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Financial frictions and the role of investment specific technology shocks in the business cycle*

Güneş Kamber†
Reserve Bank of New Zealand

Christoph Thoenissen‡
Victoria University of Wellington and CAMA

Christie Smith§
Reserve Bank of New Zealand and CAMA

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ABSTRACT

Various papers have identified shocks to investment as major drivers of output, investment, hours, and interest rates. These investment shocks have been linked to financial frictions because financial markets are instrumental in transforming consumption goods into installed capital. However, the importance of investment shocks is not robust once we explicitly account for a simple financial friction. We estimate a medium scale dynamic stochastic general equilibrium model with collateral constraints. When entrepreneurs are subject to binding collateral constraints, a reduction in the value of installed capital reduces the value of collateral and thus the amount an entrepreneur can borrow. As a result, aggregate consumption no longer co-moves with GDP and the response of investment to a positive investment shock is attenuated. In the model with collateral constraints, the role of risk premium shocks in the business cycle increases markedly, whereas investment shocks have a much diminished role.

JEL Classification: C11, E22, E32, E44.

Keywords: DSGE model, financial frictions, risk premium shocks, investment specific technology shocks, Bayesian estimation.

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CASTLECLIFFE, SCHOOL OF ECONOMICS & FINANCE, UNIVERSITY OF ST ANDREWS, KY16 9AL
TEL: +44 (0)1334 462445 FAX: +44 (0)1334 462444 EMAIL: cdma@st-and.ac.uk

www.st-and.ac.uk/cdma

1 Introduction

Do shocks to investment drive the business cycle? A number of papers over the last decade suggest that investment shocks account for the majority of the variation in key macroeconomic aggregates.[1] The role of investment shocks has also come into renewed focus following the recent financial crisis. Financial intermediation affects the transformation of savings into usable, installed capital. Likewise, investment shocks affect the economy's ability to transform consumption goods into productive capital and thus play a parallel role to the process of financial intermediation. Justiniano et al. (2011), for example, draw an explicit link between shocks to the marginal efficiency of investment and *credit risk spreads*. Credit spreads imply the existence of a material financial friction, yet the model in Justiniano et al. (2011) has no such friction.

Our principal aim in this paper is to investigate the role and transmission mechanism of investment shocks in the presence of financial frictions. More specifically, we introduce a collateral constraint, similar to that of Kiyotaki and Moore (1997) and Gerali et al. (2010), into the model of Smets and Wouters (2007).

Using a data set that extends from 1954Q3 through to 2011Q4 for the United States (US), we estimate our amended model and compute the contribution of structural shocks to the cyclical variation of output, investment, consumption and so on. We demonstrate that the introduction of financial frictions in the form of a collateral constraint materially alters which shocks are thought to be the most important drivers of the business cycle. The intuition behind our result is simple: a positive investment shock lowers the relative price of capital goods, Tobin's q, and leads to an investment boom. When entrepreneurs

[1] See for example Fisher (2006) and Altig et al. (2011) for evidence from structural vector autoregressions and Justiniano et al. (2010, 2011) for DSGE based evidence.

are subject to binding collateral constraints, however, a reduction in the value of installed capital reduces the value of collateral and thus the amount an entrepreneur can borrow. As a result, the initial response of investment to a positive investment shock is attenuated by the decline in available credit. Justiniano et al. (2011) note that the presence of various frictions can generate the co-movement between consumption and investment conditional on investment shocks. In the presence of a collateral constraint, however, the increase in investment cannot be financed via increased borrowing and is therefore accompanied by a decline in entrepreneurial consumption. Consequently, investment shocks struggle to generate the positive correlation between consumption and investment that is observed in the data.

In our model, the shock affecting the cost of borrowing – the risk premium or consumption shock – is a major driver of cyclical fluctuations in output and other macroeconomic variables. This risk premium shock accounts for around half of the variation in output and consumption, and 40 percent of the variation in investment and interest rates. There is also a striking conformity between the estimated risk premium shock and the US business cycle.[2] The collateral constraint also has a material effect on the transmission of risk premium shocks. Contrary to the transmission mechanism of investment shocks described above, a stimulatory risk premium shock causes demand to rise and Tobin's q to increase. This implies that entrepreneurs face a looser borrowing constraint, and thus the impact of the shock is amplified for both consumption and investment.

The remainder of this paper is structured as follows. Section 2 outlines the model used in the analysis. The model closely follows that of Smets and Wouters (2007) and Justiniano et al. (2010), but we add impatient entrepreneurs who are collateral constrained. Section 3 discusses the estimation of the model. Section 4 looks at the role of investment specific

[2]See Figure 2.

technology (IST) and risk premium shocks as cyclical drivers. In section 5 and section 6, we discuss the results of our paper and their robustness.

2 Model

Our model is based on the familiar New Keynesian model put forward by Smets and Wouters (2007). Households consume (and save) and supply labour. The household income that underpins consumption and saving is obtained from wages, and from dividend streams from owning the firms that produce final goods. Households smooth consumption over time by investing in deposits issued by competitive financial intermediaries. The model has various nominal and real frictions including price and wage rigidities (with backward inflation indexation), habit formation in consumption, and adjustment costs for investment. The model also has variable capital utilization and fixed costs.

Our modification of the model introduces entrepreneurial agents responsible for all investment; entrepreneurs have a higher rate of time preference than households and are therefore more impatient. This different rate of time preference means that they wish to borrow from households to exchange current consumption for future consumption. This intertemporal substitution is enabled by investment in capital goods. The assumption that the rate of time preference is different for entrepreneurs and households is motivated by a desire to have debtors and creditors simultaneously. All agents, both households and entrepreneurs, are subject to the same stochastic shocks, and thus there is no idiosyncratic risk to insure away. As discussed by Iacoviello (2005), the return to investment exceeds the return to savings so that the collateral constraint is binding, but we do not want entrepreneurs to postpone consumption to self-fund all of the desired investment, which is prevented by the entrepreneur's impatience.

Entrepreneurs are the agents who own the capital stock. They finance consumption and investment expenditure by renting out capital goods to final goods producers and through borrowing from households, via notional financial intermediaries.

In the spirit of Kiyotaki and Moore (1997) regarding the costs of recovering debt, we assume that borrowing is limited to a fraction χ of the present value of the future capital stock owned by the entrepreneur.

Mendoza (2006) provides a general specification for collateral constraints which nests the one employed in this paper. Our approach is similar to the 'margin constraint' in Aiyagari and Gertler (1999), which hinges on the value of capital owned. Debt is one-period, so the stock of capital financed by household lending to the entrepreneurs needs to to be re-financed each period. Unlike in Mendoza (2008), the collateral constraint is binding even in steady state, reflecting the fact that entrepreneurs are assumed to be more impatient than households.

In our description of the model below, we limit our discussion to those parts of the model that differ from Smets and Wouters (2007), focusing on the decision problems of households and entrepreneurs. A full set of linearized model equations is presented in Appendix A.

2.1 Households

The representative household maximizes the following utility function:

$$E_t \sum_{s=0}^{\infty} \beta^s \left[\frac{1}{1-\sigma_c} (C_{j,t+s} - hC_{t-1+s})^{1-\sigma_c} \exp\left(\frac{\sigma_c - 1}{1+\sigma_l} L_{j,t+s}^{1+\sigma_l} \right) \right] \tag{1}$$

subject to

$$C_{j,t} + \frac{B_{j,t}}{P_t} = \Pi_{j,t} + W_{j,t} L_{j,t} + \frac{R_{t-1}^f}{\pi_t} \frac{B_{j,t-1}}{P_{t-1}} \tag{2}$$

The j^{th} household maximizes utility by choosing consumption at time t, $C_{j,t}$, and hours worked $L_{j,t}$. β is the discount factor; h dictates the degree of habit persistence; σ_l is the elasticity of substitution with respect to the real wage; and σ_c in conjunction with the habit term determines the intertemporal substitution elasticity for households. The flow constraint has consumption and real deposits ($B_{j,t}/P_t$) equal to profits, $\Pi_{j,t}$, labour income (real wages $W_{j,t}$ multiplied by hours worked) and the value of real deposits from last period scaled up by the gross effective nominal interest rate R^f_{t-1} divided by the gross inflation rate, π_t. The gross effective nominal interest rate is defined as $R_t \varepsilon_{c,t}$ where $\varepsilon_{c,t}$ is a risk premium shock, as in Smets and Wouters (2007).

The household's first order conditions for consumption and deposits are summarized by the following set equations. The marginal utility of consumption at time t, denoted λ_t, is:

$$\lambda_{j,t} = \exp\left(\frac{\sigma_c - 1}{1+\sigma_l} L_{j,t}^{1+\sigma_l}\right)(C_{j,t} - hC_{t-1})^{-\sigma_c}. \tag{3}$$

The Euler equation for households can then be represented as:

$$\lambda_{j,t} = \beta E_t \left(\lambda_{j,t+1} \frac{R^f_t}{\pi_{t+1}}\right) \tag{4}$$

The savings, or deposits of the household, B_t/P_t, are lent to entrepreneurs, who use these funds to purchase capital goods. These capital goods are rented out to final goods-producing firms (which are in turn owned by the households).

2.2 Entrepreneurs

The representative entrepreneurs maximizes the expected utility:

$$E_t \sum_{s=0}^{\infty} \beta_e^s \left[\frac{1}{1-\sigma_e}(C^e_{j,t+s} - h_e C^e_{t-1+s})^{1-\sigma_e}\right] \tag{5}$$

where C^e denotes entrepreneurial consumption. Entrepreneurs are subject to following budget constraint:

$$C^e_{j,t} + Q_t K_{j,t} = \frac{B_{j,t}}{P_t} - \frac{R^f_{t-1}}{\pi_t}\frac{B_{j,t-1}}{P_{t-1}} + R^k_t Z_t K_{j,t-1} - a(Z_t)K_{j,t-1} + Q_t(1-\delta)K_{j,t-1} \tag{6}$$

In each period, the entrepreneur purchases consumption goods and new capital stock, $K_{j,t}$, at price Q_t. These purchases are financed out of rental income on capital goods $R^k_t Z_t K_{j,t-1}$, net of capital utilization costs $a(Z_t)K_{j,t-1}$, the proceeds from selling last period's un-depreciated capital stock, $Q_t(1-\delta)K_{j,t-1}$, as well as net borrowing from households. Because entrepreneurs are more impatient than households, they face the following borrowing constraint on their degree of leverage:

$$\frac{R^f_t}{\pi_{t+1}}\frac{B_{j,t}}{P_t} = \chi E_t Q_{t+1} K_{j,t}(1-\delta) \tag{7}$$

where χ is the loan-to-value ratio (LVR), which dictates the maximum permissible leverage ratio. This constraint is on the *future* value of the un-depreciated capital (hence $E_t Q_{t+1}$) because any default and required loan recovery will occur in the future. Because of the assumption that $\beta > \beta_e$, the constraint is always binding in the neighborhood of the steady state.

The optimality conditions for consumption, borrowing and capital purchases and capital utilization are as follows:

$$(C^e_{j,t} - h_e C^e_{t-1})^{-\sigma_e} - \lambda^e_{j,t} = 0 \tag{8}$$

$$\lambda^e_{j,t} - \beta_e E_t \lambda^e_{j,t+1}\frac{R^f_t}{\pi_{t+1}} - \lambda^B_{j,t}\frac{R^f_t}{\pi_{t+1}} = 0 \tag{9}$$

$$Q_t = \frac{\lambda^B_{j,t}}{\lambda^e_{j,t}}\chi Q_{t+1}(1-\delta) + \beta_e E_t \frac{\lambda^e_{j,t+1}}{\lambda^e_{j,t}}\left[R^k_{t+1} Z_{t+1} - a(Z_{t+1}) + Q_{t+1}(1-\delta)\right] \tag{10}$$

$$R^k_t = a'(Z_t) \tag{11}$$

where λ^e and λ^B are the Lagrange multipliers on the flow and borrowing constraints respectively.

The presence of λ^B in the first order conditions represents the effects of the borrowing constraint on entrepreneurs' allocation of consumption and capital purchases. Consider, for example, a case where the borrowing constraint is exogenously relaxed. This results in a decline in the shadow value of the constraint, λ^B. For constant real interest rates, the Euler equation suggests that a looser borrowing constraint would be associated with higher consumption. Likewise, for a constant path of the effective interest rate, a looser borrowing constraint implies a higher value of installed capital, Q, and thus higher investment.

