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Do central banks respond to exchange rate movements? A Markov-switching structural investigation of commodity exporters and importers☆

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ABSTRACT

We analyse whether central banks in small open commodity exporting and importing countries respond to exchange rate movements, taking into consideration that there may be structural changes in parameters and volatility. Using a Markov Switching Rational Expectations framework, we estimate the model for Australia, Canada, New Zealand, Norway, Sweden and the UK. We find that the size of policy responses, and the volatility of structural shocks, have not stayed constant over the estimation sample. Furthermore, monetary policy has responded strongly to the exchange rate for many commodity exporters, most notablyNorway. This has had a stabilizing effect on the exchange rate. In particular, although the terms of trade are highly volatile among commodity exporters, the exchange rate has about the same volatility across all importers and exporters in the recent period.

1. Introduction

During the last two decades an increasing number of small open economies have officially abandoned their fixed exchange rate arrangements to allow their currencies to float within an inflation targeting framework for monetary policy. More exchange rate flexibility is associated with macroeconomic and financial stability (see Ghosh et al. (2015)), as well as a requirement for monetary policy independence according to the classic monetary policy trilemma (see Mundell (1963)). However, small open economies will be affected differently by the global business cycles, depending on whether they are major exporters or importers of commodities. As terms of trade are often very volatile in resource rich countries, flexible exchange rates may not be enough to provide overall economic stability, as well as guarantee monetary autonomy in a world of large capital flows, see e.g. Rey (2016).[1] Inflation targeting central banks may therefore want to respond to the exchange rate to independently stabilize their economy.

Previous studies analysing whether central banks respond to the exchange rate, however, have found conflicting evidence. In particular, Lubik and Schorfheide (2007) estimate a small structural general equilibrium model for Australia, Canada, New Zealand and the UK, and find that Canada and the UK include the exchange rate in their Taylor rule. However, in another study, using more recent data, Dong (2013) finds that neither of the four countries show any clear evidence that they adjusted the interest rate in response to the exchange rate. [2]

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[1] Furthermore some also question the extent to which exchange rates are truly flexible, see Calvo and Reinhart (2002).

[2] In addition to having more recent data, the model setup also varies slightly, as Dong (2013) allows both the terms of trade to be endogenous and incomplete pass-through beyond sticky-price-only set-up.

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In this paper we take a different approach. Where previous studies have estimated structural general equilibrium models with interest rate rules for monetary policy using constant parameters, we will allow policy rule coefficients to change over time. In particular, there is ample reduced form evidence that the degree of exchange rate stabilization has changed over time in many small open economies (see Ilzetzki et al. (2017a)), and maybe more so for commodity exporters. Failure to also then allow parameters to change when analysing the role of monetary policy in exchange rate stabilization could bias the estimates, and explain the different results in the literature.

Against this background, we analyse whether central banks respond to exchange rate changes in a framework allowing for regime changes to the monetary policy responses and in the variance of shocks that hit small open economies. Our main aim is to explore whether inflation targeting central banks in commodity exporting countries put the same weight on stabilizing the exchange rate throughout the period independently of the known regime changes and the volatility of shocks, and also compared to commodity importing countries. Furthermore, given that we observe a policy regime change, we analyse how this may have impacted the responses of output and inflation to external shocks. A strong or weak policy response to the exchange rate may imply larger or smaller volatility of endogenous variables, depending on the cocktail of disturbances hitting the economy.

To answer these questions, we extend a small open economy dynamic stochastic general equilibrium (DSGE) model to include a time-varying policy rule as well as time-varying structural shocks. The constant parameter part of the model is similar in style to the model in Galí and Monacelli (2005) and adapted also in Lubik and Schorfheide (2007). Our aim of the paper is to shed light on the question about whether central banks respond to exchange rate movements using a standard framework like that in Lubik and Schorfheide (2007), but allowing for non-linearities.[3]

The time-variation that we allow for is modeled as independent Markov switching in monetary policy responses on the one hand, and in the variances of structural shocks on the other. With rational expectations, our model incorporates the fact that agents in the economy realize that regime changes are possible at any time.[4] To estimate the regime switches, we use the Newton solution algorithm developed by Maih (2015), which extends Farmer et al. (2011) by being more general and efficient. The model is estimated using Bayesian techniques accommodating different regimes within one model. We estimate a model where the parameters may switch simultaneously or independently, allowing for a simultaneous inference on both the policy parameters and the stochastic volatilities.[5]

