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A Medium-Scale New Keynesian Open Economy Model of Australia

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We estimate a new Keynesian open economy dynamic stochastic general equilibrium model of Australia with a large number of shocks, frictions and rigidities, matching a large number of observable time series. We find that both foreign and domestic shocks are important drivers of the Australian business cycle. We also find that the initial impact on inflation of an increase in demand for Australian commodities is negative, because of an improvement in the real exchange rate, although there is a persistent positive effect on inflation that dominates at longer horizons.

I Introduction

Dynamic stochastic general equilibrium (DSGE) models are relatively new, but increasingly popular, additions to the tool kits of practical macroeconomic modellers. The main motivation for developing DSGE models reflects the appetite for frameworks that place emphasis on sound micro foundations and theoretical consistency. For instance, at the central banks of Canada, Finland, Norway, Sweden and the UK, new Keynesian DSGE models play an important role in support of their forecasts and policy analysis.

Some work has been done on constructing DSGE models for Australia, with examples being Buncic and Melecky (2008) and Nimark (2009). These are relatively small-scale models. For instance, they do not include a role for physical capital and assume a perfectly competitive labour market with flexible nominal wages and the only friction present is that prices in the goods producing sector are sticky. There are advantages in terms of tractability of using small models, but also obvious disadvantages as a simple model may be silent about important aspects of the macroeconomy.

This article estimates a more richly structured new Keynesian open economy DSGE model with a sizeable number of frictions and rigidities, using Bayesian techniques on Australian data. It can be seen as an extension of the earlier work cited earlier. We use data on output, inflation, employment, consumption, real wages, investment, interest rates, the real exchange rate, exports, imports, commodity exports and prices to estimate structural parameters of the model and identify structural shocks that explain Australian business cycle fluctuations. One feature of the model is the assumption that the economy grows along a stochastic path (as in Altig *et al.*, 2005), which has an attractive implication for the estimation of the model: there is no need to prefilter the data; instead unprocessed 'raw' data can be used. The Australian studies mentioned above all estimate models on prefiltered data.

The model follows closely that of Adolfson *et al.* (2007), although we add features to the model that are potentially important for modelling the Australian economy. The main difference compared with Adolfson *et al.* is that there

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are two productive sectors in the economy: a domestic intermediate tradable sector and a commodity exporting sector. It is assumed that the demand for the exported commodity good is completely exogenous, and its price is determined in the foreign market.

Key model parameters are estimated by applying Bayesian estimation techniques. An advantage of this approach is that even a relatively large model can be estimated as a system. The estimated model can be used to give quantitative answers to several interesting questions. For instance, which shocks are important in driving the Australian business cycle? How important are shocks emanating from outside Australia? We can also use the model to trace out the effects of particular shocks, like a commodity demand shock or a monetary policy shock, on macroeconomic variables like gross domestic product (GDP) growth, inflation and real wages. As a robustness check of the impact of the priors, we also estimate the model with truncated uniform priors.

The estimated model is used to decompose the business cycle fluctuations of the observed variables into the unobserved shocks that drive them. Our results show that foreign shocks are important drivers of the Australian business cycle, but we also find that domestic shocks explain a significant fraction of the variance of the domestic observable variables, such as inflation, real wage growth, employment and the nominal interest rate.

The article is organised as follows. The next section discusses the key features of the model. Section III discusses some measurement issues and estimation strategy. Section IV presents and discusses estimation results. Section V makes some tentative conclusions.

II The Model – Main Features

The benchmark set-up of the model closely follows the open economy extension of Altig *et al.* (2005) and Christiano *et al.* (2005) by Adolfson *et al.* (2007). For a detailed discussion of the basic model, readers should refer to these sources (and Appendix II). In what follows we provide a brief sketch of the key features of the model. The model consists of a domestic economy populated with households that consume goods, supply labour and own the firms that produce the goods. Domestic households trade with the rest of the world by exporting and importing differentiated consumption and investment goods. Consumption and investment goods are also produced domestically for domestic use. There is also a representative firm that produces a commodity good that is exported abroad. The domestic economy is small in the sense that developments in the domestic economy are assumed to have only a negligible impact on the rest of the world.

Almost all the theory of the model can be understood in terms of households and firms responding to changes in relative prices. There are four main types of goods in the domestic economy: domestically produced consumption goods, imported consumption goods, domestically produced investment goods, and imported investment goods. Households will choose to consume and invest more of the type of good that is relatively cheap. The relative price between imported and domestic goods hence determines the import share in domestic consumption and investment. Similarly, the intertemporal decision to invest and consume can be understood in terms of the relative prices of goods today compared with expected future prices, which will depend on expected inflation and nominal interest rates. Households need to work to earn wages, their labour supply decision depends on the real wage offered and the marginal utility associated with the marginal increase in wage income that would come about by supplying an additional increment of labour (which leaves less time for valuable leisure).

The model has a number of frictions that slow down the alignment of relative prices and quantities to their steady-state values. All goods prices and wages are subject to Calvo-type nominal frictions. These prevent the aggregate price level from adjusting immediately to shocks. The same kind of friction is also present in households' wage-setting decisions. In addition, there are also real frictions in the model that imply that even in the absence of nominal frictions, adjustment to shocks is not instantaneous. The real frictions in the model include costs of adjusting investment and employment, and habit formation in consumption.

The structure of the model and the various frictions that determine its dynamics are outlined next in some detail. However, for a more formal description of the model, we refer interested readers to Adolfson *et al.* (2007).[1]

[1] See also Appendix II, which presents the model equations in their log-linearised form.

(i) Households

Households indexed by $j \in (0,1)$ consume goods and supply labour services to firms. Household j maximises

$$E_t^j \sum_{t=0}^{\infty} \beta^t \left[\zeta_t^c \ln(C_{j,t} - bC_{j,t-1}) - \zeta_t^h A_L \frac{h_{j,t}^{1+\sigma_L}}{1+\sigma_l} + A_q \frac{\left(\frac{Q_{j,t}}{z_t P_t^d}\right)^{1-\sigma_q}}{1-\sigma_q} \right], \qquad (1)$$

by choosing consumption of the CES bundle $C_{j,t}$ containing both domestically produced and imported goods. Households also decide how much labour $h_{j,t}$ to supply and real cash holdings $Q_{j,t}$.

(ii) Production

There is a continuum of firms, indexed by $i \in (0,1)$, that produce intermediate domestic goods using the decreasing returns to scale production function

$$Y_{i,t} = z_t^{1-\alpha} \varepsilon_t K_{i,t}^{\alpha} H_{i,t}^{1-\alpha} - z_t \phi, \qquad (2)$$

where z_t is a permanent technology shock shifting the productivity of labour permanently. The permanent technology shock introduces a unit root in firms' output and evolves as an AR(1) process,

$$\mu_{z,t} = (1 - \rho_{\mu_z})\mu_z + \rho_{\mu_z}\mu_{z,t-1} + \varepsilon_t^{\mu_z}, \qquad (3)$$

where $\mu_{z,t} = z_t/(z_{t-1})$ is the rate of labour-augmenting productivity growth with steady-state value μ_z. ε_t is a persistent (but transitory) technology shock. $K_{i,t}$ and $H_{i,t}$ are capital services and labour inputs at firm i, respectively. The last term $z_t\phi$ is a fixed cost of production that ensures zero profits (from monopolistic competition) in steady state. It can be expressed in terms of a mark-up paid over the firm's marginal cost.

Intermediate goods are combined into the final good Y_t using a constant elasticity of substitution aggregator

$$Y_t = \left[\int_0^1 (Y_{i,t})^{\frac{1}{\lambda_t^d}} \right]^{\lambda_t^d}. \qquad (4)$$

Total final goods produced domestically must be used for final domestically produced investment goods I_t^d, consumption goods C_t^d or exports X_t, thereby satisfying the resource constraint

$$Y_t = I_t^d + C_t^d + X_t. \qquad (5)$$

(iii) Nominal Frictions

There are three categories of firms operating in the economy – domestic intermediate goods producers, importing firms and exporting firms – which face nominal frictions that affect their price setting. Similarly, domestic households face constraints on the frequency with which they can adjust the prices of the labour services they sell.

Monopolistically competitive firms produce intermediate goods using labour and capital for private consumption and investment (used to form the physical capital stock, together with imported investment goods). All types of intermediate goods are sold at a time-varying mark-up over their marginal cost. The intermediate good firms are not able to re-optimise their prices in each period, and when prices are re-optimised, they are set to maximise the discounted expected value of future profits. Since prices are not re-optimised in every period, firms need to take into account future marginal costs and mark-ups when current prices are set. Firms that are unable to re-optimise their prices in a given period index their prices to the previous period's inflation. All firms operating in the intermediate goods market solve symmetric pricing problems, although the frequency of price changes and the time-varying mark-ups are allowed to differ across types of goods.

Both importers and exporters are subject to price frictions stemming from assumptions regarding the currency in which the prices of exported and imported goods are set. Import prices are set in domestic currency and there is local (domestic) currency price stickiness. This captures the idea that nominal frictions are local to the market where output is sold. For instance, foreign price shocks pass-through to domestic prices only gradually. However, in the long run, there is complete pass-through of changes in marginal costs of imported consumption and investment goods to the domestic economy. Export prices are set in the local currency of the export market, and prices are sticky in those currencies. This 'pricing-to-market' assumption, together with the sticky local currency prices, provides a short-term channel allowing for deviations from the law of one price.

Prices

Following much of the literature, price stickiness is introduced by making prices subject to the Calvo (1983) mechanism. The model allows for different degrees of price rigidities and indexation depending on the type of good and sector.[2] We can write a generic Phillips Curve for each type of good denoted by superscript s as follows:

$$\begin{aligned}\hat{\pi}_t^s - \hat{\bar{\pi}}_t^c = & \frac{\beta}{1+\kappa_s\beta}[E_t\pi_{t+1}^s - \rho_\pi\hat{\bar{\pi}}_t^c] \\ & + \frac{\kappa_s}{1+\kappa_s\beta}[\hat{\pi}_{t-1} - \rho_\pi\hat{\bar{\pi}}_{t-1}^c] \\ & - \frac{\kappa_s\beta(1-\rho_\pi)}{1+\kappa_s\beta}\hat{\bar{\pi}}_t^c + \frac{(1-\xi_s)(1-\beta\xi_s)}{\xi_s(1+\kappa_s\beta)} \\ & \times (\widehat{mc}_t^s + \hat{\lambda}_t^s), \end{aligned} \tag{6}$$

where π_t^s is the change in the log of the price index of good type s; $\hat{\bar{\pi}}_t^c$ is the perceived inflation target. Throughout the article, a hat ($\hat{\cdot}$) denotes log-linearised variables. The degree of indexation is governed by the parameter κ_s: if $\kappa_s = 0$, the Phillips Curve (Eqn 1) is purely forward-looking, and if $\kappa_s = 1$, prices are fully indexed to last period's inflation. β is the discount factor, ρ_π is the persistence of the inflation target (more on this below), ξ_s is the Calvo probability of a firm not re-optimising the price of its good in a given period, $\widehat{mc}_t^s$ is the (log deviation of) firm's marginal cost of producing good s and $\hat{\lambda}_t^s$ can be interpreted as the desired mark-up of good type s.

Marginal costs

Marginal costs differ across different types of goods and sectors. The marginal costs of domestic producers of investment and consumption goods are determined by the cost of production, that is, wages and productivity. In addition, a fraction v of wages need to be financed in advance so that marginal cost are also influenced by the interest rate R_{t-1}. Cost minimisation yields the following expression for the domestic intermediate goods producer's marginal cost

$$\begin{aligned} MC_t^d = & \frac{1}{(1-\alpha)^{1-\alpha}}\frac{1}{\alpha^\alpha}(R_t^k)^\alpha[W_t(1+v(R_{t-1}-1))]^{1-\alpha} \\ & \times \frac{1}{z_t^{1-\alpha}}\frac{1}{\varepsilon_t}. \end{aligned} \tag{7}$$

[2] Firms are also assumed to face varying degrees of competition in different markets, which implies that they may receive a different profit margin from the sale of their goods in each market.

The marginal cost of importers depends on the exchange rate and the world price level so that

$$MC_t^m = \frac{S_t P_t^*}{P_t^m}.$$

The marginal cost of exporters depends on the price of domestic goods they sell to the world market and the exchange rate.

$$MC_t^x = \frac{P_t^d}{S_t P_t^*}.$$

Wages

Wages exhibit stickiness and inertia due to nominal frictions built into the model. Each household supplies a differentiated type of labour to firms and therefore has some market power to determine its wage. However, households can only re-optimise their wage with probability $(1 - \xi_w)$ in any given period.

