon_{p,t} - \theta_p \varepsilon_{p,t-1},$$

where $\varepsilon_{p,t}$ is *i.i.d.* $N(0, \sigma_p^2)$. We refer to this as a *price markup shock*, since $\lambda_{p,t}$ is the desired markup of price over marginal cost for intermediate firms. As in Smets and Wouters (2007), the ARMA(1,1) structure for the desired markup helps capture the moving average, high frequency component of inflation.

Profit maximization and the zero profit condition imply that the price of the final good, P_t , is a CES aggregate of the prices of the intermediate goods, $\{P_t(i)\}_i$

$$P_t = \left[\int_0^1 P_t(i)^{\frac{1}{\lambda_{p,t}}} di \right]^{\lambda_{p,t}},$$

and that the demand function for the intermediate good i is

$$(2.1) \quad Y_t(i) = \left(\frac{P_t(i)}{P_t} \right)^{-\frac{1+\lambda_{p,t}}{\lambda_{p,t}}} Y_t.$$

2.2. Intermediate goods producers. A monopolist produces the intermediate good i according to the production function

$$(2.2) \quad Y_t(i) = \max \{ A_t^{1-\alpha} K_t(i)^\alpha L_t(i)^{1-\alpha} - A_t F; 0 \},$$

where $K_t(i)$ and $L_t(i)$ denote the amounts of capital and labor employed by firm i . F is a fixed cost of production, which we choose so that profits are zero in steady state (see Rotemberg and Woodford (1995) and Christiano, Eichenbaum, and Evans (2005)). A_t represents exogenous labor-augmenting technological progress. Its growth rate ($z_t \equiv \Delta \log A_t$) follows a stationary AR(1) process

$$z_t = (1 - \rho_z)\gamma + \rho_z z_{t-1} + \varepsilon_{z,t},$$

with $\varepsilon_{z,t} \text{ i.i.d. } N(0, \sigma_z^2)$, which implies that the level of technology is non stationary. This is our *neutral technology shock*.

As in Calvo (1983), every period a fraction ξ_p of intermediate firms cannot optimally choose its price, but reset it according to the indexation rule

$$P_t(i) = P_{t-1}(i) \pi_{t-1}^{\iota_p} \pi^{1-\iota_p},$$

where $\pi_t \equiv \frac{P_t}{P_{t-1}}$ is gross inflation and π is its steady state. The remaining fraction of firms, instead, choose their price, $\tilde{P}_t(i)$, by maximizing the present discounted value of future profits

$$E_t \sum_{s=0}^{\infty} \xi_p^s \beta^s \lambda_{t+s} \left\{ \left[\tilde{P}_t(i) \left(\prod_{j=0}^s \pi_{t-1+j}^{\iota_p} \pi^{1-\iota_p} \right) \right] Y_{t+s}(i) - \left[W_t L_t(i) + r_t^k K_t(i) \right] \right\},$$

subject to the demand function 2.1 and the production function 2.2. In this objective, λ_{t+s} is the marginal utility of consumption of the representative households that owns the firm, while W_t and r_t^k are the nominal wage and the rental rate of capital.

2.3. Employment agencies. Firms are owned by a continuum of households, indexed by $j \in [0, 1]$. Each household is a monopolistic supplier of specialized labor, $L_t(j)$, as in Erceg, Henderson, and Levin (2000). A large number of competitive “employment agencies” combines this specialized labor into a homogenous labor input sold to intermediate firms, according to

$$L_t = \left[\int_0^1 L_t(j)^{\frac{1}{1+\lambda_{w,t}}} dj \right]^{1+\lambda_{w,t}}.$$

As in the case of the final good, the desired markup of the wage over the household's marginal rate of substitution, $\lambda_{w,t}$, follows the exogenous stochastic process

$$\log \lambda_{w,t} = (1 - \rho_w) \log \lambda_w + \rho_w \log \lambda_{w,t-1} + \varepsilon_{w,t} - \theta_w \varepsilon_{w,t-1},$$

where $\varepsilon_{w,t}$ is *i.i.d.* $N(0, \sigma_w^2)$. This is the wage markup shock. We also refer to it as a *labor supply shock*, since it has the same effect on the household's first order condition for the choice of hours as the preference shock analyzed by Hall (1997).

Profit maximization by the perfectly competitive employment agencies implies the labor demand function

$$L_t(j) = \left(\frac{W_t(j)}{W_t} \right)^{-\frac{1+\lambda_{w,t}}{\lambda_{w,t}}} L_t,$$

where $W_t(j)$ is the wage received from employment agencies by the supplier of labor of type j , while the wage paid by intermediate firms for their homogenous labor input is

$$W_t = \left[\int_0^1 W_t(j)^{\frac{1}{\lambda_{w,t}}} dj \right]^{\lambda_{w,t}}.$$

2.4. Households. Each household maximizes the utility function

$$E_t \sum_{s=0}^{\infty} \beta^s b_{t+s} \left[\log (C_{t+s} - h C_{t+s-1}) - \varphi \frac{L_{t+s}(j)^{1+\nu}}{1+\nu} \right],$$

where C_t is consumption, h is the degree of habit formation and b_t is a shock to the discount factor, which affects both the marginal utility of consumption and the marginal disutility of labor. This *intertemporal preference shock* follows the stochastic process

$$\log b_t = \rho_b \log b_{t-1} + \varepsilon_{b,t},$$

with $\varepsilon_{b,t} \sim i.i.d. N(0, \sigma_b^2)$. Since technological progress is non stationary, we work with log utility to ensure the existence of a balanced growth path. Moreover, consumption is not indexed by j because the existence of state contingent securities ensures that in equilibrium consumption and asset holdings are the same for all households.

As a result, the household's budget constraint is

$$P_t C_t + P_t I_t + T_t + B_t \leq R_{t-1} B_{t-1} + Q_{t-1}(j) + \Pi_t + W_t(j) L_t(j) + r_t^k u_t \bar{K}_{t-1} - P_t a(u_t) \bar{K}_{t-1},$$

where I_t is investment, T_t are lump-sum taxes, B_t is holdings of government bonds, R_t is the gross nominal interest rate, $Q_t(j)$ is the net cash flow from household's j portfolio of state contingent securities, and Π_t is the per-capita profit accruing to households from ownership of the firms.

Households own capital and choose the capital utilization rate, u_t , which transforms physical capital into effective capital according to

$$K_t = u_t \bar{K}_{t-1}.$$

Effective capital is then rented to firms at the rate r_t^k . The cost of capital utilization is $a(u_t)$ per unit of physical capital. We assume $u_t = 1$ in steady state, $a(1) = 0$ and define $\chi \equiv \frac{a''(1)}{a'(1)}$. In our log-linear approximation of the model solution this curvature is the only parameter that matters for the dynamics.

The physical capital accumulation equation is

$$\bar{K}_t = (1 - \delta)\bar{K}_{t-1} + \mu_t \left(1 - S \left(\frac{I_t}{I_{t-1}} \right) \right) I_t,$$

where δ is the depreciation rate. The function S captures the presence of adjustment costs in investment, as in Christiano, Eichenbaum, and Evans (2005). We assume that, in steady state, $S = S' = 0$ and $S'' > 0$.²

The *investment shock* μ_t is a source of exogenous variation in the efficiency with which the final good can be transformed into physical capital, and thus into tomorrow's capital input. As shown by Greenwood, Hercowitz, and Krusell (1997), μ_t is also equivalent to a form of technological progress confined to the production of investment goods in a simple two-sector representation of our economy. We assume that it follows the stochastic process

$$\log \mu_t = \rho_\mu \log \mu_{t-1} + \varepsilon_{\mu,t},$$

where $\varepsilon_{\mu,t}$ is *i.i.d.* $N(0, \sigma_\mu^2)$.

In terms of wage setting, we follow Erceg, Henderson, and Levin (2000) and assume that every period a fraction ξ_w of households cannot freely set their wage, but sets them according to the indexation rule

$$W_t(j) = W_{t-1}(j) (\pi_{t-1} e^{z_{t-1}})^{\iota_w} (\pi e^\gamma)^{1-\iota_w}.$$

The remaining fraction of households chooses instead an optimal wage by maximizing

$$E_t \sum_{s=0}^{\infty} \xi_w^s \beta^s b_{t+s} \left\{ -\varphi \frac{L_{t+s}(j)^{1+\nu}}{1+\nu} \right\},$$

subject to the labor demand function.

² Lucca (2005) shows that this formulation of the adjustment cost function is equivalent (up to first order) to a generalization of the time to build assumption.

2.5. Government. A monetary policy authority sets the nominal interest rate following a Taylor-type rule of the form

$$\frac{R_t}{R} = \left(\frac{R_{t-1}}{R}\right)^{\rho_R} \left[\left(\frac{\pi_t}{\pi}\right)^{\phi_\pi} \left(\frac{Y_t}{Y_t^*}\right)^{\phi_Y}\right]^{1-\rho_R} \left[\frac{Y_t/Y_{t-1}}{Y_t^*/Y_{t-1}^*}\right]^{\phi_{dY}} \eta_{mp,t},$$

where R is the steady state of the gross nominal interest rate. As in Smets and Wouters (2007), interest rates responds to deviations of inflation from its steady state, as well as to the level and the growth rate of the output gap (Y_t/Y_t^*).³ The monetary policy rule is also perturbed by a *monetary policy shock*, $\eta_{mp,t}$, which evolves according to

$$\log \eta_{mp,t} = \rho_{mp} \log \eta_{mp,t-1} + \varepsilon_{mp,t},$$

where $\varepsilon_{mp,t}$ is *i.i.d.* $N(0, \sigma_{mp}^2)$.

Fiscal policy is fully Ricardian. The Government finances its budget deficit by issuing short term bonds. Public spending is determined exogenously as a time-varying fraction of GDP

$$G_t = \left(1 - \frac{1}{g_t}\right) Y_t,$$

where the *government spending shock* g_t follows the stochastic process

$$\log g_t = (1 - \rho_g) \log g + \rho_g \log g_{t-1} + \varepsilon_{g,t},$$

with $\varepsilon_{g,t} \sim i.i.d. N(0, \sigma_g^2)$.

2.6. Market clearing. The aggregate resource constraint,

$$C_t + I_t + G_t + a(u_t) \bar{K}_{t-1} = Y_t,$$

can be derived by combining the Government and the households' budget constraints with the zero profit condition of the final goods producers and the employment agencies.

2.7. Model solution. In this model, consumption, investment, capital, real wages and output fluctuate around a stochastic balanced growth path, since the level of technology A_t has a unit root. Therefore, the solution involves the following steps. First, we rewrite the model in terms of detrended variables. We then compute the non-stochastic steady state of the transformed model, and log-linearly approximate it around this steady state. Finally, we solve the resulting linear system of rational expectation equations to obtain its state space

³ The output gap is defined as the difference between actual output and the efficient level of output (Woodford (2003)).

representation. This forms the basis for our estimation procedure, which is discussed in the next section.