2.2.1 Capital producers

The capital stock is produced by firms, wholly owned by the entrepreneurs. The j^{th} representative capital-producing firm maximizes the following profit function:

$$E_t \sum_{s=0}^{\infty} \Lambda^e_{t+s} \left[Q_{t+s} \Delta x_{j,t+s} - I_{j,t+s} \right] \tag{12}$$

where Λ^e_t is the stochastic discount factor of the owner, in this case the entrepreneur, and net capital accumulation is defined as:

$$\Delta x_{j,t} = K_{j,t} - (1-\delta) K_{j,t-1} = \varepsilon_{\mu,t} (1 - S(I_{j,t}, I_{j,t-1})) I_{j,t} \tag{13}$$

where δ is the depreciation rate, $\varepsilon_{\mu,t}$ is an investment-specific shock, and the function $S(I_{j,t}, I_{j,t-1}))I_{j,t}$ captures investment adjustment costs. The investment adjustment cost function is quadratic in the ratio of investment to its lag. Substituting (13) into (12) yields:

$$E_t \sum_{s=0}^{\infty} \Lambda^e_{t+s} \left[Q_{t+s} \varepsilon_{\mu,t+s} (1 - S(I_{j,t+s}, I_{j,t+s-1})) I_{j,t+s} - I_{j,t+s} \right] \tag{14}$$

Assuming that the adjustment cost function $S(I_{j,t}, I_{j,t-1})$ takes the form $\frac{\kappa}{2}\left(\frac{I_{j,t}}{I_{j,t-1}} - \gamma\right)^2$, where γ is the gross steady state growth rate of the economy, the optimality condition for investment is given by:

$$\begin{aligned} 1 &= Q_t \varepsilon_{\mu,t}\left[\left(1 - \frac{\kappa}{2}\left(\frac{I_{j,t}}{I_{j,t-1}} - \gamma\right)^2\right) - \kappa\left(\frac{I_{j,t}}{I_{j,t-1}} - \gamma\right)\frac{I_{j,t}}{I_{j,t-1}}\right] \\ &+ \beta_e E_t \frac{\lambda^e_{t+1}}{\lambda^e_t} Q_{t+1}\varepsilon_{\mu,t+1}\left[\kappa\left(\frac{I_{j,t+1}}{I_{j,t}} - \gamma\right)\left(\frac{I_{j,t+1}}{I_{j,t}}\right)^2\right] \end{aligned} \tag{15}$$

Adjustment costs dampen the response of investment to various shocks and play an important role in the dynamics of Tobin's q – the relative price of firms' collateral in our model.

2.3 The rest of the model

The rest of the model directly follows Smets and Wouters (2007) and thus we only provide a very brief description. A complete set of linearized model equations is presented in Table 7 in Appendix A.

Output of final goods is a function of effective capital, labour and technology. Final goods producers rent capital services with a given degree of utilization from entrepreneurs, and labour services from household unions.

Goods and labour markets are monopolistically competitive with both prices and wages being set in a time-dependent manner as put forward by Calvo (1983), albeit with partial indexation to past inflation for those price and wage setters not called upon to reprice in a given time period.

Government spending is simply modeled as a stochastic share of GDP. Monetary policy is modeled by a generalized Taylor-type interest rate rule that links the current period policy rate to its lag, to deviations of the current period inflation rate from target, to deviations in the output gap, and to changes in the growth rate of the output gap.

The output gap is defined as the difference between output in the sticky price allocation of the model and output corresponding to a flexible price allocation. In the flexible price allocation there are no nominal rigidities in either price or wage setting, and hence there is no role for monetary policy.

2.4 Shocks

There are seven shocks perturbing the economy. The risk premium ($\varepsilon_{c,t}$) and investment specific technology shock ($\varepsilon_{\mu,t}$), discussed above, are augmented with shocks to total factor productivity ($\varepsilon_{a,t}$), the share of government spending in GDP ($\varepsilon_{g,t}$), the interest rate rule ($\varepsilon_{r,t}$), and shocks to the price and wage Phillips curves ($\varepsilon_{p,t}$ and $\varepsilon_{w,t}$).[3] These shocks all exhibit some degree of persistence, as described in the following equations:

$$\varepsilon_{c,t} = \rho_c \varepsilon_{c,t-1} + \zeta_{c,t} \tag{16}$$

$$\varepsilon_{\mu,t} = \rho_\mu \varepsilon_{\mu,t-1} + \zeta_{\mu,t} \tag{17}$$

$$\varepsilon_{a,t} = \rho_a \varepsilon_{a,t-1} + \zeta_{a,t} \tag{18}$$

$$\varepsilon_{g,t} = \rho_g \varepsilon_{g,t-1} + \zeta_{g,t} + \rho_{(g,a)} \zeta_{a,t} \tag{19}$$

$$\varepsilon_{r,t} = \rho_r \varepsilon_{r,t-1} + \zeta_{r,t} \tag{20}$$

$$\varepsilon_{p,t} = \rho_p \varepsilon_{p,t-1} + \zeta_{p,t} - \rho_{(p,\zeta)} \zeta_{p,t-1} \tag{21}$$

$$\varepsilon_{w,t} = \rho_w \varepsilon_{w,t-1} + \zeta_{w,t} - \rho_{(w,\zeta)} \zeta_{w,t-1} \tag{22}$$

$$\tag{23}$$

The various autoregressive and moving average (MA) coefficients are represented by ρ. Following Smets and Wouters (2007), we include a feedback term between the innovation in technology and government spending, $\rho_{(g,a)}$, in the shock term for exogenous government

[3]The flexible price allocation used to construct the output gap is not affected by either $\varepsilon_{r,t}$, $\varepsilon_{p,t}$ or $\varepsilon_{w,t}$.

spending, as well as MA terms in the price and wage shocks to capture high frequency fluctuations in price and wage dynamics. The innovations $\zeta_{j,t}$ are normal, independent and identically distributed.

2.5 An alternative model

To isolate the effects of borrowing constraints on the business cycle, we estimate two versions of our model: the model presented above, and an alternative model where entrepreneurs are identical to households in terms of their rate of time preference and thus do not face borrowing constraints. This alternative is essentially the model put forward by Smets and Wouters (2007).

3 Bayesian estimation

The following seven observables are used to estimate the two versions of the model: the growth rates of GDP, aggregate consumption, and investment; real wages; inflation; the short-term nominal interest rate; and hours worked. Given that we have seven stochastic shocks in the model, we avoid stochastic singularity. The data used to estimate the models are described in Appendix B. We denote 'aggregate' consumption as C^a since it corresponds to the sum of household and entrepreneurial consumption in our model. As in Justiniano et al. (2010), consumption corresponds to private consumption of non-durable goods, while investment is defined as the sum of gross domestic private investment and consumption of durable goods. The models are estimated using standard Bayesian techniques. For the most part the priors for the model are the same as those employed by Smets and Wouters. There are two innocuous caveats to this statement. First, we use a Gamma prior instead of a Normal prior for the labour-disutility parameter, σ_l, though with the same mean and variance used in Smets and Wouters.[4] Second, we estimate the household's discount rate using a Gamma prior with a mean of 0.25 and a standard deviation of 0.1, though the data are found to be somewhat uninformative for these priors. Other authors such as Iacoviello (2005) and Iacoviello and Neri (2010) calibrate this parameter directly.

The model with borrowing constraints has two parameters without analogues in the original Smets-Wouters model: (i) the loan-to-value ratio, χ, and (ii) the gap between the discount rates of the households and entrepreneurs, $\tilde{\beta}$. Given that the LVR is a device to ensure that entrepreneur's have equity in their investment ventures, the LVR is assumed to fall within (0,1). More specifically the prior for the LVR is a Beta distribution with mean 0.5 and standard deviation of 0.15. Iacoviello and Neri (2010) calibrate the LVR to be 0.85, suggesting that it is difficult to estimate without data on debt and housing holdings of credit-constrained households. Our mean posterior parameter estimates for the LVR are close to our prior value of 0.5, but the data are somewhat informative, indicating that the probability mass should be more tightly grouped around the mean value. Indeed, when taking the model to a shortened data sample, starting in the post-Volcker period, we obtain a posterior mean of 0.7 for the same prior.

The prior distribution for the discount rate gap, $\tilde{\beta}$, is a Gamma distribution with a mean of 1 and a standard deviation of 0.5. This prior distribution implicitly encompasses the calibrated discount factors for impatient borrowers used in Iacoviello (2005) and Iacoviello and Neri (2010), which range from 0.98 to 0.97. Gerali et al. (2010) estimate a similar model, but do not attempt to estimate either χ or $\tilde{\beta}$. Iacoviello provides greater discussion of plausible discount factors, and cites a number of papers on cross-sectional variation in discount factors (Carroll and Samwick 1997, for example, suggest that the plausible range for

[4]In estimation over a smaller sub-sample, positive probability mass was assigned to negative parameter values, which we rule out on a priori theoretical grounds.

discount factors is between 0.91 and 0.99). While our prior range does not fully encompass this cross-sectional variation we think it provides a sufficiently broad range for what one might assume is the average impatient entrepreneur.

Finally, we calibrate the depreciation rate to 0.025 and the share of government spending in GDP to 0.22. Following Smets and Wouters (2007), we set the Kimball aggregator parameters, ϵ_p and ϵ_w, to 10 and calibrate the steady state wage mark-up to 1.5.

Tables 1 and 2 report the posterior mean and 90 percent posterior probability intervals for the structural parameters and the standard deviations of the shocks for the model with and without collateral constraints. The reported parameter estimates for the models are based on 900,000 draws of Markov chains. Appendix C illustrates (recursive) 'trace-plots' of deciles from two Markov chains, to provide some degree of confidence that the chains have converged to their stationary (posterior) distributions.

The posterior estimates for the common structural parameters in the two models are broadly similar. They suggest a high degree of nominal price and wage rigidity, a significant degree of habit persistence and sluggish investment adjustment. Differences between the two models arise primarily in the size and persistence of investment and risk premium shocks. In the presence of borrowing constraints, investment shocks become more volatile but less persistent. Risk premium shocks, however, are estimated to be less volatile but more persistent. Introducing borrowing constraints also lowers the mean of the posterior estimates of the capital utilization and investment adjustment cost parameters, relative to the model without borrowing constraints.

4 IST and risk premium shocks and the business cycle

This section analyzes the key drivers of the business cycle by looking at the variance decomposition of the observables in both version of the model. Table 3 reports the contribution of each structural shock to the volatility of the observables for the version of the model without the borrowing constraint. The dominant role of IST shocks highlighted by Justiniano et al. (2010) is replicated in this version of the model as 55% of the variance of output growth is accounted for by IST shocks. Risk premium, neutral technology and government spending shocks jointly make up another 30% of the variance of output growth. IST shocks also account for almost all (91%) of the variance of investment growth and a large part of the variance of the nominal interest rate (43%).

In this model IST shocks are particularly important in capturing the decline in output that occurred during the Great Recession. Figure 1 shows the path of output growth when the model is driven solely by IST shocks. Here, IST shocks account for over half of the drop in output growth during the last recession. The premise of our paper is that this result is not robust to the introduction of financial frictions in the form of borrowing constraints.

Introducing a borrowing constraint on entrepreneurs affects the transmission mechanism of IST shocks and thus their relative contribution to the volatility of GDP. The variance decomposition of the observables in Table 4 illustrates that in the model with borrowing constraints, the role of IST shocks is greatly reduced. Apart from consumption and investment, IST shocks account for less than 5% of the volatility of the observable variables. Their contribution to the dynamics of investment remains significant but almost two thirds less than in the model without the borrowing constraint. The higher share of IST shocks in the volatility of consumption reflects these shocks' role in the dynamics of entrepreneurial consumption. In section 4.1, we examine this channel in more detail.

In the model with borrowing constraint, the main driver of business cycle fluctuations appears to be the risk premium, contributing between 39% and 47% to the variance of the components of GDP. Adding a borrowing constraint also increases the share of risk premium shocks in the variance of total hours and nominal interest rates.

