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Unprecedented Changes in the Terms of Trade

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RDP 2015-11

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Abstract

The ongoing development of Asia has led to unprecedented changes in the terms of trade of commodity-exporting economies. Using a small open economy model we estimate changes in the long-run level and variance of Australia's terms of trade and study the quantitative implications of these changes. We find that the long-run prices of commodities that Australia exports started to increase significantly in mid 2003 and that the volatility of shocks to commodity prices doubled soon after. The persistent increase in the level of commodity prices is smaller than single-equation estimates suggest, but our inferences rely on many observables that in general equilibrium also respond to shifts in the long-run level of the terms of trade.

JEL Classification Numbers: C11, F41, Q33

Keywords: Bayesian analysis, open economy macroeconomics, terms of trade

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1. Introduction

Over the past decade or more, the ongoing development of Asia has led to a surge in global resource commodity prices. There have been commodity price booms before, but this one, fuelled by an unprecedented era of high growth in China, has been by far the largest and most persistent.

A recurring question for commodity-exporting economies is the extent to which the recent increases in commodity prices will prove to be permanent.[1] One view is that these fluctuations are the result of an unprecedented and prolonged shift in the demand for commodities associated with the economic development of Asia. According to this view, the level of commodity prices has reached a permanently higher 'new normal'.[2] Others argue that the increase is not permanent as higher prices will eventually induce increased supply, but with some lag. This view also implies a 'new normal' for commodity prices, but one associated with greater volatility due to the emergence of large new sources of global commodity demand coupled with the inelastic nature of short-run commodity supply curves, rather than a permanently higher level.[3] Understanding whether a 'new normal' exists, what it entails and its implications is important for these economies.

In this paper, we take these competing hypotheses to the data. We first set up a model with multiple productivity trends that can capture steady-state drifts in relative prices. We then estimate the model on Australian data, allowing – but not requiring – both the long-run level of commodity prices and the volatility of shocks to commodity prices to change. A permanent change in the long-run level of commodity prices gives rise to a transition towards a new balanced growth path. The resulting economic dynamics differ greatly from those associated with

1 Because for commodity-exporting economies the bulk of recent terms of trade fluctuations come from commodity prices movements, we use the terms commodity prices and terms of trade interchangeably.

2 See Bernanke (2008), Bloxham, Keen and Hartigan (2012), Stevens (2011) and Yellen (2011).

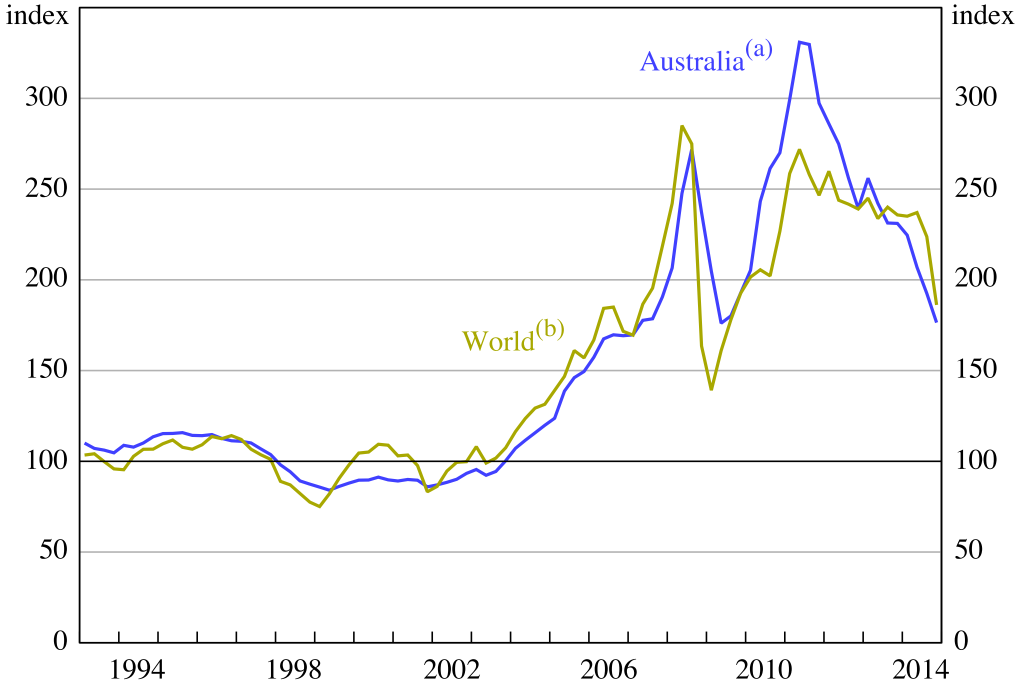
3 See Dobbs *et al* (2013).

a temporary change in commodity prices. By using a structural model that takes account of pre-existing trends in relative prices, we are able to distinguish between trends that belong to the balanced growth path, cycles around those trends, and fluctuations that originate from a transition towards a new balanced growth path.

We estimate the model on Australian data because Australia is a commodity-exporting economy that has benefited significantly from economic developments in Asia. Between 2003 and 2011, the foreign currency prices of Australia's commodity exports more than tripled (Figure 1). Over this period, broader measures of world commodity prices experienced similar increases, although the peak increase in Australia's commodity export prices was unusually large. This suggests that our analysis may be of interest to other commodity-exporting economies as well.

Figure 1: Real Commodity Price Indices

1993–2003 average = 100



Notes: (a) RBA index of commodity prices in US$ terms, deflated by US GDP deflator
(b) IMF Index of Commodity Prices, deflated by US GDP deflator

Sources: Authors' calculations; Bureau of Economic Analysis; IMF; RBA

We find support in the data for both hypotheses. In particular, we find that the long-run level of Australia's commodity prices increased by 40 per cent in mid 2003 and that the volatility of shocks to commodity prices more than doubled soon after that.

An increase of 40 per cent in the long-run level of commodity prices is probably less than one would infer from visual inspection of the data. It is also less than the 100 per cent increase that one recovers from the estimation of single-equation reduced-form specifications. Our inferences, however, rely on more observable variables than single-equation estimates. In general equilibrium, a change in the long-run level of commodity prices affects quantities and prices throughout the economy. A permanent doubling of commodity prices is unlikely because it would imply behaviour of other economic variables that is greatly at odds with what we have actually observed.

The economic consequences of the 40 per cent increase in the long-run level of commodity prices that we estimate are, however, significant. To name a few: the commodity sector's share of exports increases from 35 to 52 per cent; consumer price inflation falls temporarily by 2 percentage points with tradeable inflation and non-tradeable inflation offsetting each other; the trade deficit widens by around 2 percentage points of GDP for a decade; and the real exchange rate appreciates permanently. Even if commodity prices ultimately settle far below their recent peaks, the Australian economy is likely to look different from how it did before the terms of trade boom.

Our work builds on that of Rabanal (2009) and Siena (2014), who set up models in which steady-state productivity growth differs between the tradeable and non-tradeable sectors of the economy. To these models we add capital accumulation with a differential trend in the relative price of investment goods as well as a commodity-exporting sector that takes the relative price of its output as given. Our work also relates to a large literature on the role of terms of trade shocks in open economies, to which we cannot do justice in the space we have here.[4] Our work adds to this literature because we distinguish temporary shocks to the terms of trade – which have been the focus of the small open economy literature – from permanent shifts in the long-run level of the terms of trade. Our work is similar in spirit to that of Aguiar and Gopinath (2007), who exploit the information in consumption and net exports to identify trend growth. We use multiple observable series to identify permanent changes in the terms of trade process.

4 Instead, we point the reader to Ostry and Reinhart (1992); Mendoza (1995); Bidarkota and Crucini (2000); Bleaney and Greenaway (2001); Kent and Cashin (2003); Broda (2004); Blattman, Hwang and Williamson (2007); Medina and Soto (2007); Dib (2008); Jääskelä and Smith (2013); Charnavoki and Dolado (2014); and the references therein.

The rest of the paper is structured as follows. Section 2 discusses the model. Section 3 analyses the responses of the model to temporary and permanent changes in the terms of trade. Section 4 discusses our empirical approach, which involves calibration and estimation of date breaks and parameters. Section 5 describes the main results. Section 6 discusses the implications of these results for the Australian economy. Section 7 concludes.

2. Model

We extend a standard small open economy model with nominal rigidities by including capital accumulation as well as non-tradeable and commodity-exporting sectors. Like Rabanal (2009), we include trends in sector-specific productivity processes that give rise to relative price changes in steady state. Since the model is large, in this section we provide a descriptive overview and highlight the treatment of two important features – the behaviour of commodity prices and trends in sectoral productivity. Readers interested in the technical details of the model can refer to Appendix A for a comprehensive presentation.

2.1 The Environment

The model features two economies – a small economy (Australia) and a large economy (the rest of the world). Economic developments in the large economy affect the small economy. But developments in the small economy do not affect the large economy.

The key economic units in the small economy are firms and households. There are four types of firms in the small economy: non-tradeable, non-commodity tradeable, commodity and importing firms. Non-tradeable, non-commodity tradeable and commodity firms produce goods and services domestically using capital and labour as production inputs. Non-tradeable firms sell their output exclusively to households in the small economy. Non-commodity tradeable firms sell their output to households in the small economy and overseas. And commodity firms produce resource commodities for sale overseas. Importing firms sell goods and services produced overseas to households in the small economy. Non-tradeable, non-commodity tradeable and importing firms sell differentiated goods. These firms enjoy some pricing power in the marketplace, which is a monopolistically competitive environment. In contrast, the commodity sector is perfectly competitive.

Households derive utility from consumption and disutility from work. Labour is mobile across sectors, although households view employment in different sectors as imperfect substitutes. Household saving takes the form of bonds denominated in either domestic or foreign currency and capital which, once installed, is specific to each of the three production sectors. Households prefer to smooth consumption over time. To achieve this, when making consumption decisions, households take account of their expected future income stream. An implication of this is that the response of consumption to changes in income will depend upon the expected persistence of those changes. These differences help us to distinguish between permanent and temporary shifts in commodity prices.

We include a number of frictions in the model. In particular, we introduce price stickiness in the form of quadratic adjustment costs that firms must pay when changing their prices as well as quadratic investment adjustment costs. These frictions help the model to capture empirical regularities in Australian macroeconomic data. They also imply that firms will typically adjust prices and capital by less in response to economic disturbances that they expect will be transitory than they do in response to disturbances that they expect to be persistent. As was the case for consumption, the differing responses of prices and investment to short- and long-lived disturbances help us to identify permanent shifts in long-run commodity prices.

2.2 Commodity Prices

Commodity producers operate in an environment of perfect competition, meaning that they take prices as given. These prices are set in world markets and are unaffected by economic developments in the small economy. The price of commodities in foreign currency terms, $P^*_{X,t}$, is equal to:

$$P^*_{X,t} = \tilde{\kappa}_t P^*_t \tag{1}$$

where P^*_t is the foreign price level and $\tilde{\kappa}_t$ governs the relative price between commodities and the basket of goods and services produced overseas. This relative price follows the exogenous process:

$$\tilde{\kappa}_t = \kappa_t \left(\frac{z^*}{z_X^*} \right)^t \tag{2}$$

where the term in brackets, z^*/z_X^*, is the steady-state productivity growth differential between the large economy as a whole and the large economy's commodity sector. We include this term for technical reasons to ensure the existence of a well-defined balanced growth path – it plays no role in our analysis. Abstracting from this term, along a balanced growth path relative commodity prices experience transitory shocks according to the process:

$$\log \kappa_t = (1 - \rho_\kappa) \log \kappa + \rho_\kappa \log \kappa_{t-1} + u_{\kappa,t} \tag{3}$$

where $u_{\kappa,t}$ is independently and identically distributed $N(0, \sigma_\kappa^2)$. After detrending the variables, κ determines the long-run unconditional mean of commodity prices and the domestic economy's terms of trade.

In estimation, we allow for breaks in κ and σ_κ^2, possibly occurring at different dates in the sample. A break in κ implies a change in long-run commodity prices, while a break in σ_κ implies a change in the variance of shocks to commodity prices.

2.3 Trending Relative Prices and Productivity

Our model allows productivity growth in the various sectors of the economy to differ in steady state. These differences in productivity growth translate into steady-state drifts in relative prices. Permanent changes in commodity prices influence other relative prices in the economy. Accounting for existing trends in relative prices helps us to separate changes in relative prices due to changes in long-run commodity prices from pre-existing trends associated with the economy's balanced growth path.

To illustrate the productivity processes and their link to relative prices, consider the production function for firm i in sector j:

$$Y_{j,t}(i) = A_t \tilde{Z}_{j,t} \left(K_{j,t}(i) \right)^{\alpha_j} \left(Z_t L_{j,t}(i) \right)^{1-\alpha_j} \tag{4}$$

where $Y_{j,t}(i)$ is the output of firm i, $K_{j,t}(i)$ and $L_{j,t}(i)$ are the capital and labour inputs employed by firm i and A_t, Z_t and $\tilde{Z}_{j,t}$ are productivity processes.