Both the stickiness of nominal wages and the labour demand constraint are taken into account by households when they set their optimum wage. The fraction of households that are not able to re-optimise their wage in a given period index their wage. In doing so, they take account of the inflation target, lags of CPI inflation and wages, and the steady-state growth rate of technology.

(iv) Real Frictions

In addition to these nominal frictions, there are several sources of real frictions in the model. These frictions slow down the adjustment of quantities towards long-run steady-state values independently of the nominal frictions, and they are potentially important for the model's ability to match the data.

Capital adjustment costs

Firms rent capital from the households who own all domestic resources. Households can increase the economy's productive capacity by either investing in additional physical capital (which takes one period to come into the production process) or by increasing the utilisation rate of the current capital stock, thereby increasing the effective level of capital entering into production. However, adjusting the capital stock is assumed to be costly. In particular, the standard capital accumulation equation includes an extra term as in Christiano *et al.* (2005) such that

$$\bar{K}_{t+1} = (1-\delta)\bar{K}_t + \Upsilon_t(1-\tilde{S}(I_t/I_{t-1}))I_t, \tag{8}$$

where Υ_t is an investment-specific technology shock (it is assumed to follow a first-order autoregressive process); $\tilde{S}(\cdot)$ is a concave function such that marginal productivity of investment (in terms of produced physical capital) is decreasing in the ratio of current investment over past investment, and its minimum is at the steady state of the growth rate of real investment. Changing the rate of capital utilisation is also costly, this is captured by the utilisation cost function $a(u)$, where the utilisation rate is $u_t = K_t/\bar{K}_t$ (see Appendix II for details).

Habit formation

Household preferences are assumed to display (internal) habit persistence. So, current consumption depends on expected future consumption through the standard intertemporal consumption smoothing argument and it also depends on past consumption. The optimum consumption condition is given by the Euler equation:

$$\varsigma_t^c \frac{1}{c_t - bc_{t-1}\frac{1}{\mu_{z,t}}} = \beta E_t\left(\varsigma_{t+1}^c \frac{b}{\mu_{z,t+1}c_{t+1} - bc_t} + \psi_{z,t+1}\frac{R_t}{\pi_{t+1}\mu_{z,t+1}}\frac{P_t^c}{P_t}\right), \tag{9}$$

where the habits parameter b captures the degree of inertia in consumption.

Employment

Firms face an additional Calvo-like rigidity: they can adjust the level of employment to the preferred level only at random intervals (captured by the Calvo parameter, ξ_e). This friction creates a deviation between aggregate hours (H – actual work done) and employment (N – number of workers). The employment equation is:

$$\Delta\hat{N}_t = \frac{\beta}{1+\beta}E_t\Delta\hat{N}_{t+1} + \frac{1}{1+\beta}\hat{N}_{t-1} + \frac{(1-\xi_e)(1-\beta\xi_e)}{\xi_e(1+\beta)}(\hat{H}_t - \hat{N}_t). \tag{10}$$

International trade in assets and the UIP condition

Households can save and lend in both domestic and world currency assets. However, financial market integration is assumed to be imperfect, as captured by two extra terms that enter the standard uncovered interest rate parity condition

$$E_t\Delta\hat{S}_{t+1} = (\hat{R}_t - \hat{R}_t^*) + \tilde{\phi}_a\hat{a}_t - \hat{\tilde{\phi}}_t, \tag{11}$$

where $E_t\Delta\hat{S}_{t+1}$ is the expected nominal depreciation of the domestic currency; and $(\hat{R}_t - \hat{R}_t^*)$ is the interest rate differential. There are two risk premia terms, $\tilde{\phi}_a\hat{a}_t$ and $\hat{\tilde{\phi}}_t$. The latter is an exogenous risk premium shock. The former implies that an economy will have higher interest rates if it is a net debtor (i.e. net assets, $\hat{a}_t$, are negative), everything else equal. This term also ensures that net debt is stationary.

(v) Central Bank

As a consequence of nominal and real frictions, changes in short-term nominal interest rates are not matched one-for-one by changes in expected inflation, leading to movements in real interest rates and creating a role for monetary policy in stabilisation.

The central bank sets the nominal interest rate $\hat{R}_t$ and we approximate its decision-making process with a flexible Taylor-type rule

$$\hat{R}_t = \rho_R\hat{R}_{t-1} + (1-\rho_R) \times [\bar{\pi}_t^c + r_\pi(\hat{\pi}_{t-1}^c - \bar{\pi}_t^c) + r_y\hat{y}_{t-1} + r_x\hat{x}_{t-1}] + r_{\Delta\pi}\Delta\hat{\pi}_t^c + r_{\Delta y}\Delta\hat{y}_t + \varepsilon_{R,t}. \tag{12}$$

The nominal short rate responds to lagged interest rates $\hat{R}_{t-1}$, deviations of lagged CPI inflation $\hat{\pi}_{t-1}^c$ from the perceived medium-term inflation target $\bar{\pi}_t^c$, lagged output $\hat{y}_{t-1}$, the lagged real exchange rate $\hat{x}_{t-1}$, and changes in inflation $\Delta\hat{\pi}_t^c$ and output $\Delta\hat{y}_t$. Finally, $\varepsilon_{R,t}$ is an uncorrelated monetary policy shock.

(vi) Government

As in Adolfson *et al.* (2007), the government is represented by a VAR(2) for taxes on capital income, labour income, consumption and payrolls. These variables are treated as exogenous in the model. After taxes are collected, they are paid back to households as a lump sum transfer. The role of taxes in the economy is therefore confined to influencing marginal costs of production and marginal returns on assets.

(vii) The Foreign Economy

The foreign economy is represented by a simple VAR(4) process for trade-weighted G7 GDP (linearly detrended), inflation and a simple average of US, euro area and Japanese interest rates.

These variables are also exogenous in the model. Both the foreign and fiscal VAR models are estimated separately before estimation of the DSGE model.

(viii) Export Demand, Export Income and the Commodity Sector

A large share of Australian exports are commodities. A recent paper by Chen *et al.* (2008) documents two facts about commodity exporting countries that are relevant for the current model. First, they argue that commodity markets are largely independent of the developments in the individual exporting countries and can therefore be treated as exogenous when considering individual countries. Secondly, exchange rates of commodity exporting countries may to a large extent reflect developments in the commodity markets.

In the standard new Keynesian open economy set-up, export demand depends on total world output and the relative price of the exported good, where the relative price of the good depends on the marginal cost of production in the relevant country. The peculiarities of the commodity markets highlighted by Chen *et al.* (2008) and the prominence of commodities in Australian exports suggest that this is not an appropriate specification of export and export income for Australia. The assumption of an exogenous commodity sector has also been used previously in more empirically focused studies of the Australian economy, for example, Dungey and Pagan (2000) and Dungey and Pagan (2009). In these papers, both exports and terms-of-trade are modelled as exogenous to domestic Australian variables.

Based on these considerations, two exogenous shocks are added to the model. The first shock, $\varepsilon_{com,t}$, captures variations in exports that are unrelated to the relative cost of the exported goods and the level of world output. Demand for Australian exports are therefore given by:

$$Y_t^x = 0.3Y_t^*\left(\frac{P_t^x}{P_t^*}\right)^{\eta_x} + 0.7Y_t^*\exp(\varepsilon_{com,t}), \qquad (13)$$

where the weights 0.3 and 0.7 reflect the shares of the non-commodity and commodity sector in Australian exports. The first term in Equation (13) is the non-commodity component, with price elasticity η_x. Without the exogenous shock to export demand, the model would need to explain more of the variation in exports through changes in relative prices. This may in turn affect estimates of the elasticity η_x adversely, something that also appear to be borne out in Section IV(iv) where posterior estimates of η_x are compared for specifications of the model with and without the additional exogenous commodity shocks.

An additional reason to allow for Australian exports to depend on more than relative prices and world output is that because of data availability reasons, China is not included in the data series representing the world. Some of the demand for Australian commodities from China will therefore be absorbed by the exogenous commodity demand shock. So while the exogenous structure does not help us 'understand' the commodity sector, the extra flexibility can arguably help in preventing biases arising in the estimates of other parameters.

In addition to the demand shock, we also want to allow for windfall profits (or losses) because of exogenous variations in the world market price of the commodities that Australia exports. We therefore add a shock $\varepsilon_{Pcom,t}$ to the export income equation as well. The export income as it appears in the model implied current account is therefore given by:

$$P_tY_t^x = 0.3P_t^xY_t^*\left(\frac{P_t^x}{P_t^*}\right)^{\eta_x} + 0.7\exp(\varepsilon_{com,t})\exp(\varepsilon_{Pcom,t}). \qquad (14)$$

It is worth emphasising here the different implication of a shock to export *demand*, as opposed to a shock to export *income*: the former leads to higher export incomes and higher labour demand, whereas the latter improves the trade balance without any direct effects on the demand for labour by the exporting industry.

(ix) Exogenous Shocks

In addition to these two external shocks just mentioned, there is the set of exogenous 'domestic' shocks in the model: the non-stationary technology ($\mu_{z,t}$) and stationary technology (ϵ_t) shocks; the mark-up shocks for domestic goods (λ_t^d), imported consumption goods (λ_t^{mc}), imported investment goods (λ_t^{mi}) and wages (λ_t^h); the consumption preference shock (ζ_t^c); the labour supply shock (ζ_t^h); the investment-specific productivity shock (Υ_t); the risk premium shock ($\tilde{\phi}_t$); the monetary policy shock ($\varepsilon_{R,t}$); the medium-term (perceived) inflation target shock

(π_t^c); and the asymmetric productivity shock ($\tilde{z}_t^*$).[3] The monetary policy and the domestic mark-up shocks are white noise, all the other follow AR(1) processes.

III Measurement and Estimation Strategy

The model is estimated using Bayesian methods. This section outlines our estimation strategy, including how the priors were chosen and how the variables of the theoretical model are mapped into observable time series.

(i) Measurement

We can write the solved model in state space form:

$$\tilde{\xi}_t = F_\xi \tilde{\xi}_{t-1} + v_t, \tag{15}$$

$$\tilde{Y}_t = A_X + H' \tilde{\xi}_t + \zeta_t, \tag{16}$$

$$\begin{bmatrix} v_t \\ \zeta_t \end{bmatrix} \sim N\left(\mathbf{0}, \begin{bmatrix} Q & \mathbf{0} \\ \mathbf{0} & R \end{bmatrix}\right), \tag{17}$$

where the theoretical variables (consistent with the model) are collected in the state vector $\tilde{\xi}_t$ and the observable variables are collected in the vector $\tilde{Y}_t$. The state transition (Eqn 15) governs the law of motion of the state of the model and the measurement (Eqn 16) maps the state into observable variables. The matrices F_ξ, A_X, H' and Q are functions of the parameters of the model and, insofar as all the structural parameters have distinct implications for the observable variables, all parameters will be identified. However, no general results exist regarding whether this will be the case, although there are ways to increase the chances of identifying a large number of parameters, for instance by making the rank of H' as large as possible.

In our benchmark specification, we use much the same indicators as Adolfson *et al.* (2007). The observable variables in the vector $\tilde{Y}_t$ are (trimmed mean) CPI inflation, the real wage, real consumption, real investment, the real exchange rate, the overnight cash rate, employment, real GDP, real exports, real imports, foreign output, foreign inflation, the foreign interest rate, commodity price inflation and commodity export volumes. That is,

$$\tilde{Y}_t = \begin{bmatrix} \pi_t^{\text{cpi,trim}} & \Delta \ln(W_t/P_t) & \Delta \ln C_t & \Delta \ln I_t \\ \hat{x}_t & R_t & N_t & \Delta \ln Y_t \ldots \end{bmatrix}$$
$$\begin{matrix} \Delta \ln X_t & \Delta \ln M_t & \Delta \ln Y_t^* & \pi_t^* & R_t^* \\ \Delta p_t^{com} & \Delta \ln Com_t & & & \end{matrix} \Bigg]'. \tag{18}$$

In Equation (15), A_X captures the common quarterly trend growth rate of real variables in Equation (17).[4] The covariance matrix R of the vector of measurement errors ζ_t in Equation (16) are set to $E_t[\tilde{Y}_t \tilde{Y}_t'] \times 0.1$ so that approximately 10 per cent of the variance of the observable time series is assumed to be owing to measurement errors.

(ii) Bayesian Estimation

The parameters of the model are estimated using Bayesian methods that combine prior information and information that can be extracted from the indicators in $\tilde{Y}_t$. The methodology was introduced to models suitable for policy analysis by Smets and Wouters (2003). An and Schorfheide (2007) provide an overview of the main elements of Bayesian inference techniques in dynamic stochastic equilibrium models.