Given its importance in shaping business cycle dynamics, we now examine how the risk premium shock evolves over the business cycle. Figure 2 plots the posterior mean of our estimated risk premium shock and the NBER recession dates which start at the peak of a business cycle and end at the trough. The sample includes every recession from the late 1950s onwards. There is a striking conformity of the risk premium shock with these recessions. At the beginning of each recession the estimated risk premium shock rises sharply, implying that the effective interest rate in the model is highly countercyclical. Moreover, the risk premium and the effective interest rate start to rise *before* the peak of the boom, in almost every recession in our sample.

The increase in our measure of the risk premium shock is most pronounced during the last recession. Figure 3 illustrates the role of risk premium shocks over the last decade and a half by simulating the path of output assuming that the model is only driven by the estimated risk premium shock. Most of the drop in output growth in the last recession is due to the variation in the risk premium shock. This is in line with the observation that the last recession was driven by sharp disruptions in the financial system resulting in higher interest rate spreads.

4.1 IST shocks and collateral constraints

The following two sections flesh out the intuition behind our results starting with the role of IST shocks. In a real business cycle type model, investment rises but consumption falls following a positive IST shock (see for example Barro and King 1984). A shock that increases the marginal efficiency of investment raises the incentive to invest by more than can be accommodated by an increase in labour effort. As a result, investment can only increase sufficiently if consumption falls. This GDP-consumption co-movement puzzle precludes IST shocks from being a key driver of the business cycle in this type of model. Justiniano et al. (2010) show how this co-movement puzzle can be overcome through a combination of nominal and real rigidities plus variable capital utilization.[5] As a result, their model is able to generate a dominant role for IST shocks over the business cycle. All the features that account for the co-movement puzzle in Justiniano et al. are also present in our model, in addition to the binding borrowing constraint on entrepreneurs.

Figure 4 shows the impulse response functions following an IST shock in our estimated model. The solid lines show the median response and the shaded areas the 90% confidence intervals. As Figure 4 makes clear, there is no co-movement puzzle between GDP and household consumption. However, aggregate consumption declines because of a sharp adjustment to entrepreneurs' consumption in the wake of a positive IST shock. A positive IST shock reduces the value of Tobin's q (this is true even in a simple RBC model without adjustment costs where $1 = Q_t \varepsilon_{\mu,t}$) and thus the value of the capital stock used for collateral. The decline in the value of collateral, other things equal, reduces the firm's ability to borrow just when the demand for borrowing coming from investment is high. As a result, investment is

[5] Greenwood et al. (2000) discuss a number of ways in which the positive co-movement of consumption and investment can be derived, including habit persistence and factor immobility, intratemporal adjustment costs on investment, and intermediate inputs.

reduced relative to the case without borrowing constraints, and entrepreneurs' consumption falls. In terms of the entrepreneur's Euler equation, (9), a decline in Tobin's q tightens the borrowing constraint causing λ_t^e to rise, which, other things equal, causes entrepreneurial consumption to fall. In the estimated model entrepreneurs' consumption falls by enough to lead to a decline in aggregate consumption.

4.2 Risk premium shocks and collateral constraints

The same channel that reduces the impact of IST shocks contributes to the increase in the importance of risk premium shocks. Figure 5 shows the transmission mechanism of a risk premium shock. A negative risk premium shock lowers the effective interest rates faced by household and entrepreneurs. This results in higher consumption and output, generating an increased demand for investment and a higher price of capital. From the perspective of entrepreneurs, even in the absence of any borrowing constraint, the lower cost of servicing their debt allows them to increase both their consumption and capital purchases.

The additional asset price channel (higher Tobin's q) implies that they also face a looser borrowing constraint (both λ_t^e and $\varepsilon_{c,t}$ decline in equation (9) causing entrepreneurial consumption to rise). This engenders an amplification of the impact of risk premium shocks for both, consumption and investment. As the response of interest rates and inflation are positive, our model generates positive co-movement between macroeconomic aggregates following a risk premium shock.

Our analysis shows that the introduction of the borrowing constraint alters the transmission mechanisms of both IST and risk premium shocks. The borrowing constraint attenuates the expansionary effects of IST shocks on output, whereas the impact of risk premium shocks is amplified.

5 Discussion

Our analysis suggests that risk premium shocks, or shocks to the effective interest rate faced by households and firms, are the main driver of the business cycle. This result is attributable to the role played by simple financial frictions in the form of borrowing constraints. An expansionary risk premium shock loosens the borrowing constraint faced by entrepreneurs and thus reduces the cost of transforming household savings into productive capital.

Justiniano et al. (2011), in a model without explicit financial frictions, attribute this role to IST shocks. A positive IST shock raises the marginal efficiency of investment and thus the rate with which household savings are transformed into productive capital. As a supply type shock, a positive IST shock also yields a decline in the price of capital. In the presence of borrowing constraints, the counter-cyclical asset price movement tends to tighten the borrowing constraint and thus reduces the effectiveness of IST shocks.

Christensen and Dib (2008) compare a model with and without a financial accelerator mechanism, where firms' net worth affects the 'external finance premium' and thus the firms' costs of borrowing. Even though there are significant differences between their approach and ours (in terms of sample period, model and estimation technique),they too find that the role of IST shocks in the forecast variance of GDP diminishes in the presence of financial frictions, albeit to a much lesser extent. The financial friction in Christensen and Dib (2008) has a mild effect on the transmission mechanism quantitatively, but the dynamics are qualitatively unchanged. In our model, financial frictions reverse the short term impact of IST shocks on aggregate consumption, and thus have both quantitative and qualitative effects on the response of output.

A number of recent papers in the literature view the financial sector as a source of shocks driving the business cycle. For example, Nolan and Thoenissen (2009) show in a Bernanke et al. (1999) type model that shocks to entrepreneurial net worth play a key role in the dynamics of GDP. Hirakata et al. (2011) also introduce shocks to financial intermediation in a BGG-type model and find shocks to financial intermediation play an important role in the dynamics of investment, in particular accounting for the collapse of investment during the financial crisis. Jermann and Quadrini (2012) investigate the importance of shocks originating in the financial sector when firms face borrowing constraints. As in the previous literature, these financial shocks are found to be quantitatively important.

In relation to this literature, our results highlight the importance of risk premium shocks. Although this type of shock is present in canonical DSGE models such as Smets and Wouters (2007), their role as a driver of the business cycle only comes to the fore once we introduce the collateral constraint.

Our results share some similarities with Iacoviello (2005), who points out that, in a model with real estate investments, the effects of borrowing constraints on the amplification of shocks depend on the response of asset prices and consumer price inflation. In his framework, where household debt is denominated in nominal terms, shocks that generate a negative correlation between inflation and output (such as supply shocks), are decelerated while the impact of demand shocks are amplified. Our contribution extends this channel to the case of investment shocks.

6 Robustness over the sample

This section analyzes the robustness of our results to alternative sample periods. Our baseline estimation period runs from 1954Q3 through to 2011Q4 (the latest available data) and therefore encompasses the estimation periods of, amongst others, Justiniano et al. (2010,

2011) and Smets and Wouters (2007). This estimation period spans two recent episodes that have the potential to affect our results: the Great Moderation, from the Volcker disinflation up to the Financial Crisis; and the post 2009Q1 period where the zero lower bound for the federal funds rate becomes binding. To check for the robustness of our results, we re-estimate the model for the 1984Q1 to 2009Q1 period.

Tables 5 and 6 present the estimation results and variance decomposition for this alternative sample. Our parameter estimates are broadly consistent with those obtained in the baseline estimation. The main changes relate to the dynamics of investment. As the volatility of investment is lower during that period, the model requires a higher investment adjustment cost parameter as well as a lower volatility for the IST shock. The posterior mean of the investment adjustment cost parameter is about three times larger, while the posterior mean of the standard deviation of the IST shock is halved.

The main conclusion regarding the drivers of the business cycle is unchanged. The risk premium shock remains the dominant driver of the volatility in the components of GDP.

7 Conclusion

At the heart of our paper is an identification problem that affects the interpretation of the key drivers of the business cycle. We demonstrate that the introduction of financial frictions materially alters which shocks are thought to be the most important drivers of the business cycle. When entrepreneurs are subject to binding collateral constraints, a reduction in the value of installed capital reduces the value of collateral and thus the amount an entrepreneur can borrow. We find that the dynamic responses of output and consumption to a positive investment shock are materially altered by such collateral constraints. While an investment shock prompts more investment and positive output growth, the behaviour of consumption is completely altered, since the impact effect is for consumption to fall. The investment shock causes collateral values to decline, which reduces entrepreneurs' ability to obtain external finance. Thus, to increase investment entrepreneurs are forced to reduce their consumption. Investment shocks can then no longer generate the positive co-movement that is evident between consumption and investment. Instead, in the model with collateral constraints, risk premium shocks increase markedly in importance, whereas shocks to investment have a much diminished role, contributing only 4% of the variation in output.

References

Aiyagari, S. R. and M. Gertler (1999). Overreaction of asset prices in general equilibrium. *Review of Economic Dynamics 2*(1), 3–35.

Altig, D., L. Christiano, M. Eichenbaum, and J. Linde (2011, April). Firm-specific capital, nominal rigidities and the business cycle. *Review of Economic Dynamics 14*(2), 225–247.

Barro, R. J. and R. G. King (1984). Time-separable preferences and intertemporal substitution models of business cycles. *Quarterly Journal of Economics 99*, 817–839.

Bernanke, B. S., M. Gertler, and S. Gilchrist (1999). The financial accelerator in a quantitative business cycle framework. In J. B. Taylor and M. Woodford (Eds.), *Handbook of Macroeconomics*, Volume 1 of *Handbook of Macroeconomics*, Chapter 21, pp. 1341–1393. Elsevier.

Brooks, S. P. and G. O. Roberts (1998). Convergence assessment techniques for Markov chain Monte Carlo. *Statistics and Computing 8*(4), 319–335.

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

Carroll, C. D. and A. A. Samwick (1997). The nature of precautionary wealth. *Journal of Monetary Economics 40*(1), 41–72.

Christensen, I. and A. Dib (2008, January). The financial accelerator in an estimated New Keynesian model. *Review of Economic Dynamics 11*(1), 155–178.

Fisher, J. D. M. (2006, June). The dynamic effects of neutral and investment-specific technology shocks. *Journal of Political Economy 114*(3), 413–451.

Gerali, A., S. Neri, L. Sessa, and F. M. Signoretti (2010). Credit and banking in a DSGE model of the euro area. *Journal of Money, Credit and Banking 42*(s1), 107–141.

Greenwood, J., Z. Hercowitz, and P. Krusell (2000). The role of investment-specific technological change in the business cycle. *European Economic Review 44*, 91–115.

Hirakata, N., N. Sudo, and K. Ueda (2011). Do banking shocks matter for the U.S. economy? *Journal of Economic Dynamics and Control 35*(12), 2042–2063.

Iacoviello, M. (2005). House prices, borrowing constraints, and monetary policy in the business cycle. *American Economic Review 95*(3), 739–764.

Iacoviello, M. and S. Neri (2010). Housing market spillovers: Evidence from an estimated DSGE model. *American Economic Journal: Macroeconomics 2*(2), 125–164.

Jermann, U. and V. Quadrini (2012). Macroeconomic effects of financial shocks. *American Economic Review 102*(1), 238–271.

Justiniano, A., G. Primiceri, and A. Tambalotti (2011, January). Investment shocks and the relative price of investment. *Review of Economic Dynamics 14*(1), 101–121.

Justiniano, A., G. E. Primiceri, and A. Tambalotti (2010). Investment shocks and business cycles. *Journal of Monetary Economics 57*(2), 132–145.

Kiyotaki, N. and J. Moore (1997). Credit cycles. *Journal of Political Economy 105*(2), 211–248.

