INVESTMENT SHOCKS AND THE RELATIVE PRICE OF INVESTMENT

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Abstract. We estimate a New-Neoclassical Synthesis business cycle model with two investment shocks. The first, an investment-specific technology shock, affects the transformation of consumption into investment goods and is identified with the relative price of investment. The second affects the production of installed capital from investment goods or, more broadly, the transformation of savings into the future capital input. We find that this shock is the most important driver of U.S. business cycle fluctuations in the post-war period and that it is likely to proxy for more fundamental disturbances to the smooth functioning of the financial sector. To corroborate this interpretation, we show that it correlates strongly with interest rate spreads and that it played a particularly important role in the recession of 2008.

Keywords: Business cycles, financial factors, investment-specific technology, DSGE model

1. Introduction

Discussion of the sources of business cycles has recently regained center stage in the public and academic debates, with the United States and the rest of the World mired in a severe recession. The proximate cause of this slump was a severe contraction in housing prices and activity, which precipitated, and has been fed by, a deep financial crisis.

These events are hard to reconcile with the conventional macroeconomic view of the past twenty five years, that business cycles are best understood as efficient responses of a frictionless economy to movements in total factor productivity. We argue that a more promising view of the driving forces of macroeconomic fluctuations in general, and of the current recession in particular, is one that attributes them largely to investment shocks—disturbances that affect the transformation of current savings into the future capital input.

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Greenwood, Hercowitz, and Huffman (1988) were the first to suggest that investment shocks could be a viable alternative to neutral technology shocks as sources of business cycles in a general equilibrium environment. The appeal of these disturbances was later enhanced by the work of Greenwood, Hercowitz, and Krusell (1997) and Fisher (2006). The former suggested that investment-specific technological progress—a kind of investment disturbance identified with trend reductions in the price of investment relative to consumption—is reponsible for the major share of growth in the post-war U.S. The latter showed, using structural VARs, that the shock responsible for permanent changes in the relative price of investment accounts for a large part of the fluctuations in output and hours. Both these contributions rely on the observation that, in equilibrium, technological improvements in the production of investment goods should be reflected in their relative price.

In a recent paper (Justiniano, Primiceri, and Tambalotti (2008), JPT hereafter), we showed that an investment shock that determines the efficiency of newly produced investment goods, as in Greenwood, Hercowitz, and Huffman (1988), is the key driver of business cycles in a medium-scale, estimated New-Neoclassical Synthesis model. Our procedure to identify this shock, however, ignored any restriction on its behavior imposed by the observation of the relative price of investment. In fact, our estimates implied an investment disturbance four times as volatile and only weakly correlated with available measures of the relative price of investment (see JPT, Section 7). Instead, using these measures to identify all investment shocks in an estimated DSGE model similar to ours, Schmitt-Grohe and Uribe (2008) found that their contribution to macroeconomic fluctuations is negligible.

In this paper, we study the relationship between investment shocks and the relative price of investment more closely. We do so in a generalization of the baseline model of JPT, in which the production of consumption, investment and capital goods is explicitly decentralized into separate sectors. The point of this stylized decentralization is to highlight that the process of capital accumulation can be affected by at least two kinds of shocks. On the one hand, investment-specific technology (IST) shocks influence the transformation of consumption into investment goods. On the other hand, shocks to the marginal efficiency of investment (MEI) affect the process by which investment goods are transformed into productive capital.

Our first contribution is to disentangle the role of these two shocks in business cycles. This is feasible because, in the equilibrium of our model, the IST shock is exactly equal to the inverse of the price of investment relative to consumption. When we impose this restriction, by including the relative price of investment among the observables, we find that MEI shocks are the single most important source of macroeconomic fluctuations. These shocks explain between 48 and 71 percent of the variance of output, hours and investment at business cycle frequencies, although they account for little of the volatility of consumption. On the contrary, the contribution of the IST shock is negligible, as in Schmitt-Grohe and Uribe (2008).[1]

The prominent role played by MEI shocks in business cycles leaves open the question of their ultimate origin. The paper's second contribution is to point out that these investment shocks might proxy for more fundamental disturbances to the intermediation ability of the financial system. This interpretation is based on the agency cost model of Bernanke and Gertler (1989) and Carlstrom and Fuerst (1997). Just like their agency cost, in fact, MEI shocks influence the efficiency with which investment goods can be turned into capital ready for production. To corroborate this interpretation, we show that the sequence of MEI shocks implied by our estimates is highly correlated with interest rate spreads and that it accounts for most of the fall in output and hours in 2007 and 2008.

One qualification to our results is that the equality between the relative price of investment and the inverse of IST productivity would not hold in general in more realistic versions of our multi-sector model. For example, if the production of investment goods takes place in a non-competitive sector with nominal rigidities, the resulting markup creates an endogenous wedge between the relative price of investment and the inverse of the IST shock, as we show in the Appendix. In fact, the presence of such a wedge is a common phenomenon in non-competitive economies (e.g. Floetotto, Jaimovich, and Pruitt (2009)).

The overall message we draw from these results is that the strategy of identifying all shocks to the capital accumulation process with the relative price of investment is not robust to reasonable generalizations of the simplest two-sector theoretical framework and can therefore deliver misleading results.

The paper proceeds as follows. Section 2 presents a streamlined multi-sector version of the canonical DSGE model for the study of business cycles. Section 3 derives an equivalent one-sector representation that highlights the role of investment shocks in the capital accumulation process. Sections 4 and 5 describe our approach to inference and the main estimation results,

[1] In a very recent paper on the soruces of the Great Moderation, Liu, Waggoner, and Zha (2009) also find that IST shocks identified with the relative price of investment account for almost none of the variability of macroeconomic variables, while a shock to depreciation plays a fairly important role.

with particular emphasis on the variance decomposition. Section 6 elaborates on the economic interpretation of MEI shocks. Section 7 concludes.

2. The Model

This section outlines our model of business cycles in the U.S. economy. It is a medium scale DSGE model with a neoclassical growth core, which we augment with several departures from the canonical assumptions on tastes, technology and market structure. All these departures are now quite common in the literature. This model is an ideal framework for the study of business cycles, for two reasons. First, it fits the data well, as demonstrated for example by Del Negro, Schorfheide, Smets, and Wouters (2007) and Smets and Wouters (2007). Second, it encompasses a number of views on the origins of business cycles that have been proposed in the literature.

Relative to JPT's baseline model, here we allow for non-stationary investment-specific technological progress. Moreover, we distinguish explicitly between consumption and investment goods on the one hand and installed capital on the other. These three goods are produced in three different sectors. In particular, a chain of intermediate and final good firms produces the final good, using capital and labor as inputs. The final good can either be consumed by households or used as an input by investment good producers. Investment goods, in turn, are used as inputs for the production of capital. The rest of the model is standard, with households who consume, accumulate capital, and supply labor services, and a government.