A_t is a stationary productivity process, common to the non-tradeable, non-commodity tradeable and commodity sectors, that evolves as:

$$\log A_t = \rho_A \log A_{t-1} + u_{A,t} \tag{5}$$

Z_t is a labour-augmenting productivity process, also common to the non-tradeable, non-commodity tradeable and commodity sectors, whose growth rate, $z_t = Z_t/Z_{t-1}$, evolves as:

$$\log z_t = (1-\rho_z)\log z + \rho_z \log z_{t-1} + u_{z,t} \tag{6}$$

where z determines the steady-state growth rate of aggregate technology in the economy. The processes A_t and Z_t differ because an innovation to A_t has a temporary effect on the level of productivity, while an innovation to Z_t has a permanent effect on the level of productivity.

The final productivity process, $\tilde{Z}_{j,t}$, is a stationary sector-specific productivity process that follows:

$$\tilde{Z}_{j,t} = z_j^t Z_{j,t} \tag{7}$$

The parameter z_j determines the differential growth rate, along the balanced growth path, between the output of sector j and real GDP. The stationary process $Z_{j,t}$ gives rise to temporary departures from the differential trend by:

$$\log Z_{j,t} = \rho_j \log Z_{j,t-1} + u_{j,t} \tag{8}$$

Along a balanced growth path aggregate variables, including GDP, consumption and the capital stock, grow at the rate of aggregate productivity, z. Sectoral variables, such as the output of non-tradeable goods, $Y_{N,t}$, and the quantity of these goods that enter consumption and investment baskets, $C_{N,t}$ and $I_{N,t}$, grow at aggregate productivity growth adjusted by the sector-specific trends. For example, the steady-state growth rate of non-tradeable output is $z \times z_N$.

Balanced growth requires that the shares of each sector in nominal GDP remain constant. For this to occur, the relative prices of each sector must offset the sector-specific productivity growth rates. For example, the relative price between non-tradeable goods and consumption goods, $P_{N,t}/P_t$, must grow at z_N^{-1} along a balanced growth path. In this way, differential trends in productivity growth lead to drifts in relative prices.

In addition to differential productivity growth between the economy's production sectors, we also allow for differential productivity growth between investment and consumption goods as well as between goods produced in the small economy and those produced abroad. As was the case for sectoral productivity growth differentials, these differentials lead to drifts in relative prices along the balanced growth path.

3. Temporary and Permanent Changes in Commodity Prices

In this section we illustrate the responses of economic variables to temporary and permanent changes in commodity prices in our model and discuss how these responses allow us to identify shifts in long-run commodity prices.

The responses of commodity prices to temporary and permanent shocks are different. We reproduce Equation 3 here to illustrate how:

$$\log \kappa_t = (1-\rho_\kappa)\log \kappa + \rho_\kappa \log \kappa_{t-1} + u_{\kappa,t}$$

A positive temporary shock, $u_{\kappa,t}$, raises commodity prices on impact, but implies an expected path of falling commodity prices as they revert to their original steady state.[5] In contrast, the contemporaneous impact of a permanent change in the long-run level of commodity prices, $\Delta\kappa$, is dampened by the persistence of the process, so that the initial increase is only $(1-\rho_\kappa)\log(\Delta\kappa)$. But it implies an expected path of commodity prices to a permanently higher level.

To illustrate the economic implications of these alternative commodity price paths, Figure 2 compares similarly sized temporary and permanent shocks to commodity prices. For this exercise, we set the parameters of the model to the posterior mode of our estimates below. Also in line with our estimates, we scale the shocks to induce a 42 per cent increase in commodity prices.

5 We assume that $|\rho_\kappa| < 1$, implying that κ_t is stationary.

In some respects, temporary and permanent commodity price increases have similar effects on the economy. Both raise the income of domestic residents. This causes an expansion in domestic demand and an increase in non-tradeable inflation. Similarly, temporary and permanent commodity price increases both prompt an exchange rate appreciation that lowers the inflation rate of tradeable goods and services.

Figure 2: Responses to an Increase in Commodity Prices

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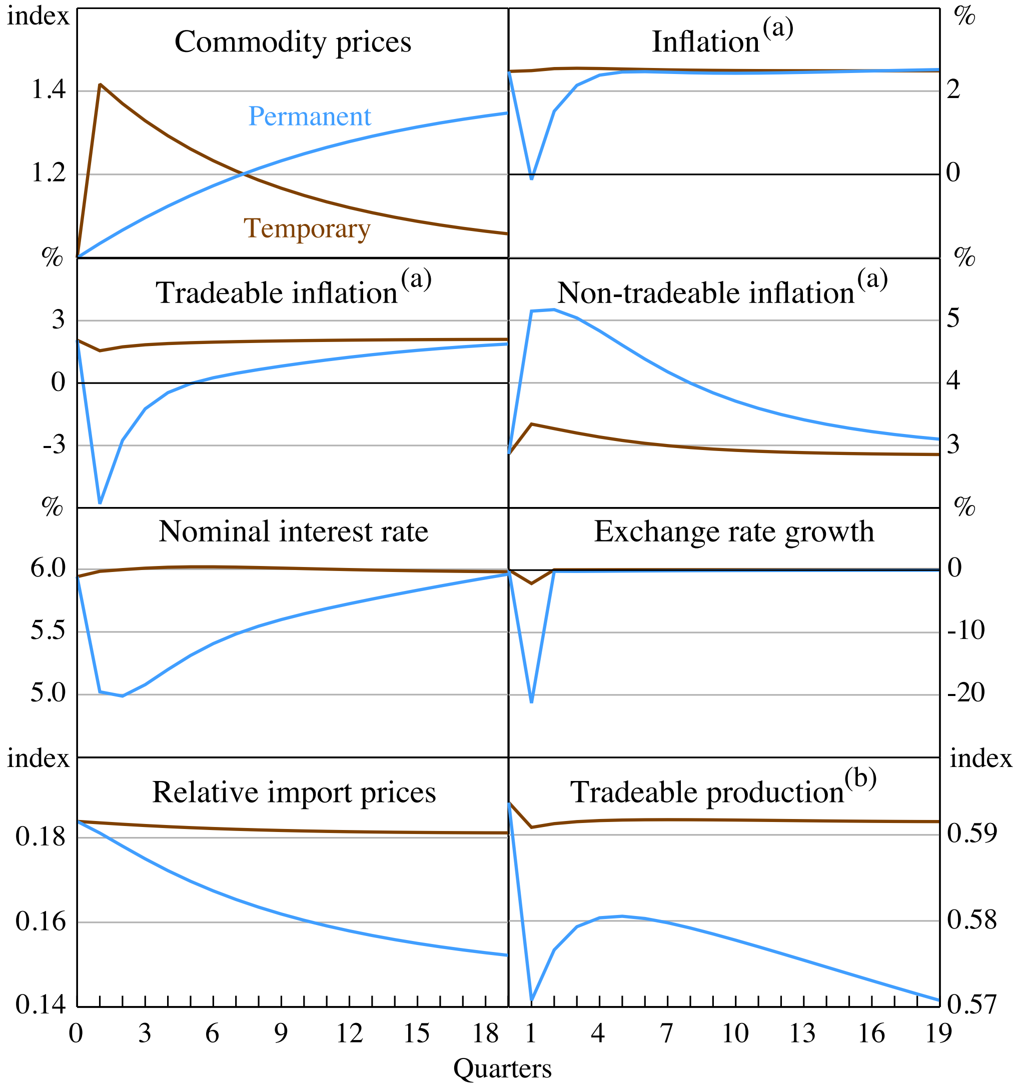
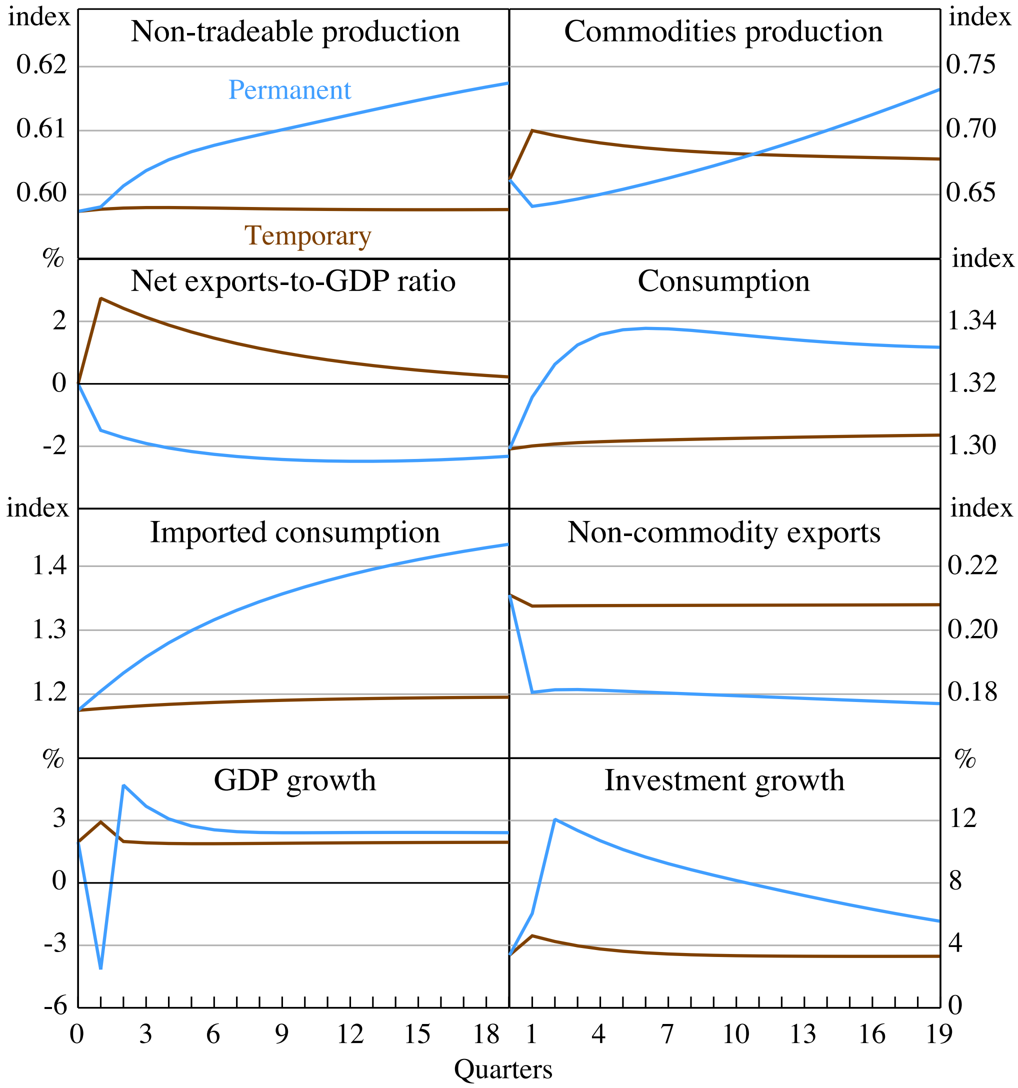


Figure 2: Responses to an Increase in Commodity Prices
(continued)



Notes: (a) Annualised
(b) Non-commodity tradeable sector

However, although the direction of the responses of many variables are the same, the magnitudes are different. Following a permanent increase in commodity prices, the initial appreciation of the exchange rate is estimated to be half as large as the long-run change in commodity prices. In contrast, following a temporary increase, the appreciation of the exchange rate is only five per cent as large as the change in commodity prices. Because the determination of the exchange rate depends on expectations, it appreciates by more when the change in commodity prices is permanent in anticipation of larger future inflows of foreign currency. These inflows are larger not only because commodity prices are expected to be permanently higher but also because commodity sector output expands permanently. The price effect is magnified by a quantity effect when the change in commodity prices is permanent.

Inflation provides another example of the difference between temporary and permanent changes in commodity prices. Once again, permanent changes have much larger effects on both tradeable and non-tradeable inflation than temporary changes. But the fall in tradeable inflation is particularly large when the change in commodity prices is permanent, due to the larger exchange rate appreciation. As a result, in the permanent case aggregate inflation is estimated to fall by 2 percentage points for a short time because the deflationary impact of lower import prices dominates the increase in non-tradeable prices that comes from rising incomes. In contrast, a temporary increase in commodity prices is estimated to be mildly inflationary.

These different inflation responses have implications for interest rates. A permanent increase in commodity prices initially puts downward pressure on nominal interest rates due to the disinflation and an initial contraction in output. Eventually, nominal interest rates increase as the disinflationary effect of the exchange rate appreciation diminishes and output growth remains higher in the transition to the new steady state. In contrast, a temporary increase in commodity prices leads to higher interest rates immediately.

In the case of temporary changes in commodity prices, the increase in consumption and investment is smaller than the change in domestic incomes. Domestic residents save part of the temporary income boost and the net exports to GDP ratio increases. In contrast, a permanent increase in commodity prices raises expected long-run income by more than short-run income. Reflecting these expectations, consumption and investment expand by more than the initial increase in income and the net exports to GDP ratio decreases.