The analysis is applied (independently) to six small-open-economy countries: Australia, Canada, New Zealand, Norway, Sweden and the UK, that are differently affected by the global business cycle: Australia, Canada, Norway and New Zealand are commodity exporters, of which Canada and Norway are major oil exporters. Sweden and the UK are commodity importing countries. By analysing these countries we believe our results can be generalized to a broader set of countries, and we are able to shed light on differences in exchange rate policy between commodity exporters and importers. We use quarterly data with the longest available sample possible: Starting in 1964 for Canada and the UK; 1968 for Australia, 1974 for New Zealand and 1982 for Norway and Sweden. Over the sample analysed, all countries have also formally abandoned exchange rate targeting and adopted inflation targeting as a framework for monetary policy. Consistent with the structural model, the exchange rate that countries potentially stabilize in our model is measured as the nominal effective exchange rate (measured with time-varying trade weights).

We have three main findings. First, there is strong evidence that neither policy responses nor the volatility of structural shocks have remained constant throughout the sample period analysed in any of the six countries. For each country, we identify both “high” and “low” exchange-rate-response regimes, as well as “high” and “low” volatility regimes. Still, the timing of the policy parameter changes and the persistence of the high response regime vary from country to country: Australia stands out and responds strongly to the exchange rate only in certain brief periods early in the sample. In Sweden and the UK, the central banks switch from a high to a low exchange rate response regime shortly after severe periods of currency crises and the collapse of their fixed exchange rate regime - UK after the collapse of the Bretton Woods system in 1972 and Sweden after the regime to European Currency Union (ECU) broke down in 1992 and they adopt inflation targeting (1993). The central banks in three of the commodity exporting countries Canada, New Zealand and Norway, however, remain in a high response regime until the end of the 1990s, some time after adopting inflation targeting. For Norway, the central bank also responds strongly to the exchange rate even after adopting inflation targeting. These are new results in the literature, giving a more nuanced picture of the weights that central banks give to stabilizing the nominal exchange rate. In particular, the results stand in contrast to the perception one gets by observing official (“de jure”) monetary policy frameworks.

Second, we show that policy rules with a high response to the exchange rate exacerbate the effects of external shocks on the domestic variables in advanced economies. In particular, for resource rich Norway, that has responded strongly to the exchange rate in most of the sample, the effect of the terms-of-trade shocks on output and inflation are clearly exacerbated relative to the other countries. However, volatility of the terms of trade is much higher in Norway than in the other countries, which is most likely due to the size of the petroleum sector. Given this volatility, and a formal regime of inflation targeting, it may seem surprising that the terms of trade shocks do not explain even more of the variance in the nominal exchange rate in Norway than they do. The fact that the central bank in Norway has stabilized the exchange rate somewhat more than in the other countries may have contributed to this. Still, other objectives may be satisfied, and exchange rate stabilization may be optimal given the different exposure to commodity markets.[6]

Third, there is a striking similarity in the timing of the switch between the high and low volatility regimes across countries, independently of the chosen policy rules.[7] This suggests that common international volatility shocks may play a role, both for the commodity exporters and the commodity importers in our sample.

Our paper contributes to a large literature on exchange rates and monetary policy, see in particular Taylor (2001), Engel and West (2006), Galí and Monacelli (2005), Lubik and Schorfheide (2007) and Clarida et al. (1998), that study from various perspectives monetary policy response to nominal or real exchange rate changes.[8] Relevant are also the papers that analyse the interdependence between monetary policy responses and exchange rates dynamics in an inflation targeting area, see for instance Scholl and Uhlig (2008), Bjørnland (2009) and Bjørnland and Halvorsen (2014). To the best of our knowledge, our

[3] Our model can be further improved by, say, allowing for endogenous terms of trade and incomplete pass-through, as in Lubik and Schorfheide (2007). However, for the question we are trying to answer, we believe the framework in Lubik and Schorfheide (2007) is sufficient.

[4] This means that the so-called “peso problem” (see e.g. Evans (1996)) can be consistently dealt with in our framework.

[5] Our study is also unique in another important way; we don't de-trend the data prior to estimation. We believe non-filtered data are important to let the Markov-switching framework inform about medium-term changes in the dynamics of the data, which detrending effectively eliminates. Our hypothesis is that the variables can be stationary but from different distributions reflected by different regimes.