The multi-sector decentralization of the capital accumulation process we propose, although extremely streamlined, helps to clarify the distinction between shocks that affect the relative price of investment and shocks that do not. This distinction is crucial, since we want to discipline our inference on the role of investment shocks in business cycles with observations on the relative price of investment. The inclusion of this relative price among the observables in our estimation procedure is the second important difference in this paper with respect to the approach we followed in JPT.

2.1. **Consumption good producing sector.** The final consumption good is produced by a chain of intermediate and final good producers. We start by describing their optimization problems.

2.1.1. *Final good producers.* At every point in time t, perfectly competitive firms produce the final 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.

The final good is purchased at a price P_t both by households, who use it for consumption, and by the firms operating in the investment sector, who use it as an input for producing investment goods. Profit maximization and the zero profit condition imply that the price 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

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

2.1.2. *Intermediate goods producers.* Each intermediate good $Y_t(i)$ is produced by a monopolist according to the production technology

$$Y_t(i) = \max \left\{ A_t^{1-\alpha} K_t(i)^\alpha L_t(i)^{1-\alpha} - A_t \Upsilon_t^{\frac{\alpha}{1-\alpha}} F; 0 \right\}, \tag{2.2}$$

where $K_t(i)$ and $L_t(i)$ denote the amounts of effective capital and labor employed by firm i. A_t represents exogenous labor-augmenting technological progress or, equivalently, a *neutral technology shock*. The level of neutral technology is non-stationary and its growth rate ($z_t \equiv \Delta \log A_t$) follows a stationary AR(1) process

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

with $\varepsilon_{z,t}$ $i.i.d.N(0, \sigma_z^2)$. The variable Υ_t represents instead investment-specific technological progress, whose properties will be detailed below. The composite technological process $A_t \Upsilon_t^{\frac{\alpha}{1-\alpha}}$ multiplies the fixed costs of production, F, to ensure the existence of a stochastic growth path. We choose the value of F so that profits are zero in steady state (see Rotemberg and Woodford (1995) and Christiano, Eichenbaum, and Evans (2005)).

As in Calvo (1983), every period a fraction ξ_p of intermediate firms cannot optimally choose their 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

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

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 household that owns the firm, while W_t and r_t^k are the nominal wage and the rental rate of capital.

2.2. **Investment good producing sector.** Perfectly competitive firms purchase a fraction Y_t^I of the final good, transform it into investment goods (I_t) and sell them to capital producers at a price P_{It}. Their objective is to maximize the profit function

$$P_{It} I_t - P_t Y_t^I,$$

subject to the production technology

$$I_t = \Upsilon_t Y_t^I.$$

where the term Υ_t is a time varying slope of the linear production function and represents *investment-specific technological (IST) progress*. It is non-stationary and its growth rate ($\upsilon_t = \Delta \log \Upsilon_t$) evolves exogenously according to the process

$$\upsilon_t = (1-\rho_\upsilon)\gamma_\upsilon + \rho_\upsilon \upsilon_{t-1} + \varepsilon_{\upsilon,t},$$

with $\varepsilon_{\upsilon,t}$ $i.i.d. N(0, \sigma_\upsilon^2)$.

2.3. **Capital good producing sector.** Perfectly competitive firms purchase the investment good and transform it into installed capital, which is then sold to households. The technology for producing new capital, i_t, is given by

$$i_t = \mu_t \left(1 - S\left(\frac{I_t}{I_{t-1}} \right) \right) I_t. \tag{2.3}$$

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 $S'' > 0$. The shock μ_t corresponds to an exogenous disturbance to the *marginal efficiency of investment* (MEI) i.e. the efficiency with which investment goods can be transformed into capital, which is then used for production. 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 $i.i.d.N(0, \sigma_\mu^2)$.

The objective of capital producers is to maximize the expected discounted value of future profits

$$E_t \sum_{s=0}^{\infty} \beta^s \lambda_{t+s} \left[P_{kt+s} i_{t+s} - P_{It+s} I_{t+s} \right],$$

where P_{kt} denotes the price of installed capital. Their objective is intertemporal, due to the particular form of adjustment costs postulated in 2.3, whereby a higher level of investment today reduces installation costs tomorrow, everything else equal.

2.4. **Households.** Each household maximizes the utility function

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

where $C_t \equiv Y_t - Y_t^I$ is consumption, h is the degree of habit formation, $L_t(j)$ denotes the supply specialized labor 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

$$P_t C_t + P_{kt} i_t + T_t + B_t \leq R_{t-1} B_{t-1} + Q_t(j) + \Pi_t + W_t(j) L_t(j) + r_t^k u_t \bar{K}_{t-1} - P_t \frac{a(u_t)}{\Upsilon_t} \bar{K}_{t-1},$$

where 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 installed 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, expressed in terms of units of consumption, corresponds to $a(u_t)/\Upsilon_t$ per unit of physical capital. It is scaled by the technological progress in the investment good producing sector to ensure the existence of a balanced growth path. We assume $u_t = 1$ in steady state, $a(1) = 0$ and define $\chi \equiv \frac{a''(1)}{a'(1)}$. The physical capital accumulation equation is

$$\bar{K}_t = (1-\delta)\bar{K}_{t-1} + i_t,$$

where δ is the depreciation rate.

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" combine 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

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

In terms of wage setting, we also 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

$$W_t(j) = W_{t-1}(j) \left(\pi_{t-1} e^{z_{t-1} + \frac{\alpha}{1-\alpha} \upsilon_t} \right)^{\iota_w} \left(\pi e^{\gamma_z + \frac{\alpha}{1-\alpha} \gamma_\upsilon} \right)^{1-\iota_w}.$$

The remaining fraction of households chooses instead an optimal wage by maximizing their utility, subject to the labor demand function.

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

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

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

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 GDP gap (X_t/X_t^*).[2] 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 $i.i.d.N(0, \sigma_{mp}^2)$.

[2] The GDP gap is the difference between actual GDP $(C_t + I_t + G_t)$ and its efficient level (Woodford (2003)).

2.6. **Model solution.** In this model, consumption, investment, capital, real wages and output fluctuate around a stochastic balanced growth path, since the levels of neutral and investment-specific technology have a unit root. The resulting composite trend is given by $A_t \Upsilon_t^{\frac{\alpha}{1-\alpha}}$, with steady state growth rate

$$\gamma_* = \gamma_z + \frac{\alpha}{1-\alpha}\gamma_\upsilon.$$

Therefore, the solution involves the following steps. First, we rewrite the model in terms of detrended stationary 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.

