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A Multi-sector Model of the Australian Economy*

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This paper describes the dynamic stochastic general equilibrium (DSGE) model currently in use at the Reserve Bank of Australia. The model extends previous DSGE models of the Australian economy by incorporating multiple production sectors, including a resource sector. We estimate the model, describe its dynamic properties, illustrate its use in scenario analysis and use it to identify the sources of Australian business cycle fluctuations.

I *Introduction*

Over recent decades, the Australian economy has faced several large macroeconomic shocks. These have included: a once-in-a-generation commodity price cycle, the 1990s Asian currency and financial crisis, several periods of rapid housing price growth and, following the financial crisis, the largest synchronised global recession since the 1930s. In all of these examples, the aggregate adjustments to these shocks were felt unevenly across the economy. For instance, the cycle in commodity prices led to shifts in the size of the resource sector relative to the rest of the economy, while the most recent housing price boom was associated with increased construction activity, which is largely non-traded.

Economists interested in understanding and modelling developments such as those listed above have access to a number of dynamic stochastic general equilibrium (DSGE) models of the Australian economy. Buncic and Melecky (2008) and Nimark (2009) estimated small-scale DSGE models, largely for the purpose of examining the dynamic effects of monetary policy shocks. More recently, Jääskelä and Nimark (2011) constructed a medium-scale DSGE model that includes physical capital as well as a large number of shocks and frictions and was used for several years for forecasting and scenario analysis at the Reserve Bank of Australia (RBA). The existing models can all, to a greater or lesser degree, describe the economy-wide effects of developments such as commodity price movements, monetary policy shocks or fluctuations in overseas demand. But they are silent on the implications of these developments for different sectors of the economy.

Such a narrow focus on aggregate responses is undesirable for two reasons. First, researchers and policymakers may be interested in the behaviour of sectoral variables. For example, they may want to know how commodity price movements affect industries outside of the mining sector, or the sensitivity of non-tradeable inflation to various economic shocks. Second, the sectoral composition of the economy may affect the transmission of disturbances to aggregate variables. For instance, in quantifying the implications of exchange rate movements the fact that a large portion of economic activity takes place in the non-tradeable sector may be relevant. Similarly, the response of mining output to a commodity

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price boom may be muted if physical capital cannot move freely to the resources sector from other parts of the economy.

In this paper we present a DSGE model of the Australian economy currently in use at the RBA. The key innovation of the model is that it features a rich sectoral production structure, including a non-tradeable sector, a resources sector and a non-resources tradeable sector. We estimate the model on Australian data using Bayesian methods. We then use the estimated model to trace out the effect of a number of macroeconomic shocks, including commodity price and monetary policy shocks, on aggregate and sectoral economic variables and to quantify the sources of business cycle volatility over recent decades.

As well as the more-detailed production structure, a major difference between the model described in this paper and the medium-scale DSGE models typically used in other central banks is that ours includes fewer real and nominal frictions. This largely reflects the fact that the model described in this paper is intended primarily for use in scenario analysis rather than as a forecasting tool. For scenario analysis, it is desirable to have a model that is detailed enough to answer questions of particular relevance to a small open commodity-exporting economy like Australia, while still being simple enough to make the economic mechanisms at work within the model transparent and straightforward to communicate. The latter task is considerably eased by keeping the number of frictions to a minimum. Nonetheless, we show that despite the absence of these shocks and frictions the model is able to account for much of the behaviour of the observable data series that we use in estimation. An additional advantage of our approach is that it can be readily augmented to include additional features required to answer specific questions in a targeted manner. The expectation is that this model can be used as a baseline, with additional features – such as a housing or financial sector – being added or subtracted, depending on the specific policy question at hand.

The rest of the paper is organised as follows. Section II describes the main features of the model. Section III outlines the estimation strategy and Section IV explores the dynamics of the estimated model. Section V provides an example of how the model can be used to construct a scenario involving an extended period of lower resource prices. Section VI uses the model to uncover the sources of Australian business cycle fluctuations over recent decades. Section VII concludes.

II The Model

The economic units in the model are households, firms and policymakers.

Households derive utility from consumption and disutility from labour services, which they supply to firms. Households' saving takes the form of bonds, denominated in either domestic or foreign currency, and capital, which is specific to each of the three production sectors.

The domestic economy consists of five sectors: a non-tradeable sector, a resource sector, a non-resource tradeable sector, an imports sector and a sector that produces final goods and services. Firms in the non-tradeable, resource and non-resource tradeable sectors produce output using labour, capital and resource goods as inputs. The imports sector purchases goods from abroad and sells them in the domestic economy. Firms in the non-tradeable, non-resource tradeable and imports sectors are imperfectly competitive, so that individual firms have some pricing power. In contrast, resource commodities are homogeneous and the price of these goods (in foreign currency) is determined entirely abroad. The final goods sector transforms the domestically sold output of the non-tradeable, non-resource tradeable and imports sectors into final goods that are then sold to households for use in consumption or investment or to the public sector. The economy exports resources and non-resource tradeable goods.

The model's monetary authorities adjust the nominal interest rate to stabilise inflation and aggregate output. Fiscal policy is specified as an exogenous government spending process that is funded through lump-sum taxation.

Although the model's structure is primarily driven by economic theory and accounting identities, we include a number of frictions in the model. These frictions help the model to capture the empirical regularities in Australian macroeconomic data. In particular, we introduce price stickiness in the non-tradeable, non-resource tradeable and imports sectors in the form of sector-specific quadratic adjustment costs that firms must pay when changing their prices. Price stickiness means that monetary policy affects real activity in the short run as well as prices. We also include quadratic investment adjustment costs. These allow the model to match the amount of investment volatility seen in the data.

The model's dynamics are driven by a collection of exogenous shock processes. These include consumption preference shocks, government spending shocks, investment technology shocks, resource price shocks, sector-specific and aggregate technology shocks and mark-up shocks as well as shocks to output, inflation and interest rates in overseas economies.

For brevity, we include the basic equations below and confine the model solution and log-linearised equations to Appendix A.

(i) Households

Households maximise their lifetime utility, which increases with aggregate consumption (C_t) and decreases with hours worked (H_t). Preferences are described by the expected utility function

$$E_0 \sum_{t=0}^{\infty} \beta^t \left\{ \xi_{c,t} \ln(C_t - hC_{t-1}) - A_L \frac{H_t^{1+\eta}}{1+\eta} \right\}, \quad (1)$$

where β is the intertemporal discount rate and η parameterises the responsiveness of hours worked to a change in real wages. The parameter h controls how much the household weights previous consumption when evaluating its current utility. A_L is a scaling term that we include to ensure that average hours in the model match those in the data. $\xi_{c,t}$ are preference shocks that account for changes in consumption not explained by other economic features of the model. These innovations follow a stationary autoregressive process.

Households have access to incomplete international financial markets in which they can buy or sell domestic and foreign bonds. They also supply capital and labour to firms in the non-traded (n), non-resource traded (m) and resource (z) sectors. Households own equity in domestic firms, which provides them with profits, and own an endowment of land, L, that provides rental income. Households can use their income from capital, labour, land and asset holdings to purchase new bonds, consumption goods or investment goods.

The capital stock is sector-specific and evolves according to the law of motion

$$K_{j,t+1} = (1-\delta)K_{j,t} + \Upsilon_t \left[1 - F_t\left(\frac{I_{j,t}}{I_{j,t-1}}\right)\right] I_{j,t}, \quad (2)$$

for $j \in \{n,m,z\}$, where δ is the depreciation rate of capital, which is common across sectors, and $F_t(\cdot)$ represents costs of adjusting the level of investment in industry j. The functional form for these costs satisfies the standard assumption that the marginal cost of a small adjustment to the rate of investment growth in steady state is zero, but that these costs increase substantially as the desired change in investment becomes larger.[1] The variable Υ_t is a shock to the marginal efficiency of investment and follows a stationary autoregressive process.

The hours worked index includes hours allocated to the non-traded, non-resource tradeable and resource sectors,

$$H_t = \left[H_{n,t}^{1+\sigma} + H_{m,t}^{1+\sigma} + H_{z,t}^{1+\sigma}\right]^{\frac{1}{1+\sigma}}, \quad (3)$$

where $\sigma \geq 0$ controls the willingness of households to substitute labour between sectors.

Households enter each period with domestic bonds, B_{t-1}, and foreign bonds, $S_t B_{t-1}^*$, where S_t is the nominal exchange rate.[2] All bonds are risk-free and mature after one period. Households can purchase new domestic and foreign bonds at the price $1/R_t$ and $S_t/(R_t^* v_t)$, where R_t and R_t^* are the gross nominal interest rates between periods t and $t+1$ in the domestic and foreign economies. The variable v_t is a country-specific risk premium that increases in the real quantity of outstanding foreign debt and a risk premium shock, ψ_t,

$$v_t = \exp\left[-\chi\left(\frac{S_t B_t^*}{P_t Y_t}\right) + \psi_t\right] \quad (4)$$

where ψ_t follows a stationary autoregressive process.

The household's budget constraint is given by

$$P_t C_t + P_t I_t + \frac{B_t}{R_t} + \frac{S_t B_t^*}{R_t^* \psi_t} \leq \sum_{j=n,m,z} \left(W_{j,t} H_{j,t} + R_{j,t} K_{j,t}\right) + R_{L,t} L + B_{t-1} + S_t B_{t-1}^* + \Gamma_t - T_t, \quad (5)$$

where P_t is the price of the final good in the economy, $I_t = \Sigma_{j=n,m,z} I_{j,t}$ is aggregate investment, $W_{j,t}$ and $R_{j,t}$ are the wage rate and rate of return on capital in sector j, $R_{L,t}$ is the rate of return on land, $\Gamma_t = \Sigma_{j=n,m,z} \int_0^1 \Gamma_{j,t}(i)di$ are aggregate profits and T_t are lump-sum transfers to the government.

[1] Formally, $F(\mu) = F'(\mu) = 0$ and $F''(\mu) = \Phi > 0$, where μ is the steady-state growth rate of total factor productivity.

[2] Note that S_t is defined as the domestic price of foreign currency, so that an increase in S_t represents a depreciation of the nominal exchange rate.

(ii) The Non-traded Sector

The non-traded sector consists of a continuum of firms that produce intermediate goods using capital, labour and resources as inputs. The firms sell their output to a retailer, which transforms the intermediate products into a homogeneous good that it sells to the final goods sector. The transformation of intermediate goods into the non-traded sector's composite good follows the constant elasticity of substitution (CES) function

$$Y_{n,t} = \left[\int_0^1 Y_{n,t}(i)^{\frac{\theta^n-1}{\theta^n}} di\right]^{\frac{\theta^n}{\theta^n-1}}, \tag{6}$$

where $Y_{n,t}(i)$ is the output of firm i and θ^n governs the degree of substitutability between the output of different non-traded firms. The demand function for each firm's output is

$$Y_{n,t}(i) = \left(\frac{P_{n,t}(i)}{P_{n,t}}\right)^{-\theta^n} Y_{n,t}, \tag{7}$$

where $P_{n,t}(i)$ is the price of firm i's good and $P_{n,t}$ is the price of the composite non-traded good. The production function of firm i is

$$Y_{n,t}(i) \le a_{n,t}\left(\mathcal{M}_t H_{n,t}(i)\right)^{\alpha_n}\left(K_{n,t}(i)\right)^{\gamma_n}\left(Z_{n,t}(i)\right)^{1-\alpha_n-\gamma_n}, \tag{8}$$

where $H_{n,t}(i)$, $K_{n,t}(i)$ and $Z_{n,t}(i)$ are the quantities of labour, capital and resource input used by firm i, and α_n, γ_n and $1-\alpha_n-\gamma_n$ are the input shares of labour, capital and resources in the production of non-traded goods. $a_{n,t}$ is a stationary non-tradeable sector-specific technology shock that follows a first-order autoregressive processes. $\mathcal{M}_t$ is a permanent productivity process that follows a random walk with drift.

We introduce price stickiness into the non-traded sector by assuming that firms face a quadratic cost of adjusting their prices, along the lines of Rotemberg (1982). Given this friction, firms choose prices and factor inputs to maximise real profits, which are given by

$$\Gamma_{n,t}(i) = \frac{P_{n,t}(i)Y_{n,t}(i)}{P_t} - \frac{MC_{n,t}(i)Y_{n,t}(i)}{P_t} - \frac{\tau_\pi^n}{2}\left[\frac{P_{n,t}(i)}{\Pi_{n,t-1}^{\chi}\Pi^{1-\chi}P_{n,t-1}(i)} - 1\right]^2 \frac{P_{n,t}Y_{n,t}}{P_t}, \tag{9}$$

where the term in square brackets represents the quadratic price adjustment costs. $\Pi_{n,t-1}$ represents the rate of inflation for the non-traded sector as a whole in period $t-1$, and Π is the central bank's target for aggregate inflation. $MC_{n,t}(i)$ are the nominal marginal costs of firm i, given by

$$MC_{n,t}(i) = \frac{\varepsilon_{\pi_n,t}}{a_{n,t}}\left[\frac{W_{n,t}}{\alpha_n \mathcal{M}_t}\right]^{\alpha_n}\left[\frac{R_{n,t}}{\gamma_n}\right]^{\gamma_n}\left[\frac{P_{z,t}}{1-\alpha_n-\gamma_n}\right]^{1-\alpha_n-\gamma_n}, \tag{10}$$

where $\varepsilon_{\pi_n,t}$ is a mark-up shock that increases marginal costs in the non-tradeable sector for reasons unrelated to changes in wages, rates of return on capital or resource prices, and $P_{z,t}$ is the domestic-currency price of resources.

(iii) The Non-resource Tradeable Sector

The non-resource tradeable sector consists of a continuum of firms that produce intermediate goods using capital, labour and resources as inputs. In the domestic sector, firms sell their output to a retailer, which transforms the intermediate products into a homogeneous good that it sells to the final goods sector. In the foreign sector, firms sell their output to an exporter that transforms the intermediate products into a homogeneous good for sale in overseas markets. Firms can charge separate prices for goods that they sell domestically and goods that they export. The transformation of each firm's intermediate good into the non-resource tradeable sector's composite good follows the CES function

$$Y^j_{m,t} = \left[\int_0^1 Y^j_{m,t}(i)^{\frac{\theta^m-1}{\theta^m}} di\right]^{\frac{\theta^m}{\theta^m-1}}, \tag{11}$$

for $j \in \{d,x\}$, where d denotes goods that are sold domestically and x denotes goods that are exported. $Y^j_{m,t}(i)$ is the output of firm i for market j, and θ^m governs the degree of substitutability between the output of different non-resource tradeable firms. The demand functions for each firm's output in the domestic and overseas markets are

$$Y^d_{m,t}(i) = \left(\frac{P_{m,t}(i)}{P_{m,t}}\right)^{-\theta^m} Y^d_{m,t}, \tag{12}$$

$$Y^x_{m,t}(i) = \left(\frac{P^*_{m,t}(i)}{P^*_{m,t}}\right)^{-\theta^m} Y^x_{m,t}. \tag{13}$$

Each firm produces according to the production function

$$Y_{m,t}(i) \leq a_{m,t}\left(\mathcal{M}_t H_{m,t}(i)\right)^{\alpha_m}\left(K_{m,t}(i)\right)^{\gamma_m} \left(Z_{m,t}(i)\right)^{1-\alpha_m-\gamma_m}, \tag{14}$$

where $H_{m,t}(i)$, $K_{m,t}(i)$ and $Z_{m,t}(i)$ are the quantities of labour, capital and resources used by firm i, and α_m, γ_m and $1-\alpha_m-\gamma_m$ are the input shares of labour, capital and resources in the production of non-resource traded goods. $a_{m,t}$ is a stationary non-resource traded sector-specific technology shock that follows a first-order autoregressive process.