Permanent and temporary changes in commodity prices also have different implications for production. When the change in commodity prices is permanent, the commodity sector initially contracts. An increase in the long-run level of commodity prices has a relatively small contemporaneous impact on foreign-currency commodity prices. But the nominal exchange rate appreciates immediately, which lowers the domestic-currency revenue of the commodity sector. As a consequence, the *domestic-currency* price of commodities initially falls before reaching a permanently higher level. This delays the expansion of the commodity sector. In contrast, a temporary increase in commodity prices induces an immediate expansion in commodity output.[6]

Higher long-run commodity prices also cause an expansion of the non-tradeable sector. For the non-commodity tradeable sector, domestic demand rises when commodity prices increase permanently. But the exchange rate appreciation causes a significant fall in foreign demand. Overall, non-commodity tradeable production initially contracts. Along the transition to a new balanced growth path, production in this sector experiences a brief recovery due to the expansion in domestic demand. However, a permanent increase in commodity prices ultimately causes a reallocation of inputs across sectors. The commodity sector and non-tradeable sector expand to take advantage of higher prices, while the non-commodity tradeable sector contracts.

In sum, even when the direction of the responses of macroeconomic variables to temporary and permanent commodity price movements are the same, the magnitude of the responses are often very different. And for some variables, for example inflation and the trade balance, even the direction of their responses to commodity price changes depends on the permanence of the changes. It is these differences that allow our estimation procedure to distinguish between permanent and temporary movements in commodity prices.

4. Empirical Analysis

The model's structural parameters can be thought of as belonging to two categories: those that can only determine dynamics – persistence parameters, adjustment cost parameters, policy rule parameters and the standard deviations of the model's structural shocks – and those that, in addition to influencing the dynamics, pin down the steady state. We estimate the first category of parameters and calibrate the second, with the exception of h, the parameter that determines the degree of habit persistence, and $\Delta\kappa$, the change in the long-run level of commodity prices, both of which we estimate.

6 In our sample, actual changes in commodity prices included a mix of temporary and permanent components. Consequently, the net effect of price changes on the commodity sector was somewhere in between these two cases.

4.1 Calibration

We calibrate for two reasons. First, not all parameters are well identified given the usual choice of observable variables. Second, estimation could imply a steady state at odds with long-run features of the data. Accordingly, we set the parameters governing the steady state so that the model's balanced growth path is in line with the first moments of the data.

The traditional approach of matching sample means seems inappropriate in our case because we postulate a possible break in the long-run level of the terms of trade, which in turn leads to changes in unconditional means. We instead focus on matching features of the data over the first part of the sample, before commodity prices started to rise rapidly. To be precise, although our estimation sample spans 1993:Q1 to 2013:Q4, we calibrate the model's parameters to match moments of the data over the period 1993 to 2002, which was a time of relative stability in the terms of trade (Table 1). In the initial steady state, we first set the long-run level of relative commodity prices, κ, to 1. Before other parameters are calibrated, this choice is a normalisation. After that, of course, a change in κ alters the steady state. For the data to be consistent with the model in estimation we normalise the index of real commodity prices so that it averages 1 over the sub-sample.

Our calibration strategy is as follows. We calibrate the model at a quarterly frequency. We assume that the steady-state rate of labour augmenting productivity growth, z, is 1.0049, which matches the average growth rate of per capita GDP over our sample.[7] We set the central bank's inflation target, Π, to an annual rate of 2.5 per cent. This is the middle of the Reserve Bank of Australia's inflation target and roughly equal to the mean of inflation over our sample. We set the household's discount rate, β, equal to 0.99625. Together, these three parameters imply a steady state nominal interest rate of 6 per cent.

We set the foreign productivity growth differential, z^*, to match the average growth rate of Australia's major trading partners. We set the sector-specific productivity

7 We calibrate this parameter using the average growth over our full sample of data rather than the shorter 1993 to 2002 sample because the shorter sample featured an unusually rapid period of economic growth in Australia associated with a steep recovery from a deep recession in the early 1990s and a period of rapid productivity growth due, in part, to a series of microeconomic reforms in the 1980s. Consequently, the full-sample average is likely to better reflect the long-run productivity growth rate.

growth differentials, z_H and z_N, so that the inflation rates of tradeable and non-tradeable goods match their rates in the data. This means that, in steady state, non-tradeable prices increase faster than consumer prices, while tradeable prices increase more slowly.

Table 1: Calibrated Parameters

Parameter	Description	Value
β	Household discount rate	0.9963
δ	Capital depreciation rate	0.005
ν	Labour supply parameter	2
ω	Intersectoral labour supply elasticity	1
ξ_N	Constant on non-tradeable labour supply	100
ξ_H	Constant on tradeable labour supply	209
ξ_X	Constant on commodities labour supply	4 167
ψ_b	Risk premium	0.001
γ_N	Non-tradeables consumption weight	0.48
γ_H	Home-produced tradeables weight	0.643
γ_N^I	Non-tradeables investment weight	0.664
γ_H^I	Home-produced tradeables investment weight	0.172
γ_H^*	Determinant of foreign demand	0.877
η	Elasticity of substitution in the domestic economy	0.8
η^*	Elasticity of substitution in the foreign economy	0.8
z	Steady-state productivity growth	1.0049
z_v	Investment growth rate differential	1.0035
z_N	Non-tradeable growth differential	0.999
z_H	Home-tradeable growth differential	1.002
z_X	Commodity growth differential	1.0
z^*	Foreign productivity growth differential	1.0003
α_N	Capital share in non-tradeables	0.358
α_H	Capital share in tradeables	0.438
α_X	Capital share in commodities	0.70
Π	Domestic inflation target	1.0062
Π^*	Foreign inflation target	1.0055
θ_N	Mark-up in non-tradeables	11
θ_H	Mark-up in home tradeables	11
θ_F	Mark-up in imports	11
b^*	Steady-state net foreign assets-to-GDP ratio	0

We set the capital shares in each sector, α_N, α_H and α_X, according to their average values in national accounts data.[8] The mark-up parameters, θ_N, θ_H and θ_F, are set so that each sector has an an average mark-up of 10 per cent. However, we estimate the price adjustment cost parameters that determine the slope of the Phillips curves for these sectors.

We set the parameter governing the elasticity of labour supply, ν, to 2, which is a standard value in the literature. In line with Horvath (2000), we set the parameter governing the willingness of workers to move between sectors in response to wage differentials, ω, to 1. Given those parameters, we adjust the parameters governing the amount of labour supplied to each sector in steady state, ξ_N, ξ_H and ξ_X, so that the shares of hours worked in each sector approximates those in the data.

We set the parameters governing the share of non-tradeable, non-commodity tradeable and imported goods in the small economy's consumption and investment baskets to match averages in the data and the parameter governing steady-state foreign demand for non-commodity tradeable goods to match the share of exports in GDP.

Table 2 compares the moments implied by the model's steady state to their empirical counterparts. At the calibrated parameters values of Table 1, the model's steady state does quite well. An exception is investment growth, whose mean is somewhat lower in the model than in our sample. Because investment is volatile and can contract significantly in recessions, it is likely that the growth rate of investment in our sample (which does not include a recession) is overstated. If we extend the sample to begin in 1990:Q1 – which includes a recession – the average growth rate of investment is 3.5 per cent. This is close to the model implied growth rate of 3.4 per cent.[9]

8 Appendix B provides additional detail regarding our classification of industries into tradeable, non-tradeable and commodity-exporting.

9 We did not calibrate the model to match this parameter specifically. Instead, we set z_v, which governs the growth rate of investment, so as to match the rate of inflation of investment goods prices.

Table 2: Steady State Properties of the Model			
Target	**Data**		**Model**
	1993–2013	1993–2002	
Macro aggregates (annualised, per cent)			
Per capita output growth	1.96	2.64	1.96
Per capita investment growth	4.31	4.39	3.43
Inflation	2.63	2.50	2.50
Tradeable inflation	1.65	2.09	2.09
Non-tradeable inflation	3.41	2.86	2.86
Investment deflator inflation	1.29	1.09	1.09
Expenditure (per cent of GDP)			
Consumption	74.6	75.8	72.7
Investment	26.3	24.7	27.3
Exports	19.5	19.3	19.7
Consumption basket (per cent of consumption)			
Non-tradeable consumption	55.2	53.4	53.4
Home tradeable consumption	27.3	30.0	30.0
Imported tradeable consumption	17.5	16.6	16.6
Investment basket (per cent of investment)			
Non-tradeable investment	67.4	66.4	66.4
Home tradeable investment	2.6	5.7	5.8
Imported investment	30.0	27.9	27.8
Exports (per cent of exports)			
Resource exports	42.1	34.6	34.6
Other exports	57.9	65.4	65.4
Employment (per cent of hours worked)			
Non-tradeable	67.6	65.0	64.3
Home tradeable	31.1	34.0	33.2
Commodity	1.3	1.0	2.5

Note: Model ratios calculated at initial regime with $\bar{\kappa} = 1.0$ and $h = 0.5$

4.2 Estimation

We estimate the model using Bayesian methods, as is common in the estimated DSGE literature.[10] Our case, however, is non-standard because we allow for structural change and jointly estimate two sets of distinct parameters. These are: (i) the structural parameters of the model, ϑ, that have continuous support; and (ii) the dates of structural changes, $\mathbf{T} = (T_\kappa, T_{\sigma_\kappa})$ that have discrete support (T_κ is

10 See An and Schorfheide (2007) for a description of these techniques.

the date break in the mean and T_{σ_κ} is the date break in the variance of commodity prices).

The joint posterior density of ϑ and $\mathbf{T}$ is:

$$p(\vartheta,\mathbf{T}|\mathscr{Y}) \propto \mathscr{L}(\mathscr{Y}|\vartheta,\mathbf{T})p(\vartheta,\mathbf{T}), \tag{9}$$

where $\mathscr{Y} \equiv \{y_t^{obs}\}_{t=1}^{T}$ is the data and y_t^{obs} is a $n_{obs} \times 1$ vector of observable variables.

The likelihood is given by $\mathscr{L}(\mathscr{Y}|\vartheta,\mathbf{T})$ and $p(\vartheta,\mathbf{T})$ is the prior probability of observing the parameters ϑ and $\mathbf{T}$. Kulish and Pagan (2012) discuss how to construct $\mathscr{L}(\mathscr{Y}|\vartheta,\mathbf{T})$ in models with forward-looking expectations and structural changes. The priors for the structural parameters and the date breaks are taken to be independent, so that $p(\vartheta,\mathbf{T}) = p(\vartheta)p(\mathbf{T})$. We use a flat prior for $\mathbf{T}$ so $p(\mathbf{T}) \propto 1$, which is proper given its discrete support. We set a trimming parameter to prevent breaks in the long-run mean of commodity prices from occurring with the first or last four years of our sample. Our online appendix describes the posterior sampler.

We estimate the model using quarterly Australian macroeconomic data for the period 1993:Q1 to 2013:Q4. The starting date coincides with a period around the beginning of inflation targeting in Australia, providing us with a sample in which the macroeconomic policy environment has been broadly stable.

Our data series includes aggregate and sectoral Australian variables and foreign variables. The aggregate data include GDP, investment, consumption, net exports, hours worked, the cash rate, trimmed mean inflation and the percentage change in the nominal exchange rate. The national accounts variables and hours worked are all expressed in per capita terms and seasonally adjusted. Output, investment, consumption and hours all enter as percentage changes, while net exports enter as a share of nominal GDP. We also include two sectoral variables in the model: the inflation rate of non-tradeable goods and the ratio of nominal non-tradeable consumption to aggregate nominal consumption. The foreign variables that we include in the model are output growth, interest rates and inflation. We take the growth rate of Australia's major trading partners' GDP constructed by the Reserve Bank of Australia as the measure of foreign output growth. For interest rates we use the average of the policy rates in the United States, the euro area and Japan.[11]

11 Prior to the introduction of the euro, we construct this series using the German policy rate.

For the foreign inflation rate, we use the trade-weighted average inflation rate of Australia's major trading partners. The 14 series we use in estimation are shown in Figure 3. Appendix B contains a complete description of the data sources, calculations and transformations.