[6] Similar arguments are also put forward ion Catão and Chang (2013) and De Paoli (2009).

[7] Note, to economize on parameters and strengthen identification of different regimes, we let the switch in variances for different shocks be synchronized.

[8] For an early article analysing exchange rate stabilization, see Obstfeld and Rogoff (1995), or, see Corsetti et al. (2010) and Engel (2014) for more recent surveys on the large literature on monetary policy and exchange rate determination.

paper is the first paper to address the specific question of regime shifts in the monetary policy responses to the exchange rate.

Our work also contributes more generally to a broader literature that emphasizes the importance of allowing for parameters and volatility of shocks to change when analysing policy questions. So far, only a few papers in the literature address this issue in open economies, see for instance Liu and Mumtaz (2011), Dybowski et al. (2018) and Jin and Xiong (2020).[9] However, changes in shock variances and/or studies of the great moderation in closed economies such as the US have for some time been documented, see e.g. Stock and Watson (2005), Sims and Zha (2006), Lubik and Schorfheide (2004), Smets and Wouters (2007), and Bjørnland et al. (2018). Through our Markov Switching framework we are able to compare the estimated effects of shocks, across different types of monetary policy regimes, and across countries where exports are important to a varying degree. Thus, the fact that we are applying the same analysis across small open economies and yet get different results for the various countries, is a strong indication that we are picking up relevant information about changing regimes in open economies.

Finally, our paper is also related to the literature on exchange rate regime classification. The development of exchange rate regimes over time is well documented in Ilzetzki et al. (2017a), Ilzetzki et al. (2017b) and Klein and Shambaugh (2012). In particular, the "bipolar view" of exchange rate regimes, where countries either tend to let their exchange rate float relatively freely or firmly peg their exchange rates, is not an accurate description of reality, see e.g. Brooks et al. (2004). This paper provides results consistent with multiple changes in the adopted regimes.

The remainder of the paper is structured as follows. We start by discussing some stylized facts and acknowledging the periods of known policy changes in Section 2. Section 3 describes the New Keynesian model for small open economies (SOE) which is extended with regime switching, while the solution algorithms are described in Section 4. Data, priors and details on estimation procedure are presented in Section 5, and the results are reported in Section 6. Section 7 discusses robustness, and Section 8 concludes.

2. Stylized facts and known policy changes in advanced small open economies

While the six countries we analyse are all small and open inflation targeting countries, the dates for when they adopted an inflation targeting framework vary, see Ilzetzki et al. (2017b): Commodity exporter **New Zealand** was the pioneer, creating inflation targeting as a concept and establishing it by law in 1989. Their background was a history of exchange rate targeting but an unstable inflation rate. The regime in New Zealand became more flexible over time, after a quite rigid start, see McDermott and Williams (2018). Oil exporter **Canada** was the next country to adopt inflation targeting. In Canada, the exchange rate was pegged to the US dollar until 1970, thereafter it stayed within a narrow band, before it floated in 1973. Eventually Canada adopted an inflation target in 1991, but has changed the explicit target and range several times since then, see Bordo et al. (1999). However, since the end of 1995, the target for the annual rate of total consumer price inflation has been the 2% midpoint of a 1 to 3% range.[10] The next two nations to adopt inflation targeting were **UK** and **Sweden**. They switched to inflation targeting in October 1992 and January 1993 respectively, after currency crises and the collapse of their fixed exchange rate regimes to the ECU in the fall of 1992. In so doing, UK was the first country in Europe to adopt inflation targeting. The countries have adhered to a policy of not intervening systematically in the foreign exchange market since then. Note that although Sweden formally announced inflation targeting in 1993, it was not applied before 1995. **Australia** was in 1993 the next adopter of inflation targeting. In commodity exporter Australia, the transition to the new regime happened without a reform of the legal framework, as in New Zealand, and also without a dramatic exit from a fixed exchange rate regime, as in Sweden and the UK. Instead, the transition has been described as "evolutionary rather than revolutionary", see Debelle (2018). Oil exporter **Norway** has had a history of various fixed exchange rate arrangements. Interventions to fix the Norwegian krone were abandoned in December 1992, and the foreign exchange regime thereafter became more flexible, see Alstadheim (2016). Monetary policy was still oriented towards maintaining a stable exchange rate in relation to European currencies (but now without defining a central exchange rate to be defended by interventions). Yet with volatile terms of trade, this became challenging. From 1999, monetary policy was more explicitly geared towards stable consumer price inflation though, and eventually, in early 2001, a formal inflation targeting framework was adopted in Norway as well.