As in the non-tradeable sector, we introduce price stickiness by assuming that individual firms in this sector face quadratic price adjustment costs in the currency of the market in which their goods are sold.[3] Taking account of this friction, firms choose prices and factor inputs to maximise real profits, which are given by

$$\begin{aligned}\Gamma_{m,t}(i) = {} & \frac{P_{m,t}(i)Y^d_{m,t}(i)}{P_t} + \frac{S_t P^*_{m,t}(i)Y^x_{m,t}(i)}{P_t} \\ & - \frac{MC^d_{m,t}(i)Y_{m,t}(i)}{P_t} - \frac{MC^x_{m,t}(i)Y_{m,t}(i)}{P_t} \\ & - \frac{\tau^m_\pi}{2}\left[\frac{P_{m,t}(i)}{\Pi^\chi_m \Pi^{1-\chi} P_{m,t-1}(i)} - 1\right]^2 \frac{P_{m,t}Y^d_{m,t}}{P_t} \\ & - \frac{\tau^{m*}_\pi}{2}\left[\frac{P^*_{m,t}(i)}{\Pi^{*\chi}_{m,t-1}\Pi^{1-\chi}P^*_{m,t-1}(i)} - 1\right]^2 \frac{S_t P^*_{m,t}Y^x_{m,t}}{P_t}.\end{aligned} \tag{15}$$

$P_{m,t}(i)$ is the price charged by firm i for goods sold in the domestic market, $P^*_{m,t}(i)$ is the price charged by the firm for goods sold in the overseas market, $P_{m,t}$ and $P^*_{m,t}$ are the prices of the sector's aggregate goods and $MC_{m,t}(i)$ are the nominal marginal costs of firm i, given by

$$\begin{aligned}MC^j_{m,t}(i) = {} & \frac{\varepsilon^j_{\pi_n,t}}{a_{m,t}}\left[\frac{W_{m,t}}{\alpha_m \mathcal{M}_t}\right]^{\alpha_m}\left[\frac{R_{m,t}}{\gamma_m}\right]^{\gamma_m} \\ & \left[\frac{P_{z,t}}{1-\alpha_m-\gamma_m}\right]^{1-\alpha_m-\gamma_m},\end{aligned} \tag{16}$$

for $j \in \{d,x\}$, where $\varepsilon^j_{\pi_m,t}$ is a mark-up shock.

Domestic demand for non-resource commodities is determined by the optimising decisions of domestic households and firms. We assume that foreign demand for these goods is given by

$$Y^x_{m,t} = \omega^*\left(\frac{P^*_{m,t}}{P^*_t}\right)^{\zeta^*} Y^*_t, \tag{17}$$

where $Y^x_{m,t}$ is the quantity of non-resource tradeable goods that are exported, P^*_t is the foreign price level and Y^*_t is the level of foreign economic activity.

(iv) The Resources Sector

The resources sector produces homogenous output under perfect competition taking prices as given. Under these conditions, the sector behaves as though it consists of a single firm that produces output according to the production function

$$Y_{z,t} = a_{z,t}\left(\mathcal{M}_t h_{z,t}\right)^{\alpha_z}\left(K_{z,t}\right)^{\gamma_z}\left(\mathcal{M}_t L\right)^{1-\alpha_z-\gamma_z}, \tag{18}$$

where α_z and γ_z are the effective input share of labour and capital in the resources sector. L is land used in the production of resources. The stationary sector-specific technology shock, $a_{z,t}$, follows a first-order autoregressive process.

We include land in the resources production function for several reasons. As a matter of empirical realism, non-produced natural resource inputs are a major input into mining production. Failing to account for these inputs can significantly alter estimates of resource sector productivity (Topp *et al.*, 2008). This is not the case for other sectors of the economy, which explains why models that do not include a mining sector typically ignore this factor of production (Harding & Negara, 2008). In addition, including land as a fixed input means that the production function exhibits decreasing returns to scale in capital and labour. This helps the model to capture the relative unresponsiveness of natural resource output to

[3] Formally, we assume that prices are sticky in local currency terms.

changes in commodity prices, at least over short horizons.

The resources firm takes prices as given and chooses labour and capital each period in order to maximise its profits, given by

$$\Gamma_{z,t} = P_{z,t}Y_{z,t} - W_{z,t}h_{z,t} - R_{z,t}K_{z,t} - R_{L,t}L, \quad (19)$$

where $P_{z,t}$ is the price of resources in domestic currency.

The price of resources in foreign currency, $P^*_{z,t}$, is determined in world markets and is unaffected by economic developments in the domestic economy. In the long run, we assume that the law of one price holds for resources. However, we allow for a delay in the short-term pass-through of resource price movements into the prices that Australian resource firms receive. We do this to account for two real-world frictions in the degree of resource price pass-through. First, a proportion of Australia's resource exports is sold according to predetermined price contracts. Second, some resource firms hedge their overseas currency exposures. The specific functional form that we assume for domestic-currency resource prices is $P_{z,t} = (S_tP^*_{z,t})^{1/2}(P_{z,t-1})^{1/2}$. Although not immediate, the pace of pass-through in the resources sector is still assumed to be rapid: half of any change in overseas resource prices feeds into domestic resource prices in the quarter in which the price change occurs, and around 95 per cent flows through within the first year.

(v) The Imports Sector

The output of the imports sector is an aggregate constructed from a continuum of imported varieties according to the production technology

$$Y_{f,t} = \left[\int_0^1 Y_{f,t}(i)^{\frac{\theta^f-1}{\theta^f}} di\right]^{\frac{\theta^f}{\theta^f-1}}, \quad (20)$$

where $Y_{f,t}(i)$ is the quantity of variety i imported and θ^f governs the degree of substitutability between different imported goods varieties. The demand function for each variety is

$$Y_{f,t}(i) = \left(\frac{P_{f,t}(i)}{P_{f,t}}\right)^{-\theta^f} Y_{f,t}. \quad (21)$$

Importing firms also face quadratic price adjustment costs and choose prices to maximise

$$\Gamma_{f,t}(i) = \frac{P_{f,t}(i)Y_{f,t}(i)}{P_t} - \frac{MC_{f,t}(i)Y_{f,t}(i)}{P_t} - \frac{\tau^f_\pi}{2}\left[\frac{P_{f,t}(i)}{\Pi\chi_{f,t-1}\Pi^{1-\chi}P_{f,t-1}(i)} - 1\right]^2 \frac{P_{f,t}Y_{f,t}}{P_t}, \quad (22)$$

where marginal costs for importing firms are

$$MC_{f,t}(i) = \varepsilon_{\pi_f,t}\frac{S_tP^*_{f,t}}{P_{f,t}}, \quad (23)$$

in which $\varepsilon_{\pi_f,t}$ is a mark-up shock.

(vi) Public Demand

The government issues bonds and raises lump-sum taxes to pay for expenditure on goods and services according to the budget constraint

$$P_tG_t + B_{t-1} = T_t + \frac{B_t}{R_t}. \quad (24)$$

Public demand, G_t, is treated as an exogenous process that evolves according to

$$\ln\left[\frac{G_t}{\mathcal{M}_t}\right] = (1-\rho_g)\ln(g) + \rho_g \ln\left[\frac{G_{t-1}}{\mathcal{M}_{t-1}}\right] + \varepsilon_{g,t}, \quad (25)$$

where g is calibrated so that the steady-state share of public demand in GDP in the model matches its average share in the data.

Because taxes are lump sum, Ricardian equivalence holds. This means that, for a given path of government expenditure, the timing of taxation does not affect household or firm decisions. We make the simplifying assumption that in equilibrium domestic debt is in zero net supply, so that $B_t = 0$ for all t.

(vii) The Final Goods Sector

The final goods sector assembles the domestically sold output of the non-traded, non-resource tradeable and imports sectors according to the production function

$$DFD_t = \left[\omega_n^{\frac{1}{\zeta}}Y_{n,t}^{\frac{\zeta-1}{\zeta}} + \omega_m^{\frac{1}{\zeta}}(Y^d_{m,t})^{\frac{\zeta-1}{\zeta}} + \omega_f^{\frac{1}{\zeta}}Y_{f,t}^{\frac{\zeta-1}{\zeta}}\right]^{\frac{\zeta}{\zeta-1}}, \quad (26)$$

where $\omega_m + \omega_n + \omega_f = 1$ and ω_m, ω_n and ω_f govern the shares of the non-resource tradeable, non-tradeable and imported good in the final domestic good. $Y^d_{m,t}$ stands for those tradeable goods sold domestically and DFD_t stands for domestic final demand. Profit maximisation by the final goods producer ensures that the corresponding price index is

$$P_t = \left[\omega_n P_{n,t}^{1-\zeta} + \omega_m P_{m,t}^{1-\zeta} + \omega_f P_{f,t}^{1-\zeta}\right]^{\frac{1}{1-\zeta}}. \qquad (27)$$

(viii) The Central Bank

The central bank sets the short-term nominal interest rate, R_t, according to a Taylor-type monetary policy rule

$$\ln\left(\frac{R_t}{R}\right) = \rho_r \ln\left(\frac{R_{t-1}}{R}\right) + (1-\rho_r)\left[\phi_\pi \ln\left(\frac{\Pi_t}{\Pi}\right) + \phi_{\Delta_y} \ln\left(\frac{Y_t^{\text{va}}}{Y_{t-1}^{\text{va}}}\right) + \phi_q\left(\frac{Q_t}{Q_{t-1}}\right)\right] + \varepsilon_{r,t}, \qquad (28)$$

where Π_t is the CPI inflation rate and $Y_t^{\text{va}}/Y^{\text{va}}$ is the deviation of real GDP (defined below) from its non-stochastic trend. The nominal interest rate depends on past nominal interest rates and also responds to current values of CPI inflation, the level and growth rate of output and the change in the real exchange rate.

(ix) Market Clearing, the Current Account and Output

Goods market clearing requires that

$$Y_{m,t} = Y^d_{m,t} + Y^x_{m,t}, \qquad (29)$$

$$Y_{z,t} = Y^x_{z,t} + Z_{n,t} + Z_{m,t}, \qquad (30)$$

$$DFD_t = C_t + I_t + G_t. \qquad (31)$$

Equation (29) says that all non-resource tradeable goods that the economy produces must be sold at home or abroad. Equation (30) says that all resources produced must be exported or used in the production of other domestic goods. Equation (31) is the market clearing condition for the domestic final good.

Net exports in nominal terms, NX_t, are equal to the sum of resource and non-resource export values less import values

$$NX_t = P_{z,t} Y^x_{z,t} + S_t P^*_{m,t} Y^x_{m,t} - S_t P^*_{f,t} Y_{F,t}. \qquad (32)$$

The current account equation governs the evolution of the economy's net foreign assets and is given by

$$\frac{S_t B_t^*}{R_t^* v_t} = S_t B^*_{t-1} + NX_t. \qquad (33)$$

The non-resource tradeable and non-tradeable sectors use resources as inputs into the production of $Y_{m,t}$ and $Y_{n,t}$. This introduces a wedge between production and value added in these sectors. We calculate the latter value, which is the relevant concept for the measurement of GDP, by subtracting resource inputs from total production. Because we are interested in constructing a measure of real aggregate economic activity (that is, one that abstracts from price changes), we fix relative prices at their steady-state values when calculating value added.[4] For example, $Y^{\text{va}}_{m,t} = Y_{m,t} - (P_z/P_m)Z_{m,t}$. It follows that real GDP is defined as

$$Y_t^{\text{va}} = \left(\frac{P_n}{P}\right) Y^{\text{va}}_{n,t} + \left(\frac{P_m}{P}\right) Y^{\text{va}}_{m,t} + \left(\frac{P_z}{P}\right) Y_{z,t}. \qquad (34)$$

(x) The Foreign Economy

As in Galí and Monacelli (2005), we specify the foreign economy as a closed-economy variant of the model described above. For ease of interpretation, we present the equations for this economy with all variables in log deviations from their steady state.

The foreign IS curve is

$$\hat{y}^*_t = E_t\{\hat{y}^*_{t+1}\} + \left(\hat{r}^*_t - E_t\{\hat{\pi}^*_{t+1}\}\right) + E_t\{\hat{\xi}_{y^*,t+1}\} - \hat{\xi}_{y^*,t} \qquad (35)$$

where a ˆ denotes the deviation of a log-linearised variable from its steady state, y^*_t is foreign output, r^*_t is the foreign interest rate, π^*_t is foreign inflation and $\xi_{y^*,t}$ is a foreign demand shock that follows an autoregressive process. Foreign prices are determined by the Phillips curve

$$\hat{\pi}^*_t = \beta E_t\left\{\hat{\pi}^*_{t+1}\right\} + \frac{\kappa^*}{100}\hat{y}^*_t + \varepsilon_{\pi^*,t}, \qquad (36)$$

[4] Although price levels in the model are non-stationary, relative prices have well-defined steady states.

where $\varepsilon_{\pi^*,t}$ is a cost push shock. And foreign interest rates follow the Taylor-type rule

$$\hat{r}_t^* = \phi_{r^*}\hat{r}_{t-1}^* + (1-\phi_{r^*})\left(\phi_{\phi^*}\hat{\pi}_t^* + \phi_y\hat{y}_t^*\right) + \varepsilon_{r^*,t}. \quad (37)$$

We assume that the relative price of resources in terms of foreign currency is stationary, but subject to transitory deviations according to an autoregressive process. We allow for two shocks, foreign demand shocks and resource-specific price shocks, to affect real resource prices, which evolve according to the process

$$\hat{p}_{z,t}^* = (1-\rho_{p_z^*})\hat{p}_z^* + \rho_{p_z^*}\hat{p}_{z,t-1}^* + \rho_{zy,t}\varepsilon_{y^*,t} + \varepsilon_{p_z^*,t}, \quad (38)$$

where $\hat{p}_{z,t}^* = \log[P_{z,t}^*/P_t^*]$ is the relative price of resources in foreign currency.[5]

(xi) Exogenous Processes

The rate of growth of labour-augmenting technology, $\mu_t = \ln(\mathcal{M}_t/\mathcal{M}_{t-1})$, follows the process

$$\mu_t = \ln(\mu) + \varepsilon_{\mu,t}, \quad \varepsilon_{\mu,t} \sim N(0,\sigma_\mu^2), \quad (39)$$

where $\ln(\mu)$ is the trend rate of productivity growth.

The structural shocks that follow first-order autoregressive processes evolve according to

$$\hat{\varsigma}_t = \rho_\varsigma\hat{\varsigma}_{t-1} + \varepsilon_{\varsigma,t}, \quad \varepsilon_{\varsigma,t} \sim N(0,\sigma_\varsigma^2), \quad (40)$$

for $\varsigma = \{\xi_c, \Upsilon, \psi, a_n, a_m, a_z, \xi_{y^*}\}$. The remaining exogenous processes $\varepsilon_{\pi_n}, \varepsilon_{\pi_m}, \varepsilon_{\pi_m^*}, \varepsilon_{\pi_f}, \varepsilon_r, \varepsilon_g, \varepsilon_{\pi^*}, \varepsilon_{r^*}$ and $\varepsilon_{p_z^*}$ are assumed to be white noise.

III Estimation

(i) Data

We estimate the model using quarterly data for the period 1992Q1–2013Q4, a total of 88 quarters. The observed variables of the model are: the growth rates of Australian GDP, consumption, investment, public demand, resource exports and non-resource exports and foreign GDP; the growth rates of value-added output in the Australian non-tradeable, non-resource tradeable and resource sectors; trimmed mean CPI inflation and non-tradeable inflation in Australia and inflation abroad; the growth of foreign-denominated resource prices; and the level of the nominal policy interest rates at home and abroad.[6]

We use seasonally adjusted data where available and measure all national accounts data in real terms. We also pre-filter the data by removing the sample mean of each variable prior to estimation. We use standard data sources for all of the Australian variables. For the foreign variables, we use the trade-weighted average GDP growth of Australia's major trading partners; the average inflation of the G7 economies; and the simple average of the policy interest rates in the United States, euro area and Japan.

(ii) Calibration

We parameterise the model at a quarterly frequency (Table 1). The steady-state rate of productivity growth, μ, is set to 0.8 per cent and the inflation rate to 2.5 per cent at an annualised rate. These values are consistent with the average rate of Australian GDP growth over our sample and the midpoint of the RBA's inflation target. We set the household's discount factor, β, equal to 0.9996. Together, these three parameters imply that the model's steady-state cash rate is equal to 6 per cent.

We set the inverse of the Frisch labour supply elasticity, η, equal to 1. This is a standard value in the literature and close to the estimate for Australia in Justiniano and Preston (2010b). We set the parameter governing the willingness of workers to move between sectors, σ, equal to 1, which is consistent with Horvath (2000). With this parameterisation, workers in the model do not view jobs in different sectors as perfect substitutes, but they are willing to move between sectors if relative wage movements are large enough.

We set the parameters governing the share of non-tradeable, non-resource tradeable and imported goods in the domestic final goods basket, ω_n, ω_m and ω_f, to match the share of these goods in nominal GDP. We set the intersectoral elasticity of final demand, ζ, and the elasticity of demand for domestic non-resource goods overseas, ζ^*, equal to 0.8. These values are in line with the range of estimates in the literature (Stockman & Tesar, 1995; Justiniano & Preston, 2010b; Rabanal & Tuesta, 2012).