Figure 3: Observable Variables
(*continued next page*)

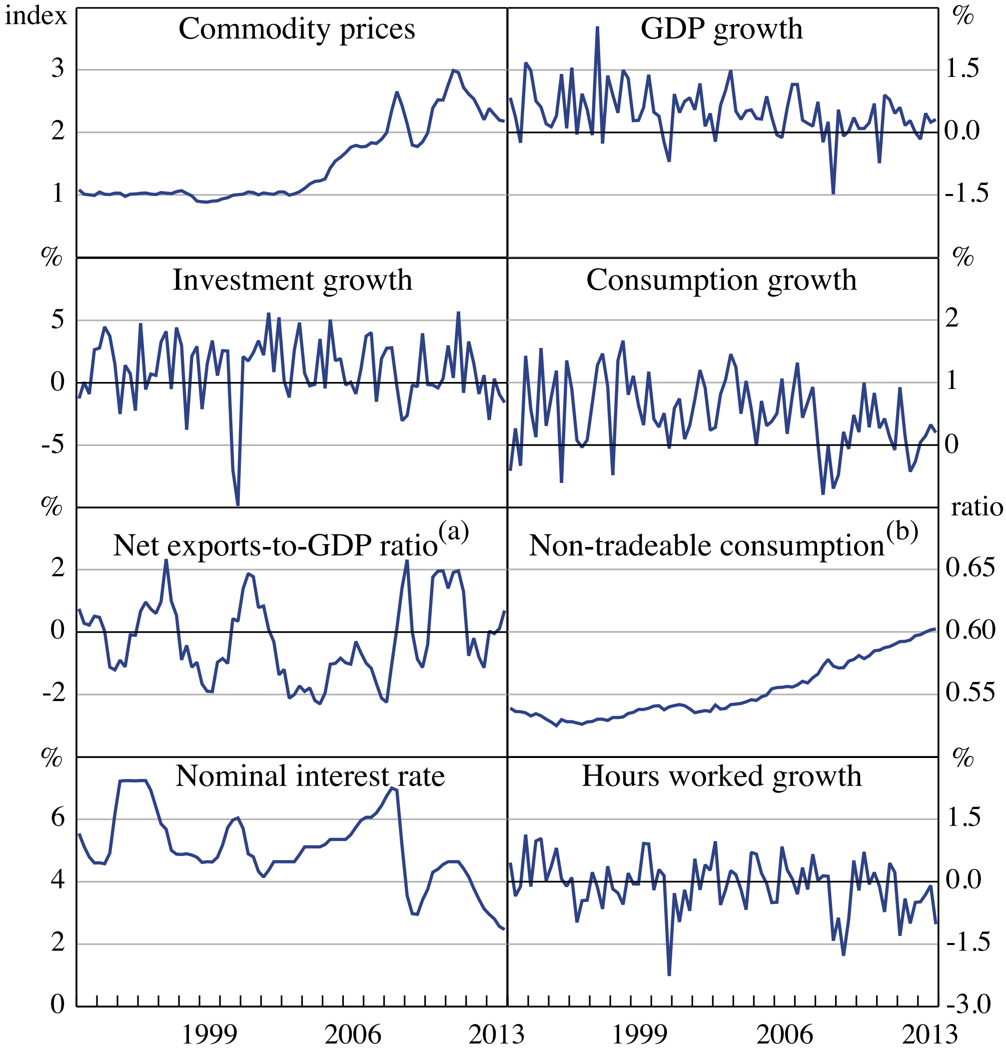
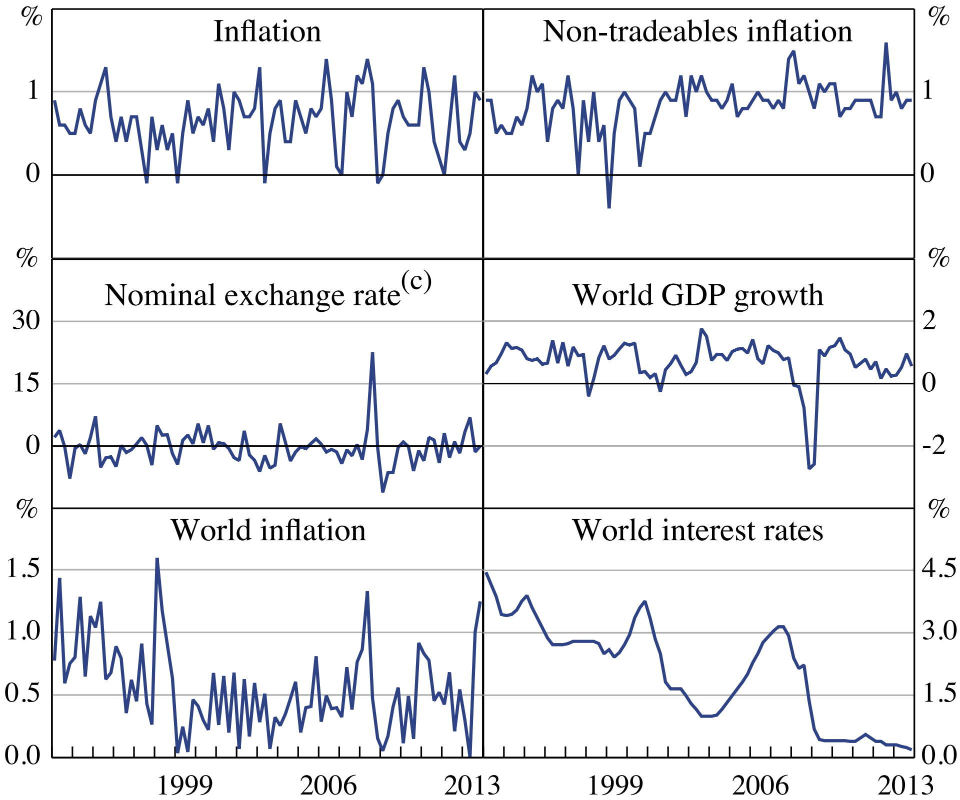


Figure 3: Observable Variables
(*continued*)



Notes: (a) De-meaned
(b) Share of total consumption
(c) Growth rate

Sources: ABS; Authors' calculations; RBA; Thomson Reuters

Macroeconomic data are measured with noise and economic concepts in the model do not always match the measures in the data. To account for this, we add measurement error in estimation.

4.3 Priors

We choose a uniform prior with support -0.25 to 3.5 for $\Delta\kappa$, which is the parameter of most interest in our analysis. This means that the estimation is free to choose a steady state in which the long-run level of commodity prices declined by 25 per cent, increased by 350 per cent or took any value in between. We set the same inverse gamma priors for the standard deviation of shocks to commodity prices in the initial volatility regime, σ_κ, as we do for the standard deviation of shocks to commodity prices in the later volatility regime, σ'_κ. That is, we do not take a stand on whether commodity price shocks have become more or less volatile over our sample.

Our other choices are in line with the literature. We impose loose beta distributions on the autoregressive parameters and inverse gamma distributions on the standard deviations of the shocks. For the parameters of the monetary policy rule we set a prior mean of 1.5 for the response of the nominal interest rate to inflation and of 0.3 for the response to real output growth.

5. Results

5.1 Structural Parameters and Date Breaks

Table 3 summarises the estimates of key structural parameters. We consign the estimates of the parameters of the exogenous process to Appendix C.

Table 3: Prior and Posterior Distribution of Structural Parameters

Parameter	**Prior distribution**			**Posterior distribution**			
	Shape	Mean	Std dev	Mode	Mean	5%	95%
Commodity prices							
$\Delta\kappa$	Uniform	[–0.25, 3.50]		0.42	0.41	0.32	0.49
σ_κ	Inv gamma	0.1	2	0.05	0.05	0.03	0.07
σ'_κ	Inv gamma	0.1	2	0.11	0.12	0.09	0.15
ρ_κ	Beta	0.5	0.5	0.90	0.89	0.84	0.94
Monetary policy rule							
ρ_R	Beta	0.5	0.2	0.88	0.88	0.85	0.91
ϕ_π	Normal	1.5	0.5	2.24	2.30	1.80	2.84
ϕ_y	Normal	0.3	0.2	0.34	0.37	0.14	0.61
Frictions							
h	Beta	0.5	0.2	0.66	0.66	0.55	0.78
Υ''	Normal	2	1	2.89	3.13	2.03	4.36
$Slope_N$	Gamma	5	3	2.68	2.93	2.03	4.08
$Slope_H$	Gamma	5	3	13.41	13.99	9.57	19.30
$Slope_F$	Gamma	5	3	1.05	1.38	0.61	2.46
Log marginal density: 3 589.6							

Notes: $Slope_N = 100(\theta_N - 1)/\psi_N$, $Slope_H = 100(\theta_H - 1)/\psi_H$, $Slope_F = 100(\theta_F - 1)/\psi_F$

In estimation we allow for breaks in κ and σ_κ because we want to allow the model to fit the data without necessarily having to resort to a change in κ. As it turns out, the data strongly prefer a specification in which κ and σ_κ both increase. The left panel of Figure 4 shows the posterior distribution of $\Delta\kappa$. The long-run level of commodity prices is estimated to have increased by 42 per cent, with a distribution that ranges between 30 and 50 per cent. The posterior distribution substantially shrinks the uncertainty relative to our uninformative prior on $\Delta\kappa$ and the density is bounded well away from zero.

At the same time, the estimates point to a significant increase in the volatility of shocks to commodity prices. At the mode, the standard deviation of shocks to commodity prices has more than doubled. The right panel of Figure 4 shows the posterior distribution of the ratio of the standard deviations of shocks to commodity prices in the two regimes, that is $\sigma'_\kappa/\sigma_\kappa$. The distribution has no mass at unity or values below. Thus, there is no likelihood that the volatility of commodity price shocks has fallen or stayed the same.

The monetary policy rule, habits and investment adjustment costs parameters are in line with other estimated small open economy models (Jääskelä and Nimark 2011; Adolfson *et al* 2013). Like Rabanal (2009) and Rees, Smith and Hall (2015), we find heterogeneity in the degree of price stickiness across sectors. At the mode, the slope of the Phillips curve in the tradeable sector is five times steeper than in the non-tradeable sector, which is in turn steeper than in the importing goods-producing sector.

Figure 4: Posterior Distributions

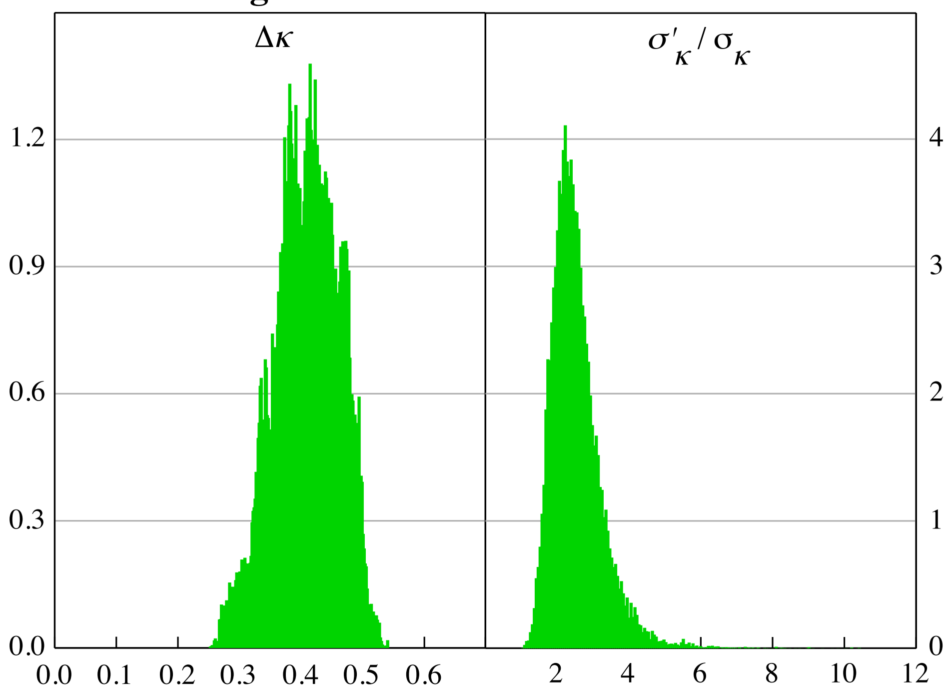
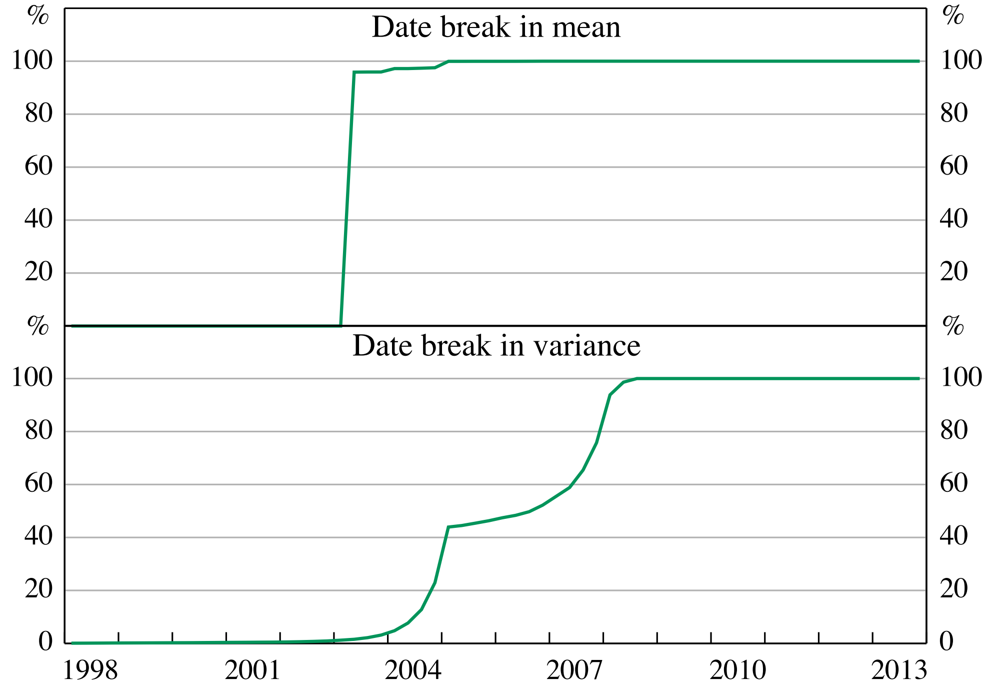


Figure 5 shows the cumulative posterior densities of T_{κ}, the date break in the unconditional mean of commodity prices, and $T_{\sigma_{\kappa}}$, the date break of the variance. The data strongly prefer 2003:Q2 for the timing of the date break in the unconditional mean. The probability that the break occurred in this quarter is around 95 per cent. This date is close to that identified by Gruen (2011), who places the start of boom in 2002:Q2. Single-equation Bai and Perron (1998) tests place the date break in κ a quarter later then suggested by our model, that is 2003:Q3.