Conceptually, the estimation works in the following way. Denote the vector of parameters to be estimated Θ and the log of the prior probability of observing a given vector of parameters $\mathcal{L}(\Theta)$. The function $\mathcal{L}(\Theta)$ summarises what is known about the parameters prior to estimation. The log likelihood of observing the dataset $\tilde{Y}_t$ for a given parameter vector Θ is denoted $\mathcal{L}(\tilde{Y} \mid \Theta)$. The posterior estimate $\hat{\Theta}$ of the parameter vector is then found by combining the prior information with the information in the estimation sample. In practice, this is done by numerically maximising the sum of the two over Θ, so that $\hat{\Theta} = \arg\max[\mathcal{L}(\Theta) + \mathcal{L}(\tilde{Y} \mid \Theta)]$.

The priors

Our assumptions for the prior distributions of the estimated parameters closely correspond to

[3] The asymmetric productivity shock enters the measurement equation, as explained in footnote 4. Its role is to allow for temporary deviations of real growth rates between Australia and the rest of the world that may be caused by the fact that the VAR(4) for world output, inflation and interest rates is estimated separately from the main model. The interpretation of the asymmetric technology shock should therefore not be literal.

[4] For example, the growth rate in foreign output is measured as $\log(\mu_z) + \Delta\tilde{z}_t^* + \Delta y_t^*$, where y_t^* is from the foreign VAR model of Section II(vii).

those in Adolfson *et al.* (2007) (see also Smets & Wouters, 2003) with some exceptions: we impose simple uniform priors on the indexation parameters, the elasticities of substitution and standard deviations of the structural shocks. In the benchmark specification, we impose rather tight priors on some of the policy parameters, particularly on r_x, which control the adjustment of the short-term interest rate to the real exchange rate. The priors on the parameters governing nominal stickiness, the persistence of the exogenous variables and the parameter governing the importance of habit formation are all assigned relatively dispersed beta distributions. These priors are used to ensure that these parameters are bounded below unity.

The priors for the remaining parameters are truncated uniform, where the truncation ensures that the parameters stay in the domain prescribed by the fact that variances are positive and other bounds implied by economic theory. In Tables A2 and A3, we also report the estimated distributions of the parameters imposing constant weight priors, and Section IV(iv) reports various robustness checks.[5]

Computing the likelihood

Given the state space form, Equations (15) and (16), the likelihood for a given set of parameters can be evaluated recursively

$$\mathcal{L}(\tilde{Y}|\Theta) = -0.5\sum_{t=0}^{T}[p\ln(2\pi) + \ln|\Omega| + u_t'\Omega^{-1}u_t], \tag{19}$$

where p is the dimension of $\tilde{Y}_t$ and

$$\Omega = H'PH + R, \tag{20}$$

is the covariance of the one-step ahead forecast errors u_t. These can be computed from the innovation representation

$$u_t = \tilde{Y}_t - A_X - H\prime\hat{\xi}_t, \tag{21}$$

$$\hat{\xi}_{t+1} = F_\xi\hat{\xi}_t + Ku_t, \tag{22}$$

where K is the Kalman gain

$$K = F_\xi PH(H'PH + R)^{-1}, \tag{23}$$

$$P = F_\xi(P - PH(H'PH + R)^{-1}H'P)F_\xi' + Q. \tag{24}$$

[5] For more details, see Chernozhukov and Hong (2003).

IV Empirical Results

This section reports the results of the estimation exercise.

(i) The Benchmark Specification

In the benchmark estimation of the model we use the inflation-targeting sample, that is, data from 1993:Q2 to 2007:Q3. We estimate a total of 56 parameters compared with the 51 parameters estimated by Adolfson *et al.* (2007). While Adolfson *et al.* calibrate the elasticity of consumption goods to changes in the relative price of imported and domestically produced goods (η_c), and the persistence of the medium-run inflation target (ρ_π) and wage mark-up (λ_w), we estimate these parameters. We also estimate the persistence and innovation variance of the commodity demand and price shocks that are absent in Adolfson *et al*. The calibrated parameters are provided in Table A1.

Tables 1 and 2 report the statistics of the prior and estimated posterior distributions of the structural parameters. The same information is given in Figures A1–A5, where we plot the estimated posterior distributions of the model's parameters together with their prior distributions as well as their constant weight prior estimates.

The parameters appear to be for the most part tightly estimated given that posterior standard deviations are smaller than the prior standard deviations. It seems, however, that the data are not very informative regarding the degree of price stickiness in the imported consumption, imported investment and export sectors ($\xi_{m,c}$, $\xi_{m,i}$ and ξ_x), since the posterior distributions do not differ a lot from their prior distributions. The constant weight prior posterior distributions of the ξ parameters provide further evidence of parameter under-identification: the posterior distributions tend to be rather flat. In a situation like this, the prior plays a crucial role in making inferences. The priors (and estimated parameter values) imply that prices are *re-optimised* at least around every three quarters.[6]

Data seem more informative on the indexation parameters (κ_w, κ_d, $\kappa_{m,c}$, $\kappa_{m,i}$ and κ_x), which vary significantly across the different sectors of

[6] Note that there is a difference between price re-optimisation and price re-setting, because there is partial indexation in the model: prices change every quarter for all producers, a fraction ξ because producers re-optimise and a fraction $1-\xi$ because of dynamic indexation.

TABLE 1
Prior and Posterior Distributions – Structural Parameters

Parameter	Distribution	Prior		Posterior			
		Mode	SD	Mean	SD	5%	95%
			Price stickiness				
ξ_w	Beta	0.675	0.050	0.629	0.048	0.550	0.706
ξ_d	Beta	0.675	0.010	0.688	0.009	0.673	0.704
$\xi_{m,c}$	Beta	0.675	0.010	0.674	0.010	0.658	0.691
$\xi_{m,i}$	Beta	0.675	0.010	0.674	0.010	0.657	0.690
ξ_x	Beta	0.675	0.010	0.678	0.053	0.588	0.761
ξ_e	Beta	0.675	0.050	0.620	0.038	0.555	0.677
			Indexation				
κ_w	Trunc. uniform	[0,1]		0.552	0.229	0.145	0.906
κ_d	Trunc. uniform	[0,1]		0.890	0.091	0.714	0.992
$\kappa_{m,c}$	Trunc. uniform	[0,1]		0.347	0.226	0.037	0.783
$\kappa_{m,i}$	Trunc. uniform	[0,1]		0.083	0.081	0.004	0.247
κ_x	Trunc. uniform	[0,1]		0.089	0.087	0.005	0.258
			Mark-ups				
λ_d	Inv. gamma	1.200	2.000	10.60	4.456	5.461	19.63
$\lambda_{m,c}$	Inv. gamma	1.200	2.000	2.129	0.740	1.229	3.597
$\lambda_{m,i}$	Inv. gamma	1.200	2.000	3.437	0.983	2.154	5.358
			Investment friction and habits				
$\tilde{S}''$	Normal	7.694	2.500	5.709	1.801	3.048	8.973
b	Beta	0.650	0.100	0.760	0.051	0.673	0.843
			Substitutions of elasticity				
η_c	Trunc. uniform	[1,∞)		1.301	0.286	1.016	1.911
η_i	Trunc. uniform	[1,∞)		1.462	0.318	1.078	2.076
η_f	Trunc. uniform	[1,∞)		1.129	0.123	1.007	1.378
			Risk premium				
$\tilde{\phi}_a$	Inv. gamma	0.010	0.001	0.001	0.001	0.000	0.002
			Technology growth				
μ_z	Trunc. uniform	1.008	0.001	1.009	0.000	1.009	1.009
			Monetary policy				
ρ_R	Beta	0.800	0.050	0.836	0.025	0.793	0.874
r_π	Normal	1.750	0.100	1.750	0.097	1.587	1.909
$r_{\Delta\pi}$	Normal	0.000	0.100	0.090	0.066	−0.018	0.198
r_x	Normal	0.010	0.005	−0.009	0.004	−0.016	−0.003
r_y	Normal	0.125	0.100	−0.024	0.011	−0.043	−0.009
$r_{\Delta y}$	Normal	0.000	0.100	0.035	0.020	0.004	0.068

Note: Trunc., truncated; Inv., inverse.

the economy. (As a cross-check, we imposed informative priors on these parameters, centred around 0.5, and obtained similar posterior distributions as shown in Figure A1, albeit slightly less dispersed.) The indexation parameters on imported investment goods ($\kappa_{m,i}$) and exports (κ_x) are quite low, suggesting that these Phillips Curves are mostly forward-looking. The indexation parameters for the domestic good (κ_d), the imported consumption good ($\kappa_{m,c}$) and the wage (κ_w) imply more persistence. The habit formation parameter (b) has a posterior mean of 0.76, reflecting a large degree of inertia in consumption. The value of the elasticity of substitution between home and foreign consumption goods (η_c) is only 1.30, much lower than the calibrated value in Adolfson *et al.* (2007). This could reflect relatively high estimates of

Table 2
Prior and Posterior Distributions – Exogenous Processes

		Prior		Posterior			
Parameter	Distribution	Mode	SD	Mean	SD	5%	95%
		Exogenous processes – AR(1) coefficients					
ρ_{μ_z}	Beta	0.500	0.275	0.946	0.021	0.906	0.970
ρ_{ε}	Beta	0.500	0.150	0.593	0.074	0.467	0.713
ρ_{Υ}	Beta	0.500	0.150	0.426	0.084	0.291	0.565
$\rho_{\tilde{z}^*}$	Beta	0.500	0.275	0.550	0.278	0.083	0.957
ρ_{ζ^c}	Beta	0.500	0.275	0.970	0.029	0.912	0.996
ρ_{ζ^h}	Beta	0.500	0.275	0.076	0.060	0.007	0.196
$\rho_{\tilde{\phi}}$	Beta	0.500	0.100	0.485	0.100	0.323	0.654
$\rho_{\lambda_{m,c}}$	Beta	0.500	0.275	0.999	0.000	0.998	0.999
$\rho_{\lambda_{m,i}}$	Beta	0.500	0.275	0.092	0.084	0.007	0.261
ρ_{λ_x}	Beta	0.500	0.275	0.093	0.085	0.007	0.261
$\rho_{\bar{\pi}}$	Beta	0.500	0.275	0.608	0.123	0.380	0.797
ρ_{pcom}	Beta	0.500	0.275	0.965	0.023	0.923	0.992
ρ_{com}	Beta	0.500	0.275	0.998	0.001	0.996	0.999
		Exogenous processes – standard deviations ($\times 10^{-2}$)					
σ_{μ_z}	Trunc. uniform	[0,∞)		0.127	0.029	0.084	0.180
σ_{ε}	Trunc. uniform	[0,∞)		1.228	0.197	0.929	1.573
σ_{Υ}	Trunc. uniform	[0,∞)		0.954	0.167	0.701	1.249
$\sigma_{\tilde{z}^*}$	Trunc. uniform	[0,∞)		0.054	0.039	0.005	0.130
σ_{ζ^c}	Trunc. uniform	[0,∞)		0.090	0.024	0.056	0.134
σ_{ζ^h}	Trunc. uniform	[0,∞)		0.402	0.051	0.323	0.489
$\sigma_{\tilde{\phi}}$	Trunc. uniform	[0,∞)		0.402	0.303	0.033	0.974
σ_{λ_d}	Trunc. uniform	[0,∞)		0.144	0.030	0.097	0.194
$\sigma_{\lambda_{m,c}}$	Trunc. uniform	[0,∞)		0.360	0.103	0.216	0.551
$\sigma_{\lambda_{m,i}}$	Trunc. uniform	[0,∞)		3.870	0.995	2.325	5.621
σ_{λ_x}	Trunc. uniform	[0,∞)		5.178	1.002	3.639	6.956
σ_r	Trunc. uniform	[0,∞)		0.022	0.016	0.002	0.053
$\sigma_{\bar{\pi}}$	Trunc. uniform	[0,∞)		0.554	0.136	0.358	0.780
σ_{com}	Trunc. uniform	[0,∞)		2.368	0.247	2.003	2.809
σ_{pcom}	Trunc. uniform	[0,∞)		4.895	0.773	3.743	6.627

Note: Trunc., truncated; Inv., inverse.

steady-state price mark-ups (λ_d, $\lambda_{m,c}$, $\lambda_{m,i}$). It is worth noting, however, that when we calibrated the mark-up parameters at the prior modes, this raised the estimate of η_c but did not produce drastically lower marginal likelihoods.