We set the intrasectoral elasticities of substitution for the non-traded, non-resource traded and

[5] Note that the foreign demand shock, $\hat{\xi}_{y^*,t}$, follows the exogenous autoregressive process: $\hat{\xi}_{y^*,t} = \rho_{\xi_{y^*}}\hat{\xi}_{y^*,t} + \varepsilon_{y^*,t}$. It is the innovation to this process, $\varepsilon_{y^*,t}$, that enters the equation for commodity prices.

[6] Appendix B contains a description of the data series used in estimation.

Table 1
Calibrated Parameters

Parameter	Description	Value
Technology and policy		
μ	Steady-state total factor productivity growth rate	1.008
π	Steady-state inflation rate	1.0062
ι	Risk premium coefficient	0.001
δ	Capital depreciation rate	0.0175
b^*	Governs steady-state trade deficit	25
g	Governs share of public demand in expenditure	2.2
Households		
β	Household's discount factor	0.9996
ω_n	Controls share of non-tradeables in domestic final demand	0.63
ω_h	Controls share of non-resource tradeables in domestic final demand	0.12
ω_f	Controls share of imports in domestic final demand	0.25
ζ	Intersectoral elasticity of substitution in domestic final demand	0.8
ζ^*	Elasticity between domestic and foreign goods overseas	0.8
η	Labour supply elasticity	1
σ	Intersectoral labour supply elasticity	1
Non-traded sector		
α_n	Labour share in non-traded sector	0.7
γ_n	Capital share in non-traded sector	0.24
θ^n	Elasticity of substitution in non-traded sector	6
Non-resource sector		
α_h	Labour share in non-resource traded sector	0.6
γ_h	Capital share in non-resource traded sector	0.32
θ^m	Elasticity of substitution in non-resource traded sector	6
ω_m^*	Governs share of non-resource tradeable goods that are exported	2.5
Resource sector		
α_z	Labour share in resource sector	0.2
γ_z	Capital share in resource sector	0.25
p_z^*	Governs share of resources in exports	2.5
Imports sector		
θ^f	Elasticity of substitution in imports sector	6

import sectors, θ_n, θ_m and θ_f, equal to 6. This implies an average mark-up in these sectors of 20 per cent.

We calibrate technological parameters in the production functions of the three domestic production sectors using data on factor incomes for each of these sectors. We set the quarterly depreciation rate of capital in each sector equal to 1.75 per cent, which is around the average value of this parameter in the Australian national accounts. Finally, we set the parameter governing the steady-state level of government spending, g, and that governing the steady-state foreign asset level, b^*, to match the average share of public demand in nominal GDP over the sample and the average trade deficit.

Table 2 compares some important steady-state ratios of the model to their averages in the data over our estimation sample. The model successfully captures many of these key features of the data.

(iii) Bayesian Estimation

To estimate the model, we follow standard practice in the DSGE literature and use Bayesian techniques that place informative priors on the estimated parameters.[7] Informative priors are useful because they regularise the posterior distribution of the model so that it remains numer-

[7] See An and Schorfheide (2007) for a description of Bayesian DSGE model estimation. We use the MATLAB package Dynare to estimate the model.

TABLE 2
Steady-State Properties of the Model

Target	Average 1993–2013	Model
Expenditure (per cent of GDP)		
Household consumption	56.9	55.8
Private investment	21.4	22.7
Public demand	22.5	22.5
Exports	19.5	19.6
Imports	20.6	20.6
Production (per cent of GVA)		
Non-tradeable	64.0	64.0
Other tradeable	26.3	23.1
Mining	9.7	12.9
Trade (per cent of exports)		
Resource exports	40.1	40.1
Other exports	59.9	59.9
Investment demand (per cent of private investment)		
Non-tradeable	58.5	58.4
Other tradeable	27.8	27.7
Mining	13.7	13.9

ically stable, while also compensating for the brief span of available data and ensuring that the resulting parameter estimates are economically sensible. Within that scope, we tried to make the prior distributions as loose as possible. For instance, most of the AR(1) coefficients are given priors that allow them to take posterior values almost spanning the stable unit interval, while ensuring that they do not collapse to zero or one.

In our estimation, we allow for measurement errors in all variables except for the nominal interest rates in Australia and abroad. Measurement errors account for the possibility that macroeconomic data may be measured with substantial noise.[8] They also reflect the fact that the economic concepts recorded in official data series may differ from those in the model. We calibrate the variances of the measurement errors so that they correspond to 10 per cent of the variance of each data series.[9]

We use the Metropolis–Hastings algorithm to take draws from the posterior distribution of the model's parameters, after using numerical procedures to locate the mode. We take 100,000 draws from the posterior distribution and discard the first 50,000 as burn-in. The values of the posterior draws indicated that the initial estimate of the posterior mode was adequate. While multiple modes can occur in theory, the use of informative prior distributions makes this possibility remote in practice.

Following Kulish and Rees (2011), we estimate the model in two stages. In the first, we estimate the large economy's parameters. In the second, we estimate the remaining small economy's parameters, taking as given the posterior mean values of the common parameters from the first stage.

Table 3 summarises the results from the first stage of the estimation. Focusing first on the exogenous processes, we find that shocks to the prices of Australia's export commodities are large and persistent, which is a common finding in the literature (Jääskelä & Nimark, 2011; Kulish & Rees, 2015). Like Justiniano and Preston (2010b) and Kulish and Rees (2011), we find that shocks to overseas output are considerably larger than shocks to overseas inflation and monetary policy. The shocks to overseas output and monetary policy are highly persistent, while the inflation shocks are more transitory.

The coefficients of the foreign Taylor rule imply a strong response to inflation and a modest response to deviations of output from its steady-state level. Although it is difficult to compare these parameters to other studies as our overseas output, inflation and interest rate series represent averages across multiple economies, these estimates appear plausible. The estimated response of resource prices to foreign output shocks is small and not significantly different from zero. Our estimates suggest that the overseas Phillips curve is quite flat, a common finding in the literature.

Table 4 shows the parameter estimates for the domestic block. Rather than estimate the price adjustment costs, τ_n, τ_m, τ_{m^*} and τ_f, about which we have no strong prior beliefs, we instead estimate the slopes of the Phillips curve, which are a monotonic transformation of these parameters.[10] As was the case for the foreign block, the domestic Phillips curves are estimated to be extremely flat. To put the parameter estimates in context, they are

[8] See Rees *et al.* (2015a) for an illustration of measurement error in Australian GDP.

[9] Because economic concepts in the data differ from those in the model (for example, national accounts aggregates are measured in chain volume terms, whereas in the model we use fixed weight indices), we must allow for some measurement error to estimate the model. To test the sensitivity of our results to measurement error, we have re-estimated the model with half as much measurement error. This exercise generates very similar parameter estimates.

[10] Specifically, we estimate $\kappa_j = 100(\theta_j - 1)/\tau_j$ for $j \in \{n, m, m^*, f\}$.

TABLE 3
Model Results: Foreign Block

	Prior distribution			Posterior distribution			
Parameter	Shape	Mean	SD	Mode	Mean	5%	95%
ρ_{ξ^*}	beta	0.500	0.150	0.96	0.95	0.93	0.98
ρ_{e^*}	beta	0.500	0.150	0.30	0.32	0.18	0.47
ρ_{r^*}	beta	0.750	0.100	0.94	0.93	0.91	0.95
ϕ_{π^*}	normal	1.500	0.100	1.38	1.48	1.14	1.80
ϕ_{y^*}	normal	0.125	0.050	0.22	0.21	0.12	0.28
ρ_{zy}	normal	0.000	0.200	0.22	0.19	−0.11	0.50
$\phi_{\Delta y^*}$	normal	0.125	0.050	0.13	0.14	0.09	0.19
$\rho_{p_z^*}$	beta	0.500	0.150	0.94	0.94	0.90	0.97
κ^*	gamma	1.000	0.800	1.60	3.53	0.43	7.33
Standard deviations (× 100)							
σ_{z^*}	gamma	0.5	0.4	5.65	5.68	4.96	6.35
σ_{y^*}	gamma	0.5	0.4	1.56	1.34	0.92	1.76
σ_{r^*}	gamma	0.5	0.4	0.06	0.07	0.05	0.09
σ_{π^*}	gamma	0.5	0.4	0.19	0.20	0.16	0.24
σ_{μ}	gamma	0.5	0.4	0.11	0.14	0.01	0.26

equivalent to Calvo parameters of between 0.87 for non-resource exports and 0.95 for non-tradeable goods, implying that firms on average wait between 7 and 19 quarters before adjusting prices. These durations are longer than typical microeconomic estimates of the frequency of firm price adjustment. However, the parameter estimates are similar to those produced by single equation estimates of Australian Phillips curves (e.g. Norman & Richards, 2012), as well as other estimated medium-scale open economy DSGE models (e.g. Adolfson *et al.*, 2012). Non-tradeable prices are estimated to be the stickiest, followed by import prices, with the non-resource tradeable sector exhibiting the most price flexibility. This ordering is consistent with Kulish and Rees (2015).

The habits parameter, h, has a posterior mean of 0.77, which is similar to that estimated in Jääskelä and Nimark (2011), and indicative of a large degree of inertia in consumption. The parameter governing the degree of investment adjustment costs, Φ, is estimated to be 1.78, which is less than half as large as the equivalent parameter in Jääskelä and Nimark. This smaller value may be due to the multi-sector structure of our model, which allows investment to respond differently across sectors without necessarily affecting aggregate investment in the economy. The coefficients on the domestic Taylor rule are similar to those on the foreign Taylor rule. Consistent with Lubik and Schorfheide (2007) and Kam *et al.* (2009), we find no evidence that monetary policy in Australia responds directly to exchange rate movements.

Figure 1 shows the data used in estimation and one-sided Kalman filtered one-step-ahead predictions from the model. For most series, the model captures the low-frequency variations in the data reasonably well, but it struggles to match some of the high-frequency movements, particularly for volatile variables such as the exchange rate or resource prices. The model also over-predicts GDP growth in the period after the global financial crisis, largely because of a sequence of large prediction errors for the growth rate of the non-tradeable sector. Understanding the causes of these prediction errors and improving the fit of the model in this dimension will be an important part of our ongoing model development program.

To further explore the empirical fit of the model, Table 5 compares the second moments of the observable variables in the data to those implied by estimated model. In the table, the second column presents the empirical standard deviations and the third column contains their model counterparts. The fourth column contains the 95 per cent confidence interval for the model-based moments. For many variables, the model is able to replicate the empirical moments closely. However, it overstates the standard deviation of GDP growth. This

Table 4
Model Results: Domestic Block

	Prior distribution			Posterior distribution			
Parameter	Shape	Mean	SD	Mode	Mean	5%	95%
h	beta	0.5	0.15	0.76	0.76	0.67	0.85
$\kappa_{\pi n}$	gamma	50	30	0.20	0.29	0.06	0.55
$\kappa_{\pi f}$	gamma	50	30	0.75	1.06	0.24	1.87
$\kappa_{\pi m}$	gamma	50	30	1.24	1.61	0.33	2.91
$\kappa^*_{\pi m}$	gamma	50	30	1.27	2.10	0.34	4.00
χ	beta	0.3	0.15	0.20	0.22	0.08	0.35
Φ	gamma	4	1	1.68	1.80	1.16	2.37
ρ_r	beta	0.75	0.1	0.87	0.86	0.82	0.90
ϕ_π	normal	1.5	0.2	1.38	1.42	1.07	1.74
ϕ_y	normal	0.125	0.05	0.12	0.12	0.04	0.19
$\phi_{\Delta y}$	normal	0	0.025	0.05	0.05	0.01	0.08
ϕ_q	normal	0	0.05	0.00	0.00	−0.01	0.01
ρ_g	beta	0.5	0.15	0.32	0.34	0.17	0.51
$\rho_{\xi c}$	beta	0.5	0.15	0.71	0.68	0.54	0.84
ρ_Υ	beta	0.5	0.15	0.32	0.34	0.15	0.53
ρ_ψ	beta	0.5	0.15	0.87	0.84	0.77	0.91
ρ_{an}	beta	0.5	0.15	0.78	0.71	0.57	0.86
ρ_{am}	beta	0.5	0.15	0.52	0.47	0.31	0.63
ρ_{az}	beta	0.5	0.15	0.87	0.84	0.73	0.95
Standard deviations (× 100)							
σ_g	gamma	0.5	0.4	2.15	2.21	1.86	2.52
$\sigma_{\xi c}$	gamma	0.5	0.4	2.13	2.26	1.56	2.95
σ_Υ	gamma	0.5	0.4	5.48	5.72	4.02	7.44
σ_ψ	gamma	0.5	0.4	0.50	0.62	0.36	0.85
σ_{an}	gamma	0.5	0.4	2.67	2.65	2.13	3.15
σ_{am}	gamma	0.5	0.4	5.19	5.14	4.35	5.98
σ_{az}	gamma	0.5	0.4	1.77	1.80	1.53	2.03
σ_r	gamma	0.5	0.4	0.11	0.12	0.10	0.13
$\sigma_{\pi n}$	gamma	0.5	0.4	0.22	0.23	0.18	0.28
$\sigma_{\pi f}$	gamma	0.5	0.4	0.43	0.45	0.22	0.68
$\sigma_{\pi m}$	gamma	0.5	0.4	0.79	0.79	0.47	1.11
$\sigma^*_{\pi m}$	gamma	0.5	0.4	3.56	3.74	3.16	4.40

Note: $\kappa_{\pi_n} = 100 \times \frac{\theta^n - 1}{\tau^n_\pi}$, $\kappa_{\pi_f} = 100 \times \frac{\theta^f - 1}{\tau^f_\pi}$, $\kappa_{\pi_m} = 100 \times \frac{\theta^m - 1}{\tau^m_\pi}$, $\kappa_{\pi^*_m} = 100 \times \frac{\theta^n - 1}{\tau^{m^*}_\pi}$.

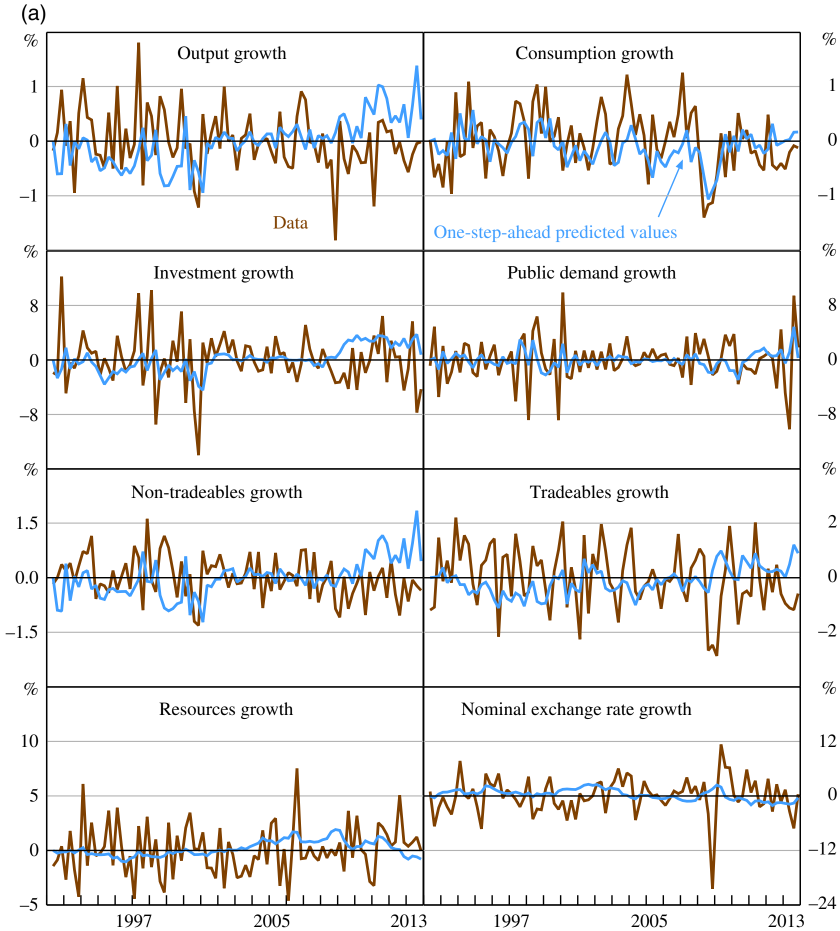
largely reflects the fact that it generates too much volatility in non-tradeable output and, to a lesser extent, non-resource tradeable output.