3. BAYESIAN INFERENCE

3.1. Data and priors. We estimate the model using the following vector of observable variables

$$(3.1) \quad [\Delta \log Y_t, \Delta \log C_t, \Delta \log I_t, \log L_t, \Delta \log \frac{W_t}{P_t}, \pi_t, R_t],$$

where Δ denotes the temporal difference operator. The data is quarterly and spans the period from 1954QIII to 2004QIV. A precise description of the data series used in the estimation can be found in appendix A.

We use Bayesian methods to characterize the posterior distribution of the structural parameters of the model (see An and Schorfheide (2007) for a survey). The posterior distribution combines the likelihood function with prior information.⁴ In the rest of this section we briefly discuss the specification of the priors.

We fix a small number of parameters to values commonly used in the literature. In particular, we set the quarterly depreciation rate of capital (δ) to 0.025 and the steady state government spending to GDP ratio ($1 - 1/g$) to 0.22, which corresponds to the average value of G_t/Y_t in our sample. Table 1 reports the priors for the remaining parameters of the model. Although these priors are relatively diffuse and broadly in line with those adopted in previous studies (Del Negro, Schorfheide, Smets, and Wouters (2007), Levin, Onatski, Williams, and Williams (2005)), some of them deserve a brief discussion.

For all but two persistence parameters we use a Beta prior, with mean 0.6 and standard deviation 0.2. One of the two exceptions is neutral technology, which already includes a unit root. For this reason, the prior for the autocorrelation of its growth rate (ρ_z) is centered at 0.4 instead. We use 0.4 also to center the prior for the persistence of the monetary policy shocks, because the policy rule already allows for interest rates inertia.

The intertemporal preference, price and wage markup shocks are normalized to enter with a unit coefficient in the consumption, price inflation and wage equations respectively (see Smets and Wouters (2007) and appendix B). The priors on the innovations' standard deviations

⁴ In section 8 we show that results are robust to estimating the model by maximum likelihood (i.e. with flat priors).

are quite disperse and chosen in order to generate volatilities for the endogenous variables broadly in line with the data. The covariance matrix of the innovations is assumed diagonal.

To evaluate jointly the economic content of the priors on the exogenous processes and the structural parameters, we analyze their implications for the variance decomposition of the observable variables. This analysis is more useful than a series of comments on the priors for specific coefficients, especially given that the focus of the paper is on the sources of fluctuations. Turning to table 2, we see that our priors reflect a view of business cycles in line with the RBC tradition. The variability of output, consumption, investment and hours is due for the most part to neutral technology shocks, while the role of investment shocks is negligible.

3.2. Parameter estimates. In table 1, we report the estimates of the model's parameters. We present posterior medians, standard deviations and 90 percent probability intervals. In line with previous studies, we estimate a substantial degree of price and wage stickiness, habit formation in consumption and adjustment costs in investment (see for example Altig, Christiano, Eichenbaum, and Linde (2005), Del Negro, Schorfheide, Smets, and Wouters (2007) and Smets and Wouters (2007)). Capital utilization is not very elastic, as also found by Del Negro, Schorfheide, Smets, and Wouters (2007). In response to a 1 percent positive change in the rental rate of capital, utilization increases by slightly less than 0.2 percent.

Our estimates of the income share of capital (α) and of the Frisch elasticity of labor supply ($1/\nu$) are both lower than the values typically adopted in the RBC literature, but close to those of Smets and Wouters (2007). In any case, none of our results depend crucially on these estimates of α and ν , as we show in section 8.

3.3. Model fit. Given our posterior estimates, how well does the model fit the data? We address this question by comparing a set of statistics implied by the model to those measured in the data. In particular, we study the standard deviation and the complete correlation structure of the observable variables included in the estimation.

Table 3 reports the standard deviation of our seven observable variables, in absolute terms as well as relative to that of output growth. For the model, we report the median and the 90 percent probability intervals that account for both parameter uncertainty and small sample uncertainty. The model overpredicts the volatility of output growth, consumption and investment, but it matches their relative standard deviations fairly well. The match with

hours is close in both cases. There is also a tendency to underpredict the volatility of nominal interest rates and inflation, which might be due to the fact that the model does not replicate the very high correlation between these two variables.

With as many shocks as observable variables, why does the model not capture their standard deviation perfectly? The reason is that a likelihood-based estimator tries to match the entire autocovariance function of the data, and thus must strike a balance between matching standard deviations and all the other second moments, namely autocorrelations and cross-correlations. These other moments are displayed in figure 1, for the data (grey line) and the model (black line), along with the 90 percent posterior intervals for the model implied by parameter uncertainty and small sample uncertainty.

Focus first on the upper-left 4-by-4 block of graphs, which includes all the quantities in the model. On the diagonal, we see that the model captures the decaying autocorrelation structure of these four variables very well. The success is particularly impressive for hours, for which the model-implied and data autocorrelations lay virtually on top of each other. In terms of cross-correlations, the model does extremely well for output (the first row and column) and for hours (the fourth row and column), but fails to capture the contemporaneous correlation between consumption and investment growth. This correlation is slightly positive in the data, but essentially zero in the model.

In sum, relative to smaller scale RBC models (Cooley and Prescott (1995), King and Rebelo (1999)), we do slightly worse in matching the properties of consumption, especially its correlation with investment. However, our model performs considerably better in terms of hours worked. This is an important result, because one of our main objectives is to investigate the sources of fluctuations in hours.

With respect to prices, the model is overall quite successful in reproducing the main stylized facts. We emphasize two issues: first, the model does not capture the full extent of the persistence of inflation and the nominal interest rate, even in the presence of inflation indexation and of a fairly high smoothing parameter in the interest rate rule. Second, we match very closely the correlation between output and inflation, which is highlighted for example by Smets and Wouters (2007) as an important measure of a model's empirical success.

4. SHOCKS AND BUSINESS CYCLES

In this section, we present the central result of the paper: investment shocks are the most important source of business cycle fluctuations. First, we document this finding quantitatively, by looking at the variance decomposition implied by the estimated model. We focus in particular on output and hours. Second, we provide some intuition for the result by studying the impulse responses of some key variables to the main shocks in the model. This exercise also allows us to informally discuss how those shocks are identified by our empirical procedure.

4.1. Variance decomposition. Table 4 reports the contribution of each shock to the unconditional variance of the *observable* variables included in the estimation. From the first row of the table, we see that investment shocks account for more than 50 percent of the fluctuations in the growth rate of output, by far the largest share. Figure 2 provides a time series decomposition of this contribution to overall variance by plotting year-to-year GDP growth in the data (the grey line) and in the model, conditional on the estimated sequence of the investment shocks alone (the black line). The comovement between the two series is striking. In particular, investment shocks appear largely responsible for “dragging” GDP growth down at business cycle troughs. This is especially evident for the last two downturns, as well as for the recessions of the sixties. The main exceptions are the “twin” recessions of the early eighties, in which in fact monetary factors are widely believed to have played a fundamental role.

Looking at the other shocks and variables in table 4, two results stand out. First, the neutral technology shock remains fairly important in our estimates. It explains around one quarter of the volatility of output, consumption and real wages. Second, the wage markup shock, which in this model is indistinguishable from Hall’s (1997) labor supply shock, plays a prominent role in the fluctuations of wages, inflation and especially hours. It accounts for between one half and two thirds of their volatility.

The variance decomposition of hours in table 4 is puzzling. The investment shock explains only 20 percent of the volatility of hours, less than half its contribution to output. Yet, the close comovement of hours and output is perhaps the most notable feature of business cycles. Table 5 sheds some light on this apparent contradiction, by focusing on fluctuations in the *level* of all variables at business cycle frequencies.⁵

⁵ We compute the spectral density of the observable variables implied by the DSGE model and transform it to obtain the spectrum of the level of output, consumption, investment and wages. We define business cycle

Over the business cycle, investment shocks explain approximately 60 percent of the fluctuations in hours, as well as 50 percent of those in output and more than 80 percent of those in investment. We conclude that investment shocks are the leading source of business cycles.

One qualification to this result comes from consumption. Investment shocks are responsible for only a small fraction of its variability, which is instead largely driven by the intertemporal preference shock. The fact that most movements in consumption come from an otherwise irrelevant shock is a symptom of the well-known failure of standard consumption Euler equations to capture the empirical relationship between consumption and interest rates, as argued in Primiceri, Schaumburg, and Tambalotti (2005).

Another interesting result emerging from the comparison of tables 4 and 5 is that the role of wage markup shocks virtually disappears when we restrict attention to business cycle frequencies. This is particularly noticeable for hours, with a drop in the share of variance attributed to wage markup shocks from 65 percent overall to only 6 percent at business cycle frequencies. Figure 3 clarifies this point by plotting the share of the variance of hours due to the wage markup shock, as a function of the spectrum frequencies. According to our definition, business cycles correspond to a frequency range between 0.19 and 1.05, which is highlighted by dotted vertical lines in the picture. The contribution of wage markup shocks is extremely significant at very low frequencies, but declines steeply as we move towards the business cycle range, in which it is mostly below 10%.

This result is roughly consistent with Hall's (1997) finding of an important role for labor supply shocks in the overall variability of hours, although his cyclical decomposition attributes a large role to those shocks also at business cycle frequencies, while ours does not. More recently, Hall (2008) shows that the role of labor supply shocks is significantly diminished in a model with countercyclical wage markups. As we will see in section 5, the countercyclicality of markups is also a key ingredient in our results.

4.2. Model dynamics and shock identification. Our results so far suggest that to understand business cycles, we must understand investment shocks, since these shocks are the largest contributors to fluctuations in several key macroeconomic variables. But what properties of these and the other shocks allow us to separately identify their contributions? This section provides some intuition for how this identification is achieved, by studying the impulse

fluctuations as those corresponding to periodic components with cycles between 6 and 32 quarters, as in Stock and Watson (1999).

responses of several key variables to some of the shocks. In particular, we focus on the three shocks that are responsible for the bulk of fluctuations according to our estimates. They are the investment shock, the neutral technology shock and the wage markup (or labor supply) shock.

Figure 4 reports the impulse responses to the investment shock. Following a positive impulse, output, hours, investment, real wages and labor productivity all rise persistently and in a hump-shaped pattern. The reaction in investment is contemporaneous and roughly proportional to that in output, but larger by a factor of almost five. This factor is close to the ratio of the unconditional volatilities of the two series.

The response of hours is very similar to that of output, in terms of dynamic profile and scale. This accounts for the very similar shares of business cycle fluctuations in output and hours explained by investment shocks, given that the cyclical components of the two series have very similar volatilities. The increase in hours is not associated with a drop in average labor productivity, as would be the case in a standard neoclassical model. The procyclicality of labor productivity in response to investment shocks is the combined result of the endogeneity of capital utilization (Greenwood, Hercowitz, and Huffman (1988)) and of the increasing returns implied by the presence of fixed costs in production.