Table 1
Stylized facts.

	AU	CA	NZ	NO	SW	UK
Exchange rate	3.78/4.01	1.60/2.95	3.55/3.43	1.58/2.34	3.30/2.50	3.10/2.41
Terms of trade	3.46/3.05	1.27/2.08	3.85/2.69	4.23/5.05	1.88/1.23	1.94/0.88
GDP	1.24/0.56	1.13/0.58	1.32/0.96	1.28/1.27	1.18/1.12	1.13/0.58
Inflation	1.18/0.54	0.80/0.55	1.55/0.50	0.68/0.51	0.82/0.41	1.56/0.65
Interest rate	4.06/1.44	3.28/1.86	0.45/0.22	1.83/2.03	1.78/2.35	2.97/2.31

Note: Each cell reports the standard deviations in the period prior to 1993 to the left and in the period post 1993 to the right. Start dates reflects data availability, see section 5.1.

The above discussion of formal regime changes illustrates several reasons why estimating exchange rate responses with a split sample is not satisfactory: First, the announcement of official ("de jure") inflation targeting (and flexible exchange rates) may not come at the same time as the actual adoption of ("de facto") inflation targeting and more exchange rate flexibility. A country may want to gradually adapt to the new target, see Reinhart and Rogoff (2004). Secondly, inflation targeting is often practised flexibly, taking into account other goals such as the stability of output, and also - directly or indirectly - exchange rate fluctuations. It is therefore not obvious how to split the sample based on formal policy change. Our approach is therefore to examine the relevant parameters in a structural model, in order to uncover evidence of ("de facto") changed behavior by policymakers.

Finally, stylized facts suggest there have been large changes in the volatility of macroeconomic variables over the sample we are analysing, changes which are important to incorporate when analysing our question of interest. Table 1 illustrates this, by reporting standard deviations of some key macro variables before and after the exchange rate turbulence in 1992/1993.[11] There are three key findings: First, we find that volatility has declined over time for GDP and inflation in all six countries, although for New Zealand the decline in GDP volatility is negligible. On the other hand, the decline in volatility of inflation is substantial for all countries, and in particular for New Zealand and the UK. Hence, good policies (i.e. adopting an inflation targeting framework instead of targeting the exchange rate) and maybe also good luck, have made the small open economies overall more stable.

[9] Liu and Mumtaz (2011) is most related to us, as they analyse regime shifts in the UK using a Markov switching open economy DSGE model, although the focus there is on changes in volatility and breaks in structural parameters in general, and not on the open economy issues in particular. Dybowski et al. (2018) estimate a time-varying parameter (TVP) Bayesian VAR model for Canada, while Jin and Xiong (2020) analyse the link between the exchange rate and oil prices in Russia, using a Markov switching framework.

[10] Note, however, that until September 1998, the Bank of Canada intervened in the foreign exchange market in a systematic and automatic fashion to avoid significant upward or downward pressures on the Canadian dollar. Since September 1998, the policy has been to intervene only in exceptional circumstances.

[11] By 1993, all countries had formally given up targeting the exchange rate.

Second, volatility of terms of trade have fallen in the post 1993 period for all countries but Canada and Norway. This is not very surprising, given that these two countries are important oil and gas exporters. High volatility in oil prices is reflected in the terms of trade. Still, volatility remains quite high also after 1993 in the other two resource rich countries Australia and New Zealand. Norway stands out, however, with terms of trade being almost 5 times as volatile compared to UK, which has the lowest volatility in terms of trade.

Third, despite this, the exchange rate has about the same volatility across the countries in the recent inflation targeting period, but with Australia and New Zealand at the higher end, and the three European countries, Norway, Sweden and the UK, at the lower end. This could suggests that monetary policy has had a role to play in the stabilization of the exchange rate (and subsequently inflation), even though these countries have adopted inflation targeting and are both commodity exporters and importers. Hence, by responding (flexibly) to the exchange rate, they may also have managed to shelter the economy from terms of trade fluctuations, and better stabilize the economy. We now formally address these issues using a structural model.