The final column of Table 5 shows how much of the estimated variance of each variable is accounted for by the model's structural shocks as opposed to measurement error. A value of 1 implies that all of the variance of that variable in the model was accounted for by structural shocks, while a value of 0 implies that all of the variance was accounted for by measurement error. Given that we have calibrated the variance of the measurement error for each variable to equal 10 per cent of the variance of the variable in the data, we would expect values in this column of around 0.9.[11] The model struggles to explain the behaviour of non-resource exports, ΔY^x_m, where measurement error accounts for 17 per cent of the variance in the model. However, the model's structural shocks can account for most of the behaviour of the other observed variables.

Appendix C of the working paper version of this article (Rees *et al.*, 2015b) contains plots of the posterior and prior distributions of the parameters for the domestic economy. Most of the parameters appear to be reasonably well

[11] Except for the nominal interest rate, whose measurement error we set equal to 0.

FIGURE 1
Data and One-Sided Predictions



Note: All data series were demeaned prior to estimation.

identified, with the posterior distribution being more concentrated than the prior distribution. Appendix D of the working paper contains plots of the shocks, calculated at the posterior mean of the model parameters.

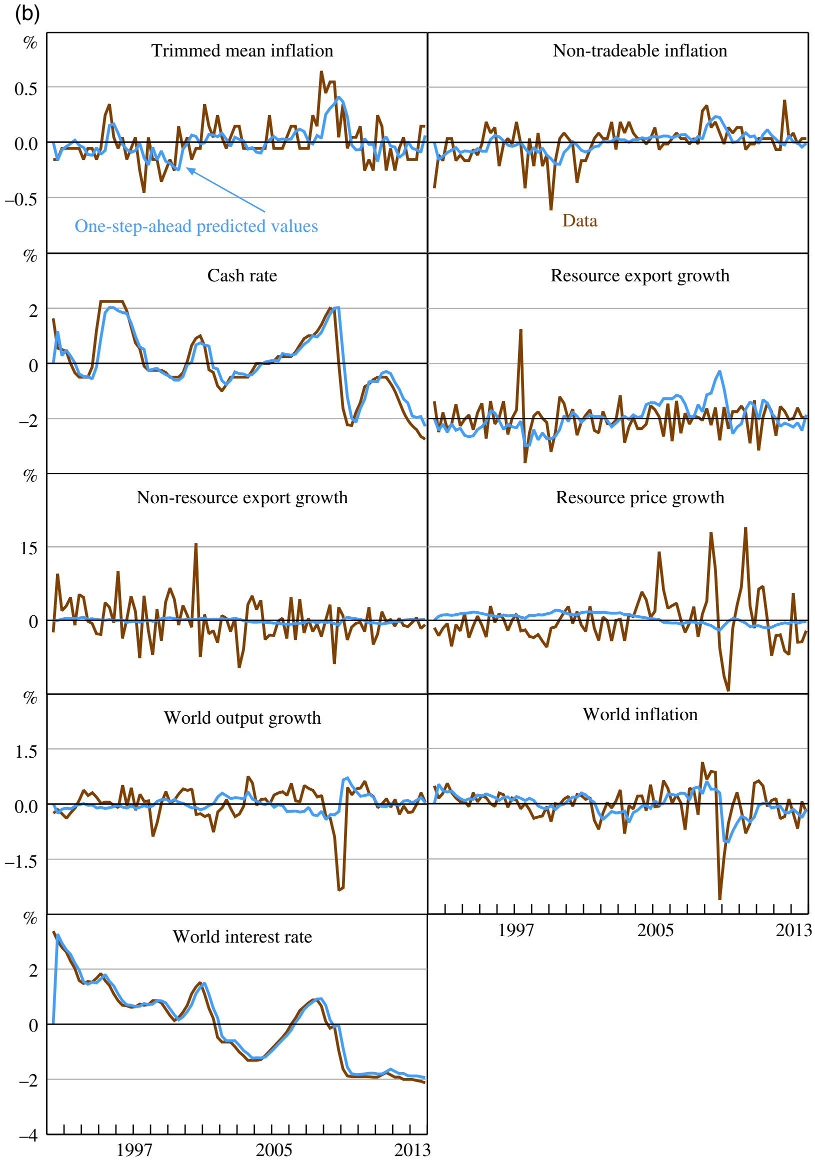
IV The Dynamics of the Estimated Model

In this section, we explore some of the economic mechanisms at work in the estimated model by examining dynamic responses to unanticipated shocks to monetary policy, resource prices and risk premiums. This set of shocks is relevant for understanding the behaviour of the Australian economy over recent decades and allows us to compare our model to others in the literature. These are also shocks that illustrate how aggregate disturbances can have differing implications for the various sectors of the economy.

(i) Monetary Policy Shocks

We start our discussion with a monetary policy shock, illustrated in Figures 2 (aggregate variables) and 3 (selected sectoral variables). The graphs show the response to a one-standard-deviation positive shock, which raises the cash rate on impact by around 40 basis points.

FIGURE 1
(Continued)



The domestic variables respond in a manner consistent with economic theory. Higher interest rates lead to a contraction in the real economy (relative to a baseline in which interest rates remained constant). Output follows a hump-shaped pattern, decreasing by 0.25 per cent at its trough, before returning to steady state after 5 years. The components of domestic demand behave in a similar manner. The response of consumption is around half as large as the response of GDP, while the contraction in investment is much larger. The nominal and real

TABLE 5
Moments of the Data and the Model

Variable	Standard Deviation: Data (%)	Model (%)	Model 95% Confidence Interval	Structural explanation $1-\frac{\text{var(Measurement error)}}{\text{var(Model)}}$
ΔY	0.56	0.95	[0.84-1.13]	0.96
ΔC	0.55	0.62	[0.52-0.74]	0.92
ΔI	3.92	3.99	[3.00-5.59]	0.90
ΔG	3.31	2.89	[2.51-3.36]	0.87
π	0.20	0.29	[0.24-0.35]	0.95
r	1.22	1.01	[0.88-1.16]	1.00
ΔS	4.08	4.10	[3.59-4.78]	0.90
π_N	0.31	0.32	[0.26-0.39]	0.91
ΔY_Z^{va}	2.33	2.24	[1.96-2.58]	0.89
ΔY_N^{va}	0.57	1.09	[0.92-1.36]	0.97
ΔY_M^{va}	1.14	1.95	[1.73-2.22]	0.97
ΔY_z^{x}	4.47	6.56	[6.06-7.21]	0.94
ΔY_m^{x}	4.08	3.54	[3.09-4.17]	0.83

exchange rates both appreciate, which lowers the inflation rate of imported goods and services. In conjunction with the slowdown in economic activity, this causes a decrease in CPI inflation. Import volumes also contract following a positive monetary policy shock, as the effects of higher interest rates on domestic demand overwhelm the substitution effects associated with the stronger exchange rate. The response of export volumes, however, is unexpected; they increase on impact, before decreasing below their baseline level after 10 quarters. The initial increase in exports, which is common to both resource and non-resource exports, is due to lower domestic wages and cheaper capital, both of which reduce firms' costs.

In response to tighter monetary policy, output contracts in the non-tradeable and non-resource tradeable sectors, reflecting the sensitivity of these sectors to domestic demand conditions. In contrast, the decrease in resource output is delayed and reflects a persistent contraction in investment, which lowers this sector's productive capacity. Inflation decreases in both the traded and non-traded sectors. However, the fall in tradeables inflation is larger, due to the fact that prices are estimated to be more flexible in this sector. Investment contracts by similar amounts in all of the domestic production sectors.

Several other Australian macroeconomic models have examined the aggregate impacts of monetary policy shocks and it is informative to compare their estimates against ours. The response of economic activity to monetary policy shocks is larger in our model than in the the DSGE models of Buncic and Melecky (2008) and Jääskelä and Nimark (2011) and the structural VAR model of Dungey and Pagan (2009). Like Jääskelä and Nimark, our expenditure responses display a hump shape, with the peak contraction in activity occurring after 1 year. The response of inflation in our model is smaller than in Jääskelä and Nimark, although it appears to be in line with other studies. Like us, Jääskelä and Nimark report a fall in imports in response to a monetary policy tightening. However, unlike us, they report an initial decrease in export volumes.[12]

(ii) Risk Premium Shocks

We turn next to the effects of a shock to the risk premium term in the uncovered interest rate parity condition, shown in Figures 4 and 5. Technically, this shock alters the price at which domestic residents can sell foreign-currency-denominated bonds to foreigners, thus acting to change the risk premium attached to these bonds. In practice, this shock causes a change in the

[12] In Dungey and Pagan (2009), the contraction in GNE is larger than the contraction in GDP, implying (as in our model) that net exports make a positive contribution to GDP growth.

FIGURE 2
Impulse Responses to a Monetary Policy Shock: Aggregate Variables

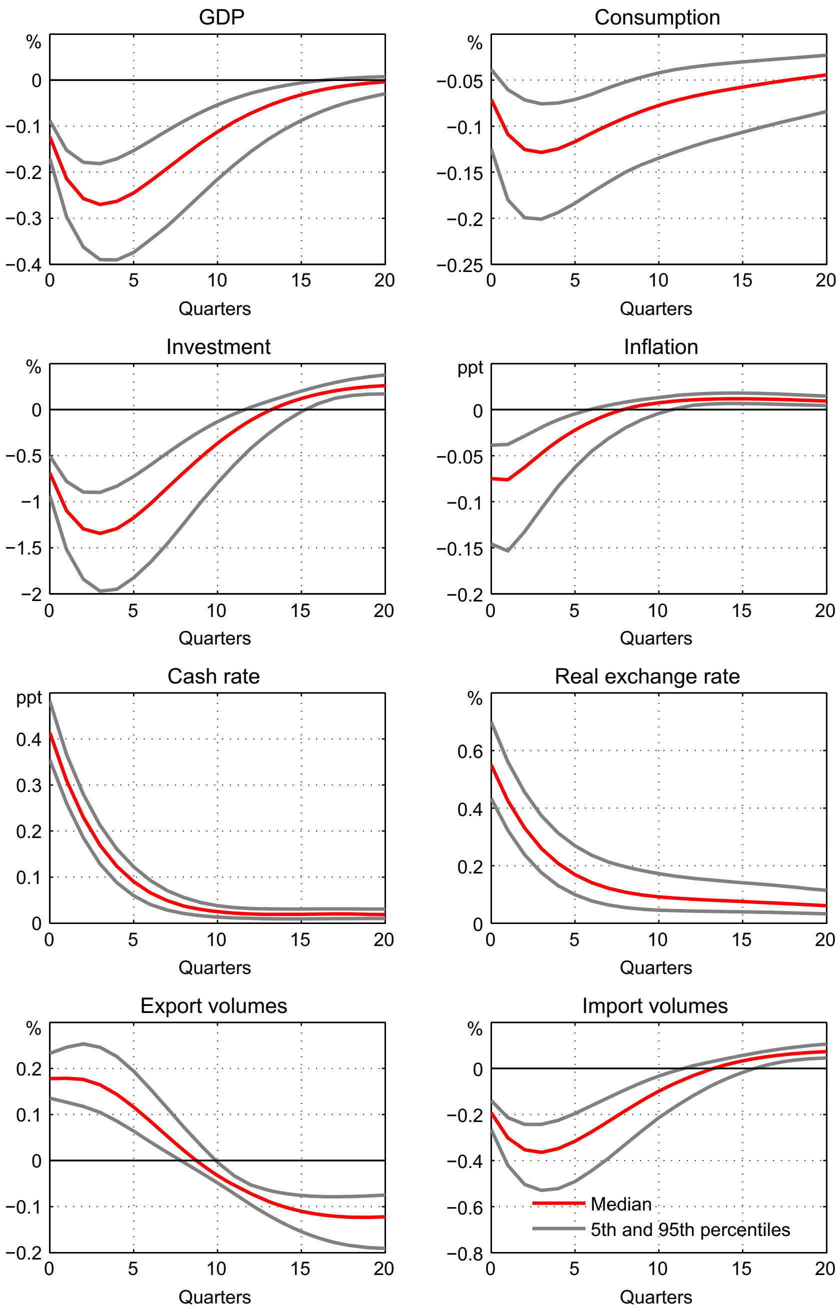
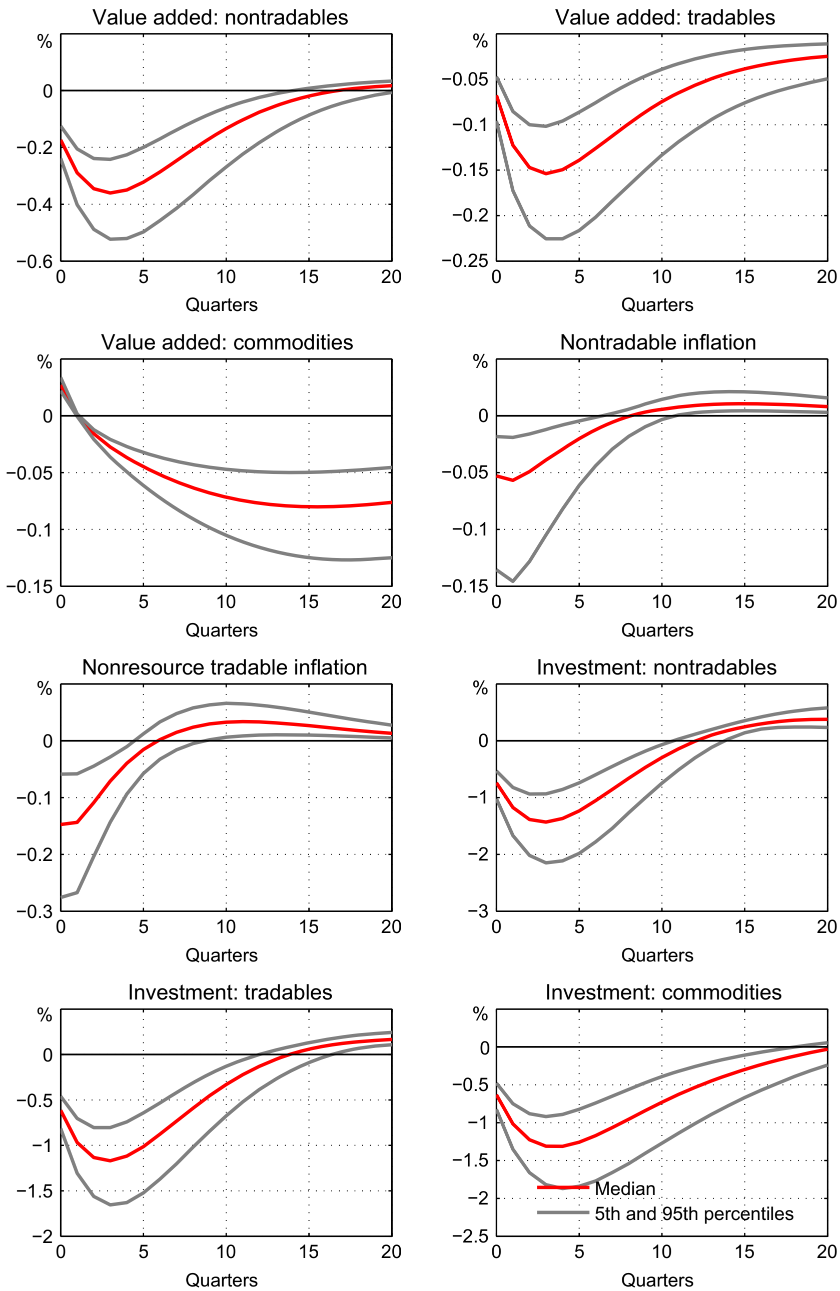


FIGURE 3
Impulse Responses to a Monetary Policy Shock: Selected Sectoral Variables



nominal 'exchange rate' that is unrelated to domestic or overseas economic conditions. In this sense it is similar to a pure exchange rate' shock. The graphs show the effect of a one-standard-deviation negative shock, which appreciates the real exchange rate by around 3.5 per cent on impact. The appreciation of the nominal exchange rate lowers the price of overseas goods relative to domestically produced goods. This leads households and firms to substitute away from domestic goods towards imports. As a consequence, export volumes decrease and import volumes increase. Aggregate output contracts by around 0.1 per cent over the first two quarters, before returning to its steady state over the subsequent 2 years.

Despite the contraction in economic activity, the appreciation of the exchange rate expands domestic demand. Consumption and investment both increase in a hump-shaped pattern, with a peak after 6–8 quarters. The expansion in demand reflects two factors. First, the appreciation raises the purchasing power of domestic residents; for a given level of domestic production, they can now afford to consume more imports. Second, monetary policy responds to the shock by lowering the cash rate. Lower interest rates have a positive impact on domestic demand. The decrease in interest rates is partly due to the contraction in real economic activity. It also reflects the deflationary impacts of the exchange rate appreciation, which lowers annualised inflation by 0.1 per cent on impact. The decrease in inflation is largely due to a fall in the rate of imported and domestically produced tradeable inflation. In contrast, the decrease in non-tradeable inflation is modest.