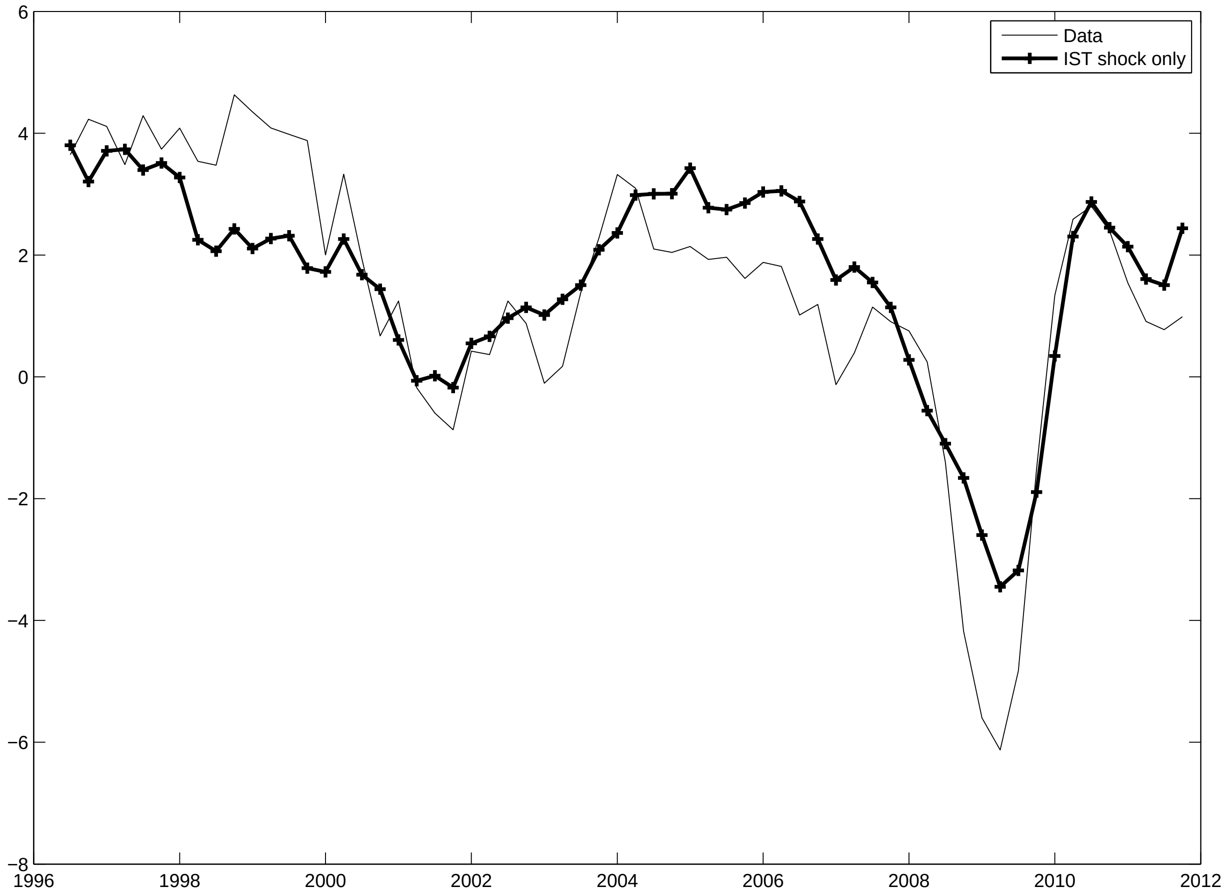
Mendoza, E. G. (2006). Lessons from the debt-deflation theory of sudden stops. *American Economic Review 96*(2), 411–416.

Mendoza, E. G. (2008, October). Sudden stops, financial crises and leverage: A Fisherian deflation of Tobin's Q. NBER Working Papers 14444, National Bureau of Economic Research.

Nolan, C. and C. Thoenissen (2009, May). Financial shocks and the US business cycle. *Journal of Monetary Economics 56*(4), 596–604.

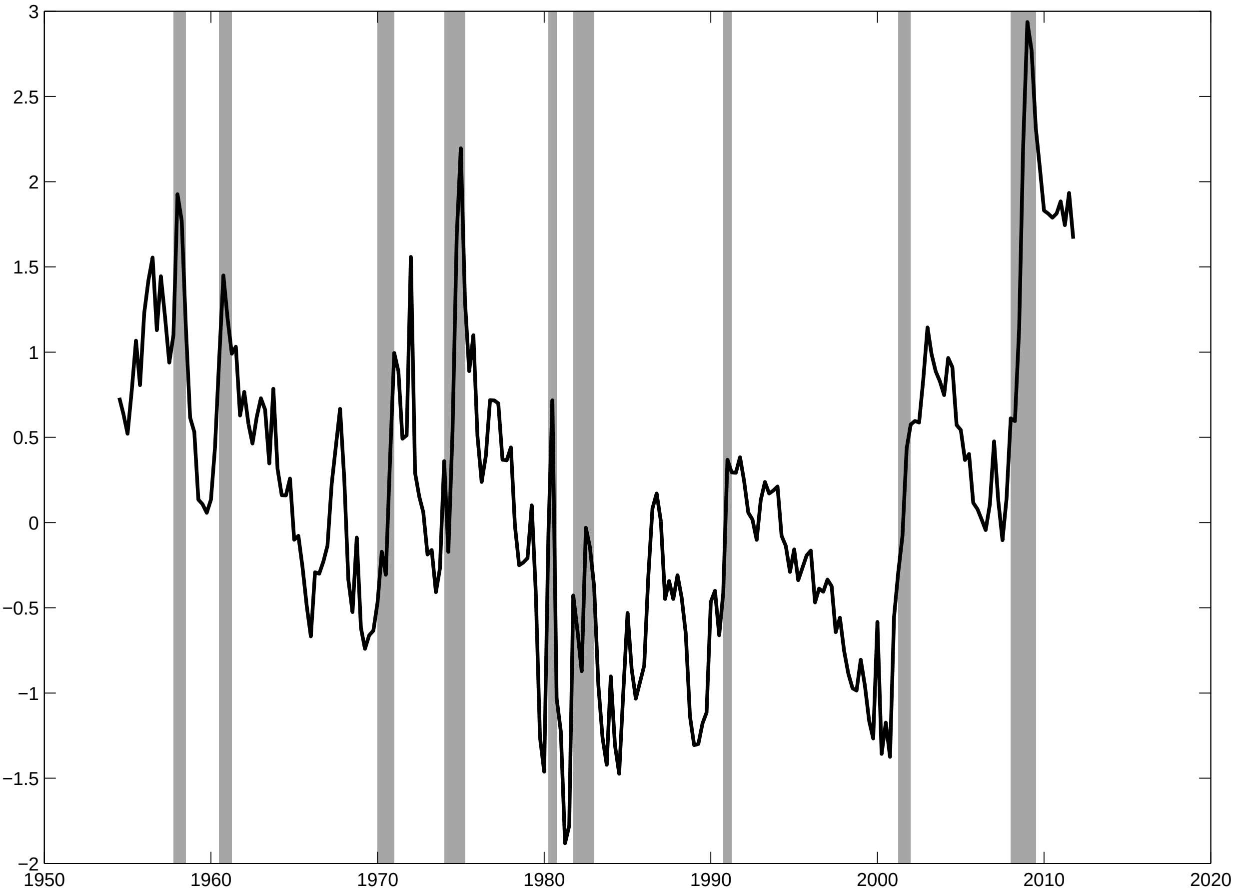
Smets, F. and R. Wouters (2007, June). Shocks and Frictions in US Business Cycles: A Bayesian DSGE Approach. *American Economic Review 97*(3), 586–606.

Figure 1: Role of IST shock in the Great Recession in the model *without* borrowing constraints



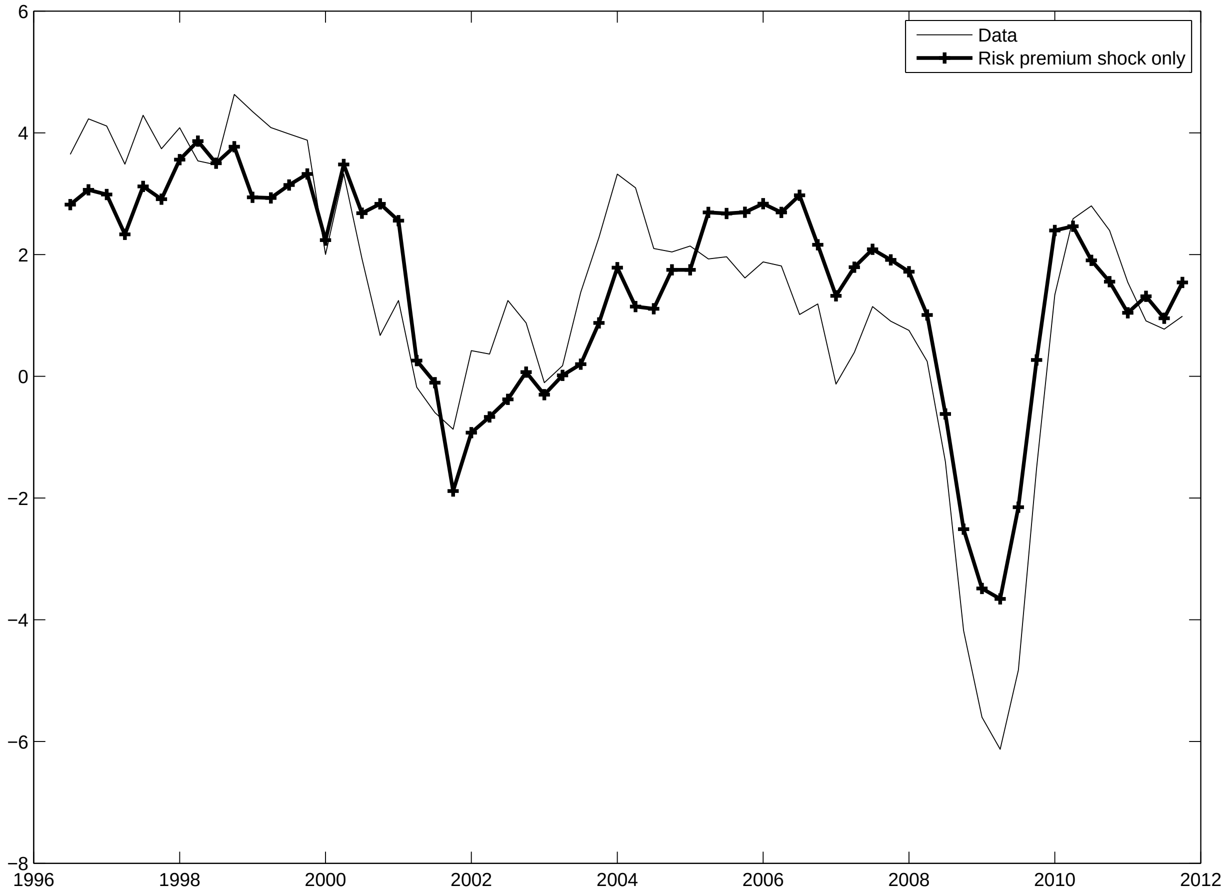
Notes: The solid line labelled *Data* shows the year-on-year growth rate of GDP. The solid-crossed line, labelled *IST shocks only*, shows the growth rate of GDP that would have occurred if only the estimated IST shocks assume non-zero values. The estimated shocks are obtained via the Kalman smoother on the estimated posterior mean of the Smets-Wouters model with no borrowing constraints.