3. A regime-switching small open economy model

Our model is a simplified version of Galí and Monacelli (2005), adapted from Lubik and Schorfheide (2007),[12] However, in contrast to these papers, our model accommodates independent Markov switching in the structural shocks that hit the economy and in the monetary policy responses. That is, we will allow some parameters to be drawn from different distributions, so they can switch through time. Additional details on the estimation of the Markov switching framework will be given in Section 4. Here we focus on explaining how we have extended the model in Galí and Monacelli (2005), with regime switches.

In brief, the model consists of a forward-looking (open economy) IS equation, a Phillips curve, an exchange rate equation and a monetary policy (interest rate) rule. Below we present the model framework. Following Lubik and Schorfheide (2007), we rewrite the (consumption) Euler equation as an open economy IS-curve:

$$y_t = E_t y_{t+1} - (\tau+\lambda)(i_t - E_t\pi_{t+1}) - \rho_z z_t - \alpha(\tau+\lambda)E_t\Delta q_{t+1} + \frac{\lambda}{\tau}E_t\Delta y^*_{t+1}, \quad (1)$$

where $0 < \alpha < 1$ is the import share (that measures the degree of openness), τ is the intertemporal substitution elasticity and we define $\lambda = \alpha(2-\alpha)(1-\tau)$. Note that the equation reduces to its closed economy variant when $\alpha = 0$. The endogenous variables are output y_t, the CPI inflation rate π_t and the nominal interest rate i_t. q_t is the terms of trade, y_t^* is world output, while z_t is the growth rate of an underlying non-stationary world technology process A_t. It is assumed that y_t^* and z_t are exogenous variables that evolve as AR processes with autoregressive coefficients ρ_{y^*} and ρ_z respectively.

Optimal price setting of domestic firms, together with an assumption of perfect risk-sharing across countries that links domestic potential output to foreign output, leads to the open economy Phillips curve

$$\pi_t = \beta E_t\pi_{t+1} + \alpha\beta E_t\Delta q_{t+1} - \alpha\Delta q_t + \frac{\kappa}{(\tau+\lambda)}(y_t - \bar{y}_t), \quad (2)$$

where $\bar{y}_t \equiv -\alpha(2-\alpha)(1-\tau)/\tau y_t^*$ is domestic potential output in the absence of nominal rigidities. Again this reduces to the closed economy variant with $\alpha = 0$. In a standard New-Keynesian model, κ is the slope coefficient. It is related to the price stickiness, the degree of competition and the representative firm's cost function parameters. Like Lubik and Schorfheide (2007), we treat κ itself as structural, but we do not model the underlying structure of the production side of the economy. Finally, when estimating the model, we add a demand shock ε_y to the IS equation and a cost push shock ε_π to the Phillips curve.

We introduce the nominal exchange rate (e_t) via the definition of the real exchange rate, $rer_t = \Delta e_t - \pi_t + \pi_t^*$, where π_t^* is world inflation. The real exchange rate is proportional to the terms of trade in this model. With $rer_t = (1-\alpha)\Delta q_t$, the definition of the real exchange rate then gives, up to a first order approximation, the following process for the nominal exchange rate in our model:

$$\Delta e_t = \pi_t - (1-\alpha)\Delta q_t - \pi_t^*, \quad (3)$$

The nominal exchange rate, domestic inflation, the terms of trade and foreign inflation are all observable variables. Of these, the exchange rate and the domestic inflation rate are endogenous, while the other variables will be exogenous and follow AR-processes.[13] Finally, the assumption of proportionality between the real exchange rate and the terms of trade does not hold exactly empirically, and we thus allow for measurement errors in this equation.[14]

Monetary policy is described by an interest rate rule where we assume that the central bank can adjust its instrument in response to inflation, output and the nominal exchange rate depreciation:

$$i_t = \rho_i\left(\mathcal{S}_t^{Pol}\right)i_{t-1} + \left(1-\rho_i\left(\mathcal{S}_t^{Pol}\right)\right)\left(\gamma_\pi\left(\mathcal{S}_t^{Pol}\right)\pi_t + \gamma_y\left(\mathcal{S}_t^{Pol}\right)y_t + \gamma_e\left(\mathcal{S}_t^{Pol}\right)\Delta e_t\right) + \varepsilon_{r,t}. \quad (4)$$