The contractionary effect of the exchange rate appreciation is concentrated in the tradeable parts of the economy; output in the resource and non-resource tradeable sectors declines. In contrast, the decline in non-tradeable production is much smaller, and turns positive after 4 quarters, reflecting stronger domestic demand.

The dynamics of investment in the domestic production sectors differs from that of output. Although production in the non-tradeable and non-resource tradeable sector contracts, investment in those sectors is estimated to increase following an exchange rate shock. This is because the decrease in the price of investment goods induces firms in this sector to replace labour with capital in production. Investment in the resource sector also increases, albeit with a lag.

Using a structural VAR model, Manalo *et al.* (2015) find quantitatively similar results to us. At a sectoral level, they conclude that output in trade-exposed industries, including mining, manufacturing and other business services, experiences the largest contractions in activity following an exchange rate appreciation.[13] In contrast, output in the construction and goods distribution industries, which have relatively less trade exposure, initially expands after an exchange rate appreciation. These results are broadly consistent with our findings.

(iii) Resource Price Shocks

Our third set of impulse responses shows the dynamic effects of a positive innovation to resource prices, illustrated in Figures 6 and 7. The graphs show the responses to a one-standard-deviation shock, which increases foreign currency resource prices by 5.7 per cent on impact.

Higher resource prices raise domestic income, causing a sustained expansion in domestic demand. Investment follows a hump-shaped profile, peaking after 6 quarters before returning slowly to its steady state. The peak in consumption takes longer, and is not reached even after 5 years. This reflects habits in the household's utility function (which restricts the initial increase in consumption) as well as the household's desire to smooth consumption across time in response to a temporary change in income.

The increase in resource prices causes a 0.9 per cent appreciation of the real exchange rate. The real exchange rate remains elevated for a prolonged period; after 5 years it remains 0.6 per cent above its steady-state value. Despite the appreciation, export volumes increase. This is entirely due to an expansion in resource exports, although they return to their steady-state level after 6 years. The expansion in domestic demand and real exchange rate appreciation lead to a persistent increase in import volumes.

In the model, a temporary increase in resource prices has almost no effect on CPI inflation, although the error bands around this response are wide. The aggregate responses conceal sizeable changes in relative prices, however. To expand production, resource firms demand more labour, which increases wages and costs throughout the economy. In conjunction with the expansion in

[13] Although business services industries typically have little direct trade exposure, they have a relatively high degree of indirect exposure through sales to firms in the tradeable parts of the economy.

Figure 4

Impulse Responses to a Risk Premium Shock: Aggregate Variables

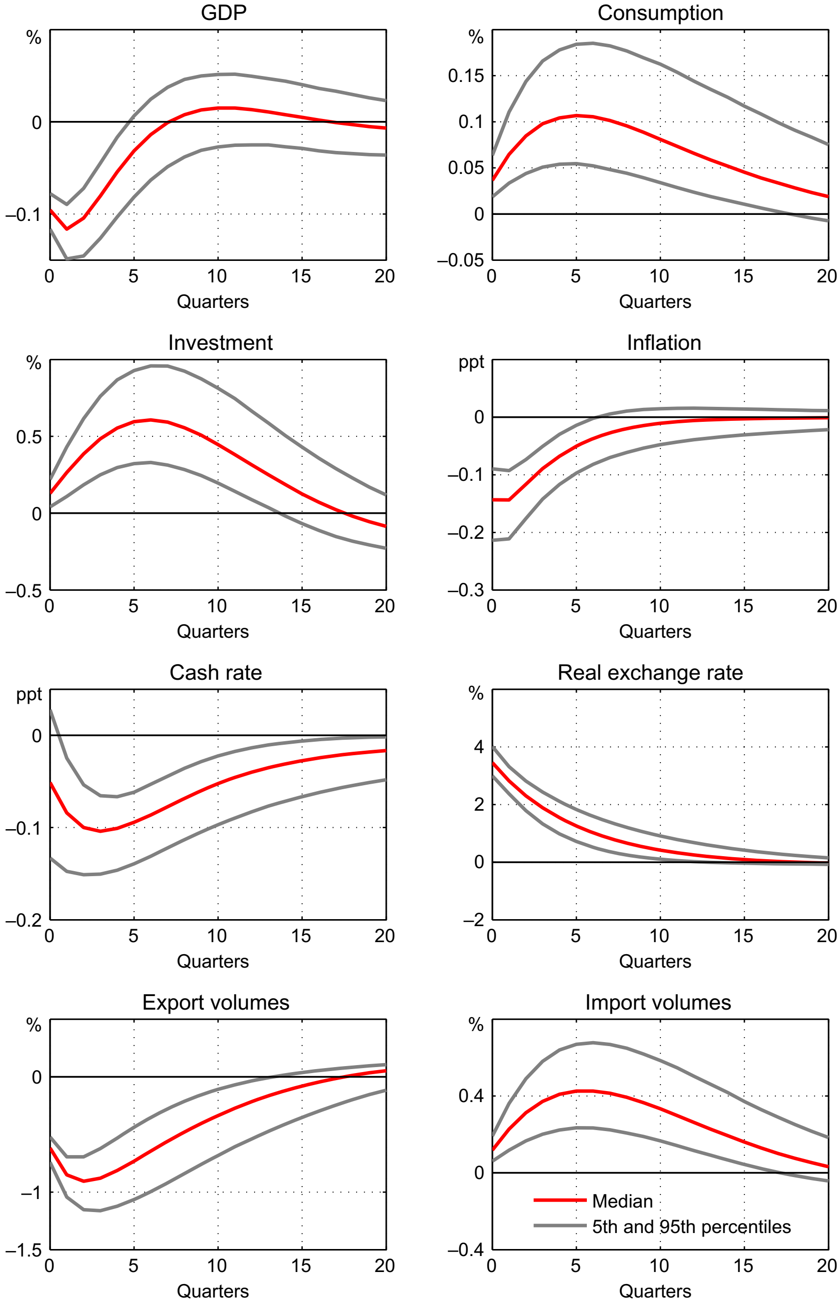


Figure 5
Impulse Responses to a Risk Premium Shock: Selected Sectoral Variables

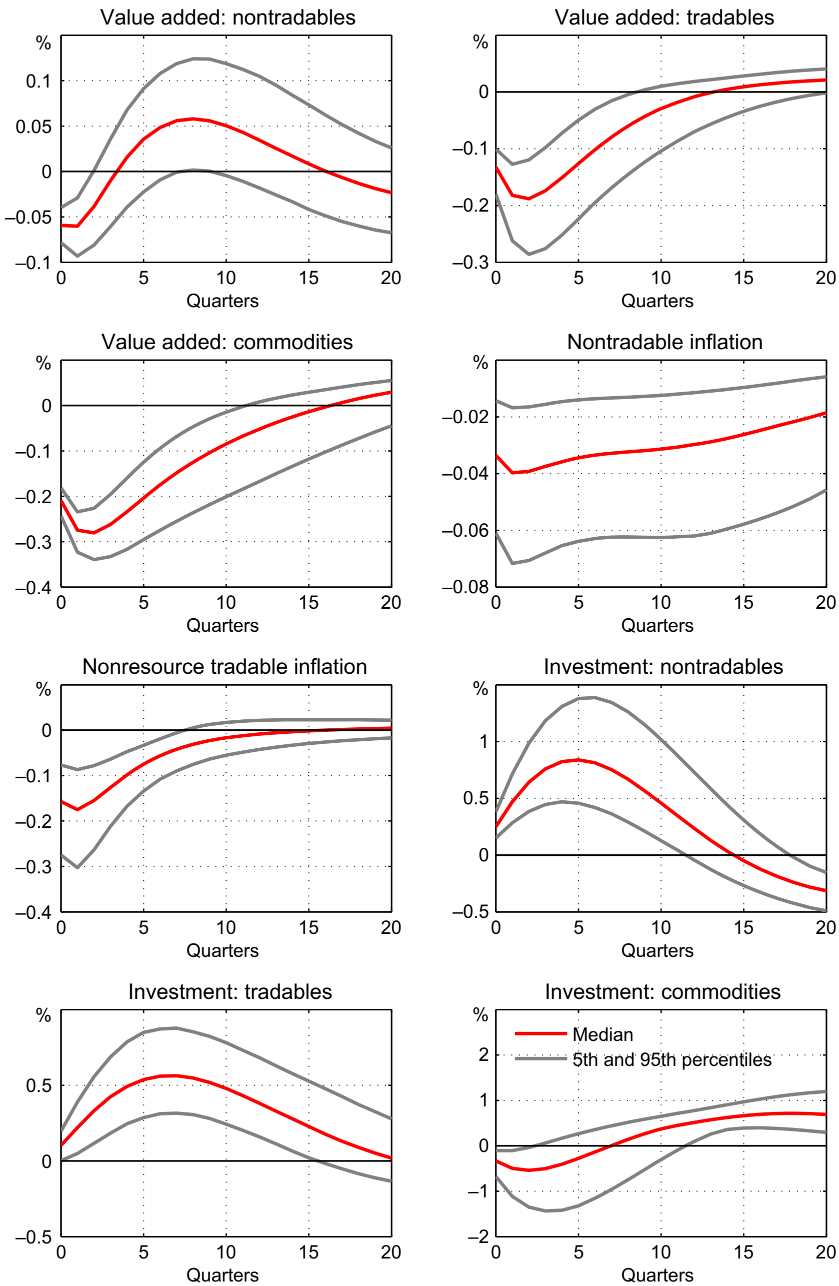


FIGURE 6
Impulse Responses to a Resource Price Shock: Aggregate Variables

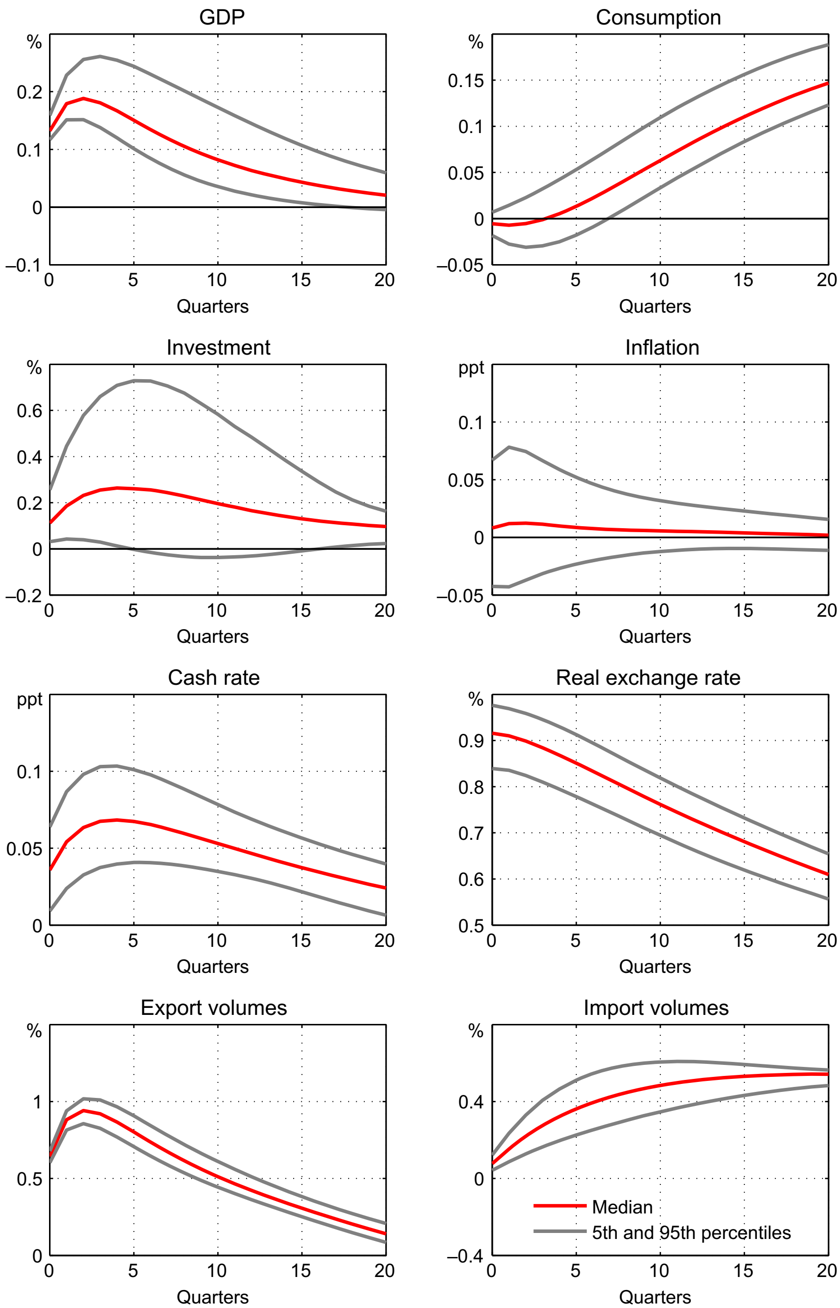
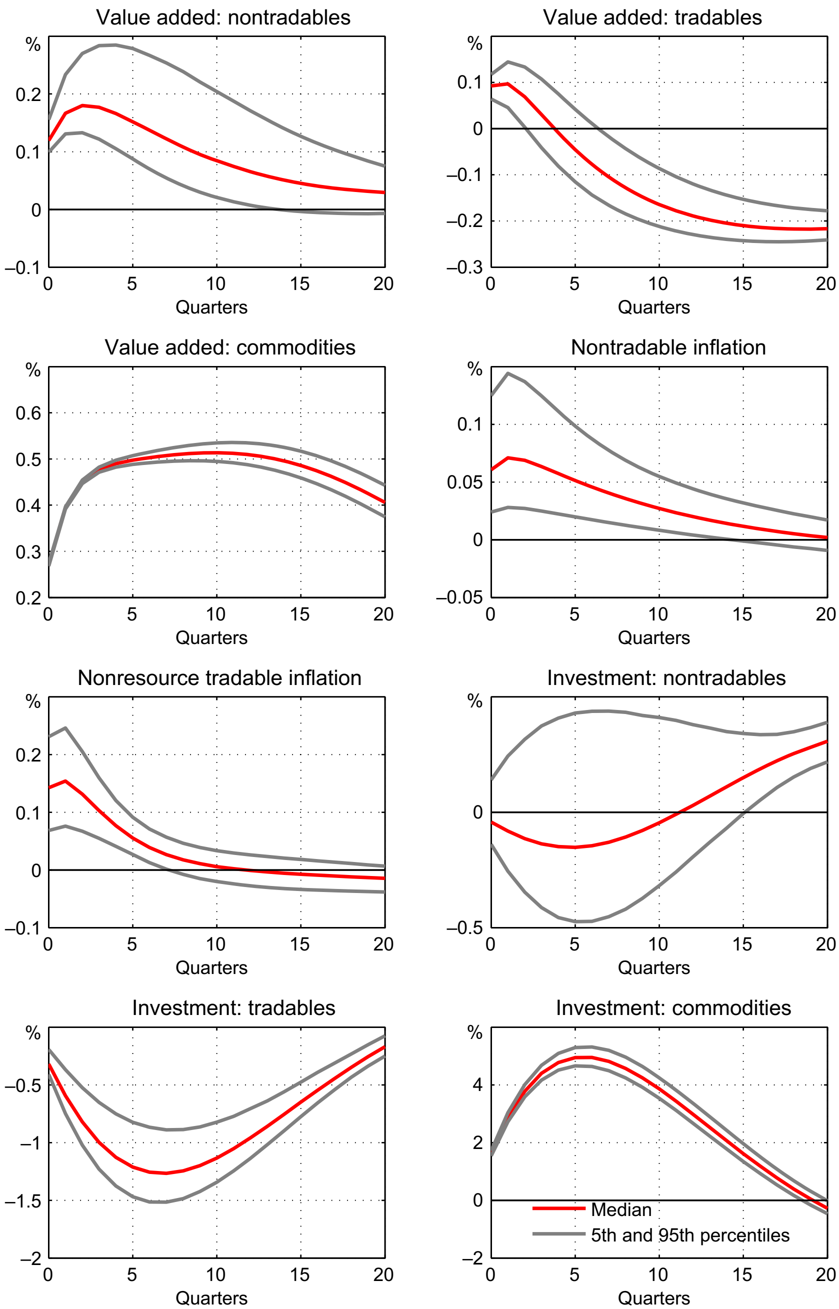


FIGURE 7
Impulse Responses to a Resource Price Shock: Selected Sectoral Variables



domestic demand, this leads to higher inflation in the non-tradeable and non-resource tradeable sectors. But the increase in domestic inflation is offset by the exchange rate appreciation, which lowers the inflation rate of imported items. Jääskelä and Smith (2013) and Downes *et al.* (2014) find that an increase in resource prices may have a small (possibly negative, at least in the short run) effect on Australian CPI inflation.