3. Investment Shocks and the Relative Price of Investment

The model we just presented distinguishes between consumption, investment and newly installed capital, and therefore produces explicit expressions for their equilibrium prices. For instance, profit maximization by the competitive investment good producers implies that their price (P_{It}) should equal marginal cost ($P_t \Upsilon_t^{-1}$). As a result, the price of investment in terms of consumption goods coincides with the inverse of the IST process

$$\frac{P_{It}}{P_t} = \Upsilon_t^{-1}. \tag{3.1}$$

Thanks to this equilibrium condition, we can derive a one-sector representation of the model. The zero profit condition of capital producers implies

$$P_{kt} i_t = P_t \tilde{I}_t, \tag{3.2}$$

where $\tilde{I}_t \equiv \frac{P_{It}}{P_t} I_t$ is real investment in units of consumption goods. The substitution of equations (3.1), (3.2) and (2.3) into the households' budget constraint and the capital accumulation equation yields a one-sector model comparable to those in Altig, Christiano, Eichenbaum, and Linde (2005), Smets and Wouters (2007) or JPT. This one-sector representation of the model features an accumulation equation for physical capital of the form

$$\bar{K}_t = (1-\delta)\bar{K}_{t-1} + \mu_t \Upsilon_t \left(1 - S_t\right) \tilde{I}_t, \tag{3.3}$$

where $S_t \equiv S\left(I_t / I_{t-1}\right)$ denotes the installation cost paid at time t.

The accumulation process captured by equation (3.3) is affected by two disturbances: the IST shock Υ_t and the MEI shock μ_t. This distinction between two investment shocks sets our model apart from those in most existing studies, which either equate the combined shock to the relative price of investment, thus implicitly ignoring μ_t (e.g. Schmitt-Grohe and Uribe (2008), Altig, Christiano, Eichenbaum, and Linde (2005)), or treat the two disturbances as a unique unobservable shock (e.g. Smets and Wouters (2007), JPT).

In this paper, we can separately identify the two disturbances because we use observations on the relative price of investment to pin down the evolution of IST progress, as suggested by equation (3.1). The discipline imposed by this approach on the properties of the IST shock implies that its contribution to fluctuations is negligible, as we will see in section 5. On the contrary, the MEI shock plays a key role in business cycles. The estimation procedure by which we achieve this identification is described in the next section.

4. Bayesian Inference and the Observable Variables

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. In the rest of this section we discuss the data used to evaluate the likelihood function and the specification of the priors.

4.1. **Data.** We estimate the model using

$$[\Delta \log X_t, \Delta \log C_t, \Delta \log I_t, \log L_t, \Delta \log \frac{W_t}{P_t}, \pi_t, R_t, \Delta \log \frac{P_{It}}{P_t}] \tag{4.1}$$

as the vector of observable variables, where Δ denotes the temporal difference operator. We use quarterly data and our dataset covers the period from 1954QIII to 2008QIII (final release).

All data are extracted from Haver Analytics. We construct real GDP by diving the nominal series by population and the chain-weighted deflator for consumption of non-durables and services, which, in line with the model, we choose as the numeraire. The real series for consumption and investment are obtained in the same manner. We define consumption as personal consumption expenditures on non-durables and services, while investment is the sum of personal consumption expenditures on durables and gross private domestic investment. We measure the labor input by the log of hours of all persons in the non-farm business sector divided by population, while real wages correspond to nominal compensation per hour in the non-farm business sector, divided by the consumption deflator. The quarterly log difference in the consumption deflator is our measure of inflation. It tracks pretty closely the deflator for aggregate output. For nominal interest rates we use the effective Federal Funds rate.

Finally, the relative price P_{It}/P_t corresponds to the ratio of the chain weighted deflators for consumption and investment as defined above. Hence, for the numerator we rely on National Income and Product Accounts (NIPA) deflators for durable consumption and private investment. Some authors have argued that NIPA's quality adjustments may underestimate the rate of technological progress in areas such as equipment and software (e.g. Gordon (1990) and Cummins and Violante (2002)). This adjustment problem, in turn, could distort the measured contribution of IST change to both growth and business cycles. For this reason, Greenwood, Hercowitz, and Krusell (1997) and Fisher (2006), for example, prefer to measure P_{It}—totally or in part—with Gordon's price series for producer durable equipment, as later updated by Cummins and Violante (hereafter the GCV deflator).

We prefer to work with NIPA deflators for our baseline estimates, since we want our sample to include the current recession, while the GCV deflator is only available until the end of 2000. Furthermore, the Bureau of Economic Analysis has introduced hedonic price indexes (in partnership with IBM) to control for quality changes in computers and peripherals, starting in 1985 . These adjustments have been extended back to 1959 to account for discontinuities, now include additional categories of goods, and deliver price declines in line with other studies based on microdata (e.g. Landefeld and Grimm (2000)).

Nonetheless, it is important to check the robustness of our results to the use of the GCV deflator, given our focus on the role of the relative price of investment in the identification of investment shocks. Therefore, we construct an alternative price index for investment by chain-weighting consumer durables, private investment in residential and non-residential structures (using NIPA deflators) and private equipment and software (using the GCV series).[3] We plot the (log) relative prices of investment to consumption (P_{It}/P_t) resulting from the two measurement procedures (NIPA and GVC) in Figure 1. The use of the GCV deflator for equipment and software results in a faster rate of decline, as also noted by Fisher (2006). In particular, the mean of $\Delta \log \frac{P_t^I}{P_t}$ from 1954:III to 2000:IV is -0.37 using NIPA data, but -0.51 with the GCV measure.

[3] The GCV deflator excludes inventories from the price of investment, although these are present in our real investment measure.

The relative price seems to exhibit a break in trend sometime around 1982:I (denoted by a dashed vertical line in Figure 1), regardless of how it is measured. The mean growth rate of the NIPA relative price falls from -0.15 for the 1954:III-1981:IV period to about -0.6 in the second part of the sample. The corresponding averages for the GCV deflator are -0.3 and -0.78 respectively. To account for this possible break when taking our model to the data, we allow the average growth rate of the IST process to vary before and after 1982:I, while keeping all other parameters unchanged.

4.2. **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 summarizes the priors for the remaining parameters of the model. These priors are relatively disperse and broadly in line with those adopted in previous studies (e.g. Del Negro, Schorfheide, Smets, and Wouters (2007) and Justiniano and Primiceri (2007)). In particular, we retain the same priors as in JPT's baseline model, except for the coefficients of the IST process, which does not appear in that model.