Turning now to consumption, we see an initially flat response, followed by a rise after a few quarters. This failure of consumption to comove on impact with the other macroeconomic variables is the main reason why the investment shock accounts for less than 10 percent of the movements in consumption, and thus for a smaller share of the variance of output, compared to investment. Moreover, this lack of comovement, which is especially pronounced for the consumption-investment pair, given the strong procyclicality of the latter, explains why the model has some difficulty in capturing the correlation between these two variables, as we pointed out in section 3.3.

Finally, looking at inflation and the nominal interest rate, we see that they both rise in response to a positive investment shock. In this respect, the investment shock displays the typical features of a textbook “demand” shock: quantities and prices move in the same direction, leading to a tightening of monetary policy. In fact, the positive comovement of prices and quantities is one of the distinguishing characteristics of the investment shock, when compared to wage markup and neutral technology shocks, whose impulse responses are depicted in figures 5 and 6.

For example, an increase in the desired wage markup depresses all quantities, but leads to a fairly persistent increase in real wages and marginal costs. As a consequence, inflation rises, followed by the nominal interest rate. Moreover, the response in hours, and in all other quantities, is extremely persistent. This persistence is the source of the large contribution of the wage markup shock to the low frequency fluctuations in the labor input highlighted in the previous section.

Similarly, output, consumption and investment all rise in response to a positive neutral technology shock. Real wages are also procyclical, but their increase lags behind the rise in the marginal product of labor, so that marginal costs and therefore inflation fall. Most notably, hours also fall on impact, although they recover after a few periods. The negative response of hours depends crucially on the presence of imperfect competition, through three main channels. First, the equilibrium price markup—the reciprocal of the real marginal cost—increases, thus counteracting the positive effect of higher productivity on labor demand. Second, the wage markup (not reported) also increases, thus shifting the labor supply schedule to the left. Third, the wealth effect on hours is stronger with monopolistic competition, since positive expected profits increase households' permanent income (Rotemberg and Woodford (1995)).

The fall in hours in response to a neutral technological improvement is sharply at odds with the predictions of a standard RBC model, but consistent with a large empirical literature (Gali (1999), Francis and Ramey (2006), Canova, Lopez-Salido, and Michelacci (2006), Fernald (2007), Basu, Fernald, and Kimball (2007), Gali and Rabanal (2004) and Smets and Wouters (2007), but see Christiano, Eichenbaum, and Vigfusson (2004), Uhlig (2003) or Chang and Hong (2006), for the opposite view.). The lack of comovement between output and hours accounts to a large extent for the limited role of neutral technology shocks as sources of fluctuations in our model. However, these disturbances generate the right comovement between output and consumption. As a result, neutral technology shocks retain a non-negligible role in the fluctuations of these two variables.

In summary, our analysis proposes a reasonably parsimonious view of the sources of business cycles. Investment shocks impart the main impetus to fluctuations, which spread from investment to output and hours. Consumption, however, is largely insulated from these disturbances and its comovement with the rest of the economy is mainly driven by neutral

technology shocks. Finally, labor supply shocks account for a large fraction of the movements in hours, but these are concentrated at very low frequencies.

As for wages and prices, their movement is mainly driven by exogenous variation in desired markups, as we would expect in an economy in which monetary policy is well calibrated. In this respect, it is especially remarkable that inflation and wages are almost completely insulated from investment shocks. The fact that these shocks explain close to half of the movements in nominal interest rates suggests that achieving this degree of nominal stabilization required a fair amount of activism on the part of monetary policy.

5. INSPECTING THE MECHANISM: HOW INVESTMENT SHOCKS BECOME IMPORTANT

In standard neoclassical environments, neutral technology shocks are the most natural source of business cycles, since they can easily produce comovement of output, consumption, investment, hours and labor productivity. In fact, Barro and King (1984) show that generating this kind of comovement in response to most other shocks is problematic. In particular, they explicitly identify investment shocks as unlikely candidates to generate recognizable business cycles. Their reasoning can be outlined as follows: a positive shock to the marginal efficiency of investment increases the rate of return on current resources, inducing agents to postpone consumption. With lower consumption, the marginal utility of income increases, shifting labor supply to the right—an intertemporal substitution effect. Along an unchanged labor demand schedule, this supply shift raises hours and output, but depresses consumption, wages and labor productivity.⁶

This is not what happens in our estimated model, though, in which investment shocks trigger procyclical movements in all the key macroeconomic variables discussed above (see figure 4.)⁷ As a consequence of this significant change in the transmission mechanism with respect to the neoclassical benchmark, investment shocks emerge from our analysis as the single most important source of business cycle fluctuations. In this section, we study more closely how the frictions included in our baseline model contribute to this result. Some of these frictions, such as endogenous capital utilization and investment adjustment costs, have been analyzed before in a similar context, most prominently by Greenwood, Hercowitz, and

⁶ Labor demand is unchanged on impact because the investment shock, unlike a shock to TFP, does not directly affect the marginal product of labor.

⁷ Consumption is the only possible exception, since it only increases with a delay of about one year, as we pointed out in section 4.2.

Huffman (1988) and Greenwood, Hercowitz, and Krusell (2000). Others, such as monopolistic competition with sticky prices and wages, have not.⁸

To organize this discussion, we start from the efficiency equilibrium condition that must hold in a neoclassical economy:

$$(5.1) \quad MRS \left(\begin{matrix} C \\ + \\ + \end{matrix}, \begin{matrix} L \\ - \end{matrix} \right) = MPL \left(\begin{matrix} L \\ - \end{matrix} \right).$$

With standard preferences and technology, the marginal rate of substitution (MRS) depends positively on consumption (C) and hours (L), while the marginal product of labor (MPL) is decreasing in hours. As a result, any shock that boosts hours on impact, without shifting the marginal product of labor schedule, must also generate a fall in consumption for 5.1 to hold at the new equilibrium (Barro and King (1984)). This is precisely what happens in response to investment shocks in a neoclassical model, as we discussed above.

Equation 5.1 also highlights the three margins on which the frictions included in our baseline model must be operating to make the transmission of investment shocks more conformable with the typical pattern of business cycles. Departures from the standard assumptions on tastes affect the form of the MRS , technological frictions affect the form of the MPL , while departures from perfect competition create a wedge between the two.

For instance, with internal habit formation, the MRS also becomes a function of past and future expected consumption. Intuitively, households become reluctant to sharply adjust their consumption, which reduces their willingness to substitute over time. As a consequence, consumption is less likely to fall significantly in response to a positive investment shock.

Endogenous capital utilization, instead, acts as a shifter of the MPL , as first highlighted by Greenwood, Hercowitz, and Huffman (1988). An improvement in the efficiency of new investment increases the utilization of existing capital, due to the drop in its relative value. Higher capital utilization, in turn, implies an increase in the marginal product of labor, shifting labor demand to the right. For a given labor supply schedule, this shift implies a rise in hours and wages, as well as in consumption. Moreover, the increase in the marginal product of labor with constant returns to scale implies that average productivity also rises.

Finally, monopolistic competition in goods and labor markets drives a wedge between the MRS and the MPL . Sticky prices and wages make this wedge endogenous, so that equation

⁸ Rotemberg and Woodford (1995) make the point that endogenous markup variation is an additional channel through which aggregate shocks might affect fluctuations, especially in employment. However, they do not consider investment shocks in their analysis.

5.1 becomes

$$(5.2) \quad \omega \begin{pmatrix} L \\ - \end{pmatrix} MRS \begin{pmatrix} C, L \\ + + \end{pmatrix} = MPL \begin{pmatrix} L \\ - \end{pmatrix},$$

where ω denotes the wedge. In our model, ω is the sum of two equilibrium markups, that of price over marginal cost and that of real wages over the marginal rate of substitution. If this markup is countercyclical (i.e. it falls when hours rise, as suggested for example by Rotemberg and Woodford (1999) and Galí, Gertler, and López-Salido (2007)), consumption and hours can move together in response to an investment shock, without violating the equilibrium condition 5.2.

More specifically, in our estimated model, a positive investment shock produces a drop in the price markup, as we can see from the fact that the real marginal cost rises in figure 4. This fall in the markup induces a positive shift in labor demand, which amplifies the shift associated with changes in utilization. At the same time, the wage markup also falls, shifting the labor supply schedule to the right. Unlike in the perfectly competitive case, though, this shift in labor supply is consistent with an increase in hours at an unchanged level of consumption.

In our economy, the endogeneity of markups is due to price and wage stickiness. However, equation (5.2) suggests that any other friction resulting in countercyclical markups would propagate investment shocks in a similar way.

In the rest of this section, we investigate the quantitative role of all these frictions in turning investment shocks into the dominant source of fluctuations. To this end, we study the variance decomposition of several restricted versions of the baseline model, in which we shut down one category of frictions at-a-time. We consider the following groups of frictions. First, we estimate a model with no habit in consumption, which corresponds to $h = 0$. Second, we fix capital utilization and eliminate investment adjustment costs by setting $1/\chi = 0.0001$ and $S'' = 0$. Third, we consider models with (nearly) competitive labor and goods markets, by calibrating $\xi_w = 0.01$, $\iota_w = 0$, $\lambda_w = 1.01$ and $\xi_p = 0.01$, $\iota_p = 0$, $\lambda_p = 1.01$. Finally, we reduce our model all the way to its standard neoclassical core, by shutting down all the frictions simultaneously.

The results of this exercise are reported in table 6. The table focuses on the contributions of investment shocks to the volatility of output and hours at business cycle frequencies, since

this is where the importance of these shocks is most evident. First, we observe that removing any of the frictions reduces the contribution of investment shocks to fluctuations. This is as expected given our preceding discussion of the effects of the frictions on the transmission mechanism.

In terms of relative contributions, imperfect competition has the most significant marginal impact. In the perfectly competitive model, the contribution of investment shocks to fluctuations in output and hours drops to 4 and 8 percent respectively. As apparent from the case in which we shut down imperfect competition in goods and labor markets separately, each of these modifications produces a roughly equal decline in the importance of investment shocks. Endogenous utilization and adjustment costs come next. Their exclusion reduces the contribution of investment shocks to fluctuations in both hours and output by more than half. The friction that plays the smallest role at the margin is time non-separability.

Finally, the last column in table 6 shows that the contribution of the investment shock disappears entirely in the frictionless model. This result suggests that our estimation procedure is not unduly affecting our findings on the role of this shock in business cycles. When we restrict ourselves to the standard neoclassical model, we recover what we would expect in light of the theoretical analysis of Barro and King (1984) and Greenwood, Hercowitz, and Huffman (1988): investment shocks do not play any role in fluctuations.⁹

Table 6 compares the contribution of investment shocks to business cycles across several models. In the baseline, investment shocks are paramount, while in some of the restricted versions they are irrelevant. Therefore, an important question is whether these restricted models are consistent with the data. The answer is no, as illustrated in table 7, where we report the log-marginal data density of all the specifications described above. The marginal data density (or marginal likelihood) is the expected value of the likelihood function with respect to the prior density and is the appropriate way of comparing models from a Bayesian perspective. According to this comparison, the fit of the baseline model is far superior to that of any of the alternatives, implying overwhelming posterior odds in its favor.¹⁰

⁹ In the estimated frictionless model, we find that the neutral technology and labor supply shocks explain 43 and 47 percent of the variance of output and 4 and 78 percent of that of hours at business cycle frequencies.