A rise in resource prices has an uneven impact on the various sectors of the economy. As one might expect, the resource sector experiences a prolonged expansion. Activity in the non-tradeable sector also increases, reflecting the pattern of domestic demand in the economy. In contrast, after a brief increase, the non-resource tradeable sector contracts. This is due largely to the appreciation of the exchange rate and an increase in firm costs, which raise the price of non-resource tradeable goods relative to goods produced overseas and lower demand for these goods in overseas markets. Consistent with the patterns of production, the increase in investment is concentrated in the resource sector; investment in the non-tradeable sector picks up 3 years after the increase in resource prices, while investment in the non-resource tradeable sector experiences a prolonged slump.

(iv) Variance Decompositions

We now examine which shocks the model suggests are the most important for the evolution of Australian economic variables.

Table 6 decomposes the unconditional variance of the observable variables into the contribution of the various structural shocks in the model. For clarity, we group the shocks into six categories. The first contains productivity shocks: the unit root (ε_μ), investment (ε_Υ) and sector-specific (ε_n, ε_m, ε_z) shocks. The second contains demand shocks: the consumption preference shock (ε_c) and the government expenditure shock (ε_g). The third contains supply shocks: the mark-up shocks in the non-traded (ε_{π_n}), non-resource traded (ε_{π_m}, $\varepsilon_{\pi_m^*}$) and import (ε_{π_f}) sectors. The fourth contains shocks to resource prices (ε_{p_z}). The fifth contains domestic monetary policy shocks (ε_r). The sixth contains shocks originating abroad: the risk premium shock (ε_ψ) and the shocks to foreign output (ε_{y^*}), inflation (ε_{π^*}) and interest rates (ε_{r^*}).

The model's productivity shocks explain a large proportion of the variation in the growth rates of Australian domestic demand and output, although demand shocks also account for around a quarter of output growth volatility. This is largely due by the investment-specific technology shock, which accounts for a large proportion of the variance in investment. The contribution of the other productivity shocks is much smaller. World shocks explain around 7 per cent of the variance of export growth, but relatively little of the other demand-side variables.

Mark-up shocks are found to explain a large proportion of the variance of CPI inflation, although productivity and world shocks together account for around 20 per cent of the variance of this variable. On the production side, domestic demand shocks are estimated to explain around a third of the variance of output growth in the non-tradeable sector, but relatively little of the

TABLE 6
Unconditional Variance Decomposition

	Shock					
Variable	Productivity	Demand	Supply	Commodity	Monetary	World
ΔY	56.2	24.9	10.4	2.6	3.0	1.9
ΔC	0.7	94.0	1.1	0.5	1.7	1.6
ΔI	91.0	0.6	1.8	0.1	5.1	1.1
ΔX	58.0	1.1	27.6	5.7	0.4	7.1
π	10.6	0.2	76.0	0.6	1.4	11.2
r	13.4	6.1	14.4	7.2	41.8	17.0
ΔY_z^{va}	96.0	0.0	0.0	2.4	0.0	1.3
ΔY_N^{va}	57.5	32.9	2.3	1.6	4.3	0.7
ΔY_M^{va}	47.4	2.6	46.6	0.5	0.2	2.5
ΔS	0.8	0.1	0.2	5.0	2.1	91.8

variation in tradeable output. The model's productivity shocks explain much of the variation in all three production sectors. Variation in the nominal exchange rate is estimated to largely be driven by world shocks (in particular, risk premium shocks).

The model suggests that resource price shocks explain relatively little of the variance of Australian macroeconomic variables, although they do explain 6 per cent of the variance of export growth, 7 per cent of the variance of the cash rate and 5 per cent of the variance of the nominal exchange rate.

World shocks are estimated to make only a small contribution to the variance of Australian macroeconomic variables other than the exchange rate and, to a lesser extent, interest rates and inflation. The modest contribution of foreign disturbances is a common finding in the open economy DSGE literature (Justiniano & Preston, 2010a). In contrast, VAR models of the Australian economy typically attribute a larger share of macroeconomic volatility to foreign disturbances (e.g. Lawson & Rees, 2008; Dungey & Pagan, 2009).

V The Model in Action: Scenario Analysis

Having discussed the technical aspects of the model in detail, in the remainder of this paper we put the model to work. The previous section described the model's dynamics using impulse response analysis. This consisted of imposing an innovation on one of the model's structural shocks for a single period and examining the responses of the model's variables to this innovation. While this type of analysis is useful for exploring the mechanisms in the model, it is not reflective of how we typically use the model internally at the RBA. For this type of purpose we typically present more complex scenarios in which we explore the model's behaviour conditional on the path of one or more variables over an extended period. In this section we use the model to construct this type of scenario.

(i) Resource Prices and the Exchange Rate

An example of the type of question that the model can address is how the economy might respond if resource prices were to fall by 10 per cent and remain at that lower level for 3 years. In the previous section we showed that such a development will typically be accompanied by a depreciation of the nominal exchange rate. However, exchange rates are affected by many idiosyncratic factors, and there will be instances in which the exchange rate does not respond to a change in resource prices immediately. To account for this possibility, we might put together two variants of this scenario: one in which the exchange rate responds endogenously and one in which the exchange rate is held constant.

Assembling a scenario like the one described above involves a degree of judgement. For example, consider the construction of a constant exchange rate path. Many of the model's shocks affect the exchange rate. One could achieve a constant exchange rate path by applying a sequence of monetary policy shocks, a sequence of consumption preference shocks, a sequence of risk premium shocks, or combinations of those (or other) shocks. The choice matters because the results of the scenario will vary depending on which combination of shocks one uses. In practice, for scenarios like this, we try to use the shocks that are closely related to the variables of interest. For example, in a scenario in which we constrain the path of resource prices and the exchange rate it seems sensible to apply a sequence of resource price and risk premium shocks.[14]

Another relevant consideration is whether agents anticipate the path of resource prices and the exchange rate. Most of the model's shocks have only transitory effects on real variables and relative prices in the economy. So, following a shock that lowers resource prices by 10 per cent, agents will expect resource prices gradually to revert back to their original level. This expectation is inconsistent with the assumption in the scenario that resource prices remain 10 per cent below their initial level for a number of years. In some scenarios, accounting for expectations can have meaningful consequences for model predictions. For example, the response of mining firms to lower resource prices is likely to depend upon whether firms expect resource prices to recover in the future or to remain low for a long period of time.

Our baseline model features only unanticipated shocks. In this set-up, the only way to achieve a prolonged path of lower resource prices in a scenario is to apply a new unanticipated shock each quarter to keep resource prices at their

[14] In most instances, if the number of structural shocks equals the number of endogenous variables whose paths one wishes to specify then there is a unique mapping between the sequence of shocks and the desired paths of the endogenous variables.

desired level. However, it is straightforward to alter the model's shock structure to allow agents to anticipate the future path of resource prices. To do this, we modify Equation (38) as follows:

$$\hat{p}^*_{z,t} = (1 - \rho_{p^*_x})\hat{p}^*_{z,t-1} + \rho_{zy,t}\varepsilon_{y^*,t} + u^1_{p^*_z,t}, \qquad (41)$$

where, for any $j \geq 1$,

$$u^j_{p^*_z,t} = u^{j+1}_{p^*_z,t-1} + \varepsilon^j_{p^*_z,t}.$$

A positive innovation to $\varepsilon^j_{p^*_z,t}$ increases foreign currency resource prices j periods in the future. One can then use the methods documented in del Negro *et al.* (2013) to calculate the sequence of shocks required to generate an anticipated path for a given endogenous variable.

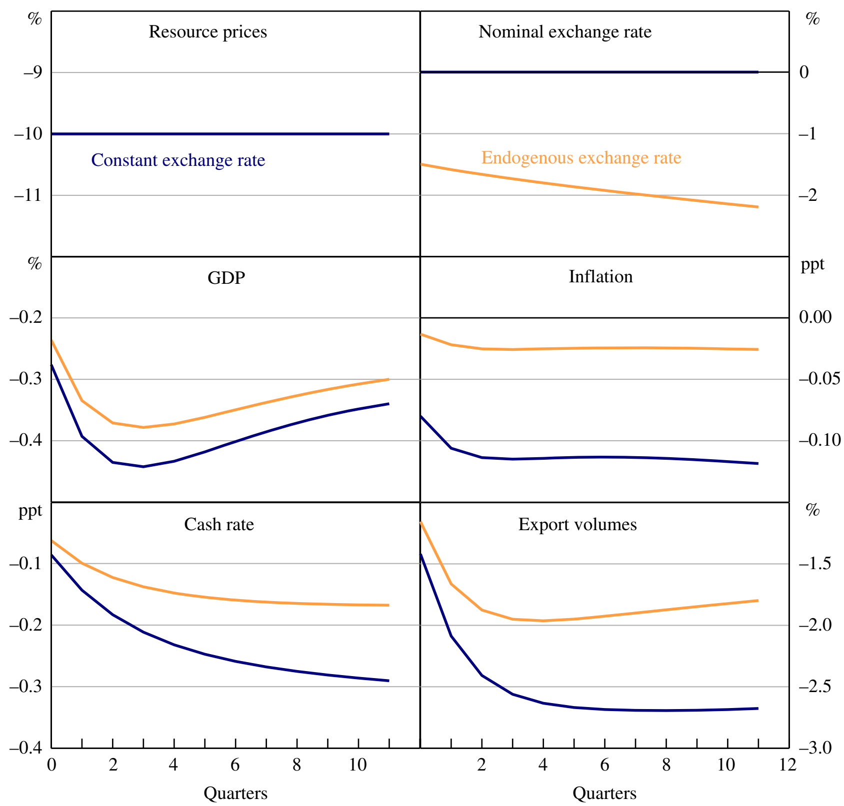
(ii) Unanticipated Shocks and Alternative Exchange Rate Scenarios

The first set of results, presented in Figure 8, shows the evolution of key macroeconomic variables for lower resource price scenarios with, and without, an endogenous exchange rate response. We construct these scenarios using a sequence of unanticipated shocks. In the next subsection we will discuss what happens when we allow agents to anticipate the path of resource prices correctly.

If allowed to respond endogenously, the nominal exchange rate initially depreciates by around 1.5 per cent. If resource prices remain low, it depreciates further in subsequent quarters, reaching around 2.5 per cent below its initial level after 3 years. A fall in resource prices is contractionary for the economy. However, an exchange rate depreciation reduces the extent of the contraction.

Figure 8

Resource Price Scenario



When the exchange rate depreciates, the level of output is around 0.1 per cent higher (relative to baseline) than it is in the scenario in which the exchange rate does not depreciate. This largely reflects a different profile for export volumes, which are 0.5 per cent lower after 1 year if the exchange rate does not depreciate than if the exchange rate does depreciate.

The effect of lower resource prices on inflation is estimated to be small. However, inflation falls by more without an exchange rate depreciation because the deflationary effects on non-tradeable inflation are no longer offset by an increase in tradeable inflation. As a consequence, the cash rate also falls by more when the exchange rate does not depreciate, although not by enough to fully offset the additional decrease in output and inflation.

(iii) Anticipated versus Unanticipated Resource Price Paths

Figure 9 compares the evolution of some key macroeconomic variables for the lower resource price scenario when agents in the model realise that resource prices will be lower for 12 quarters against a scenario in which agents do not anticipate the persistence of the resource price decline. To focus attention on the importance of resource price anticipation, we only show scenarios in which the exchange rate responds endogenously.

As one might expect, the nominal exchange rate initially depreciates by more when agents correctly anticipate the persistence of the decline in resource prices than when agents expect a timely recovery in prices. As a result, inflation also increases by slightly more in the anticipated scenario and the cash rate does not decline by as much.

FIGURE 9
Resource Price Scenario

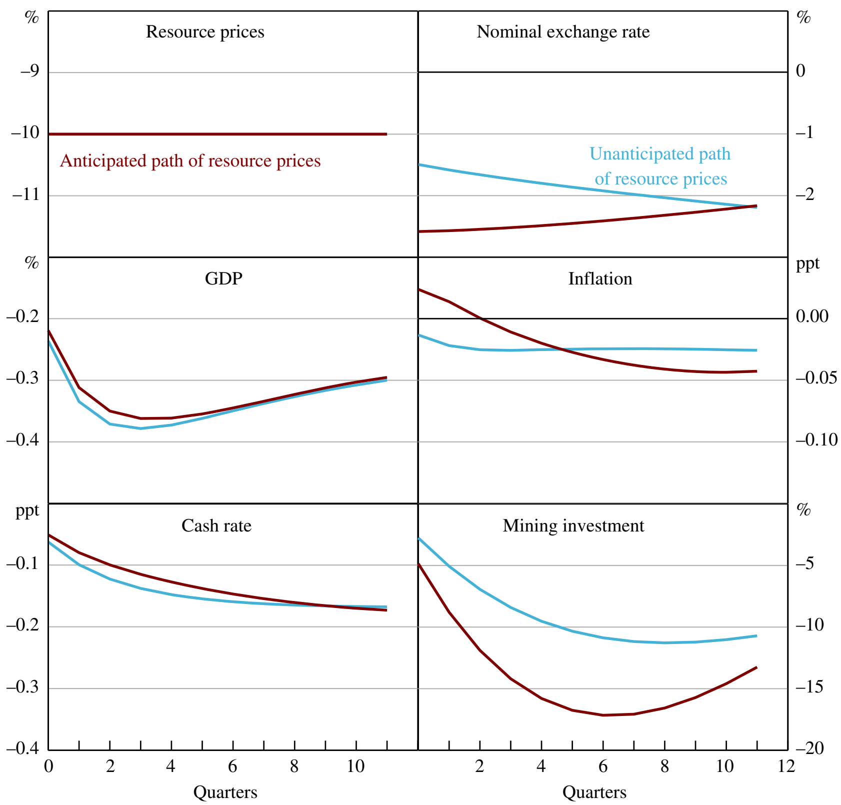
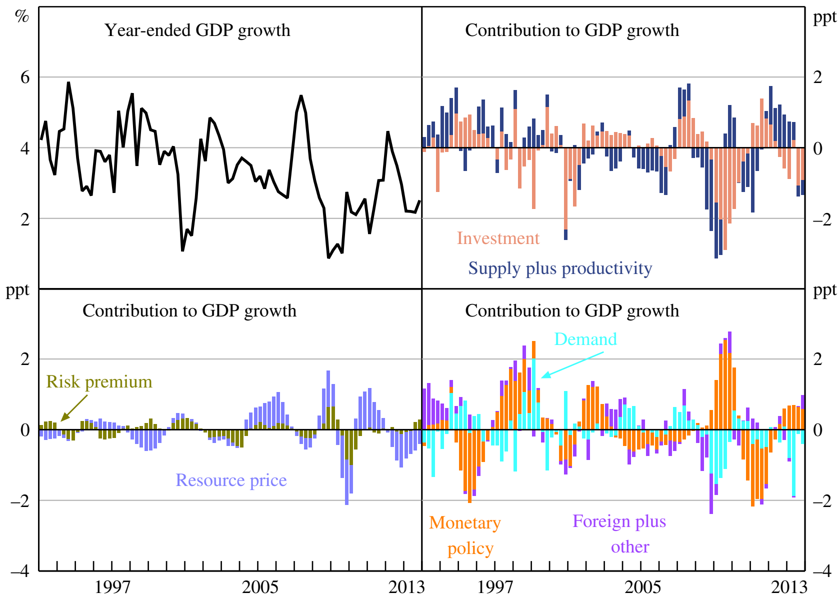


FIGURE 10
Historical Decompositions: GDP Growth



An important difference between the two scenarios is the behaviour of mining firms. Mining investment falls by almost twice as much when agents realise the decline in resource prices will persist than when the decline is expected to be temporary. Despite this, the level of GDP is marginally higher in this scenario. This reflects the additional depreciation of the exchange rate, which ensures that increased exports, and the substitution of domestic consumption and investment from imported to domestically produced goods, more than offset reduced expenditure by mining firms.

VI What Has Driven the Australian Business Cycle?