The parameters of the policy reaction function are well identified. There are some differences between the Bayesian and constant weight prior posteriors, because of the informative priors imposed on the policy parameters. The constant weight prior estimate of the inflation response in the policy rule implies a stronger reaction of interest rates to inflation movements in comparison with the Bayesian estimate.

Although we allow for both temporary and permanent productivity shocks, the estimated persistence of some of the transitory shocks is quite large. The posterior distributions of the AR parameters of the consumption preference (ρ_{ζ^c}), imported consumption mark-up ($\rho_{\lambda^{m,c}}$) and commodity price ($\rho_{\lambda^{pcom}}$) shocks all have a lot of mass close to 1.

The standard deviation of the innovations to the temporary productivity shock (σ_e) is smaller than that of the permanent productivity shock (σ_{μ_z}). Shocks for imported investment and export mark-ups, consumption preferences, commodity demand and commodity prices are the most volatile in the estimated model.

The parameter estimates of the reduced form VAR(2) for government controlled variables and VAR(4) for world output, inflation and interest rates are difficult to interpret and have little meaning apart from predicting future values of these same variables. The parameter estimates are therefore left out of the main text, but are available from the authors upon request.

FIGURE 1
One-Sided Fitted Values

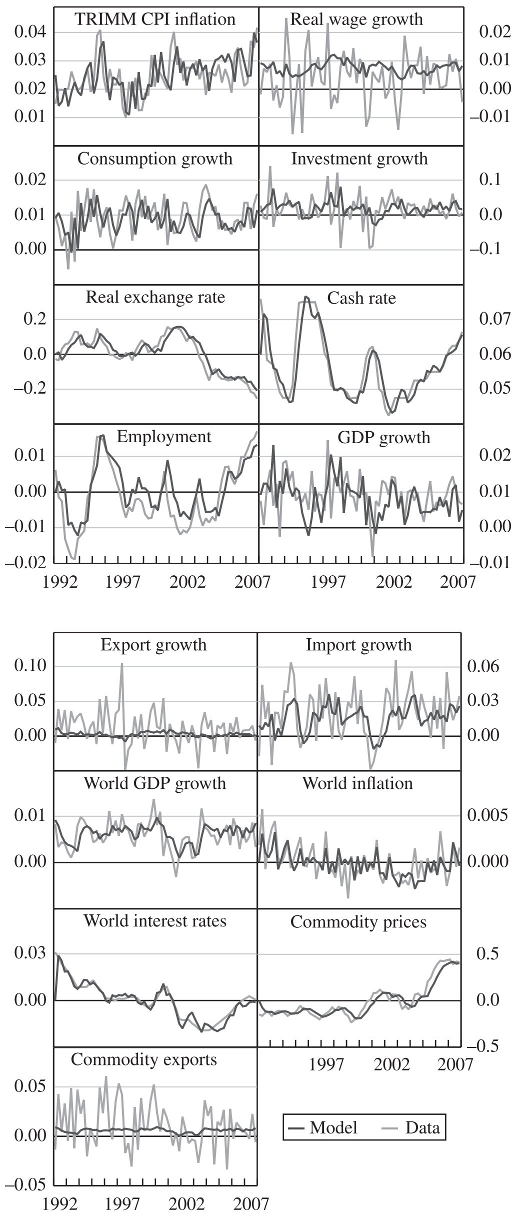


Figure 1 shows the one-sided fit of the model. The fit for most of the variables is good; the exceptions are real wage, export and commodity export growth.[7] These variables are quite volatile at a quarterly frequency, and hard to predict, so the failure of fitting these series is not necessarily a weakness of the model as the best predictor for a white noise process is its mean.

(ii) The Dynamics of the Estimated Model

Figure 2 illustrates the dynamic response to a 100 basis points monetary policy shock (median, 5th and 95th percentiles).[8] The main variables respond as we might expect. Consumption and investment decrease, which together with the appreciation of the real exchange rate means that the marginal cost of production and the price of imported goods are falling, which leads to falling inflation. The maximum response of CPI inflation to a unit shock to the interest rate is approximately 0.3 percentage points.

The magnitude and persistence of the response of CPI inflation to a monetary policy shock is quite sensitive to the prior chosen for the degree of nominal stickiness for domestic consumption goods (as captured by the Calvo parameter). With a very diffuse prior on this parameter, the estimated responses were found to be much more short-lived (Fig. 2 also shows the mean response with truncated uniform priors). However, the estimated value of ξ_d with uniform priors implied that domestic firms only re-optimise prices every five years, which does not seem realistic. We find it reasonable to impose that firms re-optimise on average every three quarters.[9]

The impulse response functions can be compared with previous studies. Dungey and Pagan (2009) set up a model that explicitly takes into account the co-integrating relationships implied by a class of popular models when estimating

[7] It is also worth noting that we tried different wage indexation schemes but they did not improve the fit of the real wage series.

[8] A 1 SD monetary policy shock equals roughly 70 basis points. This is expressed on an annualised basis and recall that data are quarterly.

[9] Del Negro and Schorfheide (2008a) report a similar finding. They study the role of nominal rigidities in a new Keynesian DSGE model and find that post-1982 US data cannot discriminate between low- and high-price rigidity specifications. These two different model specifications, however, imply strikingly different dynamic effects of a monetary policy shock.

FIGURE 2
Impulse Responses to a Policy Shock

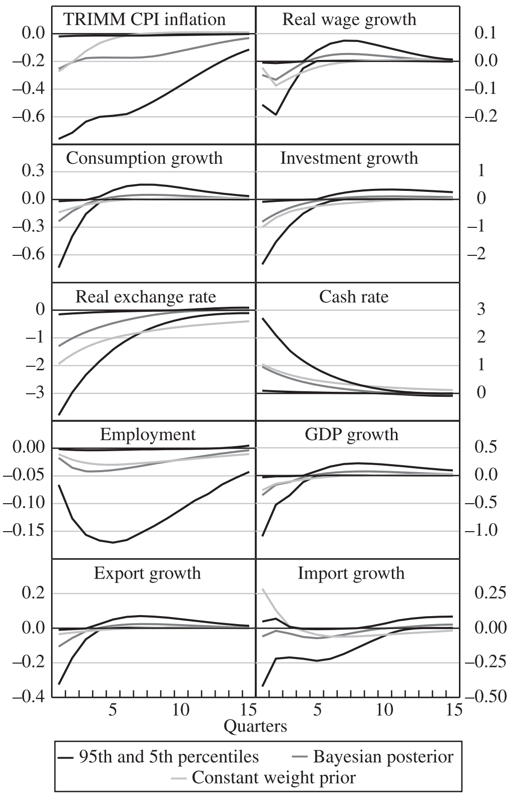
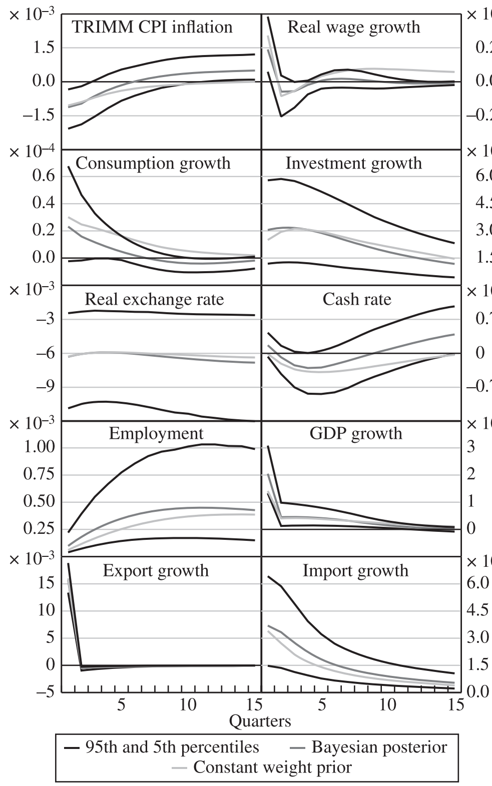


FIGURE 3
Impulse Responses to a Commodity Demand Shock



a structural VECM. They find much weaker responses of inflation and output to a monetary policy shock than we do, on the order of responses that are about one-fourth of ours (at the mean). The same is true for the impulse responses to a monetary policy shock identified by Buncic and Melecky (2008) in a smaller scale new Keynesian model, who find responses of a similar magnitude as Dungey and Pagan (2009). We also find some differences compared with those of the small-scale new Keynesian model estimated in Nimark (2009). In Nimark (2009), the impulse response of inflation to a monetary policy shock is hump-shaped, whereas in the model estimated here, it peaks in the impact period.

Given the size of the model presented here and the fact that the models are not easily nested, it is difficult to speculate about the reasons for these differences. However, these differences should not be over-emphasised: all point estimates reported by these studies lies inside the posterior 95 per cent probability interval reported in Figure 2. In addition, the SVARs and the DSGEs also agree on the qualitative effect of rasing interest rates, that is, there appear to be no price-puzzle present in the Australian data.

In Figure 3, we plot the impulse responses to a standard deviation shock to commodity demand. An increase in commodity demand generates an output expansion, an increase in employment, and a fall in inflation (at least initially). This last effect is explained by the real exchange rate appreciation, which reduces imported goods inflation, and makes imported capital goods cheaper. The exchange rate effect is strong enough to initially counteract the pressures on

TABLE 3
Variance Decomposition

	Shock				
Variable	Technology	Supply	Demand	External	Monetary policy
$\pi_t^{\text{cpi,trim}}$	0.06 (0.01–0.21)	0.73 (0.41–1.00)	0.04 (0.01–0.27)	0.08 (0.03–0.20)	0.02 (0.01–0.08)
$\Delta\ln(W_t/P_t)$	0.44 (0.31–0.58)	0.52 (0.40–0.67)	0.00 (0.00–0.00)	0.01 (0.00–0.02)	0.02 (0.00–0.06)
$\Delta\ln(C_t)$	0.26 (0.10–0.45)	0.06 (0.02–0.15)	0.64 (0.40–0.85)	0.01 (0.00–0.50)	0.01 (0.00–0.03)
$\Delta\ln(I_t)$	0.20 (0.07–0.44)	0.30 (0.11–0.60)	0.01 (0.00–0.08)	0.42 (0.25–0.60)	0.01 (0.00–0.03)
$\hat{x}_t$	0.03 (0.00–0.18)	0.90 (0.69–0.98)	0.00 (0.00–0.03)	0.05 (0.02–0.14)	0.00 (0.00–0.00)
R_t	0.10 (0.02–0.30)	0.71 (0.39–0.98)	0.05 (0.01–0.28)	0.06 (0.03–0.17)	0.01 (0.00–0.05)
E_t	0.05 (0.01–0.19)	0.85 (0.52–0.97)	0.02 (0.00–0.23)	0.05 (0.01–0.16)	0.00 (0.00–0.00)
$\Delta\ln Y_t$	0.30 (0.15–0.50)	0.23 (0.11–0.41)	0.15 (0.07–0.30)	0.25 (0.14–0.40)	0.02 (0.00–0.07)
$\Delta\ln X_t$	0.27 (0.16–0.41)	0.22 (0.12–0.37)	0.00 (0.00–0.02)	0.48 (0.35–0.63)	0.00 (0.00–0.01)
$\Delta\ln M_t$	0.10 (0.00–0.26)	0.10 (0.03–0.21)	0.02 (0.01–0.07)	0.73 (0.58–0.87)	0.00 (0.00–0.01)

Note: Figures in parentheses indicate 90 per cent posterior probability intervals.

marginal cost stemming from the expansion of employment and the increase in real wages and consumption. After about seven quarters although, the response of inflation is positive and quite persistently so.

(iii) Which Shocks are Important?

The model can be used to decompose the causes of the unconditional variances of the observable variables into their orthogonal components. The result of this exercise is displayed in Table 3, where we report the variance decompositions of the 10th, 50th and 90th percentiles of the posterior distribution for selected observable variables. The shocks are grouped into five categories. The first contains technology shocks: the stationary ($\varepsilon_{\varepsilon,t}$), unit root ($\varepsilon_{z,t}$), investment-specific ($\varepsilon_{\Upsilon,t}$) and asymmetric technology (ε_{z^*},t) shocks. The second category includes 'supply' shocks: the labour supply shock (ε_{ζ^h},t) and shocks to the mark-ups of the domestic ($\varepsilon_{\lambda_d},t$), imported consumption ($\varepsilon_{\lambda_{m,c}},t$), imported investment ($\varepsilon_{\lambda_{m,i}},t$) and export ($\varepsilon_{\lambda_x},t$) goods. The third category includes the domestic 'demand' shock (the consumption preference shock, ε_{ζ^c},t). The fourth category includes shocks associated with external factors: the uncovered interest rate parity ($\varepsilon_{\tilde{\phi}}$), commodity demand ($\varepsilon_{com,t}$), commodity price ($\varepsilon_{pcom,t}$), foreign output ($\varepsilon_{y^*},t$), foreign interest rate (ε_{i^*},t) and foreign inflation (ε_{π^*},t) shocks. Finally, we have the monetary policy shocks ($\varepsilon_{R,t}$ and $\varepsilon_{\bar{\pi},t}$). The table excludes shocks that have a small impact on all endogenous variables, which explains why the fraction of variances explained by the shocks in Table 3 add up to less than 100 per cent.