¹⁰ Del Negro and Schorfheide (2008) discuss reasons why posterior odds should be interpreted with some care when priors are not adjusted as the model specification is altered.

6. A COMPARISON WITH SMETS AND WOUTERS (2007)

Our results on the role of investment shocks are at odds with those of Smets and Wouters (2007, SW hereafter). In particular, SW recover a dominant role for the wage markup shock at medium and long horizons. Moreover, their investment shock accounts for less than 25 percent of fluctuations in GDP at any horizon. In this section, we document the sources of this discrepancy.

We start by performing our variance decomposition at business cycle frequencies using SW's model and the parameter estimates reported in table 1 of their paper. We find that the wage markup shock accounts for 11 and 14 percent of the business cycle variance of output and hours respectively. For output, this share is substantially smaller than that suggested by the forecast error variance decomposition at medium and long horizons reported in figure 1 of SW's paper. For hours, the discrepancy between spectral and forecast error variance decompositions is even larger.¹¹ Therefore, we conclude that SW's emphasis on wage markup shocks is mainly due to the difficulty in isolating business cycle frequencies using forecast error variance decompositions. Moreover, when we re-estimate SW's model, using their observables, but our longer sample from 1954QIII to 2004QIV, the shares of the wage markup shock in the business cycle variance of output and hours decline to 5 and 7 percent respectively. These numbers are very close to our baseline (table 5).

However, in this case we also find a significantly diminished role for the investment shock, as we show in the first column of table 8. The results are almost identical if we use SW's dataset to estimate our model (second column of table 8). This suggests that the minor differences between the two model specifications do not affect the variance decomposition. Therefore, the remaining discrepancy on the role of investment shocks must be due to the differences in the definitions of the observables.

Compared to us, SW exclude inventories from investment—although not from output—and include purchases of consumer durables in consumption.¹² The next two columns of table 8 analyze how the treatment of inventories and durables affects the contribution of investment shocks to the business cycle volatility of output and hours. In column three, we switch durables back from consumption into investment, as in our baseline case, but leave inventories out. In column four we do the opposite and include inventories into investment, but leave

¹¹ Smets and Wouters (2007) do not report the forecast error variance decomposition for hours.

¹² SW also use a different series for hours, but this does not have any material impact on the results.

durables in consumption. In the first case, the contribution of the investment shock to output and hours increases to 42 and 47 percent respectively. In the second case, those numbers are 35 and 44 percent. In the last column, we reproduce our baseline variance decomposition, which attributes 53 and 61 percent of the variance of output and hours to the investment shock. By comparing these numbers, we conclude that the discrepancy between our results and SW's is due almost in equal parts to the differences in the treatment of inventories and durables.

These findings suggest that research on the sources of business cycles would benefit from more explicit modeling of the behavior of durables and inventories. However, we do not think they undermine the case for the importance of investment shocks made in this paper, for at least two reasons. First, our treatment of the data is in line with most of the macroeconomic literature (see for instance Cooley and Prescott (1995), Christiano, Eichenbaum, and Evans (2005) or Del Negro, Schorfheide, Smets, and Wouters (2007)). Second, even when considering SW's dataset, two key results remain robust. First, the share of variance accounted for by supply shocks—neutral technology and wage markup shocks—remains stable around 30 percent for output and 20 percent for hours. Second, the share of variance accounted for by demand shocks—the investment shock and the intertemporal preference shock—is also fairly stable around 50 percent for output and 60 percent for hours. The only difference is in the way in which these shares are apportioned between the investment and intertemporal preference shock. Not surprisingly, the inclusion of durables and inventories in investment tends to boost the contribution of the investment shock, at the expense of the preference shock, since these are two of the most cyclical components of GDP.

7. INVESTMENT SHOCKS AND THE RELATIVE PRICE OF INVESTMENT

In our empirical investigation, we assumed that the marginal efficiency of investment, μ_t , follows an exogenous stochastic process. Consequently, we treated the investment shock as a latent variable in estimation, as in most of the empirical DSGE literature (e.g. Smets and Wouters (2007) and Del Negro, Schorfheide, Smets, and Wouters (2007)). Another prominent branch of the literature, however, builds on the observation that this same investment shock should equal the price of consumption relative to investment in a version of our model with a competitive investment sector (Greenwood, Hercowitz, and Krusell (1997), Greenwood, Hercowitz, and Krusell (2000), Fisher (2006)). In this section, we confront this observation

by considering a version of the model in which we can explicitly compare the estimated investment shock and the measured relative price.

This comparison requires a few changes to our baseline framework. First, we must include a trend in the investment shock process, since the relative price of consumption has been steadily rising in the postwar period. In this respect, we follow Greenwood, Hercowitz, and Krusell (2000) and assume that μ_t is a trend-stationary process. Moreover, we allow for a break in the trend in 1982:II, which is consistent with the recent acceleration in the rate of increase in the relative price noted for example by Fisher (2006). We calibrate the slope of this broken trend to match the average growth rate of the relative price of consumption before and after 1982:II.¹³

In addition, we make a few small modifications to the baseline model, along the lines of Altig, Christiano, Eichenbaum, and Linde (2005). For example, we assume that the cost of adjusting investment depends on the quantity of investment installed, rather than on its value in terms of consumption. Therefore, $S(I_t/I_{t-1})$ becomes $S((\mu_t I_t)/(\mu_{t-1} I_{t-1}))$, where I_t is now the real value of investment in terms of consumption.¹⁴ Consistent with this definition, we also deflate all nominal variables for the estimation by the consumption deflator, on which we also base our measure of inflation.

The second column of table 8 reports the share of business cycle variance of output and hours explained by the investment shock in this version of the model. These numbers are somewhat lower than those in the baseline, but the investment shock remains the single most important source of fluctuations in both output and investment.¹⁵

Next, we compare the smoothed estimate of the investment shock to the relative price of consumption in the data, both expressed in deviation from the same broken linear trend. The two series exhibit a similar degree of autocorrelation, but our measure of the investment shock is considerably more volatile than the relative price, with a standard deviation approximately four times as large. This excess volatility might be due, in part, to the difficulty of measuring the price of investment and of durable consumption goods in a manner consistent

¹³ We construct this relative price using the chain-weighted deflators for our components of consumption (non-durables and services) and investment (durables and total private investment).

¹⁴ We make three additional small changes to the model, which ensure the existence of a balanced growth path. We use the deterministic trend in the investment shock process to scale the fixed cost of production and to index wages, while we scale the cost of capital utilization by the inverse of μ_t itself.

¹⁵ We also experimented with a stochastic trend in μ_t . In that case, the shares of variance of output and hours explained by the investment shock are even higher (third column of table 8), although the estimated persistence of the growth rate of the investment shock is also very high.

with theory (Gordon (1990), Cummins and Violante (2002)). Another possible interpretation of this finding is that the smoothed investment shock hides unmodeled frictions in the capital accumulation process, of the kind considered for example by Christiano, Motto, and Rostagno (2007).

8. ROBUSTNESS ANALYSIS

In this section we investigate the robustness of our result to a number of alternative specifications of the model. The results of these robustness checks are summarized in table 9, in which we report the share of the variance of output and hours explained by the investment shock at business cycle frequencies.

8.1. Standard calibration of capital income share and labor supply elasticity ($\alpha = 0.3$ and $\nu = 1$). Our baseline estimates of the share of capital income (α) and of the Frisch elasticity of labor supply ($1/\nu$) differ from the standard values used in the RBC literature. To verify that our estimates of α and ν do not affect the results too much, we re-estimate the model calibrating these two parameters at the more typical values of $\alpha = 0.3$ and $\nu = 1$. The fourth column of table 9 shows that the contribution of investment shocks to the business cycle fluctuations of output and hours is now even larger than in the baseline model.

8.2. No ARMA shocks. Following Smets and Wouters (2007), the baseline model includes an ARMA(1,1) specification for the wage and price markup shocks. This assumption improves its fit of the model, but to make sure that it does not drive our results, we also estimate a version of the model with the more standard assumption that markup shocks are distributed as an AR(1). As the fifth column in table 9 makes clear, this modification leaves our results almost unchanged.

8.3. Output growth in the policy rule. We also estimate a model in which the measure of real activity included in the policy rule is output growth, rather than the output gap, since both specifications are quite common in the literature. Once again, this modification barely affects the quantitative results (column six in table 9).

8.4. Maximum likelihood. The last robustness check we conduct is with respect to the priors on the model parameters. In our baseline exercise, we follow the recent literature on Bayesian estimation of DSGE models and use the prior information reported in table 1. To verify that the priors are not responsible for our main results, we re-estimate the model by

maximum likelihood. Maximizing the likelihood is numerically much more challenging than maximizing the posterior, since the use of weakly informative priors ameliorates the problems related to the presence of flat areas of the likelihood function and of multiple local modes. These difficulties notwithstanding, we were able to compute maximum likelihood estimates for the model parameters.¹⁶ As illustrated in the last column of table 9, these estimates are entirely consistent with the baseline results. In fact, the investment shock still accounts for around 60% of the business cycle fluctuations in output and hours.

9. CONCLUDING REMARKS

What is the source of business cycle fluctuations? We revisited this fundamental question of macroeconomics from the perspective of an estimated New Neoclassical Synthesis model. We found that shocks to the marginal efficiency of investment are the main drivers of movements in hours, output and investment over the cycle. Imperfect competition with endogenous markups is crucial for the transmission of these shocks. Neutral technology shocks also retain a non negligible role in the fluctuations of consumption and output and are mainly responsible for their comovement. Finally, shocks to labor supply account for a large share of the variance of hours at very low frequencies, but their contribution over the business cycle is negligible.

One important qualification of these results is that the estimated volatility of the investment shock is much larger than the volatility of the price of investment relative to consumption measured in the data. In a two-sector representation of our model, in which the sector producing capital goods is perfectly competitive, the two would be the same. There are several possible reasons for why this is not the case in our set-up. First, measuring the price of durable goods in a manner consistent with theory is notoriously problematic. Second, a serious effort at modeling a two-sector economy would probably include sticky prices also in the capital goods sector. In such a model, we would expect investment prices to be smoother than marginal costs. Third, the estimated investment shock might hide frictions in the capital accumulation process that we did not consider. Models that explicitly include these type of frictions, such as that in Christiano, Motto, and Rostagno (2007), therefore represent a

¹⁶ More precisely, to maximize the likelihood we need to calibrate \varkappa , since the likelihood is not very informative on this parameter and this creates convergence problems in the maximization routine. Therefore, we calibrated $\varkappa = 5$, which is our prior mean. This value of \varkappa implies a low elasticity of capital utilization, which makes the propagation of investment shocks if anything more problematic.

promising avenue for future research. More generally, our results point to the investment sector, and to its Euler equation in particular, as the keys to our understanding of business cycles.