Figure 2: The risk-premium shock and NBER recession intervals in the model *with* borrowing constraints



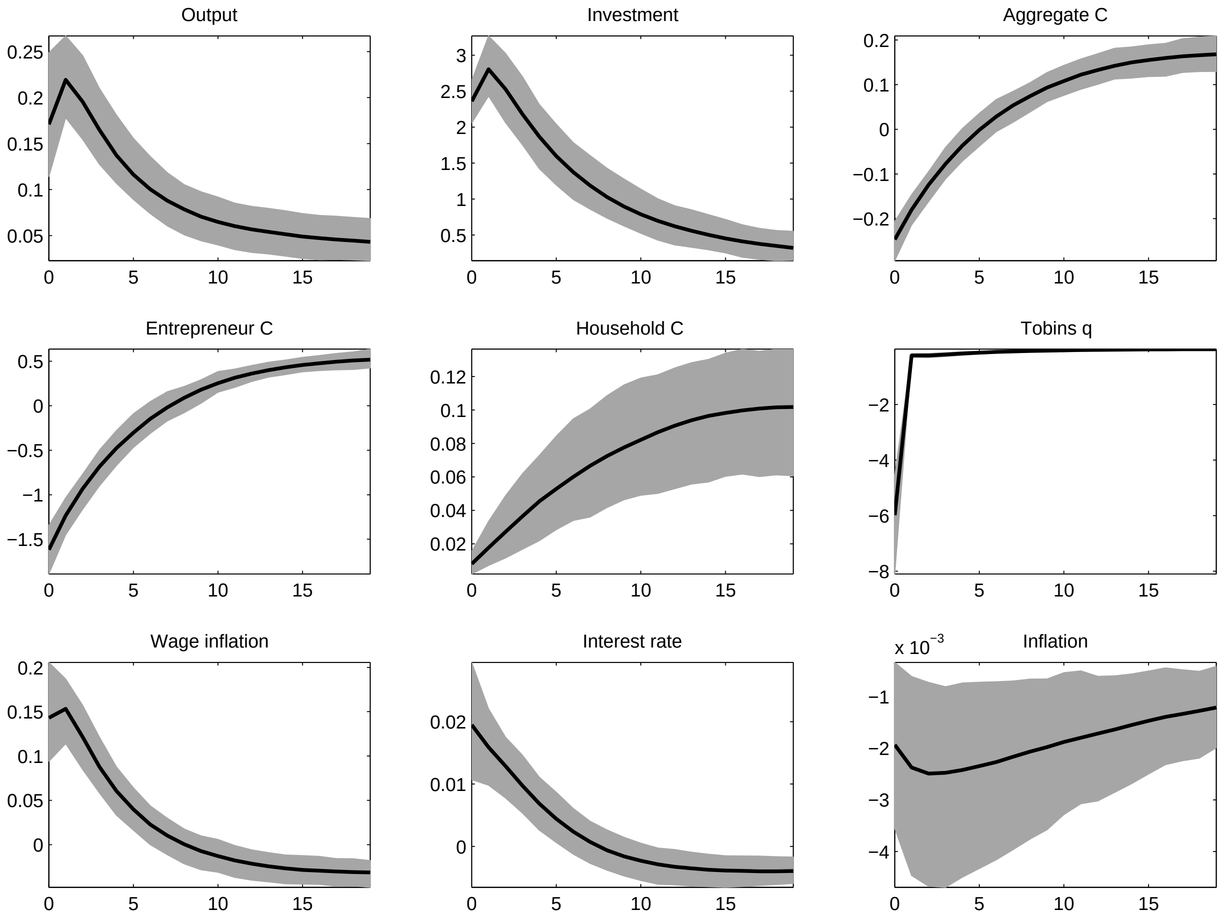
Notes: The solid line shows the estimated risk premium shocks for the model with the borrowing constraint. The estimated shocks are obtained via the Kalman smoother on the estimated posterior mean. The shaded areas correspond to the NBER recession intervals.

Figure 3: Role of Risk Premium shock in the Great Recession in the model *with* borrowing constraints



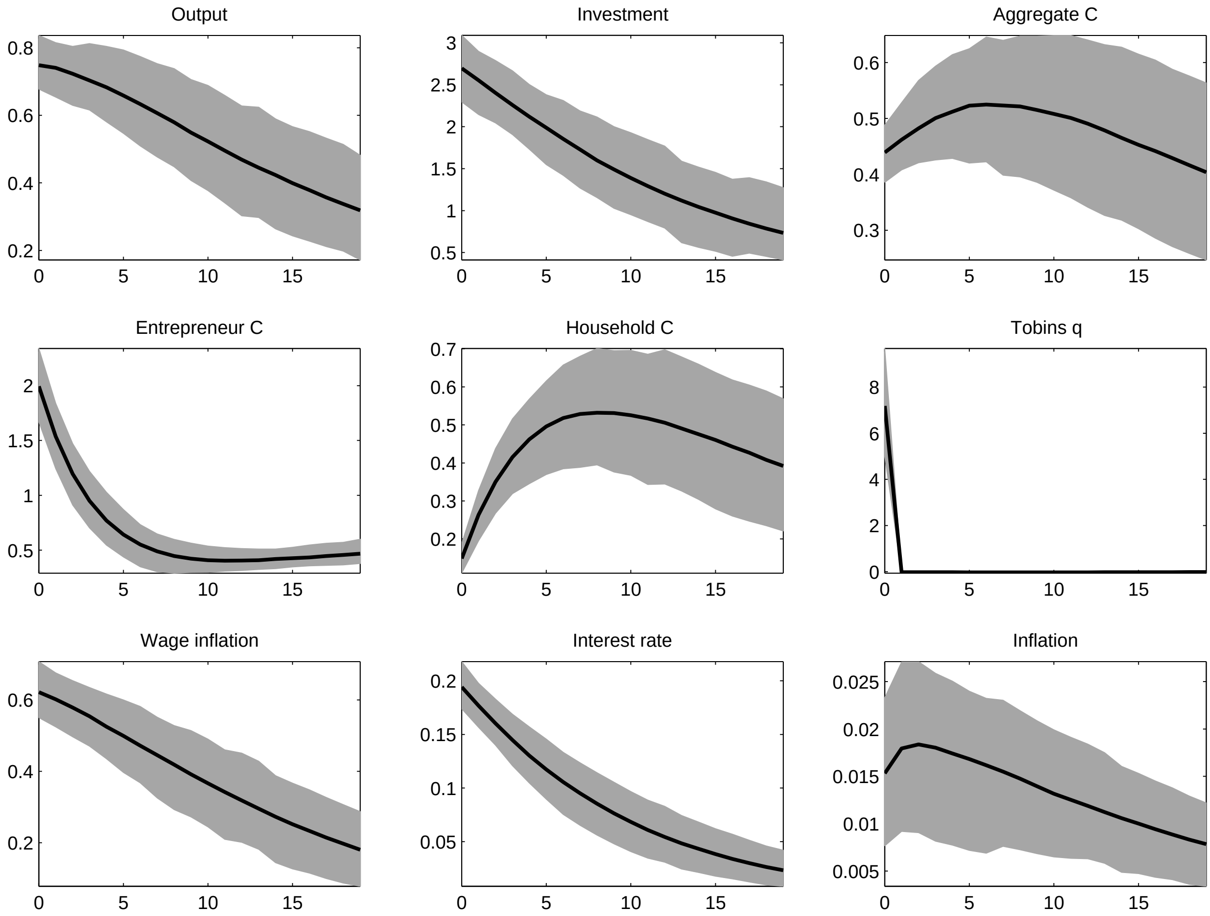
Notes: The solid line labelled *Data* shows the year-on-year growth rate of GDP. The solid-crossed line, labelled *Risk premium shocks only*, shows the growth rate of GDP that would have occurred if only the estimated Risk premium shocks assume non-zero values. The estimated shocks are obtained via the Kalman smoother on the estimated posterior mean of the model with the borrowing constraint.

Figure 4: Impulse response to an IST shock in the model *with* borrowing constraints



Notes: The solid lines are impulse response functions to a one standard deviation shock. The solid line is the posterior median, the shaded areas correspond to the 90% Bayesian confidence intervals. Responses are measured as the percentage deviations from trend except for inflation and interest rates, which are measured as the percentage point deviation from steady state values.

Figure 5: Impulse response to a risk premium shock in the model *with* borrowing constraints



Notes: The solid lines are impulse response functions to a one standard deviation shock. The solid line is the posterior median, the shaded areas correspond to the 90% Bayesian confidence intervals. Responses are measured as the percentage deviations from trend except for inflation and interest rates, which are measured as the percentage point deviation from steady state values.

Table 1: Estimation results for parameters and shock processes of model *with* borrowing constraints: 1954Q3 - 2011Q4

Parameter	Description	Prior	Mean	StdDev	Mean	CIlow	CIup
α	Share of capital	N	0.300	0.050	0.275	0.212	0.340
ϕ	Investment adjustment cost parameter	N	4.000	1.500	2.579	1.612	3.516
σ_c	Households intertemporal elasticity	N	1.500	0.375	1.033	0.979	1.087
σ_{cE}	Entrepreneur's intertemporal elasticity	N	1.500	0.375	1.322	0.779	1.845
h	habit parameter of consumers	β	0.700	0.100	0.905	0.875	0.937
h^E	habit parameter of entrepreneurs	β	0.700	0.100	0.811	0.750	0.873
θ_w	Calvo wage parameter	β	0.500	0.100	0.875	0.819	0.937
σ_l	Labour disutility parameter	Γ	2.000	0.750	0.821	0.382	1.214
θ_p	Calvo price parameter	β	0.500	0.100	0.872	0.833	0.909
ξ	Capacity utilization parameter	β	0.500	0.150	0.304	0.192	0.411
ϕ_p	Markup (goods)	N	1.250	0.125	1.297	1.202	1.393
δ_w	Wage indexation	β	0.500	0.150	0.391	0.213	0.567
δ_p	Price indexation	β	0.500	0.150	0.193	0.082	0.298
ϕ_π	Taylor rule inflation	N	1.500	0.250	1.899	1.619	2.187
ϕ_r	Taylor rule lagged interest rate	β	0.750	0.100	0.853	0.818	0.889
ϕ_x	Taylor rule output gap	N	0.125	0.050	0.074	0.044	0.106
$\phi_{\Delta x}$	Taylor rule output gap growth rate	N	0.125	0.050	0.245	0.210	0.282
$\overline{\pi}$	Steady state inflation	Γ	0.625	0.100	0.835	0.734	0.943
$\frac{100(1-\beta)}{\beta}$	Discount rate (percent)	Γ	0.250	0.100	0.250	0.092	0.398
ltv	Loan to value ratio	β	0.500	0.150	0.510	0.322	0.709
$\tilde{\beta}$	Entrepreneurs discount less househlds	Γ	1.000	0.500	0.985	0.222	1.717
lss	Log steady state hours	N	0.000	2.000	-0.580	-2.628	1.504
γ	Steady state growth rate (percent)	N	0.400	0.100	0.470	0.443	0.495
ρ_a	AR parameter technology shock	β	0.500	0.200	0.970	0.960	0.982
ρ_c	AR parameter risk premium shock	β	0.500	0.200	0.866	0.827	0.904
ρ_g	AR parameter exogenous demand shock	β	0.500	0.200	0.990	0.982	0.997
ρ_i	AR parameter investment shock	β	0.500	0.200	0.192	0.123	0.264
ρ_r	AR parameter interest rate	β	0.500	0.200	0.134	0.051	0.212
ρ_p	AR parameter price markup	β	0.500	0.200	0.945	0.906	0.982
ρ_w	AR parameter wage markup	β	0.500	0.200	0.957	0.928	0.988
ρ_{ep}	MA parameter price markup	β	0.500	0.200	0.888	0.818	0.954
ρ_{ew}	MA parameter wage markup	β	0.500	0.200	0.934	0.897	0.972
ρ_{ga}	Effect of tech shock on exog. demand	N	0.500	0.200	0.359	0.280	0.434
σ_c	Std dev. of risk premium shock	Γ^{-1}	0.100	2.000	0.387	0.341	0.430
σ_w	Std dev. of wage markup shock	Γ^{-1}	0.100	2.000	0.258	0.230	0.285
σ_p	Std dev. of price markup shock	Γ^{-1}	0.100	2.000	0.141	0.122	0.160
σ_r	Std dev. of interest rate shock	Γ^{-1}	0.100	2.000	0.216	0.197	0.236
σ_a	Std dev. of technology shock	Γ^{-1}	0.100	2.000	0.548	0.501	0.592
σ_i	Std dev. of investment shock	Γ^{-1}	0.100	2.000	2.199	1.807	2.610
σ_g	Std dev. of exog. demand shock	Γ^{-1}	0.100	2.000	0.344	0.315	0.373

Notes: The prior for a parameter is a Normal (N), Beta (β), Gamma (Γ), or inverse-Gamma (Γ^{-1}) distribution. Columns 4 and 5 indicate the mean and standard deviation of the prior distribution, and the final three columns report the posterior mean and lower and upper limits of 90% Bayesian confidence intervals from the posterior distribution.