In line with the evidence in Figure 1, we allow for different Gaussian priors for the IST growth rates pre and post-1982, γ_υ^1 and γ_υ^2 respectively. We adopt a similar approach for the growth rates of the composite trend γ_*, given that it depends on γ_υ, and that all real series grow at a lower rate in the second sub-sample.

For most persistence parameters, we use a Beta prior with mean 0.6 and standard deviation 0.2. For the autocorrelation of neutral (z) and investment-specific (υ) technology shocks instead we center the prior at 0.4, since they already include a unit root. This is also the mean of the prior for the persistence of the monetary policy because the policy rule already allows for interest rates inertia.

Regarding the remaining shocks, 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. The priors on the innovations' standard deviations are quite disperse and chosen to generate volatilities for the endogenous variables broadly in line with the data. The covariance matrix of the innovations is diagonal.

5. Estimation Results

This section presents our main results in terms of parameter estimates, impulse responses and business cycle variance decomposition.

5.1. **Posteriors: parameters and impulse responses.** The last column of Table 1 report the posterior estimates of the model's parameters. Most estimates are in line with previous DSGE studies and change very little relative to JPT's baseline. Perhaps surprisingly, the MEI shock μ_t remains quite volatile, even if the IST shock now also perturbs the investment Euler equation.

By construction, the properties of the IST shock are consistent with those of the relative price of investment. In particular, the average growth rates of the ISTS are 0.19% and 0.60% in the first and second subsamples respectively. Therefore, according to our estimates, technological improvements specific to the investment goods producing sector are responsible for approximately 10% of economic growth in $1954-1982$ and for about 40% in $1983-2008$.

To provide another perspective on the comparability of the posterior estimates in Table 1 with those in the literature, Figure 2 displays the impulse responses to the MEI shock μ_t. Following a positive shock, output, hours, investment and labor productivity all rise persistently and in a hump-shaped pattern. On the contrary, consumption increases only after a few periods. The fact that these responses closely resemble those in JPT suggests that the observability of the relative price of investment does not affect significantly the inference on the MEI shock μ_t. This conclusion is confirmed in the next section, where we study the contribution of all shocks to business cycle fluctuations.

5.2. **Investment shocks and business cycles.** In this section, we present the variance decomposition for our model at business cycle frequencies and compare it to that in JPT.

Table 2 reports the contribution of the eight shocks in the model to the variance of macroeconomic variables at business cycle frequencies. The first result we want to stress is that IST progress plays virtually no role in business cycles, although it is crucial to long-run growth. This result is in line with the findings in Schmitt-Grohe and Uribe (2008). In a real model with frictions similar to ours, they find that IST shocks—contemporanous or anticipated—account for 0 percent of the fluctuations in output, consumption, investment and hours. They also identify IST progress with the relative price of investment, as we do here.

The second key result that emerges from Table 2 is that MEI shocks are the key drivers of business cycle fluctuations. They are responsible for 48, 64 and 71 percent of the variance of GDP, hours and investment respectively, although they explain little of consumption variability. These shares are almost identical (48, 64 and 77) when we use the GCV investment deflator. In general, this model's variance decomposition demonstrates that the inclusion of the relative price of investment among the observables has almost no impact on the view of business cycles presented in JPT, as long as we recognize that not all investment shocks must be reflected in the relative price of investment.

The negligible role of IST shocks in business cycles deserves some qualification. Our model, in fact, imposes a straightjacket on these shocks: they must equal the observed relative price of invesment period by period. But this equality would not hold in richer, and arguably more realistic, environments.

For example, in an economy in which the production of investment goods employs capital and labor as inputs, and faces the same kind of nominal rigidity as that of consumption, the relative price of investment is influenced by IST progress, but also by other disturbances. This is because the markups in the two sectors in general differ over the cycle, due to the sector-specific nature of technological change, and thus of marginal costs. The ratio of these two markups would thus create a wedge between the relative price of investment and the inverse of the IST shock, as illustrated in appendix A.

Investigating the implications of this wedge for the transmission of investment shocks and their contribution to business cycles would require estimating the two-sector model of the economy described above, since a one-sector representation of such a model is not readily available. This is a task we leave to future research. In the meantime, we did conduct an alternative experiment, to test the robustness of our results to the presence of a wedge in the relative price of investment. To keep things simple, we just augmented our model with an exogenous wedge between the IST shock and the relative price. The results on the origins of business cycles described above change little in this extended model.[4]

[4] In this model, the contribution of MEI shocks to the business cycle variance of output and hours is 48 and 64 percent respectively. Details on this model, and on its variance decomposition, are available from the authors upon request.

6. Interpreting the Results: What is μ_t?

In section 5, we found that business cycles are largely driven by shocks that affect the transformation of investment goods into installed capital, rather than that of consumption into investment goods. In the model, these MEI shocks represent disturbances to the process by which investment goods—idle pieces of machinery just pushed out the door of the factory that produced them—are turned into capital inputs ready for production. This process entails a waste of physical resources in the form of installation costs, as well as an exogenous random element represented by μ_t. Sometimes the creation of productive capital is a smooth and efficient process, sometimes it is not.

In the real world, the most important influence on this process is probably the efficiency of financial markets. For example, if capital producers need to borrow to purchase investment goods, the creation of productive capital will be affected by their access to credit. Thus, one possible interpretation of the random term μ_t is as a proxy for the effectivness of the financial system in channeling household savings into productive capital.

To be more specific, it is useful to refer to the financial accelerator model of Carlstrom and Fuerst (1997)[5] In their model, entrepreneurs are the only agents with access to the technology to produce installed capital. To finance their activity, they borrow from households, through intermediaries, but their productivity is private information. The resulting agency costs represent a drain of resources in the capital formation process, so that the (physical) capital accumulation equation takes the form

$$\bar{K}_t = (1 - \delta)\bar{K}_{t-1} + (1 - \Phi_t)\, I_t,$$

where Φ_t is the aggregate amount of resources lost in the financial intermediation process. In equilibrium, this loss corresponds to the expected cost of monitoring default. This expression compares to our accumulation equation

$$\bar{K}_t = (1 - \delta)\bar{K}_{t-1} + \mu_t\,(1 - S_t)\, I_t.$$

In these two equations, both the MEI shock μ_t, net of the adjustment costs S_t, and the agency cost Φ_t, act as disturbances in the transformation of investment goods into physical capital.

[5] Chari, Kehoe, and McGrattan (2007) demonstrate the equivalence between the economy of Carlstrom and Fuerst (1997) and a prototypical growth model with an investment wedge very similar to our investment shock μ_t.