APPENDIX A. THE DATA

Our dataset spans a sample from 1954QIII to 2004QIV. All data are extracted from the Haver Analytics database (series mnemonics in parenthesis). Following Del Negro, Schorfheide, Smets, and Wouters (2007), we construct real GDP by dividing the nominal series (GDP) by population (LF and LH) and the GDP Deflator (JGDP). Real series for consumption and investment are obtained in the same manner, although consumption corresponds only to personal consumption expenditures of non-durables (CN) and services (CS), while investment is the sum of personal consumption expenditures of durables (CD) and gross private domestic investment (I). Real wages correspond to nominal compensation per hour in the non-farm business sector (LXNFC), divided by the GDP deflator. We measure the labor input by the log of hours of all persons in the non-farm business sector (HNFBN), divided by population. The quarterly log difference in the GDP deflator is our measure of inflation, while for nominal interest rates we use the effective Federal Funds rate. We do not demean or detrend any series.

APPENDIX B. NORMALIZATION OF THE SHOCKS

As in Smets and Wouters (2007), we re-normalize some of the exogenous shocks by dividing them by a constant term. For instance, one of our log-linearized equilibrium conditions is the following Phillips curve:

$$\hat{\pi}_t = \frac{\beta}{1 + \beta\iota_p} E_t \hat{\pi}_{t+1} + \frac{1}{1 + \beta\iota_p} \hat{\pi}_{t-1} + \kappa \hat{s}_t + \kappa \hat{\lambda}_{p,t},$$

where $\kappa \equiv \frac{(1-\beta\xi_p)(1-\xi_p)}{(1+\iota_p\beta)\xi_p}$, s_t is the model-implied real marginal cost and the “hat” denotes log deviations from the non-stochastic steady state. The normalization consists of defining a new exogenous variable, $\hat{\lambda}_{p,t}^* \equiv \kappa \hat{\lambda}_{p,t}$, and estimating the standard deviation of the innovation to $\hat{\lambda}_{p,t}^*$ instead of $\hat{\lambda}_{p,t}$. We do the same for the wage markup and the intertemporal preference

shock, for which we use the following normalizations:

$$\begin{aligned}\hat{\lambda}_{w,t}^* &= \left(\frac{(1 - \beta\xi_w)(1 - \xi_w)}{\left(1 + \nu\left(1 + \frac{1}{\lambda_w}\right)\right)(1 + \beta)\xi_w} \right) \hat{\lambda}_{w,t} \\ \hat{b}_t^* &= \left(\frac{(1 - \rho_b)(e^\gamma - h\beta\rho_b)(e^\gamma - h)}{e^\gamma h + e^{2\gamma} + \beta h^2} \right) \hat{b}_t\end{aligned}$$

These normalizations are chosen in such a way that these shocks enter the wage and consumption equations (respectively) with a unity coefficient. In this way it is easier to choose a reasonable prior for their standard deviation. Moreover, the normalization is a practical way to impose correlated priors across coefficients, which is desirable in some cases. For instance, imposing a prior on the standard deviation of the innovation to $\hat{\lambda}_{p,t}^*$ corresponds to imposing prior that allow for correlation between κ and the standard deviation of the innovations to $\hat{\lambda}_{p,t}$. Often, these normalizations improve the convergence properties of the MCMC algorithm.

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Table 1: Prior densities and posterior estimates for baseline model with all frictions

Coefficient	Description	Prior			Posterior ²				
		Prior Density ¹	Mean	Std	Median	Std	[5 , 95]		
α	Capital Share	N	0.30	0.05	0.17	0.006	[0.16 , 0.18]		
ι_p	Price indexation	B	0.50	0.15	0.24	0.073	[0.14 , 0.39]		
ι_w	Wage indexation	B	0.50	0.15	0.11	0.029	[0.06 , 0.16]		
γ	SS technology growth rate	N	0.50	0.03	0.48	0.023	[0.44 , 0.52]		
h	Consumption habit	B	0.50	0.10	0.79	0.023	[0.76 , 0.83]		
λ_p	SS mark-up goods prices	N	0.15	0.05	0.25	0.032	[0.19 , 0.30]		
λ_w	SS mark-up wages	N	0.15	0.05	0.15	0.033	[0.07 , 0.19]		
$\log L^{ss}$	SS leisure	N	396.83	0.50	397.16	0.480	[396.4 , 398.0]		
$100(\pi-1)$	SS quarterly inflation	N	0.50	0.10	0.71	0.078	[0.56 , 0.82]		
$100(\beta^{-1}-1)$	Discount factor	G	0.25	0.10	0.14	0.045	[0.07 , 0.22]		
ν	Inverse Frisch elasticity	G	2.00	0.75	3.59	0.674	[2.63 , 4.84]		
ξ_p	Calvo prices	B	0.66	0.10	0.84	0.016	[0.82 , 0.87]		
ξ_w	Calvo wages	B	0.66	0.10	0.71	0.019	[0.68 , 0.74]		
χ	Elasticity capital utilization costs	G	5.00	1.00	5.80	1.001	[4.38 , 7.58]		
S''	Investment adjustment costs	G	4.00	1.00	2.95	0.301	[2.43 , 3.39]		
Φ_p	Taylor rule inflation	N	1.70	0.30	1.97	0.144	[1.71 , 2.20]		
Φ_y	Taylor rule output	N	0.13	0.05	0.05	0.012	[0.03 , 0.07]		
Φ_{dy}	Taylor rule output growth	N	0.13	0.05	0.23	0.016	[0.21 , 0.26]		
ρ_R	Taylor rule smoothing	B	0.60	0.20	0.81	0.016	[0.79 , 0.84]		

(Continued on the next page)

Table 1: Prior densities and posterior estimates for baseline model with all frictions

Coefficient	Description	Prior			Posterior ²				
		Prior Density ¹	Mean	Std	Median	Std	[5 , 95]		
ρ_{mp}	Monetary Policy	B	0.40	0.20	0.16	0.048	[0.07 0.22]		
ρ_z	Neutral Technology growth	B	0.40	0.20	0.23	0.043	[0.15 0.30]		
ρ_g	Government spending	B	0.60	0.20	0.99	0.001	[0.99 0.99]		
ρ_μ	Investment	B	0.60	0.20	0.73	0.031	[0.68 0.78]		
ρ_p	Price mark-up	B	0.60	0.20	0.94	0.017	[0.91 0.96]		
ρ_w	Wage mark-up	B	0.60	0.20	0.98	0.003	[0.98 0.99]		
ρ_b	Intertemporal preference	B	0.60	0.20	0.65	0.027	[0.60 0.68]		
θ_p	Price mark-up MA	B	0.50	0.20	0.78	0.010	[0.76 0.79]		
θ_w	Wage mark-up MA	B	0.50	0.20	0.95	0.002	[0.94 0.95]		
σ_{mp}	Monetary policy	I	0.10	1.00	0.22	0.012	[0.21 0.25]		
σ_z	Neutral Technology growth	I	0.50	1.00	0.89	0.049	[0.81 0.98]		
σ_g	Government spending	I	0.50	1.00	0.35	0.017	[0.32 0.38]		
σ_μ	Investment	I	0.50	1.00	6.01	0.505	[5.02 6.79]		
σ_p	Price mark-up	I	0.10	1.00	0.14	0.002	[0.14 0.15]		
σ_w	Wage mark-up	I	0.10	1.00	0.24	0.003	[0.23 0.24]		
σ_b	Intertemporal preference	I	0.10	1.00	0.04	0.001	[0.04 0.04]		
<i>(log) Likelihood at median</i>						-1094.7			

Calibrated coefficients: depreciation rate (δ) is 0.025, g implies a SS government share of 0.22

Relative to the text, the standard deviations of the innovations are scaled by 100 for the estimation, which is reflected in the prior and posterior estimates.

¹ N stands for Normal, B Beta, G Gamma and I Inverted-Gamma I distribution

² Median and posterior percentiles from 2 chains of 120,000 draws generated using a Random walk Metropolis algorithm, where we discard the initial 20,000 and retain one in every 20 subsequent draws. Additional longer chains produced almost identical posterior moments.

Table 2: Prior variance decomposition for observable variables in the baseline model*Medians and [5,95] prior percentiles*

<i>Series Shock</i>	Policy	Neutral	Government	Investment	Price mark-up	Wage mark-up	Preference
Output growth	0.01 [0.00,0.33]	0.26 [0.02,0.88]	0.23 [0.02,0.85]	0.00 [0.00,0.04]	0.00 [0.00,0.14]	0.01 [0.00,0.39]	0.08 [0.00,0.74]
Consumption growth	0.01 [0.00,0.34]	0.31 [0.01,0.93]	0.00 [0.00,0.11]	0.00 [0.00,0.03]	0.00 [0.00,0.09]	0.00 [0.00,0.27]	0.42 [0.02,0.98]
Investment growth	0.01 [0.00,0.45]	0.38 [0.01,0.95]	0.00 [0.00,0.13]	0.03 [0.00,0.43]	0.00 [0.00,0.25]	0.01 [0.00,0.69]	0.04 [0.00,0.93]
Hours	0.02 [0.00,0.54]	0.17 [0.00,0.90]	0.07 [0.00,0.68]	0.01 [0.00,0.13]	0.00 [0.00,0.29]	0.04 [0.00,0.92]	0.05 [0.00,0.81]
Wage growth	0.00 [0.00,0.03]	0.73 [0.10,0.99]	0.00 [0.00,0.03]	0.00 [0.00,0.01]	0.04 [0.00,0.50]	0.09 [0.01,0.71]	0.00 [0.00,0.17]
Inflation	0.01 [0.00,0.66]	0.11 [0.00,0.86]	0.01 [0.00,0.19]	0.00 [0.00,0.08]	0.08 [0.00,0.79]	0.08 [0.00,0.95]	0.03 [0.00,0.81]
Interest Rates	0.02 [0.00,0.43]	0.15 [0.00,0.92]	0.02 [0.00,0.34]	0.00 [0.00,0.14]	0.02 [0.00,0.50]	0.03 [0.00,0.88]	0.11 [0.00,0.94]

Notice that median shares need not add up to one. This is particularly true with the a-priori (as opposed to posterior) variance decompositions, due to the skewness induced by the dispersed prior distribution for the standard deviation of the shocks. Mean shares add up to one, and for the case of the investment shocks do not exceed 3 percent for output and hours.