It is clear from the table that the world shocks are important drivers of the Australian business cycle: 25 per cent of the variance of non-farm GDP growth; 42 per cent of the variance of investment; and 48 and 73 per cent of export and import growth, respectively, are explained by the external shocks. Of the observed variables, consumption and real wage growth seem to be the domestically most 'isolated' variables, with a significant fraction of their variances explained by productivity and supply shocks (within this category, the labour supply shock is one of the most important drivers of real wage growth, it explains around 42 per cent of the variance of real wage growth).

Nimark (2009) finds that foreign shocks account for 27, 21 and 22 per cent of the variance of domestic output, inflation and interest rates, respectively. Medina and Soto (2007) find that foreign shocks explain approximately 45 per cent of the output variance and approximately 30 per cent of the inflation variance in the Chilean economy. Interestingly, Justiniano and Preston (2010) fail to identify significant variance shares for foreign shocks in an estimated small open economy for Canada. All of these models, however, abstract from a shock to the level of trend technology and prefilter data before estimation.

The mark-up on the price of imported consumption goods appears to be an important source of CPI inflation volatility. It is estimated to explain approximately 60 per cent of the variance of CPI inflation.[10]

Turning to the commodity demand shocks, it is worth first noting that these are orthogonal to world output (which is included as a separate observable variable), and will therefore not capture increases in demand for Australian exports because of high world output.[11] Exogenous commodity demand shocks appear to have the largest impact on the variance of export growth, explaining approximately 25 per cent of this variance.

(iv) Some Robustness Checks

Trends in the data and in the model

The model features a single stochastic trend, driven by the permanent technology shock. This implies that real variables (GDP, consumption, investment, imports, exports and the real wage) are non-stationary and grow at the same rate in the long run. The common quarterly trend growth to real variables (including $\Delta \ln Y_t^*$) is captured by the constant term (which equal to $\log(\mu_z)$) in the measurement Equation (15). We noticed, however, that some of these normalised variables embedded in the state vector ξ_t exhibit a very persistent, trend-like behaviour within the sample.

In short samples, it may be hard to distinguish a protracted cyclical difference in average growth rates (or structural breaks) from a secular trend in the data. For instance, the growth rates of investment, exports and imports are higher than the average output growth in the sample that we use to estimate the model (and the growth rates of real wages and world output have been lower than non-farm output growth).[12] If this is merely a cyclical difference, one would expect the growth rates of these variables to be lower on average than output growth in the future to return the economy to its steady-state growth path. However, if the differences in growth rates reflect a lasting trend, then the model is obviously mis-specified. If we believed that this is indeed the case, the difference in growth rates could be removed before estimating the model so as not to force the model to explain a trend in the data as part of the business cycle. It is, however, hard to think of a good reason why investment, for instance, should grow faster than output in the long run.

In the benchmark specification, we chose not to adjust the mean growth rates of the real variables, but we also estimated an alternative model with the adjusted data. When we adjusted real variables to grow at the same rate as non-farm output (i.e. the data were reconstructed to co-trend), the estimated shocks became less persistent. The drop in persistence was most notable in the asymmetric technology shock, which captures the degree of asymmetry in the growth rates between the domestic economy and the rest of the world, and in the consumption preference shock (which is a demand shock in the model).[13,14]

Alternative priors

In the baseline model, several parameters (ξ_w, ξ_d, $\xi_{m,c}$, $\xi_{m,i}$, ξ_x, ξ_e and ρ_r) are estimated with tight priors. As a robustness check, we re-estimate the model with a set of looser priors on these parameters. For the first six, the standard deviation is increased to 0.1, and for ρ_r it is doubled from 0.05 to 0.10. The results for the re-estimated model are detailed in Table A4. The results are broadly similar to the baseline

[10] One might have expected a more sizeable role for the exchange rate in driving the volatility of import prices. It may be that the mark-up shock is capturing some volatility that cannot be systematically attributable to the exchange rate.

[11] Caution should be used when interpreting what we have described as the commodity demand shock since in our set-up it may be hard to distinguish this from a supply shock.

[12] See Figure 1. The model consistently over-predicts, for instance, the growth rate of real wages.

[13] The asymmetric technology shock and the consumption preference shock are now estimated to have a (mean) AR(1) coefficient of 0.57 and 0.22, respectively. The estimate of the persistence of the asymmetric technology shock is, however, imprecise: the lower bound of its 90 per cent confidence interval is less than 0.09 and the upper bound is 0.96.

[14] We also estimated a closed economy version of the model (which is as presented in Del Negro *et al.* 2007) to see to what extent some of these issues emerge through the open economy part of the model. It turns out that simplifying the model in this way is not very helpful, which is hardly surprising given that we use the same 'domestic' real variables (consumption, investment, real wage) as observables as before when estimating the model, and any excessive trend in these variables will just be attributed to any remaining shocks in the theoretical model.

estimates. One noticeable change, however, with these looser priors is that the estimate of the domestic Calvo parameter (ξ_d) has risen from 0.69 to 0.87 and the uncertainty in the estimate of this parameter has almost tripled. The uncertainty surrounding the other Calvo parameters has also increased, although the point estimates are broadly in line with the baseline specification. The persistence of the interest rate (ρ_r) falls very slightly from 0.84 to 0.82. The paths of the impulse response functions are broadly unchanged but the confidence intervals are marginally wider. Comparing the fit with the baseline model using Geweke's (1999) Modified Harmonic Mean Measure of the marginal likelihood suggests that data cannot distinguish between the two set of priors.

In addition, we also re-estimate the model abstracting completely from the commodity sector. The results for this exercise are presented in Table A5. Fit looks much better. The Calvo parameters are much more precisely estimated, but this could reflect tight prior information imposed; the uncertainty of the indexation parameters has somewhat increased. More importantly, however, as speculated η_f is much more precisely estimated when the commodity sector is build in the model.

Measurement errors

Del Negro and Schorfheide (2008b) argue that DSGE models are intrinsically mis-specified, and that incorporating measurement errors is one way to ameliorate this problem. We investigate this hypothesis re-estimating the model assuming that measurement errors explain only 0.1 per cent of the variability of the observable series. A number of findings from this experiment are worth noting. First, the model's in-sample fit does not deteriorate markedly when the measurement errors are lowered. This suggests that model mis-specification is not present along any obvious dimensions. However, several parameters tend to drift towards implausible high levels. The mass of the posterior distributions of $\kappa_{m,i}$ and κ_d (two of the price indexation parameters) piles up towards one. In addition, mark-up parameters λ_d and $\lambda_{m,i}$ reach their upper limits (set to 30) suggesting that there may not be enough information to adequately capture the dynamics of the domestic and imported investment prices. This is hardly surprising, given that the only observable price series is CPI inflation, which is measured as a weighted average of domestic inflation (π^d) and imported (consumption good) inflation $\pi^{c,m}$.

V Conclusion

This article outlines a DSGE model with a sizeable number of frictions and rigidities and estimates it using Australian data. The model appears to fit the data reasonably well. We found that both domestic and foreign shocks are important drivers of the Australian business cycle.

There are questions that remain for future work. First, given the prominent role attributed to the rest of the world, it would be worth analysing the foreign block of the model in structural form instead of an atheoretical vector autoregression. Second, although we have estimated the model only over the inflation-targeting period, more information about the model's deep parameters might be extracted from the data by using a sample that begins at the time that the exchange rate was floated. This could be achieved by allowing for a break in the policy reaction function at the time of the introduction of inflation targeting.

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Appendix I: Data Description and Sources

Inflation ($\pi_t^{\text{cpi,trim}}$): trimmed mean Consumer Price Index excluding taxes and interest (Reserve Bank of Australia, RBA).

Real wage ($\Delta\ln(W_t/P_t)$): seasonally adjusted real consumer earnings per wage and salary earner (Australian Bureau of Statistics (ABS), Cat No. 5206.0).

Consumption ($\Delta\ln C_t$): real seasonally adjusted household final consumption expenditure (ABS, Cat No. 5206.0).

Investment ($\Delta\ln I_t$): real seasonally adjusted private final investment expenditure (ABS, Cat No. 5206.0).

Real exchange rate ($\hat{x}_t$): real trade-weighted exchange rate (RBA).

Nominal interest rate (R_t): overnight cash rate, averaged over the quarter (RBA).

Employment (N_t): seasonally adjusted employed persons (ABS, Cat No. 6206.0).

Output ($\Delta\ln Y_t$): real seasonally adjusted non-farm GDP (ABS, Cat No. 5206.0).

Exports ($\Delta\ln X_t$): real seasonally adjusted goods and services credits (ABS, Cat No. 5302.0).

Imports ($\Delta\ln M_t$): real seasonally adjusted goods and services debits (ABS, Cat No. 5302.0).

World Output ($\Delta\ln Y_t^*$): real trade-weighted G7 GDP (RBA).

World inflation (π_t^*): trade-weighted G7 headline CPI inflation (RBA).

World interest rate (R_t^*): average of US, euro area and Japanese short-term nominal interest rates (RBA).

Commodity price inflation (Δp_t^{com}): RBA Commodity Price Index (RBA).

Commodity demand ($\Delta\ln Com_t$): real seasonally adjusted exports (general merchandise) (ABS, Cat No. 5302.0).

Appendix II: The Linearised Model

This appendix presents the full log-linearised model. Hat symbols on variables denote the log-deviations from steady-state values ($\hat{X}_t = \mathrm{d}X_t/X = \ln X_t - \ln X$). Lower-case letters indicate that variables have been normalised with the trend level of technology, that is, $x_t = X_t/z_t$. Variables with no time subscript refer to steady-state values.

Nominal domestic, import and export prices are governed by Calvo (1983) contracts, augmented by indexation to the last period's inflation and the current (domestic) inflation target. The implied inflation dynamics are given by the following Phillips Curve(s):

$$\begin{aligned}\hat{\pi}_t^s - \hat{\bar{\pi}}_t^c = {} & \frac{\beta}{1+\kappa_s}[E_t\pi_{t+1}^s - \rho_\pi\hat{\bar{\pi}}_t^c] \\ & + \frac{\kappa_s}{1+\kappa_s\beta}[\pi_{t-1}^s - \rho_\pi\hat{\bar{\pi}}_{t-1}^c] \\ & - \cdots \frac{\kappa_s\beta(1-\rho_\pi)}{1+\kappa_s\beta}\hat{\bar{\pi}}_t^c + \frac{(1-\xi_s)(1-\beta\xi_s)}{\xi_s(1+\kappa_s\beta)} \\ & \times (\widehat{mc}_t^s + \hat{\lambda}_t^s), \end{aligned} \tag{25}$$

where s distinguishes between domestic (d), imported consumption (m,c), imported investment (m,i) and exported final domestic (x) goods sectors. $\hat{\bar{\pi}}_t^c$, $\widehat{mc}_t^s$ and $\hat{\lambda}_t^s$ denote the current perceived inflation target, firms' real marginal costs, and the time-varying shocks to the desired mark-ups in sector s, respectively. Parameters ρ_π, β, ξ_s and κ_s are the persistence of the inflation target shock; the discount factor; the Calvo parameter (i.e. the probability that the firm is not allowed to re-optimise in period t); and the indexation parameter, respectively. If the indexation parameter κ_s is 0, the Phillips Curve is purely forward-looking; and if $\kappa_s = 1$, prices are fully indexed to last period's inflation.