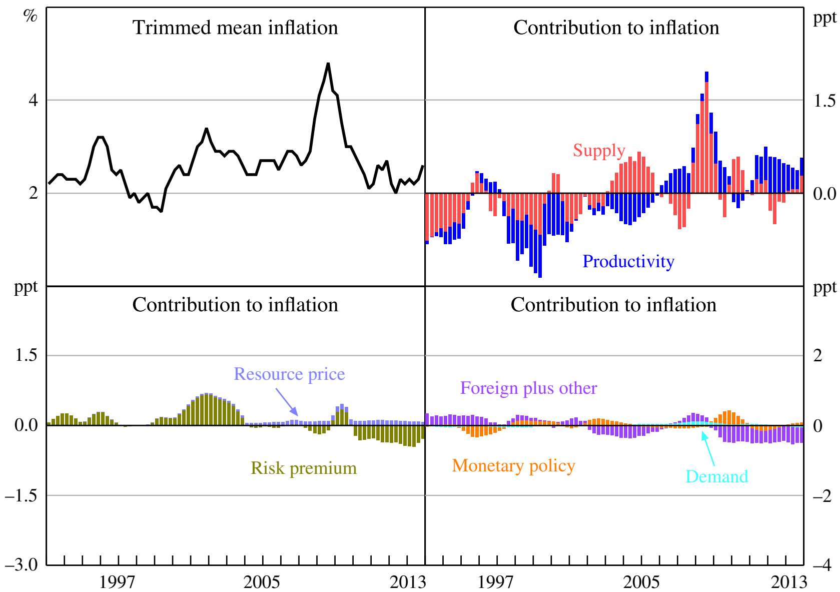
In this section, we explore the sources of Australian business cycles over recent decades. To do this, we construct a historical decomposition of Australian GDP growth and inflation over our sample, which broadly coincides with the inflation-targeting era in Australia. The idea behind a historical decomposition is as follows. The model attributes all deviations of growth and inflation (and other variables) from their steady-state values to the model's structural shocks. A historical decomposition recovers these shocks and shows the contribution of each to the evolution of GDP growth and inflation.

Figures 10 and 11 present the results of this exercise.[15] As in the variance decomposition section (Section IV), we group similar structural shocks into broader categories to make the results more interpretable. In this exercise we separate out the risk premium shock (ϵ_{ψ}) from the other world shocks. For GDP we also separate the investment-specific productivity shock (ϵ_{Υ}) from the other productivity shocks.

Over our estimation sample the Australian economy has experienced two sustained expansions (in the mid to late 1990s and mid 2000s) and three mild slowdowns (in 1995, the early 2000s and during the global financial crisis (GFC)). The period since the GFC is difficult to categorise. The economy grew strongly in the immediate aftermath of the GFC. But, on average, it has grown more slowly than in the preceding two decades.

[15] In both figures the contributions sum to the deviation of year-ended GDP growth (Fig. 10) and inflation (Fig. 11) from its sample mean.

FIGURE 11
Historical Decompositions: Inflation



The model identifies three main causes of the expansion in the 1990s: first, a sequence of strong productivity shocks that was spread fairly evenly across the decade; second, positive investment shocks in the period shortly after the 1990s recession; and third, positive demand shocks in the early and again in the late 1990s. For the most part, foreign shocks were also expansionary during this period. Risk premium and resource price shocks were generally small and often offsetting.

The model attributes the expansion of the mid 2000s largely to positive investment and resource price shocks (although foreign and demand shocks also contributed at various times). The positive investment shocks in the early years of the decade were concentrated in the non-mining sectors of the economy. The pick-up in mining investment (which was largely an endogenous response to higher resource prices) came later in the decade. In contrast, the model suggests that productivity shocks reduced the pace of GDP growth during this period, consistent with most accounts of this era (Eslake, 2011; Kearns & Lowe, 2011).

The model attributes the slowdown in 1995 largely to monetary policy shocks. The RBA increased interest rates by 275 basis points between August and December 1994 in order to limit an anticipated pick-up in inflation.[16] From the perspective of the model, which is estimated over the entire inflation-targeting era, the size of the monetary tightening appears unusually large. Hence, it labels at least some of these interest rate increases as policy 'shocks' rather than endogenous responses to strong economic conditions.

In contrast, the model attributes the early 2000s slowdown largely to negative investment shocks, particularly in the non-traded sector. This result may indicate a degree of model misspecification as it is likely to be capturing the effect of the introduction of the goods and services tax in July 2000. This induced a large amount of building investment activity to be brought forward in the first half of 2000 and consequent reduction in activity in the second half of that year. Because the model features only lump-sum taxation, it does not account for the introduction of this tax explicitly and instead assigns its effects to the model's investment shocks.

[16] For a description of monetary policy during this episode, see Debelle (1999) and Stevens (1999).

According to the model, the slowdown associated with the GFC had several causes. Early on, the economy experienced a sequence of negative foreign, resource price and productivity shocks. These were followed a few quarters later by negative demand and investment shocks. This is consistent with the idea that bad news from abroad triggered a loss of domestic confidence which, in the model, manifests itself in demand and investment shocks. During the crisis, the model suggests that the unusually large reduction in nominal interest rates was instrumental in preventing a more severe downturn.

In the period immediately following the GFC, rising resource prices made a substantial contribution to Australian GDP growth. Investment grew by even more than would be expected from rising resource prices alone and so the model's investment shocks also made a positive contribution. Also, the model's mark-up and productivity shocks, after several years of subtracting from GDP growth, contributed to higher growth once again. More recently, however, falling resource prices have subtracted from GDP growth. This has been followed by a period of unexpectedly weak investment growth and some large negative demand shocks. Although this latter period also coincided with an exchange rate depreciation, the models suggests that this can largely be explained by the other structural shocks affecting the Australian economy.

Underlying inflation has remained within the RBA's 2–3 per cent target band for much of the inflation-targeting era. Exceptions include a few quarters in 1995–6 and 2001–2, when it exceeded 3 per cent by a small amount, an episode in 2007–9, when it reached almost 5 per cent, and a period in 1997–9, when it fell below 2 per cent.

The model attributes the low inflation outcomes of the 1990s largely to a sequence of productivity and mark-up shocks.[17] These forces were particularly strong in the latter half of the decade and, according to the model, explain the unusually low inflation outcomes in 1997–9.

The deflationary impact of productivity shocks is consistent with the strong productivity outcomes recorded during this era. The contribution of lower mark-ups may reflect the effect of earlier product market reforms; see Kent and Simon (2007) for a discussion of the timing of Australian product market reforms. These reforms may have intensified competition in many industries and reduced firm mark-ups, as discussed in Forsyth (2000).[18]

The model attributes the pick-up in inflation in 1995–6 to a number of factors. There was a temporary reduction in the deflationary effects of the model's productivity and supply shocks. This coincided with a modest exchange rate depreciation and a positive contribution from the model's foreign shocks. In contrast, the model suggests that the small rise in inflation in 2001–2 was almost entirely due to the lagged effects of the exchange rate depreciation around the turn of the century, which was larger than the model can explain by fundamentals.[19]

The largest deviation of inflation from the RBA's target occurred in 2007–9. According to the model, this largely reflected a sequence of large mark-up shocks. There is some out-of-model evidence to support this finding. For example, the Australian Bureau of Statistics measure of retail trade gross margins, which captures both changes in net profit and cost of doing business, increased strongly during this period. However, in the absence of a more compelling out-of-model story for why mark-ups should have increased in this episode, we find this explanation for the acceleration in inflation at this time incomplete. It may be that the model is attributing deviations in inflation that it cannot otherwise explain to mark-up shocks.

Since the GFC, inflation has remained within the RBA's target. These relatively stable inflation outcomes conceal a number of strongly countervailing influences on inflation. The model suggests that the appreciation of the exchange rate associated with the investment phase of the mining boom exerted a strong deflationary effect on the economy. Global economic influences more generally have also lowered inflation during this period. But these deflationary forces were offset by weak productivity growth outcomes, which raised inflation. Although movements in Australian inflation are often attributed to developments in resource prices, the model indicates

[17] Although the shocks are not autocorrelated they may have persistent effects due to price rigidities.

[18] In theory, these reforms should lead to permanent changes in mark-ups and so should not be captured in our model, which focuses on cyclical variations. However, they may induce temporary transitional dynamics as the economy moves from a less competitive equilibrium to a more competitive equilibrium.

[19] This apparent departure of the Australian dollar's value from underlying fundamentals was noted by the RBA at the time, for instance in Macfarlane (2000).

that these changes have had only a modest effect on inflation over recent decades.

On the basis of these results, we believe that the model provides a plausible explanation for the behaviour of Australian GDP growth and inflation over recent decades. While many of the factors contributing to the outcomes for these variables have previously been identified elsewhere – for instance, strong productivity growth in the 1990s – the model adds value by quantifying the importance of these factors. It also helps us to separate out the contribution of shocks such as risk premium and monetary policy shocks to economic outcomes from the endogenous response of variables such as exchange rates and interest rates to economic conditions.

VII Conclusion

This paper has outlined an estimated DSGE model of the Australian economy currently in use at the Reserve Bank of Australia. The model differs from other Australian DSGE models through the inclusion of multiple sectors, including non-tradeable, resource and non-resource tradeable sectors. We estimate the model using Bayesian methods over the inflation-targeting era. We then explore the consequences of shocks to monetary policy, exchange rates and resource prices and use the model to decompose the sources of Australian business cycle fluctuations over the past two decades.

Relative to previous models of the Australian economy, the multi-sector structure of our model has several benefits. Most importantly, it gives us a deeper understanding of how changes in interest rates, exchange rates and other macroeconomic variables affect the broader economy. Such an understanding is particularly important for small open economies, such as Australia, for which many shocks (e.g. resource price shocks) are sectoral in nature. Our estimation also highlighted important differences in the characteristics of the various sectors of the economy, such as the slope of their Phillips curves. An awareness of these sectoral differences can help us to better interpret the responses of aggregate variables to macroeconomic shocks.

The model can be used to provide scenario and sensitivity analysis. It also provides a crosscheck on forecasts produced by reduced-form econometric techniques and judgement. Like most macroeconomic models in use at policy institutions, this model is likely to evolve over time. Given the important role of dwelling investment in the transmission of monetary policy, the addition of housing as a non-durable consumption good is high on our research agenda. Another possible area for development is the inclusion of a more sophisticated labour market that features involuntary unemployment and a meaningful treatment of labour force participation. Incorporating a measure of interest rate spreads would also allow us to answer some interesting questions relating to financial markets. Finally, although the model has been designed primarily for scenario analysis, it may be interesting to examine its out-of-sample forecasting performance.

Appendix A
The Log-linearised Model

This appendix provides the log-linearised model. Hat symbols denote log deviations from steady-state values (i.e. $\hat{X}_t = \ln X_t - \ln X$). Variables without a time subscript refer to steady-state values.

The equilibrium condition for household consumption is

$$\begin{aligned}(\mu - h)(\mu - \beta b)\hat{\lambda}_t = {} & (\mu - h)\left(\mu\hat{\xi}_{c,t} - h\beta E_t\{\hat{\xi}_{c,t+1}\}\right) \\ & - \left(\mu^2 + \beta h^2\right)\hat{c}_t + \mu b(\hat{c}_{t-1} + \beta E_t\{\hat{c}_{t+1}\} \\ & - \hat{\mu}_t + \beta E_t\{\hat{\mu}_{t+1}\}),\end{aligned} \tag{42}$$

where $\hat{\lambda}$ is the Lagrangian multiplier associated with the household's consumption choice.

The household labour supply decision in each sector is

$$\hat{w}_{j,t} = (\eta - \sigma)\hat{h}_t + \sigma\hat{h}_{j,t} - \hat{\lambda}_t, \tag{43}$$

for $j \in \{n,m,z\}$.

The household's choice of investment in each sector is

$$\begin{aligned}\hat{\lambda}^k_{j,t} = {} & \Phi\mu^2\left[(1+\beta)\hat{i}_{j,t} - \hat{i}_{j,t-1} - \beta E_t\{\hat{i}_{j,t+1}\}\right. \\ & \left. - \beta E_t\{\hat{\mu}_{t+1}\} + \hat{\mu}_t\right] + \hat{\lambda}_t - \hat{\Upsilon}_t\end{aligned} \tag{44}$$

for $j \in \{n,m,z\}$, where $\lambda^k_{j,t}$ is the shadow price of installed capital.

The production function for each sector is

$$\hat{y}_{j,t} = \hat{a}_{j,t} + \alpha_j\hat{h}_{j,t} + \gamma_j\left(\hat{k}_{j,t} - \hat{\mu}_t\right) + (1 - \alpha_j - \gamma_j)\hat{z}_{j,t}, \tag{45}$$

for $j \in \{n,m,z\}$.

The equilibrium condition for capital in each sector is

$$\hat{\lambda}^k_{j,t} = \frac{\mu - \beta(1-\delta)}{\mu}\left[E_t\{\hat{\lambda}_{t+1}\} + E_t\{\hat{r}_{j,t+1}\}\right] + \frac{\beta(1-\delta)}{\mu}E_t\{\hat{\lambda}^k_{j,t+1}\} - E_t\{\hat{\mu}_{t+1}\}, \tag{46}$$

for $j \in \{n,m,z\}$.

Capital in each sector accumulates according to the law of motion,

$$\hat{k}_{j,t+1} = \frac{1-\delta}{\mu}\left(\hat{k}_{j,t} - \hat{\mu}_t\right) + \frac{\mu - 1 + \delta}{\mu}\left(\hat{i}_{j,t} + \hat{\Upsilon}_t\right), \tag{47}$$

for $j \in \{n,m,z\}$.

The household's choice of domestic bond holdings is

$$\hat{r}_t = \hat{\lambda}_t - E_t\left(\hat{\lambda}_{t+1} - \hat{\pi}_{t+1} - \hat{\mu}_{t+1}\right). \tag{48}$$

The definition of the household's labour bundle is

$$\hat{h}_t = \left[\frac{H_n}{H}\right]^{1+\sigma}\hat{h}_{n,t} + \left[\frac{H_m}{H}\right]^{1+\sigma}\hat{h}_{m,t} + \left[\frac{H_z}{H}\right]^{1+\sigma}\hat{h}_{z,t}. \tag{49}$$

The Phillips curves for the non-tradeable and non-resource tradeable sectors are

$$\hat{\pi}_{j,t} = \frac{\kappa_j}{100(1+\chi\beta)}\widehat{mc}_{j,t} + \frac{\beta}{1+\chi\beta}E_t\{\hat{\pi}_{j,t+1}\} + \frac{\chi}{1+\chi\beta}\hat{\pi}_{j,t-1} + \varepsilon_{\pi_j,t}, \tag{50}$$

for $j \in \{n,m\}$, where $\kappa_j = 100(\theta^j - 1)/\tau^j_\pi$.

Marginal costs in the non-tradeable and non-resource tradeable sectors are given by

$$\widehat{mc}_{j,t} = \alpha_j\hat{w}_{j,t} + \gamma_j\hat{r}_{j,t} + \left[1 - \alpha_j - \gamma_j\right]\hat{p}_{z,t} - \hat{p}_{j,t} - \hat{a}_{j,t}, \tag{51}$$

for $j \in \{n,m\}$, where $\hat{p}_{j,t}$ refers to the deviation of the relative price of good j from its steady state, that is, $\hat{p}_{j,t} = \log[P_{j,t}/P_t] - \log[P_j/P]$.

The optimal choice of labour in the tradeable and non-resource tradeable sectors is

$$\hat{h}_{j,t} = \hat{k}_{j,t} + \hat{r}_{j,t} - \hat{w}_{j,t} - \hat{\mu}_t, \tag{52}$$

for $j \in \{n,m\}$.

The optimal choice of resource commodity inputs in the tradeable and non-resource tradeable sectors is

$$\hat{z}_{j,t} = \hat{k}_{j,t} + \hat{r}_{j,t} - \hat{p}_{z,t} - \hat{\mu}_t, \tag{53}$$

for $j \in \{n,m\}$.

The Phillips curve for the imported good retailer is

$$\hat{\pi}_{f,t} = \frac{\kappa_f}{100(1+\chi\beta)}\widehat{mc}_{f,t} + \frac{\beta}{1+\chi\beta}E_t\{\hat{\pi}_{f,t+1}\} + \frac{\chi}{1+\chi\beta}\hat{\pi}_{f,t-1} + \varepsilon_{\pi_f,t}, \tag{54}$$

where $\kappa_f = 100(\theta^f - 1)/\tau^f_\pi$.