By adding the nominal exchange rate to the more standard Taylor rule, the rule encompasses periods of exchange rate targeting and inflation targeting, which are the two regimes that we are interested in.[15] We assume that the policy coefficients γ_π, γ_y and $\gamma_e \geq 0$. We also allow for a smoothing term in the rule, with $0 < \rho_i < 1$. $\varepsilon_{i,t}$ is the exogenous monetary policy shock, which can be interpreted as the unsystematic component of monetary policy (deviation from the rule). Importantly, we allow all parameters that the monetary authorities have control over to switch throughout the sample in the following way:

$$\mathcal{S}_t^{Pol} \in \{High, \ Low\}.$$

Hence, the parameters ρ_i, γ_π, γ_y and γ_e are allowed to follow an independent two-state Markov process, where we denote the low response regime as $\mathcal{S}_t^{Pol} = Low$ and the high response regime as $\left(\mathcal{S}_t^{Pol} = High\right)$.[16] In order to ease a systematic comparison across countries, we normalize the high response regime to be the regime where the central bank responds strongly to the exchange rate, taking also into account the interest rate smoothing, i.e.,

[12] See also Del Negro and Schorfheide (2009) for a similar exposition.

[13] Note that while we specify the terms-of-trade to be exogenous, it can be decided endogenously from the model, as underscored by e.g. Del Negro and Schorfheide (2009). The same authors stick to exogenous terms-of-trade in their estimation, as they find the impulse responses using an endogenous terms of trade specification to be very similar. Still, as many of the variables in our estimation are observable, including the terms-of-trade, a tighter specification of the terms-of-trade equation would be challenging, see also Canova et al. (2014).

[14] Implicitly, equation (3) also imposes a tight UIP-condition, since changes in the real exchange rate map into a difference between real interest rates, and by implication between nominal interest rates and inflation rates at home and abroad. The measurement errors can thus alternatively be interpreted as allowing for UIP-deviations.

[15] Note that the rule indirectly also encompasses real exchange rate stabilization, in that a stabilization of the inflation rate as well as the nominal exchange rate change also stabilizes the real exchange rate, see e.g. Galí and Monacelli (2005), Lubik and Schorfheide (2007), Clarida et al. (1998), Taylor (2001), Engel and West (2006) and Caputo and Herrera (2017) *for previous studies.*

[16] To economize on parameters, and given our very flexible model specification, a natural and reasonable identifying assumption for regime change is that all policy rule parameters in a given country change at the same time. We want to identify significant changes in policy, and we achieve this by requiring the parameters to switch in a synchronized fashion. We label the regimes that we identify according to the strength of the exchange rate response. However, it is not necessarily the case that all coefficients change by much even if a regime change is identified.

$$\left(1-\rho_i\left(\mathcal{S}_t^{Pol}=High\right)\right)\gamma_e\left(\mathcal{S}_t^{Pol}=High\right)$$
$$>\left(1-\rho_i\left(\mathcal{S}_t^{Pol}=Low\right)\right)\gamma_e\left(\mathcal{S}_t^{Pol}=Low\right).$$

Turning to the terms of trade, instead of solving endogenously for the terms of trade, we follow Lubik and Schorfheide (2007) and add a law of motion for their growth rate to the system:

$$\Delta q_t = \rho_q \Delta q_{t-1} + \varepsilon_{q,t} \tag{5}$$

Finally, we assume that the volatility of the shocks in the model follows an independent two-state Markov process, of low and high volatility. As motivated above, different policy responses may also reflect changes in volatility. In particular, some inflation targeting central banks may, in certain periods, have a specific interest in explicitly reacting to and smoothing exchange rate movements as a predictor of domestic volatility. Hence, assuming a time-invariant parameter reaction function as well as constant volatility during the sample period may bias the results.

Hence, we allow the volatility of shocks to the variables to change over time;

$$\mathcal{S}_t^{Vol} \in \{HighLow\},$$

where we denote the low volatility regime as $\left(\mathcal{S}_t^{Vol}=Low\right)$ and the high volatility regime as $\left(\mathcal{S}_t^{Vol}=High\right)$. Note that data will determine if the other variables are observing the same pattern of high and low volatility. For ease of comparison across countries, we normalize the high volatility regime to be the regime where volatility (in output) is highest, i.e.

$$\sigma_y\left(\mathcal{S}_t^{Vol}=High\right) > \sigma_y\left(\mathcal{S}_t^{Vol}=Low\right).$$

Below we describe the Markov switching framework in more detail.