Table 2: Estimation results for parameters and shock processes of model *without* borrowing constraints: 1954Q3 - 2011Q4

Parameter	Description	Prior	Mean	StdDev	Mean	CIlow	CIup
α	Share of capital	N	0.300	0.050	0.126	0.055	0.198
ϕ	Investment adjustment cost parameter	N	4.000	1.500	4.882	3.235	6.548
σ_c	Households intertemporal elasticity	N	1.500	0.375	1.358	1.205	1.499
h	habit parameter of consumers	β	0.700	0.100	0.759	0.686	0.826
θ_w	Calvo wage parameter	β	0.500	0.100	0.811	0.751	0.876
σ_l	Labour disutility parameter	Γ	2.000	0.750	1.363	0.644	2.125
θ_p	Calvo price parameter	β	0.500	0.100	0.765	0.716	0.818
ξ	Capacity utilization parameter	β	0.500	0.150	0.711	0.567	0.840
ϕ_p	Markup (goods)	N	1.250	0.125	1.291	1.195	1.381
δ_w	Wage indexation	β	0.500	0.150	0.576	0.385	0.765
δ_p	Price indexation	β	0.500	0.150	0.225	0.111	0.334
ϕ_π	Taylor rule inflation	N	1.500	0.250	1.896	1.660	2.124
ϕ_r	Taylor rule lagged interest rate	β	0.750	0.100	0.797	0.759	0.836
ϕ_x	Taylor rule output gap	N	0.125	0.050	0.076	0.049	0.103
$\phi_{\Delta x}$	Taylor rule output gap growth rate	N	0.125	0.050	0.211	0.171	0.251
$\overline{\pi}$	Steady state inflation	Γ	0.625	0.100	0.871	0.768	0.975
$\frac{100(1-\beta)}{\beta}$	Discount rate (percent)	Γ	0.250	0.100	0.245	0.090	0.380
lss	Log steady state hours	N	0.000	2.000	-0.538	-2.400	1.327
γ	Steady state growth rate (percent)	N	0.400	0.100	0.450	0.420	0.482
ρ_a	AR parameter technology shock	β	0.500	0.200	0.981	0.971	0.989
ρ_c	AR parameter risk premium shock	β	0.500	0.200	0.507	0.365	0.647
ρ_g	AR parameter exogenous demand shock	β	0.500	0.200	0.986	0.978	0.994
ρ_i	AR parameter investment shock	β	0.500	0.200	0.695	0.611	0.783
ρ_r	AR parameter interest rate	β	0.500	0.200	0.256	0.152	0.367
ρ_p	AR parameter price markup	β	0.500	0.200	0.964	0.942	0.985
ρ_w	AR parameter wage markup	β	0.500	0.200	0.962	0.941	0.986
ρ_{ep}	MA parameter price markup	β	0.500	0.200	0.820	0.744	0.910
ρ_{ew}	MA parameter wage markup	β	0.500	0.200	0.921	0.882	0.962
ρ_{ga}	Effect of tech shock on exog. demand	N	0.500	0.200	0.256	0.192	0.323
σ_c	Std dev. of risk premium shock	Γ^{-1}	0.100	2.000	1.427	0.801	1.974
σ_w	Std dev. of wage markup shock	Γ^{-1}	0.100	2.000	0.261	0.234	0.289
σ_p	Std dev. of price markup shock	Γ^{-1}	0.100	2.000	0.121	0.100	0.142
σ_r	Std dev. of interest rate shock	Γ^{-1}	0.100	2.000	0.210	0.192	0.228
σ_a	Std dev. of technology shock	Γ^{-1}	0.100	2.000	0.565	0.518	0.615
σ_i	Std dev. of investment shock	Γ^{-1}	0.100	2.000	0.967	0.836	1.109
σ_g	Std dev. of exog. demand shock	Γ^{-1}	0.100	2.000	0.320	0.294	0.344

Notes: The prior for a parameter is a Normal (N), Beta (β), Gamma (Γ), or inverse-Gamma (Γ^{-1}) distribution. Columns 4 and 5 indicate the mean and standard deviation of the prior distribution, and the final three columns report the posterior mean and lower and upper limits of 90% Bayesian confidence intervals from the posterior distribution.

Table 3: Variance decomposition of model *without* borrowing constraints: 1954Q3 - 2011Q4

	Risk premium	Wage markup	Price markup	Monetary policy	Neutral Technology	IST	Government
Output growth	0.10	0.04	0.05	0.06	0.09	0.55	0.11
	[0.03, 0.18]	[0.01, 0.06]	[0.02, 0.07]	[0.04, 0.08]	[0.06, 0.12]	[0.43, 0.65]	[0.09, 0.14]
Consumption growth	0.38	0.13	0.07	0.16	0.11	0.12	0.01
	[0.22, 0.56]	[0.06, 0.21]	[0.02, 0.11]	[0.11, 0.21]	[0.07, 0.16]	[0.03, 0.21]	[0.00, 0.02]
Investment growth	0.02	0.01	0.03	0.01	0.03	0.91	0.00
	[0.00, 0.03]	[0.00, 0.02]	[0.01, 0.04]	[0.01, 0.02]	[0.02, 0.04]	[0.87, 0.95]	[0.00, 0.00]
Real wage growth	0.01	0.60	0.28	0.01	0.06	0.04	0.00
	[0.00, 0.01]	[0.51, 0.70]	[0.20, 0.39]	[0.00, 0.01]	[0.04, 0.09]	[0.02, 0.07]	[0.00, 0.00]
Total hours growth	0.03	0.32	0.18	0.04	0.03	0.31	0.09
	[0.01, 0.07]	[0.16, 0.47]	[0.07, 0.27]	[0.02, 0.06]	[0.02, 0.05]	[0.17, 0.44]	[0.03, 0.13]
Inflation	0.01	0.40	0.38	0.04	0.06	0.09	0.01
	[0.00, 0.03]	[0.25, 0.55]	[0.22, 0.52]	[0.02, 0.07]	[0.04, 0.09]	[0.02, 0.16]	[0.00, 0.01]
Interest rate	0.08	0.17	0.09	0.12	0.09	0.43	0.01
	[0.01, 0.17]	[0.08, 0.26]	[0.03, 0.15]	[0.07, 0.17]	[0.06, 0.13]	[0.27, 0.62]	[0.01, 0.02]

Notes: Each column corresponds to the contribution of a particular structural shock to the variance of observables. The values in square brackets are 90% Bayesian confidence intervals.

Table 4: Variance decomposition of model *with* borrowing constraints: 1954Q3 - 2011Q4

	Risk premium	Wage markup	Price markup	Monetary policy	Neutral Technology	IST	Government
Output growth	0.47	0.05	0.04	0.20	0.06	0.04	0.14
	[0.43, 0.53]	[0.03, 0.07]	[0.02, 0.06]	[0.18, 0.23]	[0.03, 0.09]	[0.01, 0.06]	[0.12, 0.15]
Consumption growth	0.46	0.05	0.04	0.20	0.05	0.20	0.00
	[0.40, 0.52]	[0.03, 0.08]	[0.02, 0.06]	[0.16, 0.23]	[0.02, 0.06]	[0.14, 0.25]	[0.00, 0.01]
Investment growth	0.39	0.02	0.04	0.17	0.01	0.37	0.00
	[0.31, 0.48]	[0.01, 0.04]	[0.01, 0.06]	[0.13, 0.21]	[0.00, 0.02]	[0.23, 0.50]	[0.00, 0.00]
Real wage growth	0.01	0.81	0.15	0.00	0.02	0.00	0.00
	[0.00, 0.02]	[0.76, 0.87]	[0.11, 0.19]	[0.00, 0.01]	[0.01, 0.03]	[0.00, 0.00]	[0.00, 0.00]
Total hours	0.23	0.32	0.06	0.10	0.06	0.01	0.23
	[0.12, 0.35]	[0.14, 0.49]	[0.01, 0.10]	[0.04, 0.14]	[0.02, 0.09]	[0.00, 0.02]	[0.10, 0.36]
Inflation	0.02	0.43	0.50	0.01	0.04	0.00	0.00
	[0.00, 0.05]	[0.28, 0.58]	[0.35, 0.65]	[0.00, 0.01]	[0.01, 0.07]	[0.00, 0.00]	[0.00, 0.00]
Interest rate	0.40	0.25	0.14	0.10	0.11	0.00	0.00
	[0.25, 0.55]	[0.14, 0.37]	[0.07, 0.22]	[0.06, 0.13]	[0.07, 0.15]	[0.00, 0.01]	[0.00, 0.01]

Notes: Each column corresponds to the contribution of a particular structural shock to the variance of observables. The values in square brackets are 90% Bayesian confidence intervals.

Table 5: Variance decomposition of model *with* borrowing constraints: 1984Q1 - 2009Q1

Parameter	Description	Prior	Mean	StdDev	Mean	CIlow	CIup
α	Share of capital	N	0.300	0.050	0.298	0.234	0.369
ϕ	Investment adjustment cost parameter	N	4.000	1.500	7.107	5.011	9.185
σ_c	Households intertemporal elasticity	N	1.500	0.375	1.332	1.007	1.629
σ_{cE}	Entrepreneur's intertemporal elasticity	N	1.500	0.375	0.974	0.336	1.560
h	habit parameter of consumers	β	0.700	0.100	0.782	0.690	0.880
h^E	habit parameter of entrepreneurs	β	0.700	0.100	0.911	0.873	0.956
θ_w	Calvo wage parameter	β	0.500	0.100	0.785	0.648	0.904
σ_l	Labour disutility parameter	Γ	2.000	0.750	1.132	0.394	1.866
θ_p	Calvo price parameter	β	0.500	0.100	0.780	0.687	0.899
ξ	Capacity utilization parameter	β	0.500	0.150	0.667	0.516	0.819
ϕ_p	Markup (goods)	N	1.250	0.125	1.329	1.201	1.467
δ_w	Wage indexation	β	0.500	0.150	0.384	0.162	0.602
δ_p	Price indexation	β	0.500	0.150	0.268	0.104	0.442
ϕ_π	Taylor rule inflation	N	1.500	0.250	2.194	1.804	2.580
ϕ_r	Taylor rule lagged interest rate	β	0.750	0.100	0.825	0.786	0.866
ϕ_x	Taylor rule output gap	N	0.125	0.050	0.064	0.019	0.107
$\phi_{\Delta x}$	Taylor rule output gap growth rate	N	0.125	0.050	0.154	0.115	0.193
$\overline{\pi}$	Steady state inflation	Γ	0.625	0.100	0.773	0.683	0.856
$\frac{100(1-\beta)}{\beta}$	Discount rate (percent)	Γ	0.250	0.100	0.248	0.099	0.390
ltv	Loan to value ratio	β	0.500	0.150	0.572	0.328	0.811
$\tilde{\beta}$	Entrepreneurs discount less househlds	Γ	1.000	0.500	0.989	0.235	1.690
lss	Log steady state hours	N	0.000	2.000	0.313	-1.601	2.240
γ	Steady state growth rate (percent)	N	0.400	0.100	0.362	0.269	0.447
ρ_a	AR parameter technology shock	β	0.500	0.200	0.959	0.932	0.986
ρ_c	AR parameter risk premium shock	β	0.500	0.200	0.632	0.380	0.870
ρ_g	AR parameter exogenous demand shock	β	0.500	0.200	0.952	0.911	0.991
ρ_i	AR parameter investment shock	β	0.500	0.200	0.389	0.276	0.503
ρ_r	AR parameter interest rate	β	0.500	0.200	0.278	0.149	0.403
ρ_p	AR parameter price markup	β	0.500	0.200	0.900	0.820	0.979
ρ_w	AR parameter wage markup	β	0.500	0.200	0.861	0.760	0.985
ρ_{ep}	MA parameter price markup	β	0.500	0.200	0.745	0.586	0.943
ρ_{ew}	MA parameter wage markup	β	0.500	0.200	0.800	0.680	0.940
ρ_{ga}	Effect of tech shock on exog. demand	N	0.500	0.200	0.285	0.165	0.400
σ_c	Std dev. of risk premium shock	Γ^{-1}	0.100	2.000	0.355	0.205	0.513
σ_w	Std dev. of wage markup shock	Γ^{-1}	0.100	2.000	0.323	0.267	0.378
σ_p	Std dev. of price markup shock	Γ^{-1}	0.100	2.000	0.109	0.076	0.135
σ_r	Std dev. of interest rate shock	Γ^{-1}	0.100	2.000	0.126	0.108	0.145
σ_a	Std dev. of technology shock	Γ^{-1}	0.100	2.000	0.450	0.385	0.502
σ_i	Std dev. of investment shock	Γ^{-1}	0.100	2.000	1.075	0.816	1.305
σ_g	Std dev. of exog. demand shock	Γ^{-1}	0.100	2.000	0.272	0.239	0.307

Notes: The prior for a parameter is a Normal (N), Beta (β), Gamma (Γ), or inverse-Gamma (Γ^{-1}) distribution. Columns 4 and 5 indicate the mean and standard deviation of the prior distribution, and the final three columns report the posterior mean and lower and upper limits of 90% Bayesian confidence intervals from the posterior distribution.