The date break in volatility, $T_{\sigma_{\kappa}}$, shown in the bottom panel of Figure 5, is estimated to have occurred after the increase in the unconditional mean. Its posterior density, however, is bi-modal. It peaks in 2005:Q2 and then again in 2008:Q2.

Figure 5: Posterior Cumulative Distributions of Date Breaks



The last row of Table 3 reports the log marginal density of the model. We use this metric to compare the overall fit of the model against an alternative model in which we restrict the mean of commodity prices and the variance of commodity price shocks to be constant across the entire sample.[12] The log marginal density of

12 If one assigns equal prior probabilities to alternative model specifications, differences in the log marginal data densities can be interpreted as logged posterior odds.

this alternative ‘no-breaks’ model is 3 540.3, implying a log Bayes factor of 49.3. This is decisive evidence in favour of a model that allows for structural breaks in the mean and variance of commodity prices.[13]

5.2 Estimated Transitional Dynamics

To get a sense of the magnitudes involved, we compute the transitional dynamics implied by the posterior distribution of $\Delta\kappa$ for commodity prices and other selected variables. To construct these, we sample 75 draws from the joint posterior distribution of date breaks and structural parameters. For each draw, we compute the non-stochastic transition path. This is the path the economy would have followed if there were no shocks other than a change in long-run commodity prices of size $\Delta\kappa$ occurring at T_{κ}.

Figure 6 plots observed commodity prices and their estimated long-run level. Actual commodity prices were close to their estimated long-run level until 2005. After that, increases in commodity prices were mostly driven by a succession of large, but ultimately temporary, shocks. This result accords with the evidence in Plumb, Kent and Bishop (2013) that during this period the commodity price forecasts of Australian firms and policymakers were consistently lower than actual commodity price outcomes. If the increase in commodity prices was expected to be largely permanent with only small transitory deviations around its new, higher, level we would not expect to see such persistent forecast errors. Of course, the estimation was free to capture *all* of the increase in commodity prices after 2003 with an increase in the volatility of shocks to commodity prices. But it chose to explain some of the increase with a permanent change of the long-run level of commodity prices.

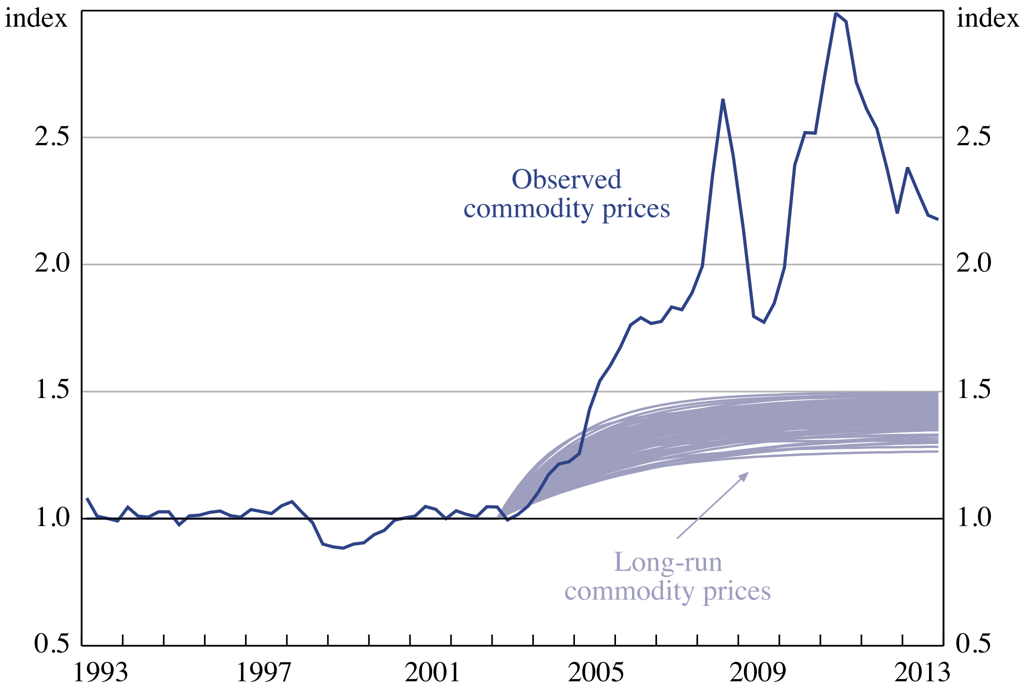
Next, we examine the implications of our model for other macroeconomic variables. Figure 7 shows the estimated transitional dynamics of the ratio of the price of non-tradeable goods to consumer goods, net exports to GDP, the real exchange rate and investment growth.[14]

13 Our baseline model also outperforms alternatives in which: (i) we allow for a change in the long-run level of commodity prices but not in the volatility of commodity price shocks; and (ii) we allow for a change in the variance of shocks to commodity prices but not in the long-run level.

14 In our model, the exchange rate is defined as the domestic price of foreign currency, so that an increase in the exchange rate represents a depreciation.

Figure 6: Observed and Long-run Commodity Prices

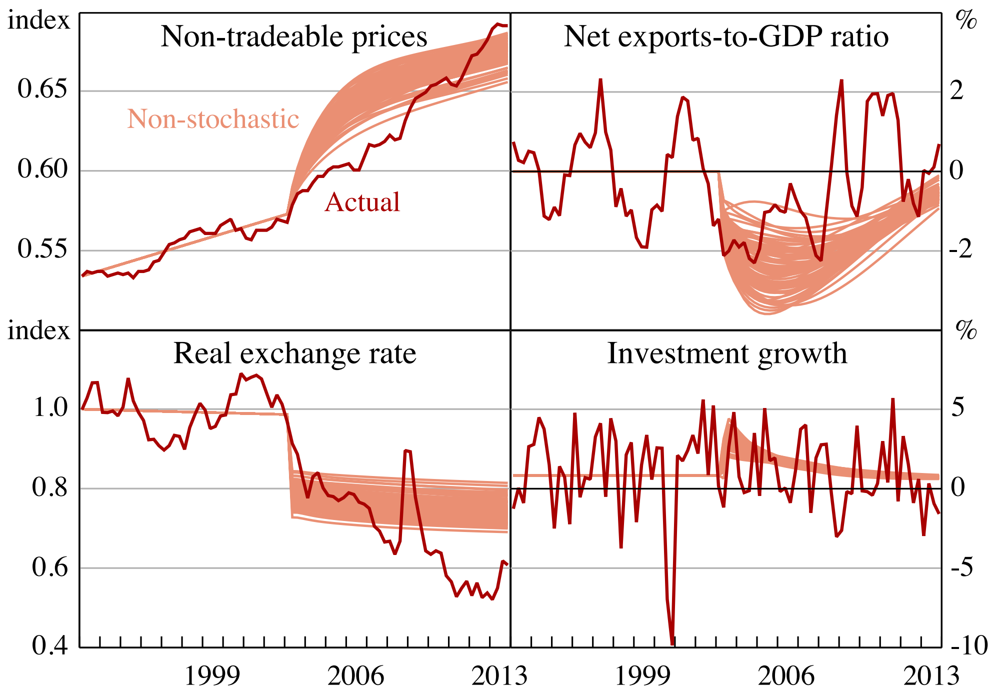
Multivariate estimation; 1993–2002 average = 1



Sources: Authors' calculations; RBA

Figure 7: Data and Estimated Transitional Dynamics

Multivariate estimation



Sources: ABS; Authors' calculations

The top left panel of Figure 7 plots the observed relative price of non-tradeable goods and the posterior distribution of the transition induced by the estimated change in long-run commodity prices. Because of the wedge between non-tradeable inflation and consumer price inflation this relative price trends at a rate that is the same on both balanced growth paths. An increase in long-run commodity prices increases this wedge temporarily along the transition to a new balanced growth path. According to our model, the increase in the relative price of non-tradeable goods over recent years is largely explained by the shift in the long-run level of the terms of trade.

The top right panel of Figure 7 shows that an increase in the long-run commodity prices leads initially to a persistent increase in the trade deficit. This is explained in part by an increase in consumption, due to higher permanent income, and in part by an increase in investment as the productive capacity of the commodity sector expands, shown in the bottom right panel. Once again, the magnitude of these movements appears reasonable compared to the actual behaviour of these series, although they are of course also influenced by other demand, supply and commodity price shocks.

The bottom left panel indicates that the estimated increase in long-run commodity prices leads to a permanent 30 per cent appreciation of the real exchange rate. The actual appreciation of the real exchange rate over our sample was larger than this, reflecting the additional contribution of positive temporary commodity price increases, as well as other economic developments.

5.3 Single-equation Estimates

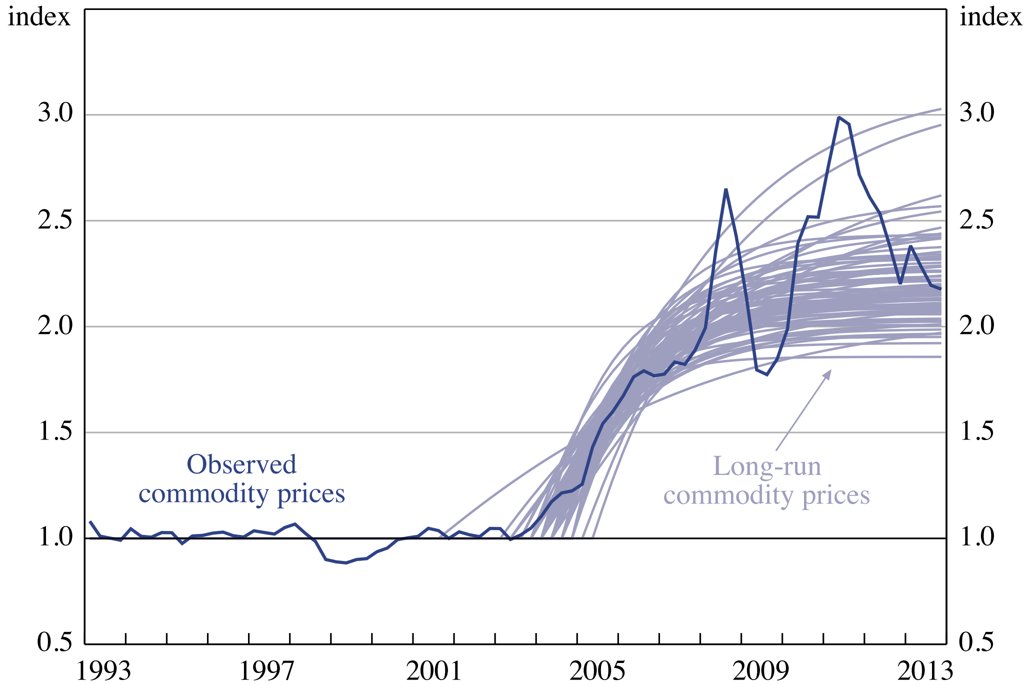
Next, we compare our inferences about long-run commodity prices with those obtained from single-equation estimates. Using the same priors, we estimate Equation (3) on the commodity price series alone. At the mode, we find a 114 per cent increase in the long-run level of commodity prices and a tripling in the volatility of shocks to commodity prices (although both variances are estimated to be lower than in our multivariate estimation).[15]

15 We find a mode of 0.02 for σ_κ and a mode of 0.07 for σ'_κ. We have also used the tests of Bai and Perron (1998) on the commodity price series without placing priors and allowed up to a maximum of five breaks. The tests prefer one break in 2003:Q3 and the estimates suggest a 90 per cent increase of the long-run level of commodity prices.

Figure 8 shows the posterior distribution of the implied transitional dynamics for long-run commodity prices from this single-equation exercise. One can fit the commodity price series better with smaller variances and a larger increase in the long-run mean. However, we consider this exercise to provide less plausible estimates of the long-run level of commodity prices because it relies on fewer observable variables. There is a trade-off in general equilibrium between fitting the commodity price series and fitting the other observables. We show this in Figure 9, which plots the transitional dynamics of the observable variables shown in Figure 7 calculated using the posterior distribution of long-run commodity prices from Figure 8.