4. Markov switching rational expectation framework

For each country, we will estimate a Markov switching model that allows for switching in volatility and parameters in the monetary policy rule. For completeness we also estimate three variants of the model with either time invariant regimes, switching in volatilities only or switching in parameters in the policy rule only. With six countries this implies that we will estimate a total of 24 models.[17] Below we will describe details.

The model outlined above can be cast in a general Markov Switching DSGE (MSDSGE) framework

$$E_t \sum_{r_{t+1}=1}^{h} p_{r_t,r_{t+1}} d_{r_t}(x_{t+1}(r_{t+1}), x_t(r_t), x_{t-1}, \varepsilon_t) = 0, \tag{6}$$

where E_t is the expectation operator, $d_{rt}:\mathbb{R}^{n_v}\rightarrow\mathbb{R}^{n_d}$ is a $n_d\times 1$ vector of possibly nonlinear functions of their arguments, $r_t=1,2,..,h$ is the regime a time t,x_t is a $n_x\times 1$ vector of all the endogenous variables, ε_t is a $n_\varepsilon\times 1$ vector of shocks with $\varepsilon_t \sim N(0, I_{n\varepsilon})$, $n_v = 3u_x + n_\varepsilon$ and $p_{rt,rt+1}$ is the transition probability for going from regime r_t in the current period to regime $r_{t+1}=1,2,..,h$ in the next period and is such that $\sum_{rt+1=1}^{h} p_{rt,rt+1}=1$.

We are interested in solutions of the form

$$x_t(r_t) = \mathcal{T}^{r_t}(w_t), \tag{7}$$

where w_t is an $n_w \times 1$ vector of state variables, $n_w = n_x + n_\varepsilon + 1$.

In general, there is no analytical solution to (6) even in cases where d_{r_t} is linear. Maih (2015) develops a perturbation solution technique that allows us to approximate the decision rules in (7) . The vector of state variables is then

$$w_t \equiv \left[x'_{t-1} \;\; \sigma \;\; \varepsilon'_t\right]',$$

where σ is a perturbation parameter.

The solution of our model takes the form

$$\mathcal{T}^{r_t}(w) \simeq \mathcal{T}^{r_t}(\overline{w}_{r_t}) + \mathcal{T}_w^{r_t}(w_t - \overline{w}_{r_t}), \tag{8}$$

where $\overline{w}_{r_t}$ is the steady state values of the state variables in regime r_t.

This solution is computed using the Newton algorithm of Maih (2015), which extends that of Farmer et al. (2011), henceforward FWZ. In particular, the algorithm is more general and efficient, as it solves a smaller system than FWZ by avoiding the computation of expectational errors. Furthermore, the algorithms avoids building and storing large Kronecker products and thereby also avoids inverting large matrices. This makes the algorithm suitable for large systems.[18]

This type of solution in (8) makes it clear that the framework allows the model economy to be in different regimes at different points in time, with each regime being governed by certain rules specific to the regime. In that case the traditional stability concept for constant-parameter linear rational expectations models, the Blanchard-Kahn conditions, cannot be used. Instead, following the lead of Svensson and Williams (2007) and Farmer et al. (2011) among others, this paper uses the concept of mean square stability (MSS) borrowed from the engineering literature, to characterize stable solutions.

5. Data and Bayesian estimation

We estimate the parameters in the model with Bayesian methods using the RISE toolbox for Matlab. The equations of the system are coded up using the RISE language in a text file. The software takes the file containing the equations and automatically computes the perturbation solution as well as the state-space form that is used for the likelihood computation. For a regime-switching model like ours, the computation of the likelihood has to be done via a filtering algorithm due to the presence of unobservable variables. An exact filtering procedure that will track all possible histories of regimes is infeasible. One solution described by Kim and Nelson (1999) consists of collapsing (averaging) the forecasts for various regimes in order to avoid an explosion of the number of paths. An alternative approach, the one we follow, is to collapse the updates in the filtering procedure. This approach yields numerically similar results as the Kim and Nelson filter but has the advantage of being computationally more efficient, see Maih (2015).