Table 3: Standard deviations and relative standard deviations in the data and in the baseline model with all frictions ¹

<i>Series</i>	Standard deviation			Relative standard deviation ²		
	Data	Median	[5 , 95]	Data	Median	[5 , 95]
Output growth	0.94	1.14	[1.00 , 1.31]	1.00	1.00	
Consumption growth	0.51	0.72	[0.62 , 0.82]	0.54	0.63	[0.53 , 0.74]
Investment growth	3.59	4.59	[3.95 , 5.36]	3.83	4.03	[3.61 , 4.50]
Hours	4.11	4.47	[3.09 , 6.75]	4.39	3.91	[2.79 , 5.81]
Wage growth	0.55	0.66	[0.59 , 0.75]	0.59	0.58	[0.50 , 0.67]
Inflation	0.60	0.49	[0.39 , 0.63]	0.64	0.43	[0.34 , 0.56]
Interest Rates	0.84	0.66	[0.52 , 0.83]	0.90	0.58	[0.45 , 0.74]

¹ For each parameter draw, we generate 1000 samples of the observable series implied by the model with same length as our dataset (202 observations) after discarding 50 initial observations. For the relative standard deviations, for each replication and parameter draw we take the ratio of the standard deviation of each series to that of output. Table reports median and 5th and 95th percentile together with the corresponding moments in the data.

² Standard deviation relative to the standard deviation of output growth

Table 4: Posterior variance decomposition for observable variables in the baseline model*Medians and [5,95] posterior percentiles*

<i>Series Shock</i>	Policy	Neutral	Government	Investment	Price mark-up	Wage mark-up	Preference
Output growth	0.04 [0.03, 0.06]	0.20 [0.15, 0.25]	0.07 [0.06, 0.08]	0.51 [0.45, 0.57]	0.04 [0.03, 0.05]	0.05 [0.03, 0.07]	0.09 [0.07, 0.11]
Consumption growth	0.02 [0.01, 0.03]	0.26 [0.21, 0.32]	0.02 [0.02, 0.03]	0.07 [0.04, 0.11]	0.01 [0.00, 0.01]	0.09 [0.06, 0.13]	0.53 [0.46, 0.60]
Investment growth	0.03 [0.02, 0.04]	0.05 [0.04, 0.07]	0.00 [0.00, 0.00]	0.87 [0.84, 0.89]	0.03 [0.02, 0.04]	0.01 [0.01, 0.01]	0.01 [0.01, 0.02]
Hours	0.02 [0.02, 0.04]	0.03 [0.02, 0.04]	0.02 [0.01, 0.03]	0.20 [0.12, 0.30]	0.05 [0.03, 0.07]	0.65 [0.52, 0.77]	0.02 [0.01, 0.03]
Wage growth	0.00 [0.00, 0.00]	0.29 [0.23, 0.34]	0.00 [0.00, 0.00]	0.03 [0.02, 0.04]	0.22 [0.18, 0.27]	0.46 [0.42, 0.50]	0.00 [0.00, 0.00]
Inflation	0.03 [0.02, 0.06]	0.07 [0.05, 0.11]	0.00 [0.00, 0.00]	0.06 [0.03, 0.11]	0.24 [0.17, 0.32]	0.56 [0.44, 0.68]	0.02 [0.01, 0.03]
Interest Rates	0.10 [0.08, 0.14]	0.05 [0.04, 0.08]	0.01 [0.01, 0.01]	0.45 [0.34, 0.57]	0.02 [0.02, 0.04]	0.24 [0.13, 0.37]	0.11 [0.08, 0.15]

Notice that median shares need not add up to one, although mean shares do.

Table 5: Variance decomposition at business cycle frequencies¹ in the baseline model with all frictions

Medians and [5,95] posterior percentiles

<i>Series \ Shock</i>	Policy	Neutral	Government	Investment	Price mark-up	Wage mark-up	Preference
Output	0.05 [0.04, 0.07]	0.24 [0.18, 0.30]	0.02 [0.01, 0.02]	0.53 [0.45, 0.61]	0.05 [0.03, 0.07]	0.04 [0.03, 0.06]	0.07 [0.05, 0.09]
Consumption	0.02 [0.01, 0.03]	0.27 [0.21, 0.33]	0.02 [0.02, 0.03]	0.08 [0.05, 0.14]	0.01 [0.00, 0.01]	0.08 [0.05, 0.12]	0.51 [0.42, 0.59]
Investment	0.03 [0.02, 0.04]	0.06 [0.04, 0.09]	0.00 [0.00, 0.00]	0.85 [0.81, 0.89]	0.04 [0.02, 0.05]	0.01 [0.01, 0.01]	0.01 [0.01, 0.02]
Hours	0.06 [0.05, 0.09]	0.10 [0.08, 0.13]	0.02 [0.02, 0.03]	0.61 [0.54, 0.67]	0.06 [0.04, 0.08]	0.06 [0.03, 0.08]	0.08 [0.06, 0.11]
Wages	0.00 [0.00, 0.01]	0.39 [0.30, 0.47]	0.00 [0.00, 0.00]	0.04 [0.02, 0.07]	0.31 [0.24, 0.38]	0.25 [0.21, 0.31]	0.00 [0.00, 0.01]
Inflation	0.03 [0.02, 0.05]	0.14 [0.10, 0.19]	0.00 [0.00, 0.00]	0.07 [0.04, 0.13]	0.40 [0.32, 0.49]	0.31 [0.25, 0.38]	0.02 [0.01, 0.03]
Interest Rates	0.18 [0.14, 0.23]	0.09 [0.07, 0.12]	0.01 [0.00, 0.01]	0.48 [0.41, 0.56]	0.04 [0.03, 0.06]	0.04 [0.03, 0.06]	0.15 [0.11, 0.19]

Since reporting median shares, these need not add up to one, although mean shares do.

¹ Decomposition of the variance corresponding to periodic components with cycles of between 6 and 32 quarters, obtained using the spectrum of the DSGE model and an inverse first difference filter for output, consumption, investment and wages to obtain the levels. The spectral density is computed from the state space representation of the model and 500 bins for frequencies covering that range of periodicities. Results are identical to those that would result from repeatedly simulating the observables, obtaining the levels and then applying a Band-Pass filter. Variance shares for periods of 2 to 32 quarters obtained with the spectrum implied by the DSGE, or by HP filtering the model observables (transformed to levels where appropriate) deliver a very similar decomposition.

Table 6: Variance share for output and hours at business cycle frequencies¹ explained by investment shocks for alternative specifications without some frictions

<i>Series</i>	Baseline	No habits ²	No investment costs and variable capital utilization ³	Perfectly competitive goods and labor markets ⁴	Perfectly competitive goods markets ⁵	Perfectly competitive labor market ⁶	Frictionless model ⁷
Output	0.53	0.38	0.23	0.04	0.30	0.31	0.02
Hours	0.61	0.50	0.30	0.08	0.50	0.41	0.03

¹ Share of the variance of output (level) and hours, corresponding to periodic components of cycles between 6 and 32 quarters explained by investment shocks alone. Obtained using the spectrum from the state-space representation of the DSGE. Variance decompositions are performed at the mode of each specification.

² h calibrated at 0.01

³ S'' calibrated at 0.01, I/χ calibrated at 0.001

⁴ $\lambda_w, \xi_w, \iota_w, \lambda_p, \xi_p$ and ι_p calibrated at 0.01

⁵ λ_w, ξ_w and ι_w calibrated at 0.01

⁶ λ_p, ξ_p and ι_p calibrated at 0.01

⁷ combines the calibration for all specifications above, except baseline

Table 7: Log-Marginal Data Densities for baseline and alternative specifications without some frictions

Specification	Log Marginal ¹
Baseline	-1215.10
No habits	-1316.75
No investment costs and variable capital utilization	-1298.04
Perfectly competitive goods and labor markets	-1466.52
Perfectly competitive goods markets	-1433.42
Perfectly competitive labor market	-1283.19
Frictionless model	-1521.88

¹ Except for the baseline, the log marginal data density is computed using the Metropolis-Laplace approximation at the posterior mode. The specification favored by the data attains the highest marginal density.

Full set of parameter estimates is available from the authors upon request

Table 8: Variance share of output and hours at business cycle frequencies¹ explained by investment shocks using alternative models and datasets

<i>Model</i>	Smets and Wouters		Ours		
<i>Dataset</i>	Smets and Wouters	Smets and Wouters	Investment includes consumer durables but not inventories	Investment includes inventories but not consumer durables	Baseline: investment includes inventories and consumer durables
<i>Series</i>					
Output	0.23	0.18	0.42	0.35	0.53
Hours	0.26	0.21	0.47	0.44	0.61

¹ Share of the variance of output (level) and hours, corresponding to periodic components of cycles between 6 and 32 quarters explained by investment shocks alone. Obtained using the spectrum from the state-space representation of the DSGE. Variance decompositions are performed at the mode of each specification.

Table 9: Robustness check for the variance share of output and hours at business cycle frequencies¹ explained by investment shocks

<i>Series</i>	Baseline	Trend stationary investment shock²	Stochastic trend investment shock³	$\nu = 1$ and $\alpha = 0.3$	No MA components⁴	Taylor rule with output growth⁵	MLE⁶
Output	0.53	0.40	0.56	0.66	0.52	0.49	0.60
Hours	0.61	0.45	0.70	0.77	0.56	0.54	0.64

¹ Share of the variance of output (level) and hours, corresponding to periodic components of cycles between 6 and 32 quarters explained by investment shocks alone. Obtained using the spectrum from the state-space representation of the DSGE. Variance decompositions are performed at the mode of each specification.

² Model with broken linear trend in investment shocks (break occurs in 1982q2)