Figure 8: Observed and Long-run Commodity Prices

Single-equation estimation; 1993–2002 average = 1



Sources: Authors' calculations; RBA

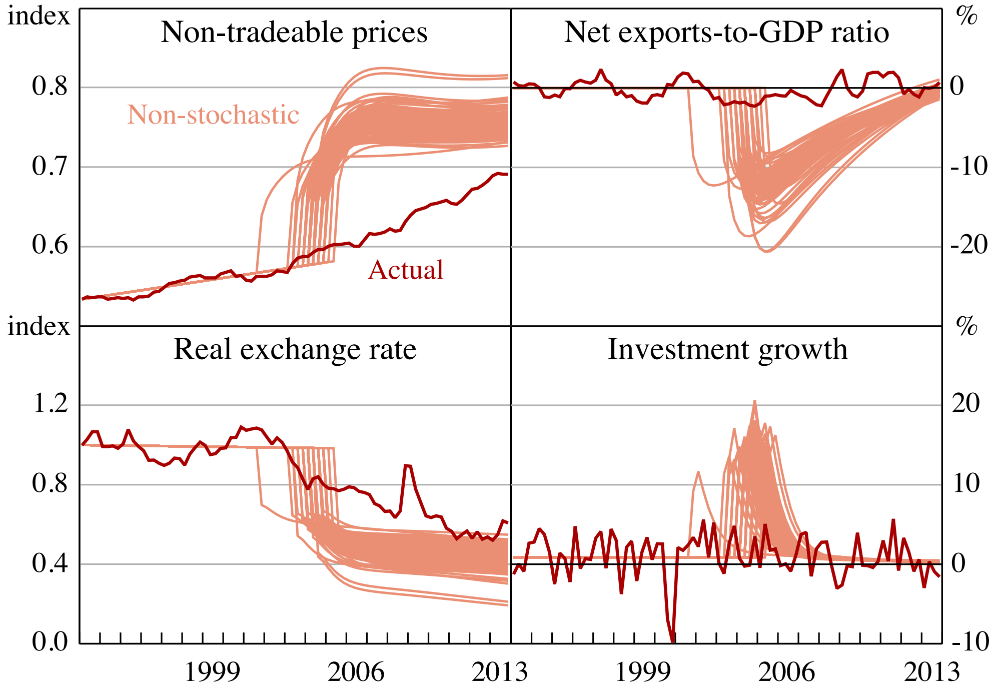
A 114 per cent increase in the long-run level of commodity prices would require larger shocks to explain the deviations between these non-stochastic transitional dynamics and the data. For example, the net exports-to-GDP ratio should have decreased by 15 percentage points and quarterly investment grown by close to 20 per cent. These numbers are far from the empirical regularities seen in the data.

This single-equation exercise is informative in two ways. First, because with theory in hand it allows us to assess the plausibility of reduced form estimates.

Second, it sheds light on how $\Delta\kappa$ is identified in estimation. In principle, the estimation procedure was free to fit commodity prices as seen in Figure 8. The reason that it did not choose that parameterisation is because it comes at the expense of a significant loss of fit for the other observable variables.

Figure 9: Data and Estimated Transitional Dynamics

Single-equation estimation



Sources: ABS; Authors' calculations

Relative to the single-equation estimates, our general equilibrium estimation reduces the size of the estimated increase in long-run commodity prices from 114 per cent to 42 per cent and increases the precision of the estimates. It is fair to wonder whether our estimate of $\Delta\kappa$ would equal zero if we were to remove commodity prices from the set of observable variables. In fact, we have run this estimation and find statistically significant evidence of a 20 per cent increase in $\Delta\kappa$.[16] The evidence for an increase in the long-run level of the terms of trade comes from all observable variables and not just from commodity prices.[17]

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16 These additional results can be found in our online appendix.

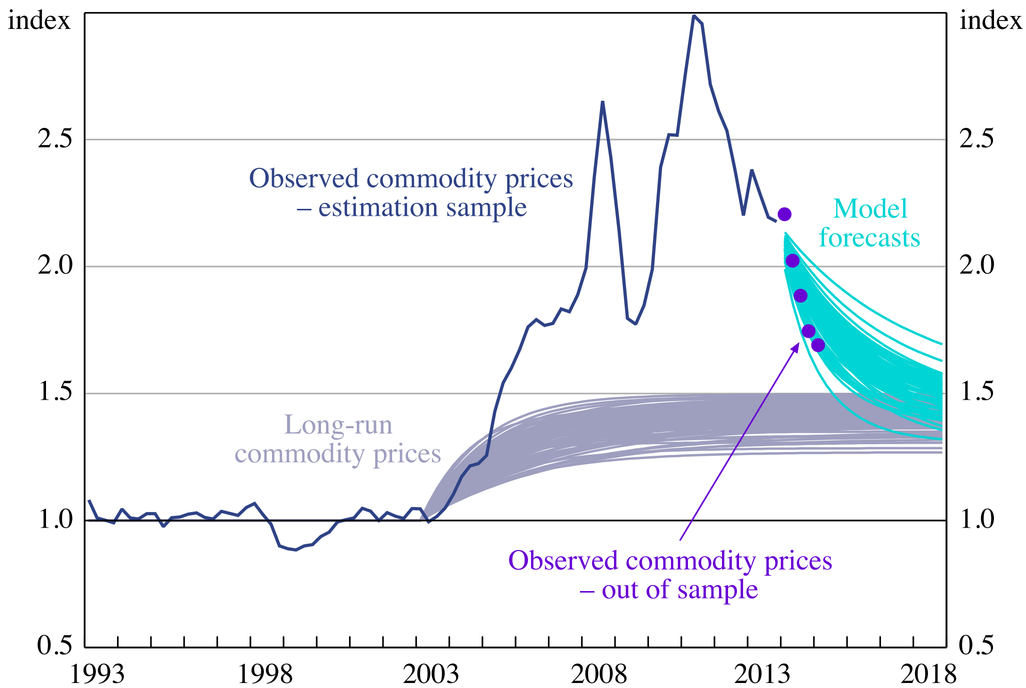
17 At the same time, the fact that the results from the estimation excluding commodity prices differ from our baseline results indicates that we are not merely recovering agents' beliefs about commodity prices.

6. Implications of Higher and More Volatile Commodity Prices

Our estimation sample ended in 2013:Q4. Since that time, commodity prices have fallen substantially. Are these developments consistent with the permanent increase in commodity prices that we estimate? To address this question, Figure 10 compares the posterior distribution of forecasts generated from our model to actual out-of-sample commodity price developments. As in Figure 6, the lines labelled 'Long-run commodity prices' show the posterior distribution of the estimated non-stochastic paths – that is, the path commodity prices would have taken in the absence of temporary shocks. In contrast, the lines labelled 'Model forecasts' show the posterior distributions of the model forecasts – that is, the path the model expected commodity prices to follow after 2013:Q4 along the transition to their long-run level, assuming no additional temporary shocks after the end of the sample. The forecasts and actual outcomes align closely. That is, recent commodity price developments are consistent with the idea that although a large part of the boom in commodity prices was temporary, a substantial portion was permanent.

Figure 10: Observed and Long-run Commodity Prices

1993–2002 average = 1



Sources: Authors' calcualations; RBA

The estimated changes in the unconditional mean and the volatility of the economy have implications for the structure of the economy as well as its sensitivity to commodity price shocks. Table 4 illustrates how the structure of the model economy changes as a result of the estimated 42 per cent increase in the long-run level of commodity prices. Other characteristics of the balanced growth path, including the growth rate of real quantities and rates of inflation are invariant in the long run to the level of commodity prices.

Table 4: Change in Economic Structure

Concept	Initial structure	Final structure
Expenditure (per cent of GDP)		
Consumption	72.7	72.0
Investment	27.3	28.0
Exports	19.7	22.0
Production (per cent of GDP)		
Non-tradeable	57.0	57.6
Home tradeable	36.2	32.3
Commodities	6.8	10.2
Exports (per cent of exports)		
Resource exports	34.6	51.8
Other exports	65.4	48.2
Relative prices (index)		
Real exchange rate	100.0	131.0

Note: The real exchange rate has been inverted so that an increase represents a real appreciation

The most striking consequence of the estimated increase in the long-run level of commodity prices is a shift in resources from the non-commodity tradeable sector to the commodity sector. The commodity sector's share of exports increases from 35 per cent to 52 per cent. And its share of value added increases from 6.8 per cent of GDP to 10.2 per cent. There is also a significant effect on the real exchange rate, which appreciates permanently by around 30 per cent.

Of course, it bears emphasising that these shifts in the model's steady state are estimates calculated at a single point in the parameter distribution. As Figure 7 illustrates, the standard errors surrounding some of these estimates are wide. Moreover, the shift in the model's steady state reflects only the effects of changes in the long-run level of commodity prices. In particular, it does not take into account factors, like unconventional monetary policy in many advanced economies, that have had a persistent influence on the level of Australia's real exchange rate in recent years.

The change in the economy's steady state and the change in the volatility of shocks to commodity prices alter the relative contribution that shocks have to the observable variables. To measure the implications of these changes, we compute unconditional variance decompositions at the estimated posterior mode for variables of interest in two regimes: a low commodity price and volatility regime ($\kappa = 1$ and $\sigma_\kappa = .05$) and a high commodity price and volatility regime ($\kappa = 1.42$ and $\sigma_\kappa = .11$) (Table 5).[18] We report only the contribution of commodity price shocks to the variances of these variables, as these show the greatest variation between the two regimes.

In the 'low regime', we estimate that shocks to commodity prices make a modest contribution to economic fluctuations. An exception is net exports, where shocks to commodity prices account for 15 per cent of the variance, and the level of the real exchange rate, where shocks to commodity prices account for about 3 per cent of the variance. In the 'high regime', the share of the variance of net exports and the level of the real exchange rate explained by shocks to commodity prices increases substantially. And commodity price shocks also make a modest, but noticeable, contribution to changes in the nominal exchange rate and non-tradeable inflation.

Table 5: Variance Decomposition

Per cent

Contribution to variance of	**Regime** Low	High
Inflation	0.0	0.3
Non-tradeable inflation	0.5	3.7
GDP growth	0.1	1.2
Investment growth	0.1	1.3
Consumption growth	0.1	0.5
Nominal exchange rate growth	0.5	4.6
Real exchange rate	3.2	44.8
Net exports-to-GDP ratio	14.8	57.8
Nominal interest rate	0.2	2.4

18 We do not report variance decompositions for the high-κ low-σ_κ regime because the joint posterior implies a low probability for this regime.

We draw two implications from our work. First, in light of our estimates, and the behaviour of commodity prices since the end of our sample, we believe that commodity prices will remain higher than they were before the commodity price boom. In the near term, the fall in commodity prices from their peak is likely to diminish growth in economic activity. But the pain would have been far worse if Australian firms, households and policymakers had behaved as if all of the increase in commodity prices during the boom had been permanent.

Second, the sensitivity of Australian economic developments to commodity price movements during the peak of the commodities boom was unusual. In the future, commodity price developments will probably not exert as much influence over aggregate economic activity, consumption, or even investment. However, a permanently higher level of commodity prices and larger commodity price shocks mean that, relative to the period before the commodity price boom, the commodity sector will account for a larger share of the economy and commodity price movements will be more important, particularly for exports and the exchange rate.

7. Conclusion

The development of Asia over the past decade or more led to unprecedented increases in global commodity prices and large increases in the terms of trade of economies that export substantial quantities of commodities. A recurrent question has been the degree to which these changes are permanent. Our objective has been to estimate the permanent change in the level and volatility of commodity export prices and to measure the consequences with the aid of a structural model.

A contribution of our paper is that we treat trends and cycles in a model-consistent way. Economic theory asserts that permanent changes in the terms of trade must influence other relative prices. In open economies, non-tradeable prices, consumer prices, investment prices, foreign output, foreign prices, real investment and real output all grow at different trend rates. Because our model's balanced growth path has these trends, we can identify the extent to which trends, cycles and breaks drive the fluctuations in the data.

We detect a change in the long-run level and volatility of Australia's terms of trade. We find that the long-run level of commodity export prices increased by around 40 per cent starting in 2003. This estimate is less than what casual observation might suggest and less than what single-equation structural break tests indicate. In forward-looking general equilibrium models a change in the long-run mean of the terms of trade manifests itself in the other observable series we use in estimation. Inferences from single-equation models that are not grounded in theory can yield implausible predictions. Using more observable variables in structural estimation helps us to identify the long-run level of commodity prices. Although general equilibrium estimates are less than what may be inferred otherwise, the estimated change in the long-run level of commodity prices has a significant impact on the economy.

Appendix A: Model

In this appendix we describe the basic structure of the model. For a full derivation of the first order conditions and results, please consult the online appendix.

A.1 Households

The preferences of a typical household in the small open economy are given by:

$$E_0\left\{\sum_{t=0}^{\infty}\beta^t\zeta_t\left[\log(C_t-hC_{t-1})-\varepsilon_{L,t}\frac{L_t^{1+\nu}}{1+\nu}\right]\right\}$$

where E_0 denotes the time 0 conditional expectation, β is the household's discount rate, C_t is consumption, L_t is labour supply and $h\in[0,1]$ governs the degree of external habit formation. The variable ζ_t is an intertemporal preference shock that follows the stochastic process:

$$\log\zeta_t=\rho_\zeta\log\zeta_{t-1}+u_{\zeta,t} \tag{A1}$$

with $u_{\zeta,t}$ independently and identically distributed $N(0,\sigma_\zeta^2)$. The variable $\varepsilon_{L,t}$ is a labour supply shock that follows the process:

$$\log\varepsilon_{L,t}=\rho_\varepsilon\log\varepsilon_{L,t-1}+u_{L,t} \tag{A2}$$

with $u_{L,t}$ independently and identically distributed $N(0,\sigma_L^2)$.