In fact, Carlstrom and Fuerst (1997) point out that their framework "is isomorphic to a model in which there are costs to adjusting the capital stock." More precisely, their assumptions result in a supply curve for new productive capital (i in our notation) that is shifted by changes in entrepreneurial net worth. Intuitively, an increase in net worth reduces the cost of external borrowing and boosts the production of capital goods. In our model, the MEI shock plays a similar economic role to that of net worth in Carlstrom and Fuerst (1997), acting as a shifter of the investment supply function. The important difference is that μ_t is just an exogenous shock in our framework, while net worth is a key endogenous variable in the agency cost model.

Figure 3 sheds more light on this relationship, by comparing the cyclical behavior of the μ_t series implied by our estimation to that of a measure of the external finance premium, the spread between the yields of the lowest rated category (Baa) of investment grade securities and the highest category (Aaa) (Levin, Natalucci, and Zakrajsek (2004)). These two series have a strong negative correlation, indicating that MEI shocks indeed tend to be negative when financial markets function less smoothly.[6] In particular, the spike in spreads in 2008QIV is associated with a large negative realization of the MEI shock.

To further corroborate the interpretation of MEI shocks as a proxy for the overall health of the financial system, Figure 4 focuses on the contribution of these shocks to the recession of 2008. This is a useful reality check on the role of these shocks, since most observers would agree that this recession, and the slowdown in growth that preceded it, were triggered and further propagated by a sequence of disruptions in financial markets.

The figure compares the evolution of output and hours in the data (the black solid line) and in a version of the model buffeted only by MEI shocks (the grey dashed line), starting at the through of the last recession (2001QIV). The model has eight shocks in total and their combination replicates the data exactly. Therefore, it is not surprising that the MEI shock alone does not track the ups and downs of the two series precisely. However, the coherence in the movements of the actual and counterfactual lines over the cycle is remarkable. In particular, μ_t generates a fall in the growth rate of output and hours that starts in 2006 and accelerates in 2008, replicating almost exactly the depth of the recession as of the end of 2008.

[6] We obtain similar correlations with the spread between Baa and Treasuries with similar maturity.

7. Concluding Remarks

In this paper, we showed that identifying all disturbances to the process of capital accumulation with the inverse of the relative price of investment can lead to misleading inferences on the role of these shocks in business cycles. We presented a simple model in which the transformation of consumption goods into investment goods and of the latter into productive capital are both affected by stochastic shocks. The contributions of these two shocks to macroeconomic fluctuations can be disentangled because only the former—investment-specific technology shocks—affect the relative price of investment. In an estimated version of this model, shocks to the production of the capital input—marginal efficiency of investment shocks—emerge as the predominant sources of variability in the key macroeconomic variables at business cycle frequencies.

Our estimated model has three main shortcomings, on which we count to work in the near future. First, it implies a countercyclical price of capital. Addressing this problem requires a more elaborate model of the capital accumulation process, as in Christiano, Motto, and Rostagno (2007) and Comin, Gertler, and Santacreu (2009), or of the frictions that impede the allocation of resources across sectors (e.g. Christiano and Fisher (2003)).

Second, the short-run comovement of consumption with the other macroeconomic variables conditional on MEI shocks is weak, as shown in JPT. As a result, these shocks account for only a small fraction of the variance of consumption. The introduction of preferences with a weak wealth effect, as in Greenwood, Hercowitz, and Huffman (1988) and Jaimovich and Rebelo (2009), should help ameliorate this problem.

Third, a very active strand of the literature on the sources of fluctuations focuses on the contrbution of news shocks. This literature includes the seminal contribution of Beaudry and Portier (2006), which pointed to the empirical importance of these shocks, as well as work in general equilibrium environments by Davis (2007), Christiano, Ilut, Motto, and Rostagno (2007), Schmitt-Grohe and Uribe (2008) and Jaimovich and Rebelo (2009). The mechanisms through which anticipated shocks can generate comovement among macroeconomic variables are similar to those transmitting investment shocks (Jaimovich and Rebelo (2009) and JPT). Therefore, incorporating news shocks in our framework should prove an interesting avenue for future research.

Appendix A. IST and the Relative Price: the Case of Sticky Prices

In this Appendix, we develop a more articulated model of the production of consumption and investment goods than the one presented in the main text. In particular, we assume that both goods are produced using capital and labor as inputs by a continuum of monopolistically competitive firms. Moreover, all these firms face a time-dependent constraint on their ability to reset prices, as for the intermediate-goods producing firms in the text. Compared to the baseline model, we strip away some complications, which are immaterial to the conclusions.

Our objective is to show that, in a model of this kind, the relative price of investment in terms of consumption is in general not equal to the inverse of the investment-specific technology factor.

A.1. **Consumption and investment producers.** A continuum of monopolistically competitive firms produces consumption goods according to the technology

$$C_t(j) = \left[A_t L_{Ct}(j)\right]^{1-\alpha} K_{Ct}(j)^{\alpha},$$

where we are ignoring the presence of fixed costs.

Similarly, the production of investment goods follows

$$I_t(j) = \Upsilon_t \left[A_t L_{It}(j)\right]^{1-\alpha} K_{It}(j)^{\alpha},$$

where Υ_t denotes IST progress. These two kinds of intermediate goods are aggregated into final consumption and investment goods by competitive firms, as in the baseline model.

The capital and labor inputs are homogenous and command a wage W_t and a rate of return r_t^k respectively. As a result, cost minimization by intermediate firms yields first order conditions

$$\begin{aligned} MC_{Ct}(j)(1-\alpha)A_t^{1-\alpha}\left(\frac{K_{Ct}(j)}{L_{Ct}(j)}\right)^{\alpha} &= W_t \\ MC_{Ct}(j)\,\alpha A_t^{1-\alpha}\left(\frac{K_{Ct}(j)}{L_{Ct}(j)}\right)^{\alpha-1} &= r_t^k \end{aligned}$$

in the consumption sector and

$$\begin{aligned} MC_{It}(j)(1-\alpha)\Upsilon_t A_t^{1-\alpha}\left(\frac{K_{It}(j)}{L_{It}(j)}\right)^{\alpha} &= W_t \\ MC_{It}(j)\,\alpha\Upsilon_t A_t^{1-\alpha}\left(\frac{K_{It}(j)}{L_{It}(j)}\right)^{\alpha-1} &= r_t^k \end{aligned}$$

in the investment sector, where MC denotes the nominal marginal cost. The homogeneity of factor markets implies that the capital labor ratio is the same for all firms and sectors

$$\frac{K_{It}(j)}{L_{It}(j)} = \frac{K_{Ct}(j)}{L_{Ct}(j)} = \frac{\alpha}{1-\alpha}\frac{W_t}{r_t^k}$$

$\forall j$, which implies the following relationship between marginal costs across sectors

$$\frac{MC_{It}}{MC_{Ct}} = \Upsilon_t^{-1}. \tag{A.1}$$

In a perfectly competitive environment with flexible prices, price is always equal to marginal cost, from which we would obtain that the relative price of investment is equal to the inverse of IST progress

$$\frac{P_{It}}{P_{Ct}} = \Upsilon_t^{-1}.$$

The identical constant returns to scale production functions and the free flow of inputs between the two sectors imply that the rate of transformation between consumption and investment goods in the flexible price equilibrium is simply Υ_t, as in our baseline model.