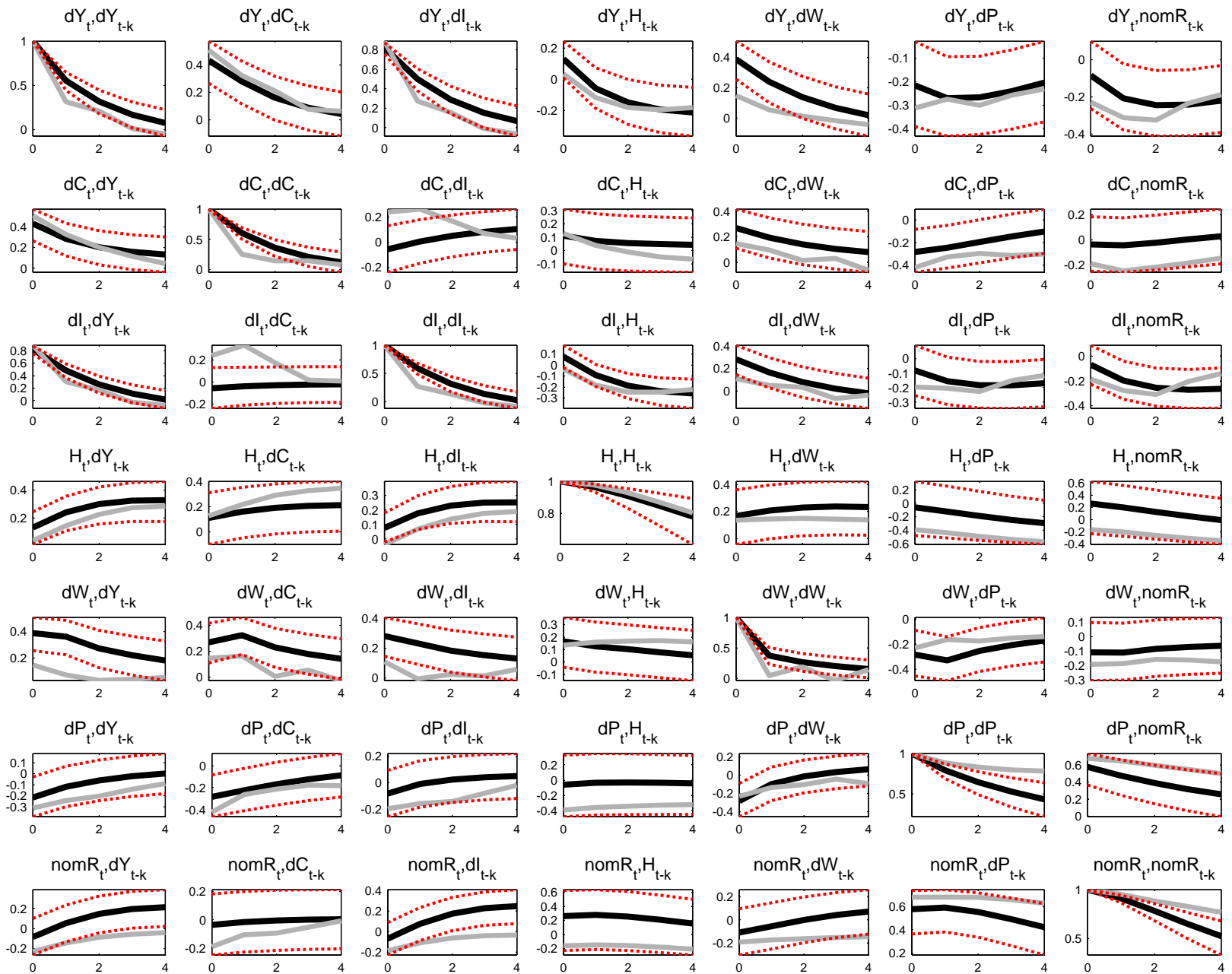
³ Model with stochastic trend in investment shocks

⁴ Moving average component for price and wage mark-up shocks calibrated to zero.

⁵ Taylor rule responds to observable output growth instead of the output gap.

⁶ Baseline specification estimated by maximum likelihood.

Fig 1: Autocorrelation for baseline specification, dsge median (dark), dsge 5-95 (dotted) & data (grey)



legend: dY =output growth, dC =consumption growth, dI =investment growth, H =hours, dW =wages growth, dP =inflation, $nomR$ =nominal interest rate

Figure 2: Year-to-year output growth, actual data and counterfactual explained by investment shocks

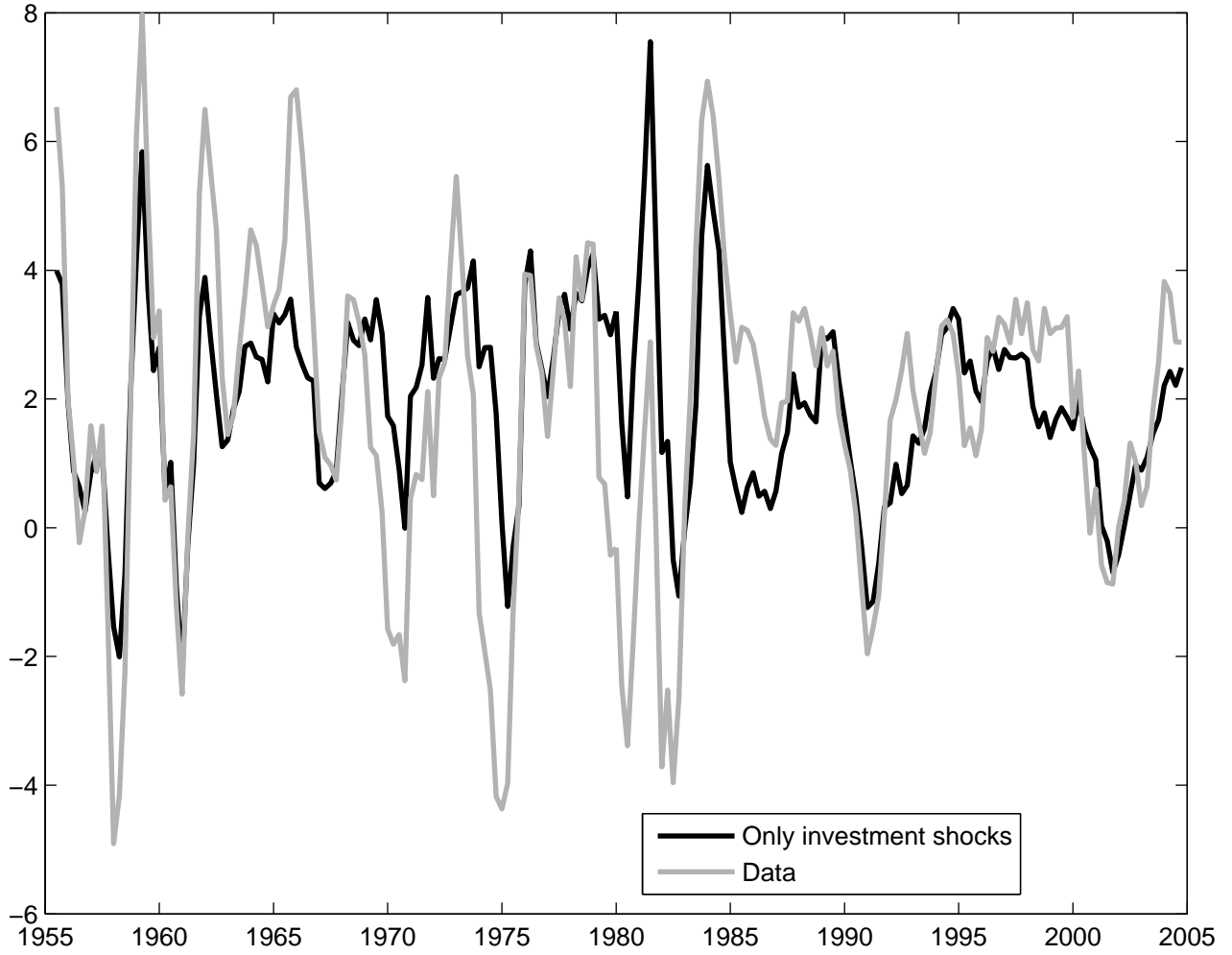
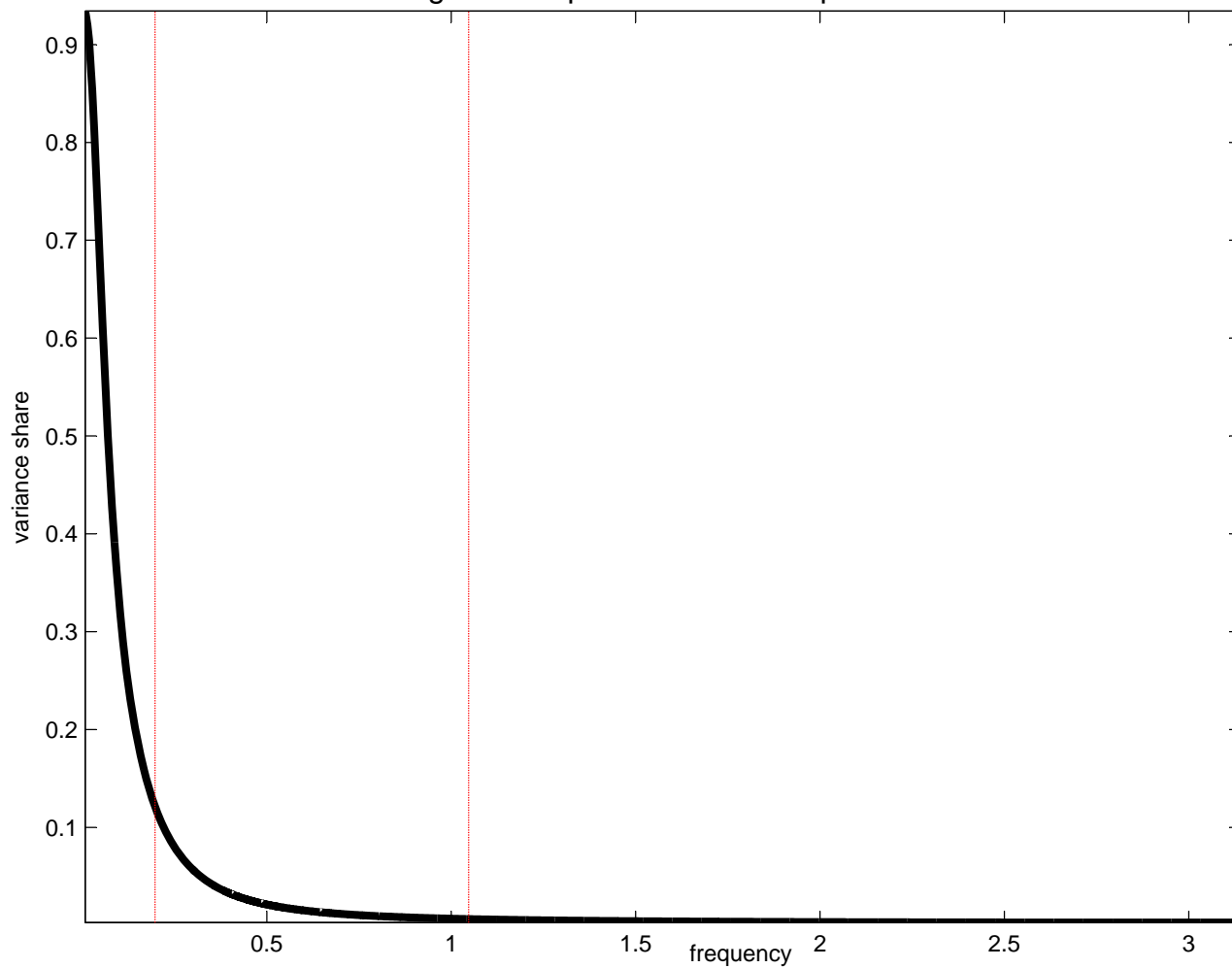


Figure 3: Variance share of Hours explained by wage mark-up shocks at all frequencies



Computed at the median of the parameter estimates.
Vertical dashed lines mark the frequency band associated with business cycles of 6 to 32 quarters.