Marginal costs $(\widehat{mc}_t^s)$ for domestic firms are given by:

$$\begin{aligned}\widehat{mc}_t &= \alpha\hat{r}_t^k + (1-\alpha)[\hat{\bar{w}}_t + \hat{R}_t^f] - \hat{\varepsilon}_t \\ &= \alpha(\hat{\mu}_{z,t} + \hat{H}_t - \hat{k}_t) + \hat{\bar{w}}_t + \hat{R}_t^f - \hat{\varepsilon}_t, \end{aligned} \tag{26}$$

where $\hat{r}_t^k$ is the real rental rate of capital. This is derived from firms' optimal conditions (total payments for capital services should equal costs of hiring labour each period) and the assumption that firms finance part of their wage bill with funds borrowed one period prior (at $\hat{R}_{t-1}$). Marginal cost is also a function of the labour input $(\hat{H}_t)$; capital services $(\hat{k}_t)$; the real wage $(\hat{\bar{w}}_t)$ and the gross effective nominal rate of interest rate paid by firms $(\hat{R}_t^f)$. Finally, $\hat{\mu}_{z,t}$ and $\hat{\varepsilon}_t$ denote the permanent and stationary technology shocks, respectively. Marginal costs for consumption and investment good importers are given by:

$$\widehat{mc}_t^{m,c} = -\widehat{mc}_t^x - \hat{\gamma}_t^{x,*} - \hat{\gamma}_t^{mc,d}, \tag{27}$$

$$\widehat{mc}_t^{m,i} = -\widehat{mc}_t^x - \hat{\gamma}_t^{x,*} - \hat{\gamma}_t^{mi,d}, \tag{28}$$

where mc_t^x is the relative price observed by the domestic exporters $(P_t/S_tP_t^x)$; $\gamma_t^{x,*}$ is the relative price between the domestically produced goods and the foreign goods; and $\gamma_t^{mc,d}$ and $\gamma_t^{mi,d}$ are the relative prices of imported consumption and investment goods.

Nominal wages are also subject to the Calvo adjustment mechanism, with indexation to the last period's CPI inflation $(\hat{\pi}_{t-1}^c)$, the current (domestic) inflation target $(\hat{\bar{\pi}}_t^c)$ and the steady-state growth rate of technology (Adolfson *et al.*, 2007 assume that wages are indexed to the current realisation of technology; see also Altig *et al.*, 2005). This yields an equation for the real wage $\hat{\bar{w}}_t$:

$$E_t\begin{bmatrix}\eta_0\hat{\bar{w}}_{t-1}+\eta_1\hat{\bar{w}}_t+\eta_2\hat{\bar{w}}_{t+1}+\eta_3(\hat{\pi}_t^d-\hat{\bar{\pi}}_t^c)+\cdots \\ \eta_4(\hat{\pi}_{t+1}^d-\rho_\pi\hat{\bar{\pi}}_t^c)+\eta_5(\hat{\pi}_{t-1}^c-\hat{\bar{\pi}}_t^c)+\eta_6(\hat{\pi}_t^c-\rho_\pi\hat{\bar{\pi}}_t^c)+\cdots \\ \eta_7\hat{\psi}_{z,t}+\eta_8\hat{H}_t+\eta_9\hat{\tau}_t^y+\eta_{10}\hat{\tau}_t^w+\eta_{11}\hat{\zeta}_t^h+\cdots \\ \eta_{12}\hat{\mu}_{z,t}+\eta_{13}\hat{\mu}_{z,t+1}\end{bmatrix}=0, \tag{29}$$

where $\hat{\psi}_{z,t}$ and $\hat{\zeta}_t^h$ denote the Lagrangian multiplier and labour supply shock, respectively. $\hat{\tau}_t^y$ and τ_t^w are labour income and payroll taxes. Parameters in Equation (29) are defined as follows:

$$b_w = \frac{\lambda_w\sigma_L - (1-\lambda_w)}{(1-\beta\xi_w)(1-\xi_w)},$$

$$\begin{pmatrix}\eta_0\\ \eta_1\\ \eta_2\\ \eta_3\\ \eta_4\\ \eta_5\\ \eta_6\\ \eta_7\\ \eta_8\\ \eta_9\\ \eta_{10}\\ \eta_{11}\\ \eta_{12}\\ \eta_{13}\end{pmatrix} = \begin{pmatrix} b_w\xi_w \\ \lambda_w\sigma_L - b_w(1+\beta\xi_w^2) \\ b_w\beta\xi_w \\ -b_w\xi_w \\ b_w\beta\xi_w \\ b_w\xi_w\kappa_w \\ -b_w\beta\xi_w\kappa_w \\ 1-\lambda_w \\ -(1-\lambda_w)\sigma_L \\ -(1-\lambda_w)\frac{\tau^y}{1+\tau^y} \\ -(1-\lambda_w)\frac{\tau^w}{1+\tau^w} \\ -(1-\lambda_w) \\ -b_w\xi_w \\ b_w\beta\xi_w \end{pmatrix},$$

where ξ_w is the Calvo wage parameter (i.e. the probability that the household is not allowed to re-optimise its wage); λ_w is the wage mark-up; and σ_L is the elasticity of labour supply. Note that η_{12} and η_{13} do not appear in Adolfson *et al.* (2007).

Households have habit formation in their preferences (captured by the parameter b). Because of this, the marginal utility of consumption depends on current, lagged and expected future levels of consumption. The equilibrium condition for household consumption, $\hat{c}_t$, is

$$E_t\begin{bmatrix}-b\beta\mu_z\hat{c}_{t+1}+(\mu_z^2+b^2\beta)\hat{c}_t-b\mu_z\hat{c}_{t-1}+\cdots \\ b\mu_z(\hat{\mu}_{z,t}-\beta\hat{\mu}_{z,t+1})+(\mu_z-b\beta)(\mu_z-b)\hat{\psi}_{z,t}+\cdots \\ \frac{\tau^c}{1+\tau^c}(\mu_z-b\beta)(\mu_z-b)\hat{\tau}_t^c+(\mu_z-b\beta)(\mu_z-b)\hat{\gamma}_t^{c,d}-\cdots \\ (\mu_z-b)(\mu_z\hat{\zeta}_t^c-b\beta\hat{\zeta}_{t+1}^c)\end{bmatrix}=0, \tag{30}$$

where $\hat{\zeta}_t^c$ is the consumption preference shock and $\hat{\tau}_t^c$ is a consumption tax.

The equilibrium condition for investment (i_t) is given by:

$$\begin{aligned}E_t\{\hat{P}_{k',t} + \hat{\Upsilon}_t - \hat{\Upsilon}_t^{i,d} - \mu_z^2\tilde{S}''[(\hat{i}_t - \hat{i}_{t-1}) - \beta(\hat{i}_{t+1} - \hat{i}_t) \\ + \hat{\mu}_{z,t} - \beta\hat{\mu}_{z,t+1}]\} = 0, \end{aligned} \tag{31}$$

where $\hat{P}_{k'}, t$ is the hypothetical price of installed capital; $\hat{\Upsilon}_t$ denotes the investment-specific technology shock and the parameter $\tilde{S}''$ is the 'slope' of the investment adjustment cost function. The log-linearised version of households' money demand is given by:

$$E_t[-\mu\hat{\psi}_{z,t} + \mu\hat{\psi}_{z,t+1} - \mu\hat{\mu}_{z,t+1} + \cdots$$
$$(\mu - \beta\tau^k)\hat{R}_t - \mu\hat{\pi}_t + \frac{\tau^k}{1-\tau^k}(\beta - \mu)\hat{\tau}^k_{t+1}] = 0, \tag{32}$$

where μ is the steady-state growth rate of money demand and τ^k is a capital income tax. The log-linearised first-order condition for the physical stock of capital, $\bar{k}_t$, is

$$E_t\left[\begin{array}{c}\hat{\psi}_{z,t} - \hat{\psi}_{z,t+1} + \hat{\mu}_{z,t+1} - \frac{\beta(1-\delta)}{\mu_z}\hat{P}_{k',t+1} + \hat{P}_{k',t} - \cdots \\ \frac{\mu_z - \beta(1-\delta)}{\mu_z}\hat{r}^k_{t+1} + \frac{\tau^k}{1-\tau^k}\frac{\mu_z-\beta(1-\delta)}{\mu_z}\hat{\tau}^k_{t+1}\end{array}\right] = 0, \tag{33}$$

where δ is the rate of depreciation. The risk premium-adjusted uncovered interest rate parity condition is given by:

$$E_t\Delta\hat{S}_{t+1} - (\hat{R}_t - \hat{R}^*_t) - \tilde{\phi}_a\hat{a}_t + \hat{\tilde{\phi}}_t = 0. \tag{34}$$

It is assumed that the international financial markets are imperfectly integrated (holding foreign bonds carries a premium), under the specific modelling assumption that the net foreign asset position of the domestic economy ($\hat{a}_t$) and the risk premium shock ($\tilde{\phi}_t$) enter into the parity condition (in which S_t is the nominal exchange rate; and R_t and R^*_t denote the domestic and foreign nominal interest rates, respectively). The risk premium term is exogenous but the net asset position is an endogenous variable.

Current period resources can be consumed (domestically or exported), invested or used to boost capital utilisation. The aggregate hours constraint can be written as:

$$\begin{aligned}&(1-\omega_c)(\gamma^{c,d})^{\eta_c}\frac{c}{y}(\hat{c}_t + \eta_c\hat{\gamma}^{c,d}_t) \\ &\quad + (1-\omega_i)(\gamma^{i,d})^{\eta_i}\frac{i}{y}(\hat{i}_t + \eta_i\hat{\gamma}^{i,d}_t) \\ &\quad + \cdots\frac{g}{y}\hat{g}_t + \frac{y^*}{y}\left(\hat{y}^*_t - 0.3\eta_f\hat{\gamma}^{x,*}_t + 0.7\widehat{com}_t + \hat{\tilde{z}}_t\right) \\ &\quad\quad = \lambda_d(\hat{\varepsilon}_t + \alpha(\hat{k}_t - \hat{\mu}_{z,t}) + (1-\alpha)\hat{H}_t) \\ &\quad\quad\quad - (1-\tau^k)r^k\frac{\bar{k}}{y}\frac{1}{\mu_z}(\hat{k}_t - \hat{\bar{k}}_t),\end{aligned} \tag{35}$$

where $\hat{\gamma}^{c,d}_t$ and $\hat{\gamma}^{i,d}_t$ are the relative price terms between the CPI and investment price indices to the domestic price level; $\hat{y}^*_t$ is foreign output; $\hat{g}_t$ is government expenditure; $\widehat{com}_t$ denotes commodity demand[15]; $\hat{\tilde{z}}_t$ is an asymmetric technology shock; ω_c is the share of imports in consumption; ω_i is the share of imports in investment; and η_c (η_i) is the elasticity of substitution between foreign and domestic consumption (investment) goods. Finally, λ_d is the domestic steady-state mark-up over factors of production and α is the share of capital in the production function.

The stock of physical capital ($\hat{\bar{k}}_{t+1}$) follows:

$$\begin{aligned}\hat{\bar{k}}_{t+1} &= (1-\delta)\frac{1}{\mu_z}\hat{\bar{k}}_t - (1-\delta)\frac{1}{\mu_z}\hat{\mu}_{z,t} + \cdots \\ &\quad \left(1 - (1-\delta)\frac{1}{\mu_z}\right)\hat{\Upsilon}_t + \left(1 - (1-\delta)\frac{1}{\mu_z}\right)\hat{i}_t.\end{aligned} \tag{36}$$

The degree of capacity utilisation (the difference between the physical capital stock and capital services) $\hat{u}_t$ is given by:

$$\hat{u}_t = \hat{k}_t - \hat{\bar{k}}_t = \frac{1}{\sigma_a}\hat{r}^k_t - \frac{1}{\sigma_a}\frac{\tau^k}{1-\tau^k}\hat{\tau}^k_t, \tag{37}$$

where σ_a is the slope of the utilisation cost function.

The money demand function (i.e. cash holdings, q) is given by:

$$\hat{q}_t = \frac{1}{\sigma_q}\left[\hat{\zeta}^q_t + \frac{\tau^k}{1-\tau^k}\hat{\tau}^k_t - \hat{\psi}_{z,t} - \frac{R}{R-1}\hat{R}_{t-1}\right], \tag{38}$$

where $\hat{\zeta}^q_t$ is a (household) money demand shock (assumed to be zero) and σ_q is the cash-money ratio.

The following identity relates money growth ($\hat{\bar{m}}_t$) to domestic inflation and changes in real growth:

$$\hat{\mu}_t - \hat{\bar{m}}_{t+1} - \hat{\mu}_{z,t} - \hat{\pi}_t + \hat{\bar{m}}_t = 0. \tag{39}$$

The loan market clearing condition is:

$$v\bar{w}H(\hat{v}_t + \hat{\bar{w}}_t + \hat{H}_t) = \frac{\mu\bar{m}}{\pi\mu_z}(\hat{\mu}_t + \hat{\bar{m}}_t - \hat{\pi}_t - \hat{\mu}_{z,t}) - q\hat{q}_t, \tag{40}$$

where v is the fraction of intermediate good firms' wage bill that is to be financed in

[15] It is assumed that commodity demand is completely inelastic.

advance; and $\hat{v}_t$ is a (firms') money demand shock (assumed to be zero).