A.2. **Sticky prices and the relative price wedge.** When prices are sticky in both sectors, it is useful to rewrite A.1 as

$$\frac{s_{It}P_{It}}{s_{Ct}P_{Ct}} = \Upsilon_t^{-1},$$

where s denotes the real marginal cost, or the inverse of the equilibrium markup. This implies

$$\frac{P_{It}}{P_{Ct}} = \frac{s_{Ct}}{s_{It}}\Upsilon_t^{-1}, \tag{A.2}$$

from which we see that the ratio of the equilibrium markups in the two sectors drives a wedge between the actual relative price and its counterpart in the competitive equilibrium, the inverse of the IST factor.

The question then becomes, under what circumstances do equilibrium markups in the two sectors coincide? We now show that the answer is never, even if we assume that the form and degree of nominal rigidity in the two sectors are the same. This demonstration follows along the lines of Proposition 3 in Benigno (2004). He shows that the efficient flexible price outcome is not feasible in a two-region economy with nominal rigidities in both. Here, we substitute two sectors to the two regions, and consider a more general production structure, but the essence of the argument remains the same.

Assume that prices are sticky in both sectors, according to the same time-dependent scheme described in the main text, with common parameter ξ_p, but with no indexation. The log-linearized Phillips curves are then

$$\begin{aligned}\hat{\pi}_{Ct} &= \beta E_t \hat{\pi}_{Ct+1} + \kappa \hat{s}_{Ct} + \kappa \hat{\lambda}_{pt} \\ \hat{\pi}_{It} &= \beta E_t \hat{\pi}_{It+1} + \kappa \hat{s}_{It} + \kappa \hat{\lambda}_{pt}\end{aligned}$$

with $\kappa \equiv \frac{(1-\xi_p \beta)(1-\xi_p)}{\xi_p}$. Taking first differences, and using equation A.2, we obtain

$$\hat{\pi}_{It} - \hat{\pi}_{Ct} = \beta E_t \left(\hat{\pi}_{It+1} - \hat{\pi}_{Ct+1} \right) + \kappa \left(\hat{s}_{It} - \hat{s}_{Ct} \right). \tag{A.3}$$

This equation, together with A.2, allows us to prove the following proposition.

Proposition 1. *An equilibrium of the two-sector economy described above, in which $P_{It}/P_{Ct} = \Upsilon_t^{-1}$ $\forall t = 1, ..., \infty$, is not feasible when prices are sticky in both sectors.*

Proof. If $P_{It}/P_{Ct} = \Upsilon_t^{-1}$ $\forall t = 1, ..., \infty$, then A.2 implies $s_{Ct} = s_{It}$ $\forall t = 1, ..., \infty$. From A.3, this implies $\hat{\pi}_{It} - \hat{\pi}_{Ct} = 0$ $\forall t = 1, ..., \infty$, or $P_{It}/P_{Ct} = P_{I0}/P_{C0}$ $\forall t = 1, ..., \infty$. A contradiction. □

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Table 1: Prior densities and posterior mode for baseline model

Coefficient	Description	Prior: Prior Density[1]	Prior: Mean	Prior: Std	Posterior: Mode[2]
α	Capital Share	N	0.30	0.05	0.17
ι_p	Price indexation	B	0.50	0.15	0.16
ι_w	Wage indexation	B	0.50	0.15	0.09
γ_*^1	SS composite technology growth rate (first sample)	N	0.40	0.025	0.39
γ_υ^1	SS IST growth rate (first sample)	N	0.20	0.025	0.19
γ_*^2	SS composite technology growth rate (second sample)	N	0.30	0.025	0.31
γ_υ^2	SS IST growth rate (second sample)	N	0.60	0.025	0.60
h	Consumption habit	B	0.50	0.10	0.85
λ_p	SS mark-up goods prices	N	0.15	0.05	0.24
λ_w	SS mark-up wages	N	0.15	0.05	0.15
$logL^{ss}$	SS hours	N	0.00	0.50	0.87
$100(\pi-1)$	SS quarterly inflation	N	0.50	0.10	0.65
$100(\beta^{-1}-1)$	Discount factor	G	0.25	0.10	0.14
ν	Inverse Frisch elasticity	G	2.00	0.75	4.47
ξ_p	Calvo prices	B	0.66	0.10	0.81
ξ_w	Calvo wages	B	0.66	0.10	0.69
χ	Elasticity capital utilization costs	G	5.00	1.00	5.25
S''	Investment adjustment costs	G	4.00	1.00	2.42
Φ_p	Taylor rule inflation	N	1.70	0.30	1.97
Φ_y	Taylor rule output	N	0.13	0.05	0.06
Φ_{dy}	Taylor rule output growth	N	0.125	0.05	0.23
ρ_R	Taylor rule smoothing	B	0.60	0.20	0.84

(Continued on the next page)

Table 1: Prior densities and posterior mode for baseline model

Coefficient	Description	Prior: Prior Density [1]	Prior: Mean	Prior: Std	Posterior: Mode [2]
ρ_{mp}	Monetary Policy	B	0.40	0.20	0.09
ρ_z	Neutral technology growth	B	0.40	0.20	0.33
ρ_υ	Investment specific technology growth	B	0.40	0.20	0.18
ρ_g	Government spending	B	0.60	0.20	0.99
ρ_p	Price mark-up	B	0.60	0.20	0.97
ρ_w	Wage mark-up	B	0.60	0.20	0.99
ρ_b	Intertemporal preference	B	0.60	0.20	0.53
ρ_μ	Marginal efficiency of investment	B	0.60	0.20	0.76
θ_p	Price mark-up MA	B	0.50	0.20	0.77
θ_w	Wage mark-up MA	B	0.50	0.20	0.95
σ_{mp}	Monetary policy	I	0.10	1.00	0.21
σ_z	Neutral technology growth	I	0.50	1.00	0.94
σ_g	Government spending	I	0.50	1.00	0.35
σ_υ	Investment specific technology growth	I	0.50	1.00	0.61
σ_p	Price mark-up	I	0.10	1.00	0.19
σ_w	Wage mark-up	I	0.10	1.00	0.22
σ_b	Intertemporal preference	I	0.10	1.00	0.05
σ_μ	Marginal efficiency of investment	I	0.50	1.00	4.96
(log) Likelihood					-1382.0
(log) Posterior					-1398.0

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 (σ) 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-Gamma1 distribution

[2] Posterior mode obtained by initializing multiple optimization runs from random starting values drawn from the support of the priors.