Table 6: Variance decomposition of model *with* borrowing constraints: 1984Q1 - 2009Q1

	Risk premium	Wage markup	Price markup	Monetary policy	Neutral Technology	IST	Government
Output growth	0.40	0.09	0.07	0.20	0.06	0.07	0.11
	[0.18, 0.61]	[0.04, 0.13]	[0.00, 0.13]	[0.11, 0.28]	[0.02, 0.11]	[0.02, 0.13]	[0.06, 0.15]
Consumption growth	0.48	0.08	0.06	0.25	0.04	0.09	0.00
	[0.25, 0.70]	[0.03, 0.13]	[0.00, 0.12]	[0.12, 0.36]	[0.01, 0.06]	[0.01, 0.16]	[0.00, 0.00]
Investment growth	0.24	0.04	0.04	0.12	0.01	0.55	0.00
	[0.04, 0.43]	[0.01, 0.07]	[0.00, 0.08]	[0.05, 0.18]	[0.00, 0.02]	[0.28, 0.78]	[0.00, 0.00]
Real wage growth	0.01	0.85	0.11	0.01	0.02	0.01	0.00
	[0.00, 0.03]	[0.74, 0.94]	[0.01, 0.18]	[0.00, 0.02]	[0.00, 0.03]	[0.00, 0.02]	[0.00, 0.00]
Total hours	0.18	0.30	0.19	0.13	0.07	0.05	0.08
	[0.03, 0.36]	[0.07, 0.52]	[0.00, 0.36]	[0.04, 0.23]	[0.01, 0.14]	[0.01, 0.09]	[0.02, 0.13]
Inflation	0.05	0.37	0.43	0.05	0.08	0.02	0.01
	[0.00, 0.12]	[0.16, 0.54]	[0.22, 0.65]	[0.01, 0.09]	[0.02, 0.13]	[0.00, 0.03]	[0.00, 0.02]
Interest rate	0.25	0.29	0.12	0.06	0.18	0.06	0.04
	[0.04, 0.53]	[0.12, 0.45]	[0.01, 0.21]	[0.02, 0.10]	[0.06, 0.29]	[0.00, 0.12]	[0.00, 0.06]

Notes: Each column corresponds to the contribution of a particular structural shock to the variance of observables. The values in square brackets are 90% Bayesian confidence intervals.

A Linearized Model

Table 7: Linearized model equations

GDP	$y_t = \frac{c^a}{y} c_t^a + \frac{i}{y} i_t + \frac{z}{y} z_t + \varepsilon_{g,t}$
Marginal utility c	$\lambda_t = -\sigma^c \frac{1}{1-\frac{h}{\gamma}} (c_t - \frac{h}{\gamma} c_{t-1}) + \frac{\sigma^c - 1}{1-\frac{h}{\gamma}} (WLC) l_t$
Euler	$\lambda_t = E_t \left(\lambda_{t+1} + r_t + \varepsilon_{c,t} - \pi_{t+1} \right)$
Marginal utility c^e	$\lambda_t^e = -\sigma^e \frac{1}{1-\frac{h^e}{\gamma}} (c_t^e - \frac{h}{\gamma} c_{t-1}^e)$
Euler Entrepreneurs	$\lambda_t^e = \lambda_{t+1}^e + \overline{\Delta} \left(r_t + \varepsilon_{c,t} - \pi_{t+1} \right) + (\overline{\Delta} - 1) \Delta_t$
Borrowing constraint	$b_t + r_t + \varepsilon_{c,t} - \pi_{t+1} = q_{t+1} + k_t$
Entrep. consumption	$\frac{c^e}{y} c_t^e + \frac{i}{y} i_t = \frac{b}{y} b_t + \frac{b}{y} \frac{RR}{\gamma \pi} (\pi_t - b_{t-1} - r_{t-1} - \varepsilon_{c,t-1}) + (rk_t + k_{t-1}) rk \frac{k}{y} \frac{1}{\gamma}$
Entrep, consumption	$\frac{c^a}{y} c_t^a = \frac{c}{y} c_t + \frac{c^e}{y} c_t^e$
Investment	$i_t = \frac{1}{1+\beta^e \gamma^{1-\sigma^e}} i_{t-1} + \left(1 - \frac{1}{1+\beta^e \gamma^{1-\sigma^e}} \right) i_{t+1} + \frac{1}{1+\beta^e \gamma^{1-\sigma^e} \gamma^2 \phi} q_t + \varepsilon_{\mu,t}$
Tobin's q	$q_t = ((1-\delta)\beta^e \gamma^{-\sigma^e} + \Delta\chi) q_{t+1} + (1 - (1-\delta)\beta^e \gamma^{-\sigma^e} - \Delta\chi) rk_{t+1}$ $+ \Delta\chi \Delta_t + \lambda_{t+1}^e - \lambda_t^e$
Production fn.	$y_t = \phi_F \left(\alpha \overline{k}_t + (1-\alpha) l_t + \varepsilon_{a,t} \right)$
Capital utilization	$\overline{k}_t = k_{t-1} + z_t$
Capital utilization	$z_t = \frac{1-\xi}{\xi} rk_t$
Capital accumulation	$k_t = \frac{1-\delta}{\gamma} k_{t-1} + \left(1 - \frac{1-\delta}{\gamma} \right) i_t + \left(1 - \frac{1-\delta}{\gamma} \right) (1 + \beta^e \gamma^{1-\sigma^e} \gamma^2 \phi) \varepsilon_{\mu,t}$
Marginal cost	$mc_t = (\alpha) rk_t + (1-\alpha) w_t - \varepsilon_{a,t}$
Wage mark up	$\mu_t^w = w_t - (\sigma^l l_t + \frac{1}{1-\frac{h}{\gamma}} (c_t - \frac{h}{\gamma} c_{t-1})$
Cost minimization	$rk_t = -(\overline{k}_t - l_t) + w_t$
Price inflation	$\pi_t = \frac{\delta_p}{1+\beta\gamma^{1-\sigma^c}\delta_p} \pi_{t-1} + \frac{\beta\gamma^{1-\sigma^c}}{1+\beta\gamma^{1-\sigma^c}\delta_p} \pi_{t+1} + \left(\frac{1-\beta\gamma^{1-\sigma^c}\theta_p}{1+\beta\gamma^{1-\sigma^c}\delta_p} \right) \frac{1-\theta_p}{(\theta_p((\phi_p - 1)\epsilon_p + 1))} mc_t + \varepsilon_{p,t}$
Wage inflation	$w_t = \frac{1}{1+\beta\gamma^{1-\sigma^c}} w_{t-1} + \left(1 - \frac{1}{1+\beta\gamma^{1-\sigma^c}} \right) (w_{t+1} + \pi_{t+1}) - \frac{1+\beta\gamma^{1-\sigma^c}\delta_w}{1+\beta\gamma^{1-\sigma^c}} \pi_t$ $+ \frac{\delta_w}{1+\beta\gamma^{1-\sigma^c}} \pi_{t-1} - \frac{1-\beta\gamma^{1-\sigma^c}\theta_w}{1+\beta\gamma^{1-\sigma^c}} \frac{1-\theta_w}{\theta_w((\phi_w - 1)\epsilon_w + 1} \mu_t^w + \varepsilon_{w,t}$
Interest rate rule	$r_t = \phi_r r_{t-1} + (1-\phi_r)(\phi_\pi \pi_t + \phi_x (y_t - y_t^{flex}))$ $+ \phi_{dx} (y_t - y_{t-1} - (y_t^{flex} - y_{t-1}^{flex})) + \varepsilon_{r,t}$

B Data

B.1 Data sources

Table 8: Raw data

Mnemonic	Source	Description
GDP	Haver	Gross Domestic Product (SAAR, Bil.$)
JGDP	Haver	Gross Domestic Product: Chain Price Index (SA, 2005=100)
CN	Haver	Personal Consumption Expenditures: Nondurable Goods (SAAR, Bil.$)
CS	Haver	Personal Consumption Expenditures: Services (SAAR, Bil.$)
CD	Haver	Personal Consumption Expenditures: Durable Goods (SAAR, Bil.$)
I	Haver	Gross Private Domestic Investment (SAAR, Bil.$)
LF	Haver	Civilian Labor Force: 16 yr + (SA, Thous)
LH	Haver	Not in the Labor Force: 16 yr + (SA, Thous)
LXNFC	Haver	Nonfarm Business Sector: Compensation Per Hour (SA, 2005=100)
LXNFH	Haver	Nonfarm Business Sector: Hours of All Persons (SA, 2005=100)
FFED	Haver	Federal Funds [effective] Rate (% p.a.)

Notes: The Haver mnemonics should be suffixed with @USECON to call the series from the Haver Excel add-in.

B.2 Data transformations

We transform the data as described in Justiniano et al.'s *Investment shocks and business cycles: technical appendix and additional results*, with a minor exception relating to nonfarm labour hours (discussed below). The mnemonics from table 8 are used in the right hand side in table 9.

For per capita labour hours we use the LXNFH series instead of the HNFBN series reported by Justiniano et al. because the latter series no longer seems to be available in Haver. LXNFH is an index with a base year in 2005. We normalize our series to replicate the properties of the series in Justiniano et al..[6] In their sample $\ln(HNFBN/(LF + LH))$ appears to have has been normalized to zero. The Federal Funds rate is divided by 4 because the model is run on quarterly data. No other demeaning or de-trending is performed on the data.

[6]The choice of parameters is very slightly modified to those found from regressing the data from Justiniano et al. on $\ln(LXNFH/(LF + LH))$.