Aggregate labour supply consists of labour supplied to the home-tradeable goods sector, $L_{H,t}$, the non-tradeable goods sector, $L_{N,t}$, and the commodity-exporting sector, $L_{X,t}$, according to the constant elasticity of substitution (CES) bundle:

$$L_t=\left[\xi_H L_{H,t}^{1+\omega}+\xi_N L_{N,t}^{1+\omega}+\xi_X L_{X,t}^{1+\omega}\right]^{\frac{1}{1+\omega}} \tag{A3}$$

Workers view employment in different sectors as imperfect substitutes. The parameter ω controls the willingness of workers to move between sectors in response to wage differentials, while the parameters ξ_H, ξ_N and ξ_X govern the relative desirability of supplying labour to each sector.

The household enter the period with $K_{j,t}$ units of capital from sector $j \in \{H, N, X\}$, B_t units of one-period risk-free bonds denominated in domestic currency and B_t^* units of one-period risk-free bonds denominated in foreign currency. During the period, the household receives wages, returns on capital and profits and pays lump sum transfers to the government. The household uses its income to purchase new bonds, to invest in new capital and to purchase consumption goods. The resulting flow budget constraint is:

$$P_t C_t + \sum_{j \in \{H,N,X\}} P_{I,t} \mathscr{I}_{j,t} + B_{t+1} + S_t B_{t+1}^* \leq R_{t-1} B_t$$
$$+ R_{t-1}^F S_t B_t^* + \sum_{j \in \{H,N,X\}} (W_{j,t} L_{j,t} + R_t^j K_{j,t} + \Gamma_{j,t}) - T_t$$

where P_t is the consumer price index, $P_{I,t}$ is the price of the aggregate investment good, $\mathscr{I}_{j,t}$ is investment in sector j, $W_{j,t}$, R_t^j and $\Gamma_{j,t}$ are the wage rate, the rate of return on capital and profits in sector j, T_t are lump-sum transfers, R_t and R_t^F are the gross interest rates on risk-free bonds in domestic and foreign currency and S_t is the nominal exchange rate, defined as the domestic price of foreign currency.

The capital stock of each sector evolves according to the law of motion:

$$K_{j,t+1} = (1-\delta) K_{j,t} + \tilde{V}_t \left[1 - \Upsilon\left(\frac{\mathscr{I}_{j,t}}{\mathscr{I}_{j,t-1}} \right) \right] \mathscr{I}_{j,t} \tag{A4}$$

for $j \in \{H, N, X\}$ where δ is the capital depreciation rate and Υ is an investment adjustment cost with the standard restrictions that in steady state $\Upsilon(\bullet) = \Upsilon'(\bullet) = 0$ and $\Upsilon''(\bullet) > 0$. $\tilde{V}_t$ governs the efficiency with which investment adds to the capital stock. It follows the process:

$$\tilde{V}_t = v \left(\frac{1}{z_I} \right)^t V_t \tag{A5}$$

where z_I is the differential between the growth rate of real investment and the growth rate of labour-augmenting technology, z. V_t is a stationary autoregressive process that affects the marginal efficiency of investment of the form:

$$\log V_t = \rho_V \log V_{t-1} + u_{V,t} \tag{A6}$$

where $u_{V,t}$ is identically and independently distributed $N(0,\sigma_V^2)$. On the balanced growth path $\mathscr{I}_{j,t}$ grows at $z \times z_I$. The term on the right hand side of Equation (A4), $\tilde{V}_t \mathscr{I}_{j,t}$, grows at z. Thus, the trend in $\tilde{V}_t$ enables a balanced growth path in which real investment grows faster than real consumption.

As explained by Schmitt-Grohé and Uribe (2003), to ensure stationarity we link the interest rate that domestic residents pay for foreign borrowing to the economy's net foreign asset position. The interest rate on foreign bonds is given by

$$R_t^F = R_t^* \exp\left[-\psi_b\left(\frac{S_t B_t^*}{NGDP_t} - b^*\right) + \tilde{\psi}_{b,t}\right] \tag{A7}$$

where R_t^* is the foreign interest rate, b^* is the steady-state net foreign asset-to-GDP ratio and $NGDP_t$ is nominal GDP. $\tilde{\psi}_{b,t}$ is a risk premium shock that follows the process:

$$\tilde{\psi}_{b,t} = \rho_\psi \tilde{\psi}_{b,t-1} + u_{\psi,t} \tag{A8}$$

where $u_{\psi,t}$ is independently and identically distributed $N(0,\sigma_\psi^2)$.

A.2 Final Goods-producing Firms

The economy features two final goods: a composite consumption good and a composite investment good. We describe each in turn.

A.2.1 Final consumption goods

Final consumption goods are produced by a representative competitive firm that combines non-tradeable and tradeable consumption goods according to the technology:

$$C_t = \left[\gamma_{T,t}^{\frac{1}{\eta}} C_{T,t}^{\frac{\eta-1}{\eta}} + \gamma_{N,t}^{\frac{1}{\eta}} C_{N,t}^{\frac{\eta-1}{\eta}}\right]^{\frac{\eta}{\eta-1}}$$

where $C_{N,t}$ is the output of the non-traded sector that is directed towards consumption and has price $P_{N,t}$ while $C_{T,t}$ is the output of the traded sector that is directed towards consumption and has price $P_{T,t}$. The deterministic processes $\gamma_{T,t}$ and $\gamma_{N,t}$ ensure, as in Rabanal (2009), that expenditure shares remain stationary along the balanced growth path.[19] $C_{T,t}$ is a composite of domestically produced and imported tradeable goods assembled according to the technology:

$$C_{T,t} = \frac{(C_{H,t})^{\gamma_H}(C_{F,t})^{\gamma_F}}{(\gamma_H)^{\gamma_H}(\gamma_F)^{\gamma_F}}$$

The Cobb-Douglas specification guarantees that the expenditure shares in the tradeable consumption basket remain constant. This assumption is convenient to find the normalisations to make the system stationary. Otherwise, γ_H and γ_F would have to trend to keep nominal expenditure shares constant in steady state. The trends in γ_H and γ_F, together with the differential growth rate of the home-tradeable producing goods, z_H, and the differential growth rate of the foreign goods producing sector, z^*, would determine the differential growth rate of the tradeable basket, that is, z_T. But to find the trends in γ_H and γ_F one must know z_T.

The non-traded, domestically produced traded and imported consumption goods are all bundles of a continuum of imperfectly substitutable goods:[20]

$$C_{j,t} \equiv \left(\int_0^1 C_{j,t}(i)^{\frac{\theta_j - 1}{\theta_j}} di \right)^{\frac{\theta}{\theta - 1}}$$

for $j \in \{H, N, F\}$. Profit maximisation and the zero-profit condition imply that the price of the final consumption good is a CES aggregate of the prices of the non-tradeable and tradeable consumption goods:

$$P_t = \left[\gamma_{T,t} P_{T,t}^{1-\eta} + \gamma_{N,t} P_{N,t}^{1-\eta} \right]^{\frac{1}{1-\eta}} \tag{A9}$$

and the price of the tradeable consumption good is a Cobb-Douglas aggregate of the home-produced and imported goods:

$$P_{T,t} = (P_{H,t})^{\gamma_H}(P_{F,t})^{\gamma_F} \tag{A10}$$

19 See the online appendix for details about the normalisations.

20 This is also the case for investment, $I_{j,t}$ for $j \in \{H, N, F\}$.

A.2.2 Final investment goods

Final investment goods are produced by a representative competitive firm according to the technology:

$$I_t = z_v^t \frac{(I_{T,t})^{\gamma_T^I}(I_{N,t})^{\gamma_N^I}}{(\gamma_T^I)^{\gamma_T^I}(\gamma_N^I)^{\gamma_N^I}}$$

where $I_{N,t}$ is the output of the non-traded sector directed towards the production of investment, $I_{T,t}$ is the output of the traded sector that is directed towards investment and z_v is a productivity trend that, jointly with the growth rates of $I_{T,t}$ and $I_{N,t}$, determines the steady state growth rate of final investment, z_I.[21] $I_{T,t}$ is a composite of domestically and foreign-produced tradeable goods that is assembled according to the technology:

$$I_{T,t} = \frac{(I_{H,t})^{\gamma_H^I}(I_{F,t})^{\gamma_F^I}}{(\gamma_H^I)^{\gamma_H^I}(\gamma_F^I)^{\gamma_F^I}}$$

The corresponding price indices are:

$$P_t^I = (P_{T,t}^I)^{\gamma_T^I}(P_{N,t})^{\gamma_N^I} \tag{A11}$$

and

$$P_{T,t}^I = (P_{H,t})^{\gamma_H^I}(P_{F,t})^{\gamma_F^I} \tag{A12}$$

As the shares of non-tradeable, domestically produced tradeable and imported goods in the investment and consumption composites differ, the price of final consumption goods, P_t, will differ from the price of investment goods, $P_{I,t}$. Similarly, the price of tradeable consumption goods, $P_{T,t}$, will differ from the price of tradeable investment goods, $P_{T,t}^I$.

21 Ireland and Schuh (2008) and Justiniano, Primiceri and Tambalotti (2011) are examples of closed economy models with a trend in the price of investment goods and a wedge between the growth rates of real investment and real output.

A.3 Intermediate Goods-producing Firms

The economy features four intermediate good producers: commodity firms, non-tradeable firms, domestic non-commodity tradeable firms and importing firms. We describe each in turn.

A.3.1 Commodity-exporting firms

Commodity firms produce a homogeneous good in a perfectly competitive market using the Cobb-Douglas production function:

$$Y_{X,t} = A_t \tilde{Z}_{X,t} \left(K_{X,t}\right)^{\alpha_X} \left(Z_t L_{X,t}\right)^{1-\alpha_X} \tag{A13}$$

where Z_t is a labour-augmenting technology shock, common to all producing sectors, whose growth rate, $z_t = Z_t/Z_{t-1}$, follows the process:

$$\log z_t = (1-\rho_z)\log z + \rho_z \log z_{t-1} + u_{z,t} \tag{A14}$$

where $z > 1$ determines the trend growth rate of real GDP and $u_{z,t}$ is independently and identically distributed $N(0,\sigma_z^2)$. The sector-specific productivity process, $\tilde{Z}_{X,t}$, follows

$$\tilde{Z}_{X,t} = z_X^t Z_{X,t} \tag{A15}$$

where $z_X > 0$ determines the differential growth rate, along the balanced growth path, between the output of the commodity-exporting sector and real GDP. The stationary process $Z_{X,t}$ gives rise to temporary departures from the differential trend by:

$$\log Z_{X,t} = \rho_X \log Z_{X,t-1} + u_{X,t} \tag{A16}$$

where $u_{X,t}$ is independently and identically distributed $N(0,\sigma_X^2)$. In Equation (A13) A_t is a stationary technology shock, also common to all sectors, that follows the process:

$$\log A_t = \rho_A \log A_{t-1} + u_{A,t} \tag{A17}$$

where $u_{A,t}$ is independently and identically distributed $N(0,\sigma_A^2)$.

Commodity producers take prices as given. These prices are set in world markets and are unaffected by domestic economic developments. Specifically, we assume that the price of commodities, in foreign currency terms, is equal to:

$$P^*_{X,t} = \tilde{\kappa}_t P^*_t \tag{A18}$$

where P^*_t is the foreign price level and $\tilde{\kappa}_t$, which governs the relative price of commodities, follows the exogenous process:

$$\tilde{\kappa}_t = \kappa_t \left(\frac{z^*}{z^*_X} \right)^t \tag{A19}$$

where z^* is the differential growth rate of foreign output and z^*_X is the differential growth rate of foreign production of commodities. The drift in the relative price of commodities reflects the relative productivity growth of the commodity sector and the foreign economy. Along the balanced growth path, relative commodity prices experience transitory shocks according to the process:

$$\log \kappa_t = (1 - \rho_\kappa) \log \kappa + \rho_\kappa \log \kappa_{t-1} + u_{\kappa,t} \tag{A20}$$

where $u_{\kappa,t}$ is independently and identically distributed $N(0, \sigma^2_\kappa)$. For the stochastically detrended variables, κ determines the unconditional mean of the terms of trade and, in turn, is one of the determinants of the economy's steady state. In estimation, we allow for breaks in κ and in σ_κ, possibly occurring at different dates in the sample.

The law of one price holds for commodities. This means that their price in domestic currency terms is:

$$P_{X,t} = S_t P^*_{X,t} \tag{A21}$$

A.3.2 Non-tradeable goods-producing firms

Non-tradeable firms sell differentiated products, which they produce using the Cobb-Douglas production function:

$$Y_{N,t}(i) = A_t \tilde{Z}_{N,t} \left(K_{N,t}(i) \right)^{\alpha_N} \left(Z_t L_{N,t}(i) \right)^{1-\alpha_N} \tag{A22}$$

$\tilde{Z}_{N,t}$ is sector-specific productivity process that follows:

$$\tilde{Z}_{N,t} = z_N^t Z_{N,t}$$

where $z_N > 0$ and $Z_{N,t}$ are transitory deviations from the sector-specific trend that follow the process:

$$\log Z_{N,t} = \rho_N \log Z_{N,t-1} + u_{N,t} \tag{A23}$$

where $u_{N,t}$ is independently and identically distributed $N(0, \sigma_N^2)$. We introduce price stickiness into this sector by assuming that firms can only change prices at some cost, following a Rotemberg (1982) pricing mechanism:[22]

$$\frac{\psi_N}{2}\left(\frac{P_{N,t}(i)}{\Pi^N P_{N,t-1}(i)} - 1\right)^2 P_{N,t} Y_{N,t}$$

where ψ_N governs the size of the price adjustment cost and Π^N is the steady-state inflation rate of non-tradeable goods prices.