Table 2: Variance decomposition at business cycle frequencies[1] in the baseline model

Series \ Shock	**Monetary Policy**	**Neutral technology**	**Government**	**Investment specific technology**	**Price mark-up**	**Wage mark-up**	**Intertemporal preference**	**Marginal efficiency of investment**
Output	0.03	0.35	0.02	0.00	0.04	0.04	0.03	0.48
Consumption	0.01	0.39	0.02	0.00	0.00	0.09	0.44	0.04
Investment	0.03	0.18	0.00	0.01	0.04	0.01	0.01	0.71
Wages	0.00	0.58	0.00	0.00	0.25	0.13	0.00	0.04
Relative Price	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00
Hours	0.05	0.12	0.02	0.00	0.06	0.06	0.04	0.64
Inflation	0.03	0.24	0.00	0.00	0.29	0.27	0.01	0.14
Interest Rates	0.15	0.14	0.01	0.00	0.04	0.05	0.06	0.55

[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 5000 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. Computed at the mode reported in table 1. Notice that shares add up to one.

Figure 1: (Log) Relative price of investment to consumption when using NIPA and GCV deflators for E&S

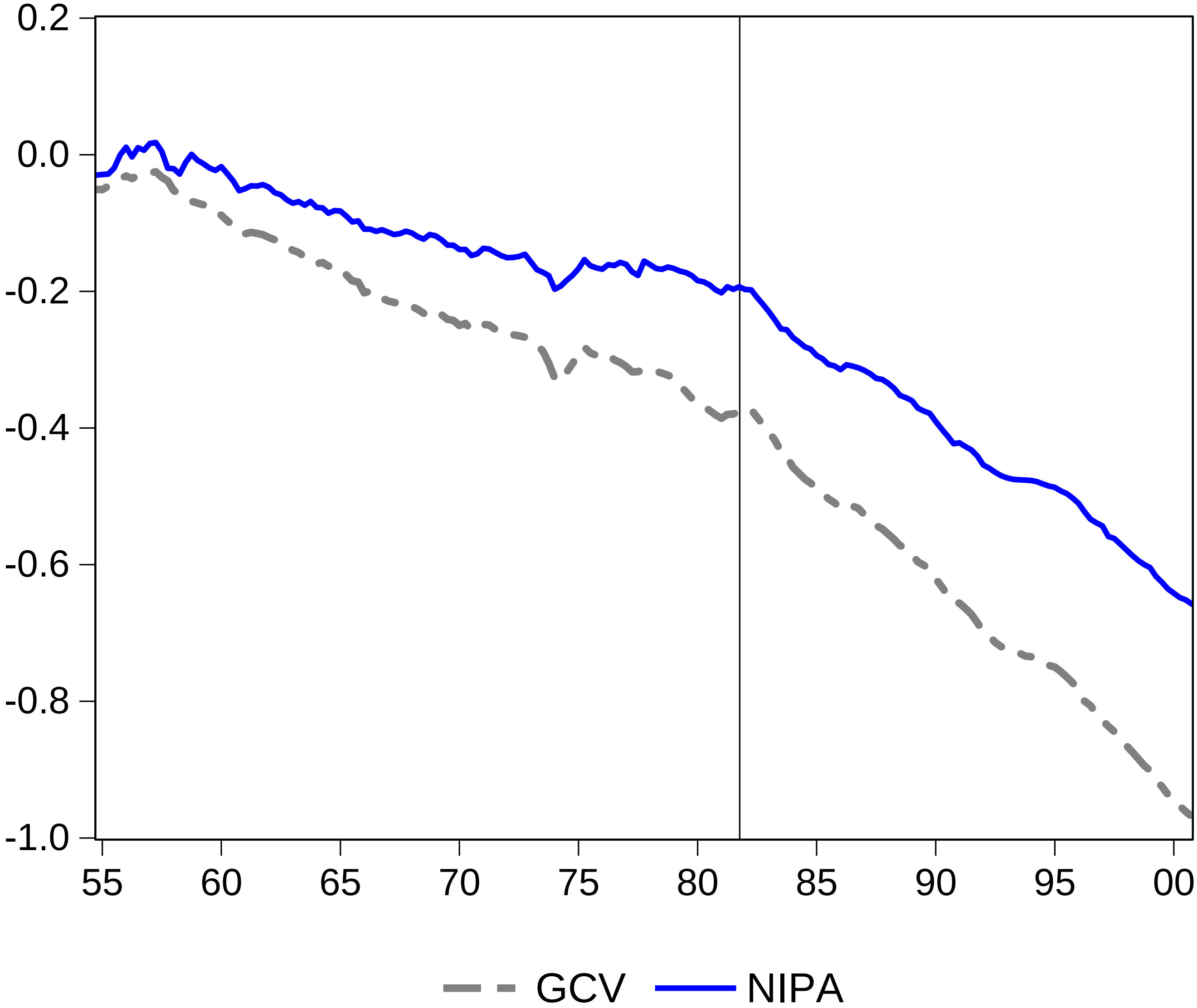

Figure 2: Impulse response to a MEI shock

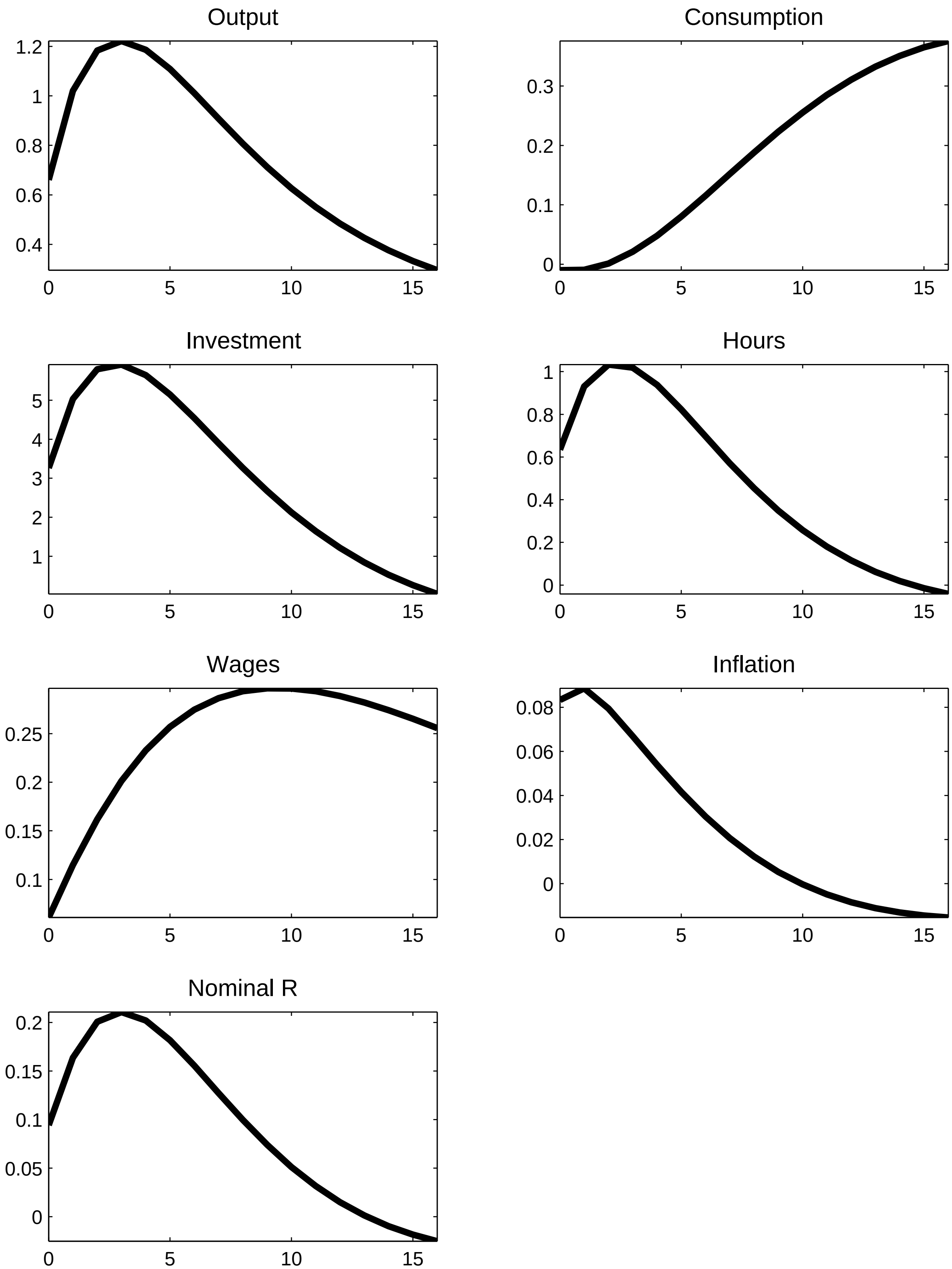

Figure 3: Credit spreads and MEI shocks

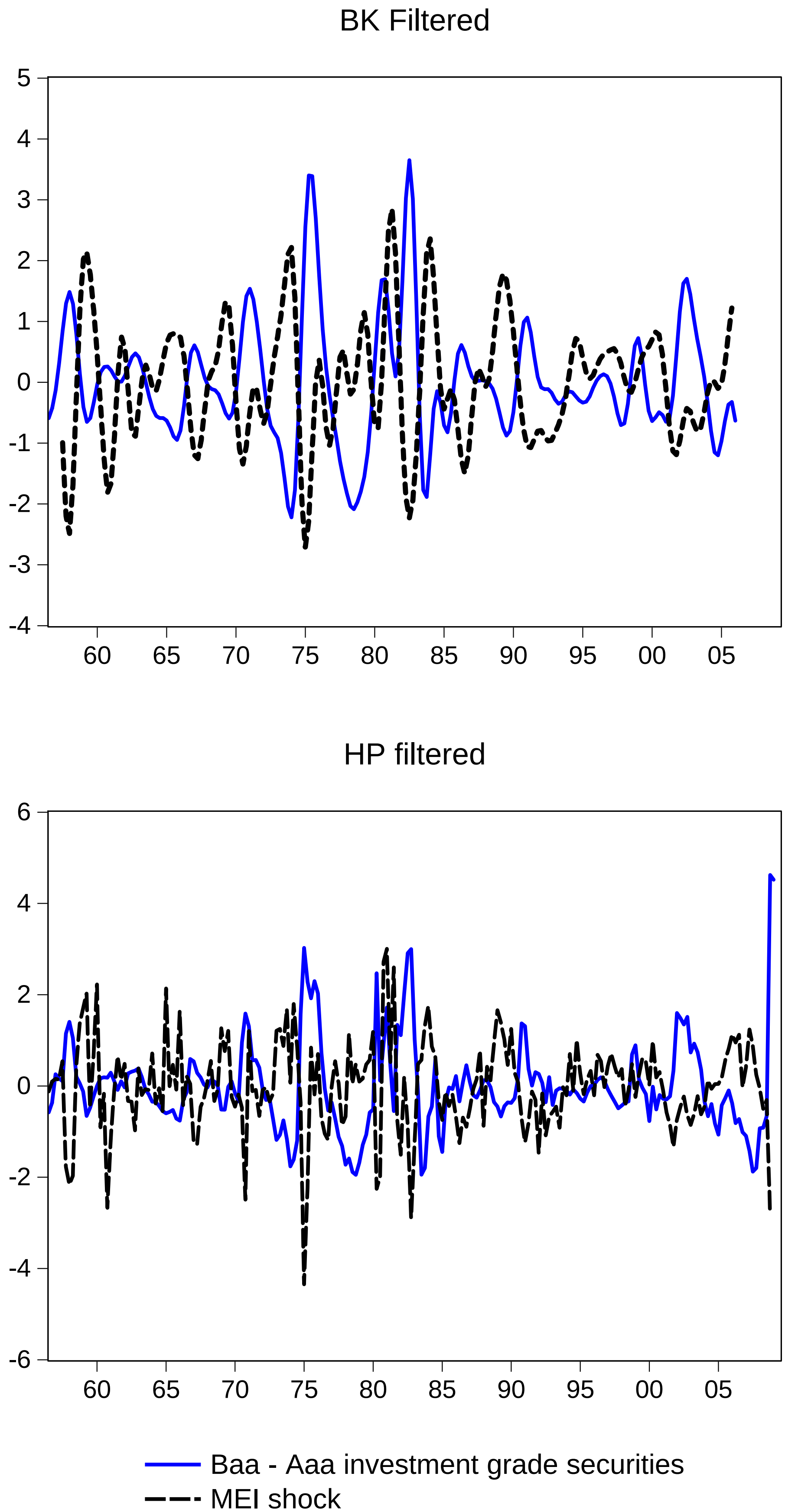

Figure 4: Recent fluctuations in output and hours explained by MEI shocks only