The law of motion for net foreign assets, $\hat{a}_t$, is:

$$\begin{aligned}\hat{a}_t = &-0.3y^*\widehat{mc}^x_t - 0.3\eta_f y^*\hat{\gamma}^{x,*}_t + 0.7y^*(\hat{p}^{com}_t + \widehat{com}_t)\\ &+ y^*\hat{y}^*_t + y^*\hat{\tilde{z}}_t + (c^m + i^m)\hat{\gamma}^f_t\\ &- c^m(-\eta_c(1-\omega_c)(\gamma^{c,d})^{-(1-\eta_c)}\hat{\gamma}^{mc,d}_t + \hat{c}_t)\\ &- i^m(-\eta_i(1-\omega_i)(\gamma^{i,d})^{-(1-\eta_i)}\hat{\gamma}^{mi,d}_t + \hat{i}_t)\\ &+ \frac{R}{\pi\mu_z}\hat{a}_{t-1}, \end{aligned} \tag{41}$$

where $\hat{p}^{com}_t$ is the relative price of commodities (P^{com}_t/P^d_t) and γ^f_t is the relative price between the home and foreign economy $(P_t/S_tP^*_t)$. The log-linearised relative prices are:

$$\hat{\gamma}^{mc,d}_t = \hat{\gamma}^{mc,d}_{t-1} + \hat{\pi}^{m,c}_t - \hat{\pi}^d_t, \tag{42}$$

$$\hat{\gamma}^{mi,d}_t = \hat{\gamma}^{mi,d}_{t-1} + \hat{\pi}^{m,i}_t - \hat{\pi}^d_t, \tag{43}$$

$$\hat{\gamma}^{x,*}_t = \hat{\gamma}^{x,*}_{t-1} + \hat{\pi}^x_t - \hat{\pi}^*_t, \tag{44}$$

$$\widehat{mc}^x_t = \widehat{mc}^x_{t-1} + \hat{\pi}_t - \hat{\pi}^x_t - \Delta\hat{S}_t, \tag{45}$$

where $\hat{\gamma}^{mc,d}_t$ is the relative price of imported consumption goods (with respect to domestic output price level); $\hat{\gamma}^{mi,d}_t$ is the relative price of imported investment goods (to domestic output price level); $\hat{\gamma}^{x,*}_t$ is the price of (home) exports relative to foreign prices and $\widehat{mc}^x_t$ is the relative price of exports (in terms of foreign currency).

Monetary policy is modelled according to the following reaction function:

$$\begin{aligned}\hat{R}_t = &\rho_R\hat{R}_{t-1} + (1-\rho_R)(\hat{\bar{\pi}}^c_t + r_\pi(\hat{\pi}^c_{t-1} - \hat{\bar{\pi}}^c_t)\\ &+ r_y\hat{y}_{t-1} + r_x\hat{x}_{t-1}) + \cdots + r_{\Delta\pi}(\hat{\pi}^c_t - \hat{\pi}^c_{t-1})\\ &+ r_{\Delta y}\Delta\hat{y}_t + \varepsilon_{R,t}. \end{aligned} \tag{46}$$

The short-term interest rate $(\hat{R}_t)$ is therefore a function of lagged CPI inflation $(\hat{\pi}^c_{t-1})$, output $(\hat{y}_{t-1})$, the real exchange rate $(\hat{x}_{t-1})$ and a monetary policy shock $(\varepsilon_{R,t})$. The CPI inflation measure is model-consistent but ignores indirect taxes

$$\hat{\pi}^c_t = (1-\omega_c)(\gamma^{d,c})^{-(1-\eta_c)}\hat{\pi}^d_t + \omega_c(\gamma^{mc,c})^{-(1-\eta_c)}\hat{\pi}^{m,c}_t.$$

Output is given by $\hat{y}_t = \lambda_d(\hat{\epsilon}_t + \alpha(\hat{k}_t - \hat{\mu}_{z,t}) + (1-\alpha)\hat{H}_t)$.

The real exchange rate is given by $\hat{x}_t = -\omega_c(\gamma^{c,mc})^{-(1-\eta_c)}\hat{\gamma}^{mc,d}_t - \hat{\gamma}^{x,*}_t - \widehat{mc}^x_t$.

Finally, employment $(\hat{E}_t)$ follows:

$$\begin{aligned}\hat{N}_t = &\frac{\beta}{1+\beta}E_t\hat{N}_{t+1} + \frac{1}{1+\beta}\hat{N}_{t-1}\\ &+ \frac{(1-\xi_e)(1-\beta\xi_e)}{\xi_e(1+\beta)}(\hat{H}_t - \hat{N}_t). \end{aligned} \tag{47}$$

TABLE A1
Calibrated Parameters

Parameter		Description	Calibrated from
β	0.999	Discount rate	Sample average real interest rate
α	0.290	Capital share output	Average compensation to capital as share of GDP
ω_c	0.200	Fraction imported cons. goods in bundle	Average share of imports in consumption basket
ω_i	0.500	Fraction imported inv. goods in bundle	Average share of imports in investment basket
δ	0.013	Depreciation rate	Match I/Y
σ_a	0.049	Capital utilisation cost parameter	As in Altig *et al.* (2005)
σ_l	1.000	Labour supply elasticity	As in Christiano *et al.* (2005)
σ_q	10.620	Real cash holdings elasticity	As in Christiano *et al.* (2005)
v	0.950	Fraction of wage paid in advance	As in Adolfson *et al.* (2007)
A_l	7.500	Labour disutility parameter	As in Adolfson *et al.* (2007)
A_q	0.380	Cash in Utility function parameter	As in Adolfson *et al.* (2007)
λ_w	1.050	Wage mark up	As in Christiano *et al.* (2005)

Note: GDP, gross domestic product.

TABLE A2
Constant Weight Prior Posterior Distributions – Structural Parameters

Parameter	Posterior Mean	SD	5%	95%
	Price stickiness			
ξ_w	0.706	0.124	0.516	0.929
ξ_d	0.985	0.021	0.940	0.999
$\xi_{m,c}$	0.743	0.066	0.618	0.834
$\xi_{m,i}$	0.468	0.165	0.178	0.730
ξ_x	0.829	0.148	0.528	0.992
ξ_e	0.774	0.040	0.699	0.833
	Indexation			
κ_w	0.921	0.069	0.777	0.995
κ_d	0.931	0.048	0.842	0.984
$\kappa_{m,c}$	0.124	0.105	0.008	0.334
$\kappa_{m,i}$	0.181	0.193	0.010	0.645
κ_x	0.060	0.045	0.004	0.147
	Mark-ups			
λ_d	7.485	0.250	7.055	7.893
$\lambda_{m,c}$	2.725	0.198	2.370	2.993
$\lambda_{m,i}$	3.259	0.371	2.841	4.151
	Investment friction and habits			
$\tilde{S}''$	4.355	0.270	3.770	4.660
b	0.825	0.063	0.719	0.935
	Substitutions of elasticity			
η_c	1.179	0.127	1.020	1.429
η_i	1.925	0.232	1.524	2.264
η_f	1.149	0.112	1.011	1.372
	Risk premium			
$\tilde{\phi}_a$	0.002	0.001	0.000	0.003
	Technology growth			
μ_z	1.001	0.001	1.000	1.002
	Monetary policy			
ρ_R	0.889	0.026	0.841	0.925
r_π	2.404	0.153	2.147	2.649
$r_{\Delta\pi}$	0.222	0.087	0.082	0.364
r_x	0.009	0.010	−0.004	0.027
r_y	0.016	0.012	−0.002	0.037
$r_{\Delta y}$	0.043	0.026	0.000	0.087

TABLE A3
Constant Weight Prior Posterior Distributions – Exogenous Processes

Parameter	Posterior Mean	SD	5%	95%
	Exogenous processes – AR(1) coefficients			
ρ_{μ_z}	0.927	0.032	0.868	0.969
ρ_ε	0.869	0.052	0.780	0.950
ρ_Υ	0.246	0.159	0.031	0.550
$\rho_{\tilde{z}^*}$	0.879	0.121	0.627	0.993
ρ_{ζ^c}	0.949	0.049	0.837	0.993
ρ_{ζ^h}	0.127	0.089	0.013	0.304
$\rho_{\tilde{\phi}}$	0.845	0.072	0.725	0.931
$\rho_{\lambda_{m,c}}$	0.993	0.006	0.981	0.999
$\rho_{\lambda_{m,i}}$	0.064	0.053	0.004	0.163
ρ_{λ_x}	0.086	0.067	0.007	0.216
$\rho_{\bar{\pi}}$	0.560	0.116	0.407	0.783
ρ_{pcom}	0.972	0.018	0.935	0.992
ρ_{com}	0.996	0.032	0.990	0.999
	Exogenous processes standard deviations ($\times 10^{-2}$)			
σ_{μ_z}	0.133	0.033	0.085	0.193
σ_ε	1.484	0.371	0.915	2.133
σ_Υ	1.479	0.272	1.017	1.912
$\sigma_{\tilde{z}^*}$	0.061	0.042	0.005	0.140
σ_{ζ^c}	0.076	0.025	0.045	0.132
σ_{ζ^h}	0.397	0.054	0.310	0.492
$\sigma_{\tilde{\phi}}$	0.463	0.208	0.155	0.842
σ_{λ_d}	0.062	0.023	0.021	0.098
$\sigma_{\lambda_{m,c}}$	0.240	0.160	0.089	0.552
$\sigma_{\lambda_{m,i}}$	7.291	2.990	4.041	13.552
σ_{λ_x}	4.562	1.267	2.997	7.055
σ_r	0.021	0.016	0.002	0.051
$\sigma_{\bar{\pi}}$	0.526	0.141	0.306	0.757
σ_{com}	2.263	0.217	2.027	2.736
σ_{pcom}	4.810	0.741	3.675	6.191