Aggregate non-tradeable output is defined by a CES aggregator:

$$Y_{N,t} \equiv \left(\int_0^1 Y_{N,t}(i)^{\frac{\theta_N - 1}{\theta_N}} di\right)^{\frac{\theta_N}{\theta_N - 1}}$$

A.3.3 Domestic non-commodity tradeable goods-producing firms

Domestic tradeable firms produce differentiated products using the Cobb-Douglas production function:

$$Y_{H,t}(i) = A_t \tilde{Z}_{H,t} \left(K_{H,t}(i)\right)^{\alpha_H} \left(Z_t L_{H,t}(i)\right)^{1-\alpha_H} \tag{A24}$$

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22 We assume that these price adjustment costs do not affect the cash flow of firms, but only affect their objective function (see De Paoli, Scott and Weeken (2010) for a discussion of this approach.) Therefore, they do not appear in the resource constraint or net export equations. Assuming instead that these adjustment costs are real costs would yield equivalent results as quadratic terms do not appear in the linearised system.

$\tilde{Z}_{H,t}$ is a stationary sector-specific productivity shock that follows:

$$\tilde{Z}_{H,t} = z_H^t Z_{H,t}$$

where $z_H > 0$ and $Z_{H,t}$ are temporary deviations from that trend according to the process:

$$\log Z_{H,t} = \rho_H \log Z_{H,t-1} + u_{H,t} \tag{A25}$$

where $u_{H,t}$ is independently and identically distributed $N(0, \sigma_H^2)$. Like their non-tradeable counterparts, tradeable firms can only change prices at some cost, following a Rotemberg (1982) pricing mechanism:

$$\frac{\psi_H}{2}\left(\frac{P_{H,t}(i)}{\Pi^H P_{H,t-1}(i)} - 1\right)^2 P_{H,t} Y_{H,t}$$

where ψ_H governs the size of the price adjustment cost and Π^H is the steady-state inflation rate of domestic non-commodity tradeable goods prices. Domestic tradeable output, $Y_{H,t}$ is an aggregate of the output of each of the domestic tradeable firms:

$$Y_{H,t} \equiv \left(\int_0^1 Y_{H,t}(i)^{\frac{\theta_H - 1}{\theta_H}} di\right)^{\frac{\theta_H}{\theta_H - 1}}$$

A.3.4 Importing firms

Importing firms purchase foreign good varieties at the price $\varsigma S_t P_t^*$ and sell them in the domestic market at price $P_{F,t}(i)$. The parameter ς represents a subsidy to importing firms, funded by lump-sum taxation. We set the subsidy equal to $\varsigma = (\theta_F - 1)/\theta_F$, thereby ensuring that mark-ups in this sector are zero in equilibrium.

Importing firms can also only change prices at some cost, following a Rotemberg (1982) pricing mechansim:

$$\frac{\psi_F}{2}\left(\frac{P_{F,t}(i)}{\bar{\Pi}^F P_{F,t-1}(i)} - 1\right)^2 P_{F,t} Y_{F,t}$$

A.4 Foreign Sector, Net Exports and the Current Account

Following Gertler, Gilchrist and Natalucci (2007), we postulate a foreign demand function for domestically produced tradeable goods, $C^*_{H,t}$, of the form:

$$C^*_{H,t} = \gamma^*_{H,t} \left(\frac{P_{H,t}}{S_t P^*_t} \right)^{-\eta^*} \tilde{Y}^*_t \tag{A26}$$

Foreign output, $\tilde{Y}^*_t$, follows the non-stationary process

$$\tilde{Y}^*_t = Z_t (z^*)^t Y^*_t$$

Transitory deviations from foreign trend growth are captured by Y^*_t which follows:

$$\log Y^*_t = \rho^*_Y \log Y^*_t + u^*_{Y,t} \tag{A27}$$

where $u^*_{Y,t}$ is independently and identically distributed $N(0, \sigma^{2\,*}_Y)$. Foreign inflation is assumed to follow:

$$\log \Pi^*_t = (1 - \rho^*_\Pi) \log \Pi^* + \rho^*_\Pi \log \Pi^*_{t-1} + u^*_{\Pi,t} \tag{A28}$$

and the foreign interest rate follows:

$$\log R^*_t = (1 - \rho^*_R) \log R^* + \rho^*_R \log R^*_{t-1} + u^*_{R,t} \tag{A29}$$

where the independently and identically distributed shocks $u^*_{\Pi,t}$ and $u^*_{R,t}$ are distributed $N(0, \sigma^{2\,*}_\Pi)$ and $N(0, \sigma^{2\,*}_R)$.

Net exports are given by:

$$NX_t = P_{H,t} C^*_{H,t} + P_{X,t} Y_{X,t} - P_{F,t} \left(C_{F,t} + I_{F,t} \right) \tag{A30}$$

and so the current account equation is given by:

$$S_t B^*_{t+1} = R^F_{t-1} S_t B^*_t + NX_t \tag{A31}$$

A.5 Monetary Policy

The domestic central bank follows a Taylor rule that responds to deviations of output growth and inflation from their steady-state levels

$$\begin{aligned} \log\left(\tfrac{R_t}{R}\right) &= \rho_r \log\left(\tfrac{R_{t-1}}{R}\right) \\ &+(1-\rho_R)\left[\phi_\pi \log\left(\tfrac{\Pi_t}{\Pi}\right)+\phi_y \log\left(\tfrac{Y_t}{zY_{t-1}}\right)\right]+u_{R,t} \end{aligned} \tag{A32}$$

where $\Pi_t = P_t/P_{t-1}$ is the inflation rate in terms of final consumption goods prices and Π is the central bank's inflation target.

A.6 Market Clearing

Market clearing for investment goods requires that production of these goods equals the quantity demanded by the three domestic production sectors

$$I_t = \mathscr{I}_{H,t} + \mathscr{I}_{N,t} + \mathscr{I}_{X,t} \tag{A33}$$

For the non-tradeable, domestic tradeable and import sectors, market clearing requires that the quantity produced equals the quantity demanded:

$$Y_{N,t} = C_{N,t} + I_{N,t} \tag{A34}$$

$$Y_{H,t} = C_{H,t} + C^*_{H,t} + I_{H,t} \tag{A35}$$

$$Y_{F,t} = C_{F,t} + I_{F,t} \tag{A36}$$

Nominal GDP is defined as:

$$NGDP_t = P_{N,t}Y_{N,t} + P_{H,t}Y_{H,t} + P_{X,t}Y_{X,t} \tag{A37}$$

and real GDP is defined as:

$$Y_t = \frac{P_N}{P}Y_{N,t} + \frac{P_H}{P}Y_{H,t} + \frac{P_X}{P}Y_{X,t} \tag{A38}$$

Appendix B: Data Sources

B.1 Data Used in Estimation

The model is estimated using 14 macroeconomic time series. Real GDP, consumption, investment, net exports and hours worked are taken from the Australian Bureau of Statistics (ABS) national accounts data (ABS Cat No 5206.0). All data are seasonally adjusted and measured in chain volume terms, except for the net exports-to-GDP ratio, which is seasonally adjusted and measured in current prices, and hours worked, which is seasonally adjusted. We convert all of the real activity series into per capita series by dividing by the Australian population, which we derive from the GDP per capita series. Our final domestic activity series is the ratio of nominal non-traded consumption to aggregate consumption. We discuss the construction of the non-traded consumption series below.

Our measures of Australian inflation are the consumer price index and non-tradeables price index, both excluding interest and tax. These series are published by the ABS (ABS Cat No 6401.0). Our measure of the nominal exchange rate is the Australian trade-weighted index and our policy interest rate is the cash rate. We source these series from the Reserve Bank of Australia (RBA) statistical tables F1.1 and F11.

For foreign GDP we use the index of Australia's major trading partners' GDP, calculated at purchasing power parity exchange rates, produced by the RBA. For foreign interest rates, we use the average policy rate in the United States, Japan and the euro area (we use German interest rates before the introduction of the euro). Finally, we calculate foreign inflation implicitly using Australian inflation and the real exchange rate index, published by the RBA in statistical table F.15.

B.2 Data Used in Calibration

This section describes the calculation of the sectoral data used to calibrate the model.

- **Tradeable and non-tradeable consumption:** We allocated private consumption categories in the national accounts to either tradeable or non-tradeable consumption to match the components of the published tradeable and non-tradeable consumption price indices (see ABS Cat No 6461.0, Appendix 2 for these categories). Tradeable consumption is the sum of private food; cigarettes & tobacco; alcohol; clothing & footwear; purchase of vehicles; communications; and recreation & culture consumption. It also includes 24 per cent of healthcare consumption, reflecting the share of pharmaceutical products, which are tradeable, in total healthcare consumption and 50 per cent of other household services. Non-tradeable consumption includes rent, electricity, gas & water; operation of vehicles; transport services; education; hotels, cafes & restaurants; insurance & financial services; as well as healthcare and other households services not allocated to tradeable consumption. We assume that the allocation of private consumption between tradeable and non-tradeable goods is the same as for private consumption. We measure imported consumption as the sum of consumption goods imports, 75 per cent of services imports and 25 per cent of intermediate imports.

- **Tradeable and non-tradeable investment:** We define tradeable investment as the sum of machinery & equipment investment and 36 per cent of both non-residential construction and public investment. We base the tradeable shares of construction on Table 1 of Burstein, Neves and Rebelo (2004). Non-tradeable investment is total investment less tradeable investment. We measure imported investment as the sum of capital goods imports plus 25 per cent of services imports and 75 per cent of intermediate imports.

- **Resource and non-resource exports:** We use the measure of resource exports published in ABS Cat No 5302.0. Non-resource exports equal total exports less resource exports.

- **Hours worked:** As hours worked data is unavailable at an industry level in Australia, we construct our measure using employment data. This will result in some inaccuracy if average hours worked varies across industries. We define tradeable employment as the sum of agriculture; mining; wholesale trade; accomodation & food; and transport, postal & warehousing employment. Our measure of employment in the resources sector is mining employment. As discussed in Plumb *et al* (2013), this understates total employment in the resources sector as it excludes workers in industries that service the operations of the mining sector. Our model calibration takes account of this feature of the data. Non-tradeable employment is all employment not categorised as tradeable or mining.

Appendix C: Additional Results

Table C1: Prior and Posterior Distribution of Shock Processes

	Prior distribution			**Posterior distribution**			
Variable	Shape	Mean	Std dev	Mode	Mean	5%	95%
ρ_H	Beta	0.5	0.2	0.91	0.90	0.85	0.95
ρ_N	Beta	0.5	0.2	0.99	0.99	0.99	1.00
ρ_X	Beta	0.5	0.2	0.82	0.81	0.70	0.90
ρ_ζ	Beta	0.5	0.2	0.70	0.61	0.34	0.81
ρ_v	Beta	0.5	0.2	0.29	0.31	0.18	0.44
ρ_L	Beta	0.5	0.2	0.87	0.82	0.66	0.93
ρ_z	Beta	0.5	0.2	0.65	0.63	0.50	0.75
ρ_A	Beta	0.5	0.2	0.53	0.54	0.29	0.78
ρ_ψ	Beta	0.5	0.2	0.69	0.68	0.54	0.81
ρ_{y^*}	Beta	0.5	0.2	0.60	0.59	0.35	0.81
ρ_{r^*}	Beta	0.5	0.2	0.97	0.97	0.96	0.98
ρ_{π^*}	Beta	0.5	0.2	0.41	0.41	0.26	0.56
σ_H	Inv gamma	0.1	2	0.020	0.020	0.017	0.024
σ_N	Inv gamma	0.1	2	0.011	0.011	0.009	0.013
σ_X	Inv gamma	0.1	2	0.069	0.068	0.059	0.081
σ_ζ	Inv gamma	0.1	2	0.016	0.014	0.012	0.022
σ_v	Inv gamma	0.1	2	0.060	0.065	0.042	0.093
σ_L	Inv gamma	0.1	2	0.042	0.045	0.034	0.058
σ_z	Inv gamma	0.01	2	0.004	0.004	0.003	0.004
σ_A	Inv gamma	0.01	2	0.002	0.002	0.001	0.003
σ_r	Inv gamma	0.01	2	0.001	0.001	0.001	0.001
σ_ψ	Inv gamma	0.01	2	0.011	0.012	0.007	0.018
σ_{y^*}	Inv gamma	0.01	2	0.002	0.002	0.001	0.002
σ_{r^*}	Inv gamma	0.01	2	0.001	0.001	0.001	0.001
σ_{π^*}	Inv gamma	0.01	2	0.003	0.003	0.003	0.004

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