Marginal costs for the imported good retailer are given by

$$\widehat{mc}_{f,t} = \hat{q}_t - \hat{p}_{f,t}. \tag{55}$$

The Phillips curve for the export good retailer is

$$\hat{\pi}_{m^*,t} = \frac{\kappa_{m^*}}{100(1+\chi\beta)}\left(\widehat{mc}_{m,t} + \hat{p}_{m^*,t} - \hat{p}_{m^*,t}\right) + \frac{\beta}{1+\chi\beta}E_t\{\hat{\pi}_{m^*,t+1}\} + \frac{\chi}{1+\chi\beta}\hat{\pi}_{m^*,t-1} + \varepsilon_{\pi_{m^*},t}. \tag{56}$$

The relative price of the non-resource tradeable good in the foreign economy is

$$\hat{p}_{m^*,t} = \hat{p}_{m^*,t-1} + \hat{\pi}^*_t + \Delta\hat{s}_t - \hat{\pi}_t. \tag{57}$$

The number of hours worked in the commodity sector is given by

$$\hat{h}_{z,t} = \hat{p}_{z,t} + \hat{y}_{z,t} - \hat{w}_{z,t}. \tag{58}$$

Capital used in the commodity sector is given by

$$\hat{k}_{z,t} = \hat{p}_{z,t} + \hat{y}_{z,t} - \hat{r}_{z,t} + \hat{\mu}_t. \tag{59}$$

The law of motion for the domestic price of resource commodities ensures that

$$\hat{p}_{z,t} = \frac{1}{2}\left(\hat{q}_t + \hat{p}^*_{z,t}\right) + \frac{1}{2}\hat{p}_{z,t-1}. \tag{60}$$

Foreign demand for domestic non-resource exports is

$$\hat{y}^x_m = -\zeta^*\left(\hat{p}^*_{m,t} - \hat{q}_t\right) + \hat{y}^*_t. \tag{61}$$

Domestic demand for non-tradeable goods, domestic non-resource tradeable goods and imported goods is

$$\hat{y}^j_t = -\zeta\hat{p}_{j,t} + \widehat{dfd}_t, \tag{62}$$

for $j \in \{n,m,f\}$.

Market clearing in the domestic non-resource tradeable sector requires that

$$y_m\hat{y}_{m,t} = y^d_m\hat{y}^d_{m,t} + y^x_m\hat{y}^x_{m,t}. \tag{63}$$

Market clearing for the resource commodity sector requires that

$$y_z\hat{y}_{z,t} = z_x\hat{z}_{x,t} + z_m\hat{z}_{m,t} + z_n\hat{z}_{n,t}. \tag{64}$$

The definition of domestic final demand is

$$\widehat{dfd}_t = \frac{c}{dfd}\hat{c}_t + \frac{g}{dfd}\hat{g}_t + \frac{i}{dfd}\hat{i}_t, \tag{65}$$

where $\hat{i}_t$ is aggregate investment, defined as

$$\hat{i}_t = \frac{I_n}{I}\hat{i}_{n,t} + \frac{I_m}{I}\hat{i}_{m,t} + \frac{I_z}{I}\hat{i}_{z,t}. \tag{66}$$

Nominal value added is given by

$$\begin{aligned}\hat{y}^{\text{nva}}_t = &\frac{p_n y^{\text{nva}}_n}{y^{\text{nva}}}\left(\hat{p}_{n,t} + \hat{y}^{\text{nva}}_{n,t}\right) + \frac{p_m y^{\text{nva}}_m}{y^{\text{nva}}}\left(\hat{p}_{m,t} + \hat{y}^{\text{nva}}_{m,t}\right)\\ &+ \frac{p_z y_z}{y^{\text{nva}}}\left(\hat{p}_{z,t} + \hat{y}_{z,t}\right).\end{aligned} \tag{67}$$

Real value added is given by

$$\hat{y}^{\text{va}}_t = \frac{p_n y^{\text{nva}}_n}{y^{\text{nva}}}\hat{y}^{\text{va}}_{n,t} + \frac{p_m y^{\text{va}}_m}{y^{\text{nva}}}\hat{y}^{\text{va}}_{m,t} + \frac{p_z y_z}{y^{\text{nva}}}\hat{y}_{z,t}. \tag{68}$$

The current account equation is

$$\begin{aligned}\frac{b^*_{t+1}}{r^*} = &\frac{b^*_t}{\pi^*\mu} + \frac{p_z z_x}{y^{\text{nva}}}\left(\hat{p}_{z,t} + \hat{z}_{x,t} - \hat{y}^{\text{nva}}_t\right)\\ &+ \frac{p^*_m y^x_m}{y^{\text{nva}}}\left(\hat{p}^*_{m,t} + \hat{y}^x_{m,t} - \hat{y}^{\text{nva}}_t\right)\\ &- \frac{q y_f}{y^{\text{nva}}}\left(\hat{q}_t + \hat{y}_{f,t} - \hat{y}^{\text{nva}}_t\right).\end{aligned} \tag{69}$$

Note that we linearise the net foreign asset-to-GDP ratio, b^*, rather than log-linearise this value (i.e. $b^*_t = (S_t B^*_t / P_t Y_t) - b^*$) to reflect the fact that it can take both positive and negative values.

Uncovered interest rate parity requires that

$$E_t\{\hat{q}_{t+1}\} - \hat{q}_t = E_t\{\hat{\pi}^*_{t+1} - \hat{\pi}_{t+1}\} + \hat{r}_t - \hat{r}^*_t - \hat{v}_t. \tag{70}$$

The risk premium on foreign borrowing evolves according to

$$\hat{v}_t = -\iota\left(b^*_t\right) - \hat{\psi}_t. \tag{71}$$

The definition of the real exchange rate is

$$\hat{q}_t - \hat{q}_{t-1} + \hat{\pi}_t - \hat{\pi}^*_t = \Delta\hat{s}_t. \tag{72}$$

The definition of consumer price inflation implies that

$$0 = \sum_j \omega_j(1-\zeta)p_j^{1-\zeta}\hat{p}_{j,t}, \tag{73}$$

for $j \in \{n,m,f\}$, where $\hat{p}_{j,t}$ is the relative price of good j, which evolves according to

$$\hat{p}_{j,t} = \hat{p}_{j,t-1} + \hat{\pi}_{j,t} - \hat{\pi}_t. \tag{74}$$

The domestic monetary policy reaction function is

$$\begin{aligned}\hat{r}_t = &\rho_r\hat{r}_{t-1} + (1-\rho_r)\left(\phi_\pi\hat{\pi}_t + \phi_y\hat{y}^{\text{va}}_t\right)\\ &+ \phi_{\Delta y}\left(\hat{y}^{\text{va}}_t - \hat{y}^{\text{va}}_{t-1}\right) + \phi_q\left(\hat{q}_t - \hat{q}_{t-1}\right) + \varepsilon_{r,t}.\end{aligned} \tag{75}$$

The foreign economy is characterised by three equations: an IS curve, a Phillips curve and a monetary policy reaction function, respectively given by

$$\hat{y}_t^* = E_t\{\hat{y}_{t+1}^*\} - \left(\hat{r}_t^* - E_t\{\hat{\pi}_{t+1}^*\}\right) + \hat{\xi}_{y,t}^* - E_t\{\hat{\xi}_{y,t+1}^*\}, \quad (76)$$

$$\hat{\pi}_t^* = \beta E_t\{\hat{\pi}_{t+1}^*\} + \frac{\kappa^*}{100}\hat{y}_t^* + \hat{e}_{\pi,t}^*, \quad (77)$$

$$\hat{r}_t^* = \rho_r^* \hat{r}_{t-1}^* + (1-\rho_r^*)\left(\phi_\pi^* \hat{\pi}_t^* + \phi_y^* \hat{y}_t^*\right) + \phi_{\Delta_y}^* \left(\hat{y}_t^* - \hat{y}_{t-1}^*\right) + \varepsilon_{r,t}^*. \quad (78)$$

The autoregressive shock processes are given by

$$\hat{\mu}_t = \varepsilon_{\mu,t} \quad (79)$$

$$\hat{a}_{n,t} = \rho_{a_n} \hat{a}_{n,t-1} + \varepsilon_{a_n,t}, \quad (80)$$

$$\hat{a}_{m,t} = \rho_{a_m} \hat{a}_{m,t-1} + \varepsilon_{a_m,t}, \quad (81)$$

$$\hat{a}_{z,t} = \rho_{a_z} \hat{a}_{z,t-1} + \varepsilon_{a_z,t} \quad (82)$$

$$\hat{\xi}_{c,t} = \rho_{\xi_c} \hat{\xi}_{c,t-1} + \varepsilon_{\xi_c,t}, \quad (83)$$

$$\hat{g}_t = \rho_g \hat{g}_{t-1} + \varepsilon_{g,t}, \quad (84)$$

$$\hat{\psi}_t = \rho_\psi \hat{\psi}_{t-1} + \varepsilon_{\psi,t} \quad (85)$$

$$\hat{p}_{z,t}^* = \rho_{p^*} \hat{p}_{z,t-1}^* + \phi_{zy} \varepsilon_{y^*,t} + \varepsilon_{p^*,t}, \quad (86)$$

$$\hat{\xi}_{y^*,t} = \rho_{\xi_y^*} \hat{\xi}_{y^*,t-1} + \varepsilon_{\xi_y^*,t}, \quad (87)$$

$$\hat{e}_{\pi,t}^* = \rho_{e_\pi^*} \hat{e}_{\pi,t-1}^* + \varepsilon_{e_\pi^*,t}, \quad (88)$$

$$\hat{\Upsilon}_t = \rho_\Upsilon \hat{\Upsilon}_{t-1} + \varepsilon_{\Upsilon,t}. \quad (89)$$

The observation equations link the model variables to the observed variables in the data: GDP growth,

$$\Delta y_t^{obs} = 100 \times (\hat{y}_t^{va} - \hat{y}_{t-1}^{va} + \hat{\mu}_t) + me_{y,t}; \quad (90)$$

consumption growth,

$$\Delta c_t^{obs} = 100 \times (\hat{c}_t - \hat{c}_{t-1} + \hat{\mu}_t) + me_{c,t}; \quad (91)$$

investment growth,

$$\Delta i_t^{obs} = 100 \times (\hat{i}_t - \hat{i}_{t-1} + \hat{\mu}_t) + me_{i,t}; \quad (92)$$

non-tradeable value added growth,

$$\Delta y_{n,t}^{va} = 100 \times (\hat{y}_{n,t}^{va} - \hat{y}_{n,t-1}^{va} + \hat{\mu}_t) + me_{y_n,t}; \quad (93)$$

non-resource tradeable value added growth,

$$\Delta y_{m,t}^{va} = 100 \times (\hat{y}_{m,t}^{va} - \hat{y}_{m,t-1}^{va} + \hat{\mu}_t) + me_{y_m,t}; \quad (94)$$

resource value added growth,

$$\Delta y_{z,t}^{va} = 100 \times (\hat{y}_{z,t}^{va} - \hat{y}_{z,t-1}^{va} + \hat{\mu}_t) + me_{y_z,t}; \quad (95)$$

non-resource exports growth,

$$\Delta y_{m,t}^{x} = 100 \times (\hat{y}_{m,t}^{x} - \hat{y}_{m,t-1}^{x} + \hat{\mu}_t) + me_{y_m^x,t} \quad (96)$$

resource exports growth,

$$\Delta z_t^x = 100 \times (\hat{z}_t^x - \hat{z}_{t-1}^x + \hat{\mu}_t) + me_{z_x,t}; \quad (97)$$

inflation,

$$\pi_t^{obs} = 100 \times \hat{\pi}_t + me_{\pi,t}; \quad (98)$$

non-tradeable inflation,

$$\pi_{n,t}^{obs} = 100 \times \hat{\pi}_{n,t} + me_{\pi_n,t}; \quad (99)$$

cash rate,

$$r_t^{obs} = 400 \times \hat{r}_t; \quad (100)$$

nominal exchange rate growth,

$$\Delta s_t^{obs} = 100 \times \Delta\hat{s}_t + me_{s,t}; \quad (101)$$

commodity prices growth,

$$\Delta p_{z,t}^{*obs} = 100 \times (\hat{p}_{z,t}^* - \hat{p}_{z,t-1}^*) + me_{p_z,t}; \quad (102)$$

foreign output growth,

$$\Delta y_t^{*obs} = 100 \times (\hat{y}_t^* - \hat{y}_{t-1}^* + \hat{\mu}_t) + me_{y^*,t}; \quad (103)$$

foreign inflation,

$$\pi_t^{*obs} = 100 \times \hat{\pi}_t^* + me_{\pi^*,t}; \quad (104)$$

foreign interest rates,

$$r_t^{*obs} = 400 \times \hat{r}_t^*. \quad (105)$$

Appendix B
Data Sources and Definitions

GDP (Δy^{obs}): Quarterly percentage change in real gross domestic product, seasonally adjusted and in chain volume terms. Source: 'Australian National Accounts: National Income, Expenditure and Product' (ABS Cat. No. 5206.0).

Consumption (Δc^{obs}): Quarterly percentage change in real household final consumption expenditure, seasonally adjusted and in chain volume terms. Source: ABS Cat. No. 5206.0.

Investment (Δi^{obs}): Quarterly percentage change in real private gross fixed capital formation, seasonally adjusted and in chain volume terms. Source: ABS Cat. No. 5206.0.

Public demand (Δg^{obs}): Quarterly percentage change in real public demand. Public demand is calculated as the sum of government final consumption expenditure and public gross fixed capital formation, with all data seasonally adjusted and in chain volume terms. Source: ABS Cat. No. 5206.0.

Resource exports ($\Delta z^{x\text{obs}}$): Quarterly percentage change in resource export volumes, seasonally adjusted and in chain volume terms. Source: RBA Statistical Table I1 International Trade and Balance of Payments.

Non-resource exports ($\Delta y_m^{x\text{obs}}$): Quarterly percentage change in non-resource export volumes. Non-resource export volumes are calculated as the difference between total export volumes and resource export volumes, with all data in seasonally adjusted and chain volume terms. Source: RBA Statistical Table I1 International Trade and Balance of Payments.

Non-tradeable value added ($\Delta y_n^{\text{vaobs}}$): Quarterly growth rate of value-added production in the non-tradeable sector. The non-tradeable sector consists of the electricity, gas, water and waste industry, the construction industry, the retail trade industry, the information, media and telecommunications industry, the finance and insurance industry, the real estate industry, the professional services industry, the administrative services industry, the public administration industry, the education industry, the healthcare industry, the arts and recreation industry, the other services industry and ownership of dwellings. We calculate the growth rate of this series by summing the growth rates of each industry weighted by that industry's share of non-tradeable value added. Sources: 'Australian System of National Accounts' (ABS Cat. No. 5204.0) and ABS Cat. No. 5206.0.

Non-resource tradeable value added ($\Delta y_m^{\text{vaobs}}$): Quarterly growth rate of value-added production in the non-resource tradeable sector. The non-resource tradeable sector consists of the agriculture, forestry and fishing industry, the manufacturing industry, the transport industry, the wholesale trade industry, and the accommodation and food services industry. We calculate the growth rate of this series by summing the growth rates of each industry weighted by that industry's share of non-tradeable value added. Sources: ABS Cat. Nos 5204.0 and 5206.0.

Resources value added ($\Delta y_z^{\text{vaobs}}$): Quarterly growth rate of value-added production in the mining industry. Source: ABS Cat. No. 5206.0.

Inflation (π^{obs}): Quarterly trimmed mean inflation excluding interest and tax changes. Source: RBA Statistical Table G1 Consumer Price Inflation.

Non-tradeable inflation (π_n^{obs}): Quarterly inflation rate of non-tradeable goods and services. Source: RBA Statistical Table G1 Consumer Price Inflation.

Cash rate (r^{obs}): Quarterly average interbank overnight cash rate. Source: RBA Statistical Table F1.1 Interest Rates and Yields – Money Market.

Nominal exchange rate (Δs^{obs}): Quarterly percentage change in the average nominal exchange rate. Source: RBA Statistical Table F11 Exchange Rates.

Resource prices ($p_z^{*\text{obs}}$): Quarterly percentage change in the RBA non-rural commodity price index measured in Special Drawing Rights. Source: RBA Statistical Table I2 Commodity Prices.

Foreign GDP ($y^{*\text{obs}}$): Quarterly percentage change of the real gross domestic product of Australia's major trading partners weighted by GDP at purchasing power parity exchange rates. Source: RBA.

Foreign inflation ($\pi^{*\text{obs}}$): Quarterly average inflation rate of the G7 economies. Source: RBA.

Foreign interest rates ($r^{*\text{obs}}$): Quarterly average policy rate of the United States, Japan and euro area (Germany before 1999). Source: RBA Statistical Table F13 International Official Interest Rates.

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