FIGURE A1
Estimates of Nominal Stickiness and Indexation Parameters

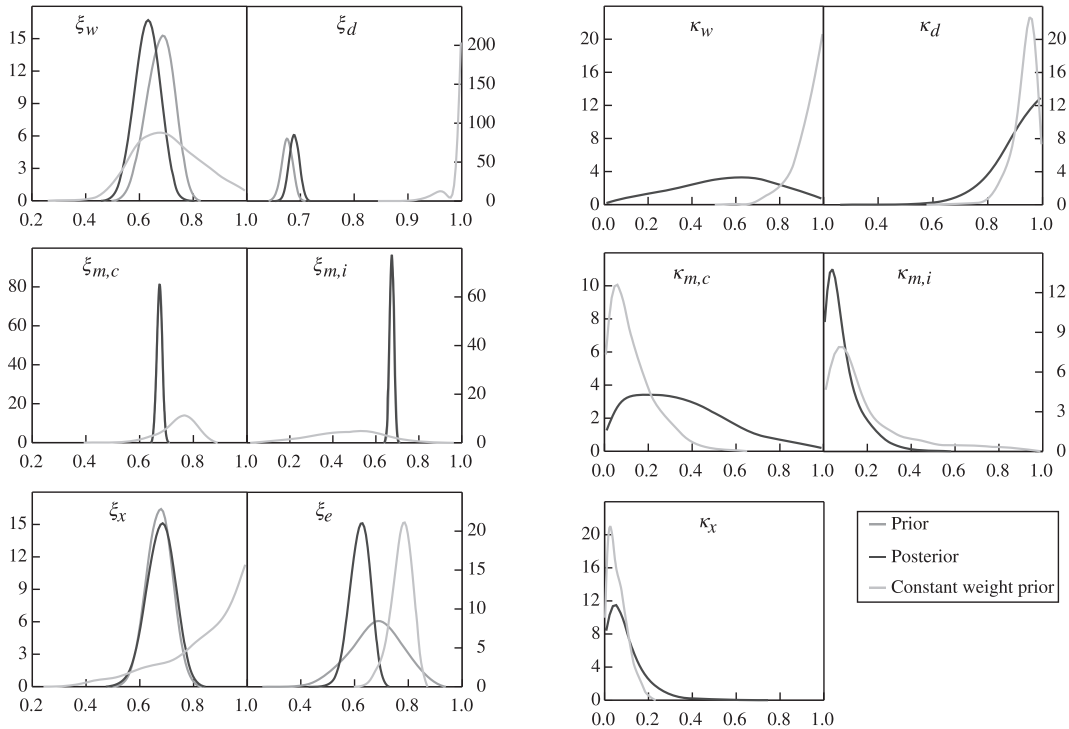

TABLE A4
Prior and Posterior Distributions – Structural Parameters

		Prior		Posterior			
Parameter	Distribution	Mode	SD	Mean	SD	5%	95%
			Price stickiness				
ξ_w	Beta	0.675	0.100	0.622	0.101	0.463	0.811
ξ_d	Beta	0.675	0.100	0.867	0.026	0.822	0.908
$\xi_{m,c}$	Beta	0.675	0.100	0.653	0.073	0.530	0.770
$\xi_{m,i}$	Beta	0.675	0.100	0.625	0.103	0.448	0.787
ξ_x	Beta	0.675	0.100	0.692	0.114	0.495	0.871
ξ_e	Beta	0.675	0.100	0.690	0.037	0.625	0.748
			Indexation				
κ_w	Trunc. uniform	[0,1]		0.634	0.231	0.195	0.959
κ_d	Trunc. uniform	[0,1]		0.895	0.071	0.761	0.985
$\kappa_{m,c}$	Trunc. uniform	[0,1]		0.261	0.215	0.017	0.706
$\kappa_{m,i}$	Trunc. uniform	[0,1]		0.101	0.101	0.005	0.297
κ_x	Trunc. uniform	[0,1]		0.087	0.086	0.005	0.256
			Mark-ups				
λ_d	Inv. gamma	1.200	2.000	10.10	5.081	4.620	20.54
$\lambda_{m,c}$	Inv. gamma	1.200	2.000	1.551	0.405	1.078	2.367
$\lambda_{m,i}$	Inv. gamma	1.200	2.000	3.279	0.931	2.140	5.017
			Investment friction and habits				
$\tilde{S}''$	Normal	7.694	2.500	6.416	1.874	3.563	9.647
b	Beta	0.650	0.100	0.776	0.065	0.674	0.899
			Substitutions of elasticity				
η_c	Trunc. uniform	[1,∞)		1.686	0.451	1.099	2.516
η_i	Trunc. uniform	[1,∞)		1.482	0.302	1.087	2.060
η_f	Trunc. uniform	[1,∞)		1.146	0.148	1.007	1.458
			Risk premium				
$\tilde{\phi}_a$	Inv. gamma	0.010	0.001	0.001	0.001	0.000	0.002
			Technology growth				
μ_z	Trunc. uniform	1.008	0.001	1.009	0.000	1.009	1.009
			Monetary policy				
ρ_R	Beta	0.800	0.100	0.818	0.033	0.761	0.868
r_π	Normal	1.750	0.100	1.751	0.100	1.586	1.914
$r_{\Delta\pi}$	Normal	0.000	0.100	0.138	0.076	0.014	0.262
r_x	Normal	0.010	0.005	−0.008	0.004	−0.014	−0.002
r_y	Normal	0.125	0.100	−0.021	0.010	−0.038	−0.007
$r_{\Delta y}$	Normal	0.000	0.100	0.029	0.020	−0.003	0.061

Note: Trunc., truncated; Inv., inverse.

Table A5
Prior and Posterior Distributions – Structural Parameters

Parameter	Distribution	Prior		Posterior			
		Mode	SD	Mean	SD	5%	95%
			Price stickiness				
ξ_w	Beta	0.675	0.100	0.626	0.048	0.546	0.705
ξ_d	Beta	0.675	0.100	0.687	0.009	0.671	0.703
$\xi_{m,c}$	Beta	0.675	0.100	0.676	0.010	0.660	0.692
$\xi_{m,i}$	Beta	0.675	0.100	0.674	0.010	0.657	0.691
ξ_x	Beta	0.675	0.100	0.621	0.047	0.541	0.695
ξ_e	Beta	0.675	0.100	0.638	0.038	0.573	0.697
			Indexation				
κ_w	Trunc. uniform	[0,1]		0.470	0.238	0.078	0.874
κ_d	Trunc. uniform	[0,1]		0.843	0.118	0.617	0.987
$\kappa_{m,c}$	Trunc. uniform	[0,1]		0.546	0.251	0.113	0.936
$\kappa_{m,i}$	Trunc. uniform	[0,1]		0.088	0.088	0.005	0.261
κ_x	Trunc. uniform	[0,1]		0.057	0.055	0.003	0.165
			Mark-ups				
λ_d	Inv. gamma	1.200	2.000	11.74	5.049	5.422	21.80
$\lambda_{m,c}$	Inv. gamma	1.200	2.000	1.792	0.534	1.154	2.824
$\lambda_{m,i}$	Inv. gamma	1.200	2.000	3.972	1.018	2.580	5.892
			Investment friction and habits				
$\tilde{S}''$	Normal	7.694	2.500	5.427	2.028	2.538	9.149
b	Beta	0.650	0.100	0.766	0.055	0.671	0.853
			Substitutions of elasticity				
η_c	Trunc. uniform	[1,∞)		1.357	0.323	1.024	1.986
η_i	Trunc. uniform	[1,∞)		1.316	0.238	1.031	1.774
η_f	Trunc. uniform	[1,∞)		2.612	0.737	1.698	4.022
			Risk premium				
$\tilde{\phi}_a$	Inv. gamma	0.010	0.001	0.001	0.001	0.000	0.002
			Technology growth				
μ_z	Trunc. uniform	1.008	0.001	1.009	0.000	1.009	1.009
			Monetary policy				
ρ_R	Beta	0.800	0.100	0.829	0.026	0.784	0.870
r_π	Normal	1.750	0.100	1.752	0.099	1.590	1.915
$r_{\Delta\pi}$	Normal	0.000	0.100	0.083	0.066	−0.026	0.190
r_x	Normal	0.010	0.005	−0.010	0.004	−0.017	−0.004
r_y	Normal	0.125	0.100	−0.021	0.012	−0.043	−0.006
$r_{\Delta y}$	Normal	0.000	0.100	0.032	0.020	0.002	0.065

Note: Trunc., truncated; Inv., inverse.

FIGURE A2
Estimates of Mark-up and Friction Parameters

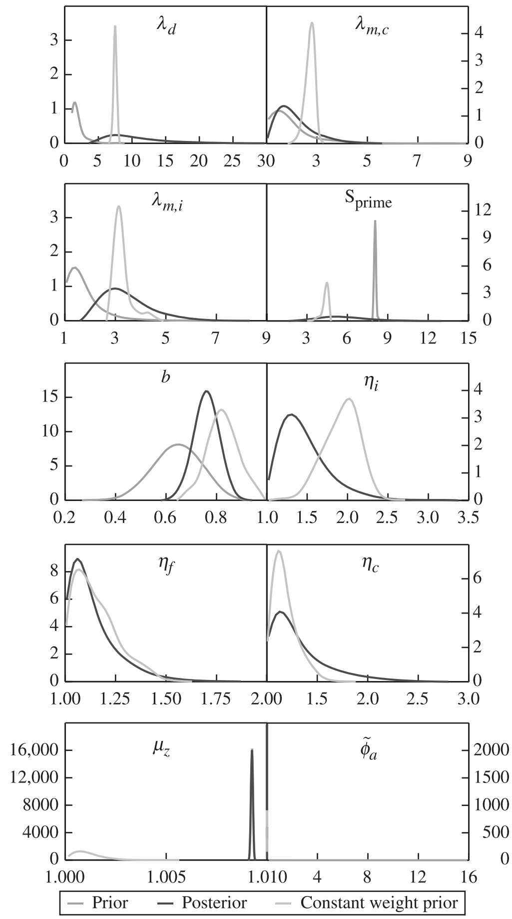

FIGURE A3
Estimates of Exogenous Processes – AR(1) Coefficients

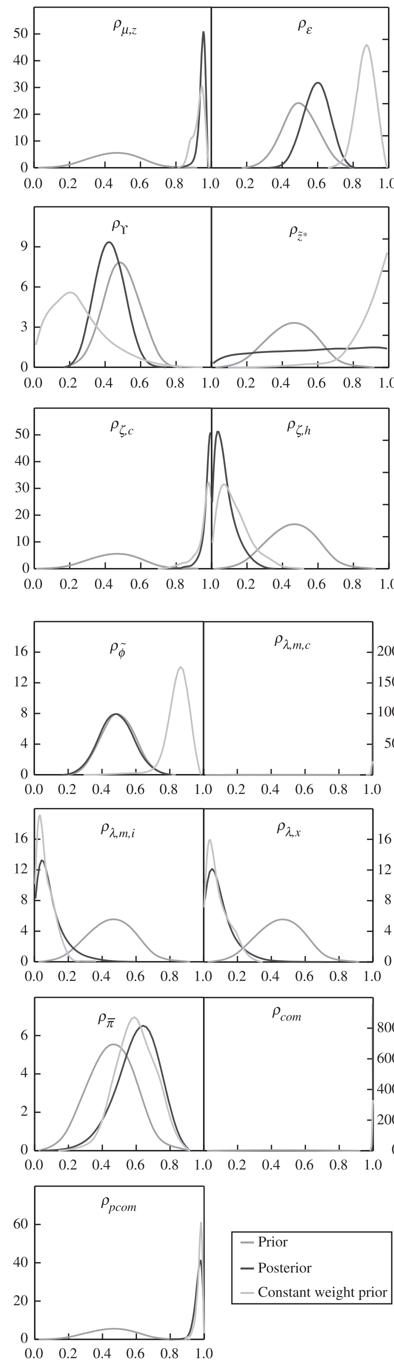

FIGURE A4
Estimates of Exogenous Processes – Standard Deviations

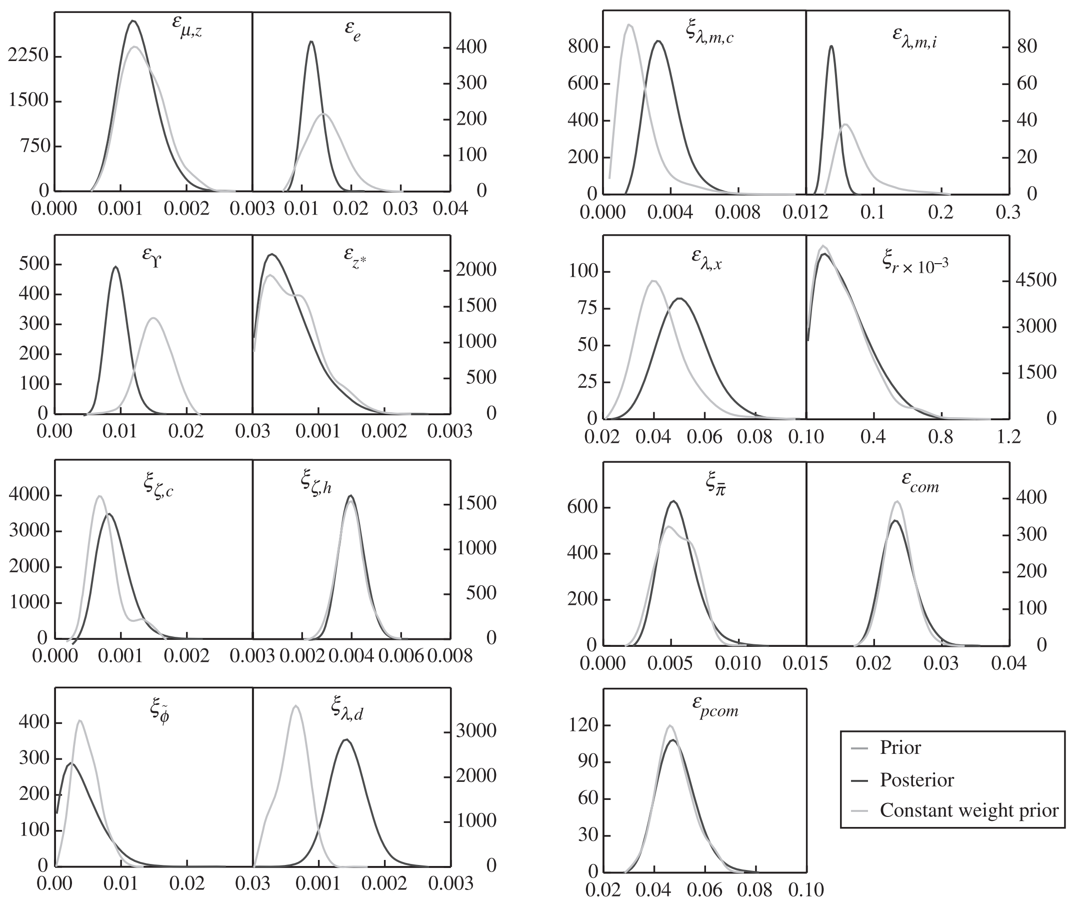

Figure A5
Estimates of Policy Reaction Parameters