Figure 4: Impulse responses to an investment shock

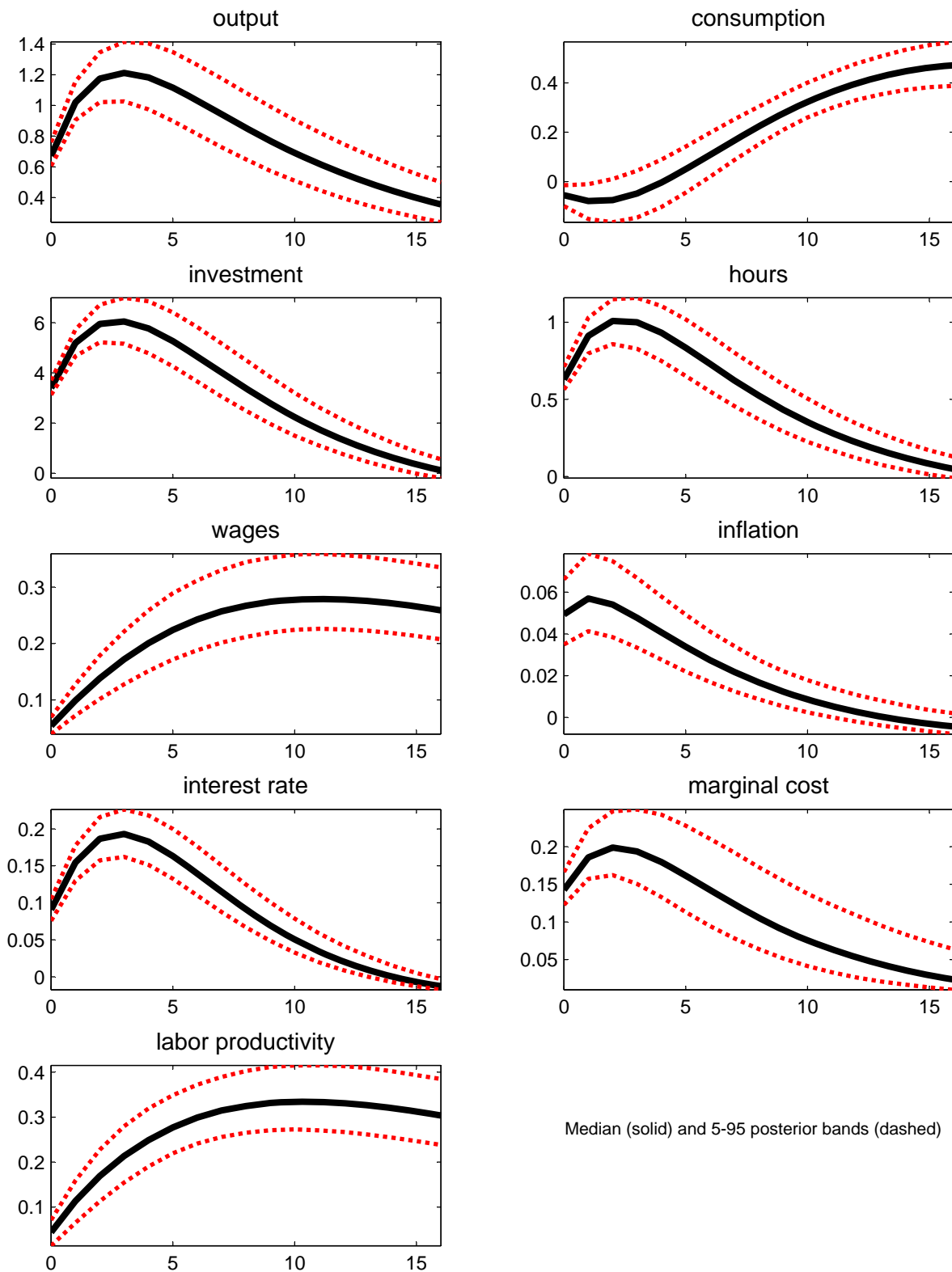


Figure 5: Impulse responses to a wage mark-up shock

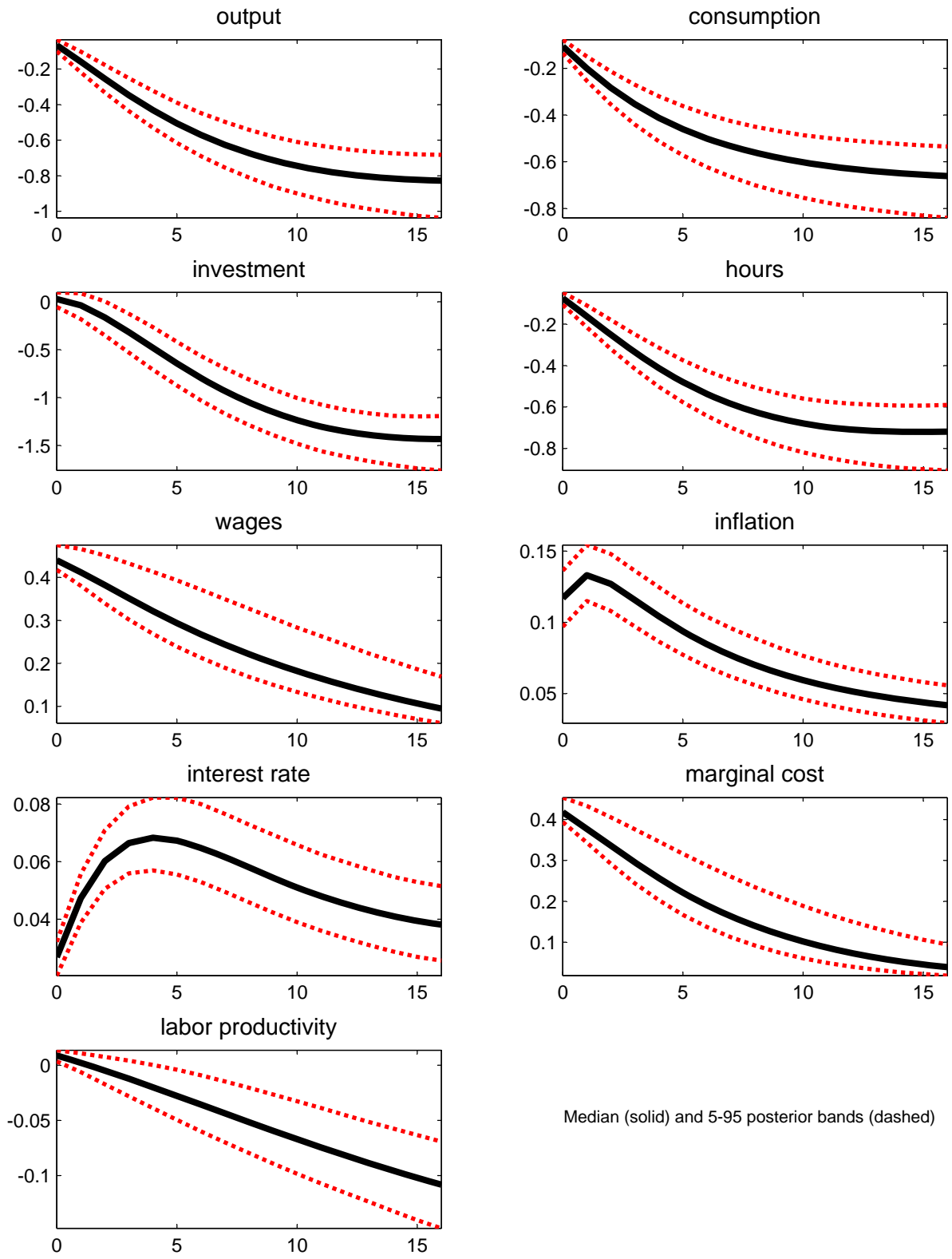
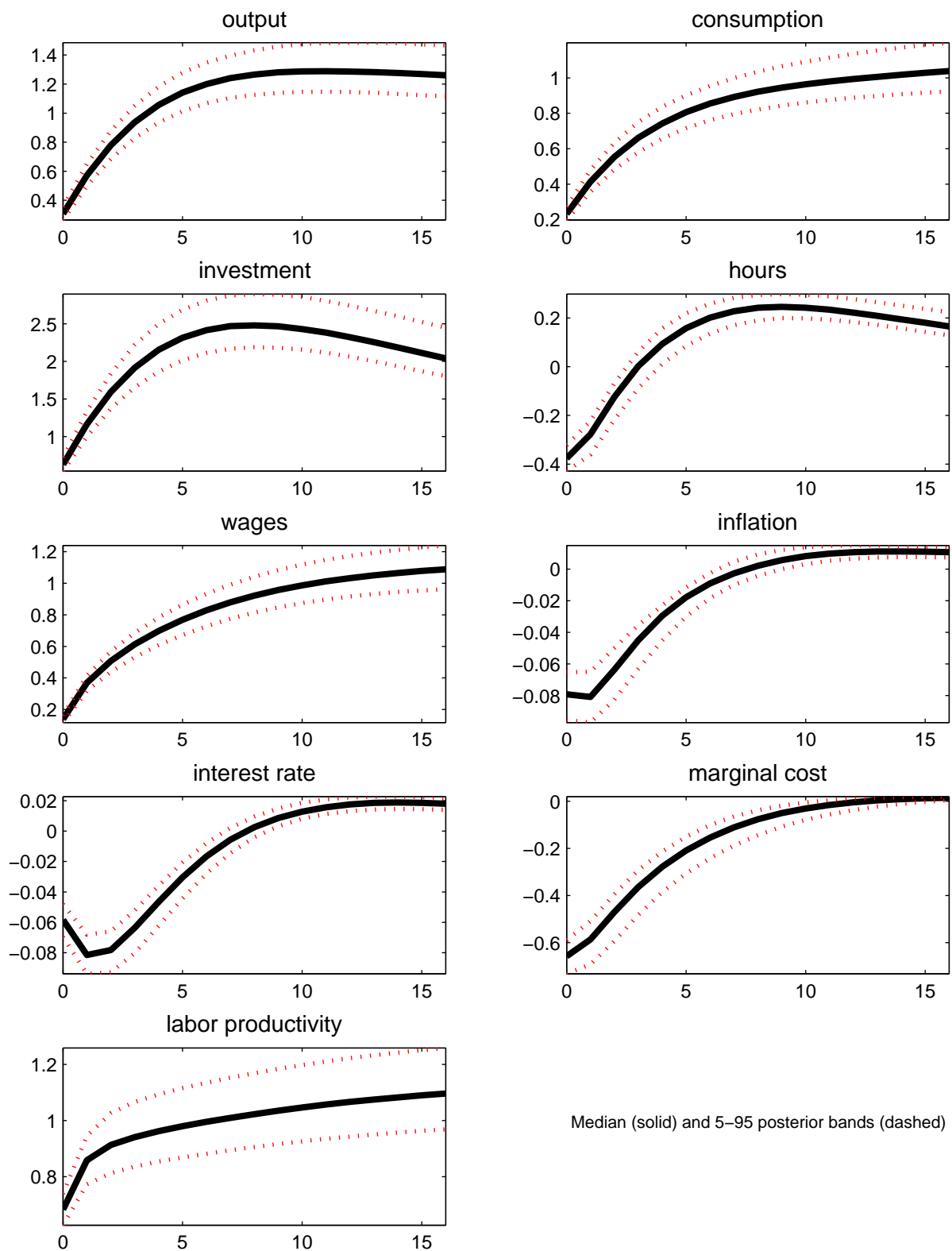


Figure 6: Impulse responses to a neutral technology shock



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