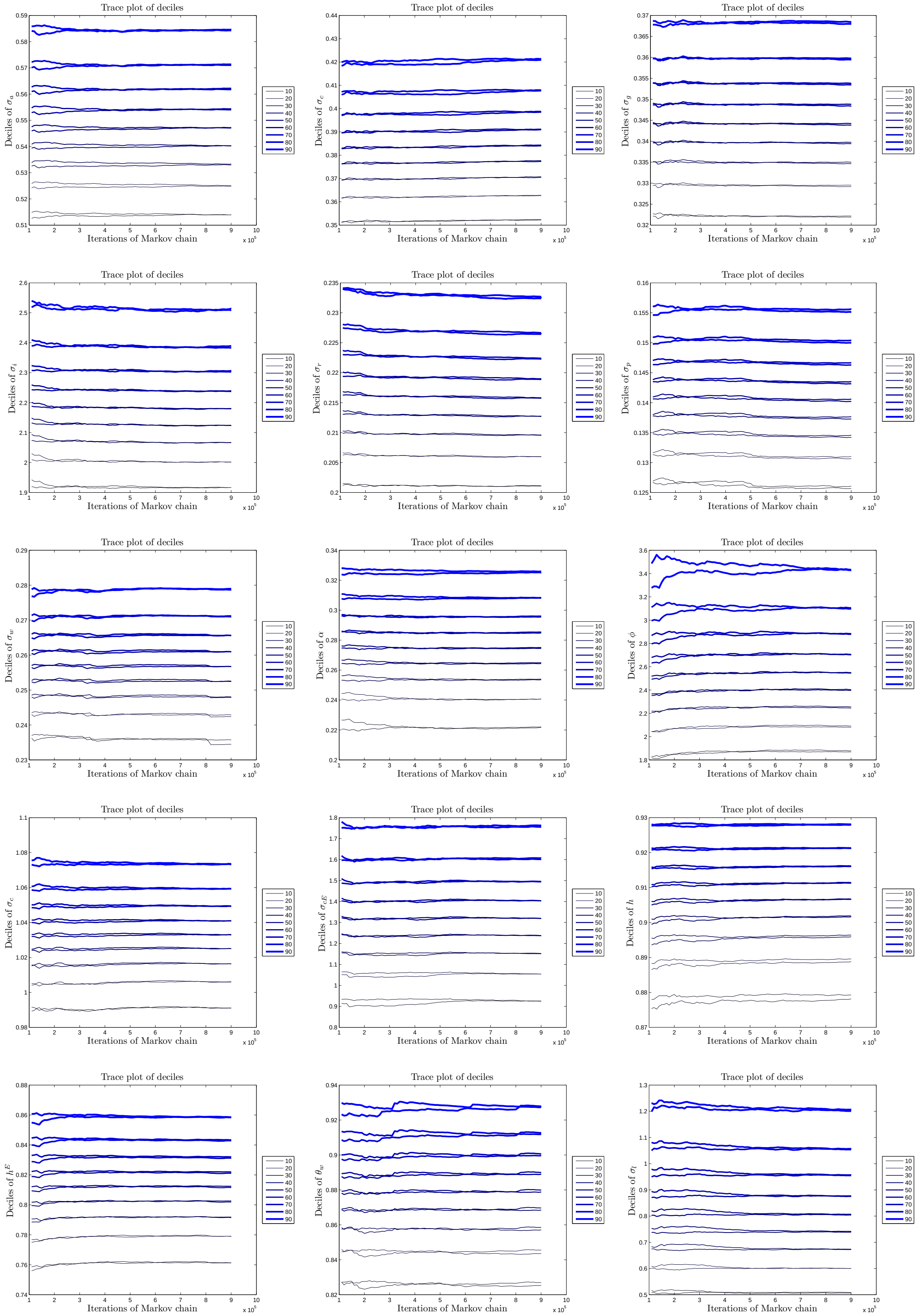
Table 9: Data transformations

Real GDP per capita $= GDP/((LH + LF) \times JGDP)$
Real Consumption per capita $= (CN + CS)/((LH + LF) \times JGDP)$
Investment per capita $= (CD + I)/((LH + LF) \times JGDP)$
Real wages $= \ln(LXNFC/JGDP)$
Inflation at time $t = 100 \times \ln(JGDP_t/JGDP_{t-1})$
Interest rate $= FFED/4$
Labour hours per capita $= \ln(LXNFH/(LF + LH)) \times 100$

Notes: The observables for Real GDP per capita, real consumption per capita, real investment per capita, and real wages are computed as 100 times the log difference of each of the series described above, ie the log approximation of quarterly percent changes.

C MCMC convergence

This appendix illustrates diagnostics to assess whether the Markov chains have converged to the posterior distributions of interest. Two Markov chains were iterated 900,000 times to estimate the posterior distribution of the vector of parameter. As noted by Brooks and Roberts (1998) and others, no diagnostic can guarantee convergence. Nevertheless, these figures provide some reassurance that the chains have indeed converged to their stationary distributions. The figures below illustrate the deciles for each chain, computed recursively as the chains are iterated forward (following a 100,000 burn-in period to reduce bias from initial conditions). Convergence implies that like-deciles from the two chain should asymptote to the same values, which should remain constant as the sample is extended. The variability evident in some deciles for some parameters seems fairly modest and is unlikely to be of economic significance.


Trace plot of deciles
Iterations of Markov chain
Deciles of σ_a
Deciles of σ_c
Deciles of σ_g
Deciles of σ_i
Deciles of σ_r
Deciles of σ_p
Deciles of σ_w
Deciles of α
Deciles of φ
Deciles of σ_c
Deciles of σ_cE
Deciles of h
Deciles of h^E
Deciles of θ_w
Deciles of σ_l
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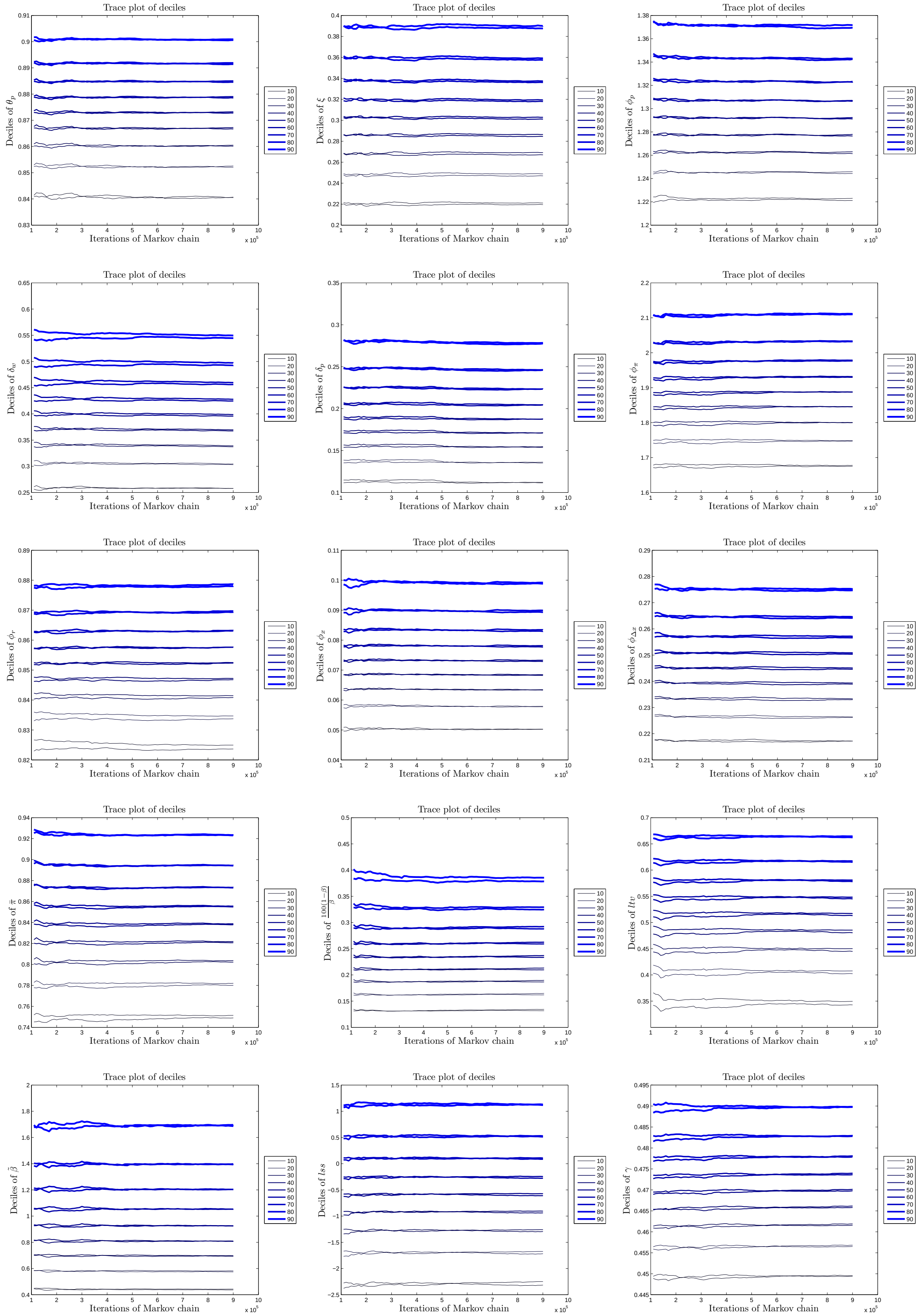
Trace plot of deciles
Iterations of Markov chain
Deciles of θ_p
Deciles of ξ
Deciles of ϕ_p
Deciles of δ_w
Deciles of δ_p
Deciles of ϕ_π
Deciles of ϕ_r
Deciles of ϕ_x
Deciles of $\phi_{\Delta x}$
Deciles of $\bar{\pi}$
Deciles of $\frac{100(1-\beta)}{\beta}$
Deciles of $\bar{l}v$
Deciles of $\bar{\beta}$
Deciles of lss
Deciles of γ
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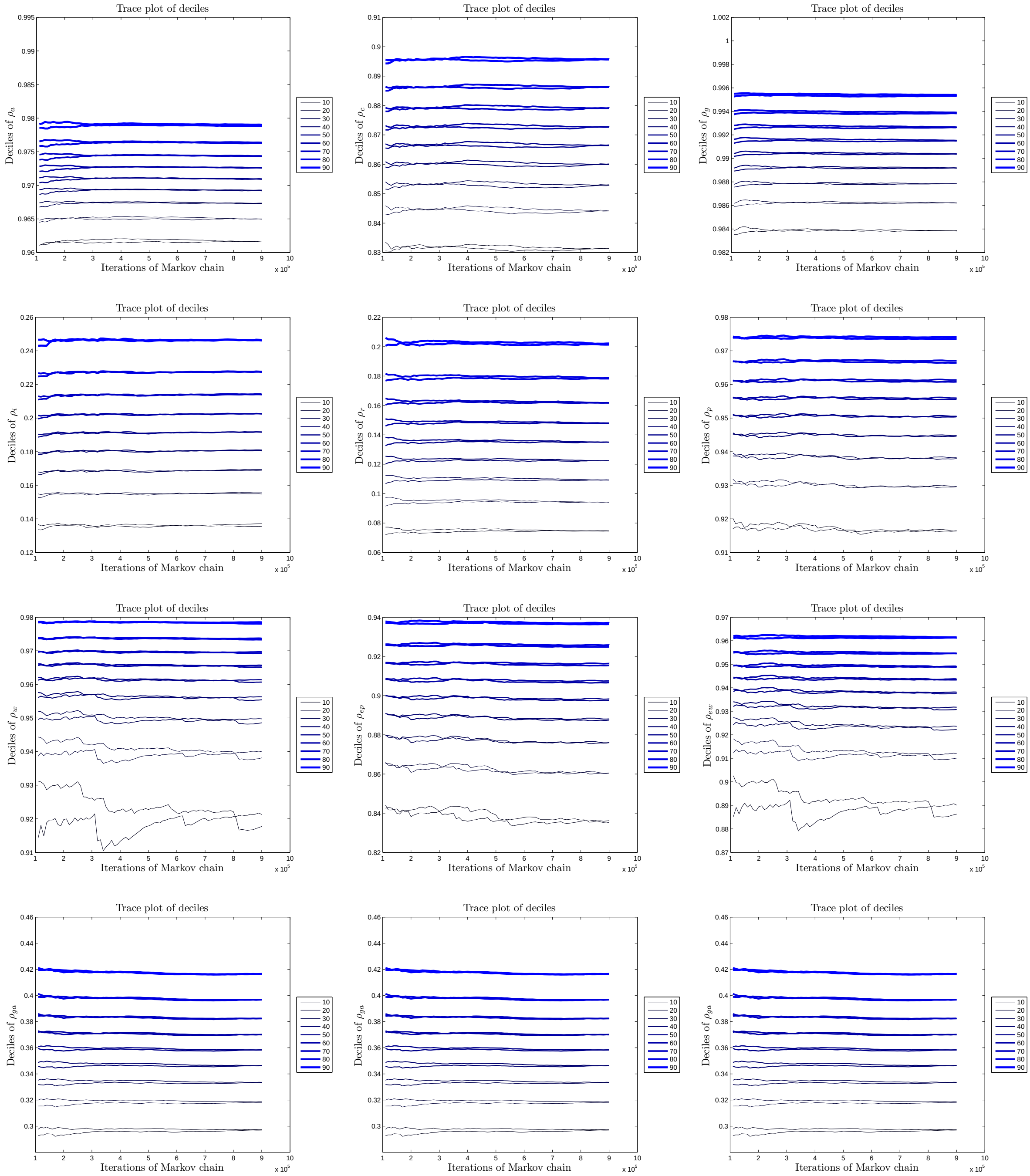

Trace plot of deciles
Iterations of Markov chain
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Deciles of ρ_a
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Deciles of ρ_w
Deciles of ρ_{cp}
Deciles of ρ_{ew}
Deciles of ρ_{ga}
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90

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Kaushik Mitra
Castlecliffe, School of Economics and Finance
University of St Andrews
Fife, UK, KY16 9AL
Email: km91@at-andrews.ac.uk; Phone: +44 (0)1334 462443; Fax: +44 (0)1334 462444.