5.1. Data

The estimation is based on quarterly time-series observations for the period 1964Q1-2015Q1 for Canada and the UK, 1968Q1-2015Q1 for Australia, 1974Q2-2015Q1 for New Zealand while for Norway and Sweden, the sample runs from 1982Q1 to 2015Q1. The start dates reflect data availability for the interest rate series and exchange rate series. For each country, there are seven observable variables: Real GDP, inflation, the short term interest rate, the nominal (trade weighted) effective exchange rate, the terms of trade and foreign output and inflation. Note that in contrast to Lubik and Schorfheide (2007) who treat foreign output and inflation as unobservable (latent) variables, we include foreign output and inflation explicitly as observables in the model in order to better identify the effects of foreign shocks. This ties the dynamics of the small open economies model more explicitly to the global shocks. We approximate foreign output and foreign inflation for each country based on the time-varying weights that were also used to calculate the effective exchange rate. As far as possible, we collect data from the national sources. All data except the nominal interest rate and the exchange rate are seasonally adjusted.

[17] In the robustness section we re-estimate all models using a shorter sample period, implying that we estimate another 16 models, that is, 32 models in total.

[18] The algorithm has been used in the solving of a system of upwards of 300 equations.

Regarding the transformation, output growth rates are computed as log differences of GDP and multiplied by 100 to convert them into quarter to quarter percentages. Inflation rates are defined as log differences of the consumer price indices and multiplied by 400 to obtain annualised percentage rates. We use the log differences (multiplied by 100) of the trade-weighted nominal effective exchange rate to obtain depreciation rates (seen as an increase). Percentage changes in the terms of trade are computed as log differences and multiplied by 100 while the nominal interest rate is measured in levels. More details about sources and transformations are given in Appendix A.

5.2. Choice of priors and estimation

Besides the model equations and the data, another input has to be provided for us to do Bayesian estimation: the prior information on the parameters. Rather than setting means and standard deviations for our parameters as it is customarily done, we set our priors using quantiles of the distributions. Specifically, we use the 90% probability intervals of the distributions to uncover the underlying hyperparameters. With the exception of the parameter α, we allow for loose priors to entertain the idea that there have been multiple regime changes in the sample. α, which is the import share, is tightly centered around 0.2, as in Lubik and Schorfheide (2007).

The full list of our prior assumptions along with the posterior mode are reported in Table 3. To compute the posterior kernel, the software (RISE) combines the (approximated) likelihood function with the prior information.[19] The sampling of the posterior distribution is not an easy task and there is no guarantee, in a complicated model like ours in which the posterior density function is multimodal, that the posterior distribution will be adequately sampled or that the optimization routines used will find the global peak of the posterior distribution of the parameters. We exploit the stochastic search optimization routines of the RISE toolbox to estimate the mode. Our stochastic search approach is based on the Artificial Bee Colony (ABC) optimization (see Karaboga and Akay (2011)).[20] The algorithm alternates between phases of exploration (global search) and phases of exploitation (local search) and avoids stalling by randomly restarting the locations in which exploitation does not lead to any improvement of the likelihood.[21]

With a mode or starting point in hand, our strategy to simulate the posterior distribution is to run 5 parallel chains of the Adaptive Parallel Tempering (Miasojedow et al. (2012)), a generic Markov chain Monte Carlo sampling method which allows good mixing with multimodal target distributions, where conventional Metropolis-Hastings algorithms often fail. The adaptive algorithm tunes both the temperature schedule, which efficiently copes with multimodality,[22] and the parameters of the random-walk Metropolis kernel automatically. In particular, the scale parameter in particular is adapted so as to maintain an acceptance ratio of about 0.234.

The whole process is rather computationally intensive. For a given parameter draw, the first-order perturbation solution of the model is computed following the Newton algorithms described in Maih (2015), setting the convergence criterion to the square root of machine epsilon. If a solution is found, it is checked for MSS. If the MSS test is passed, the likelihood of the data is computed using the solution found and then combined with the prior distribution of the parameters. This process, which has to be repeated millions of times, takes several weeks to complete. We monitor convergence using various tools such as trace plots as well as the Potential Scale Reduction Factor statistic as outlined in Gelman et al. (2004).

6. Results

We start out by estimating the parameters in a time invariant model before turning to our preferred regime switching model; a model where both parameters and volatility are allowed to switch over time. As stated above, the sample runs from 1964Q1 to 2015Q1 for Canada and the UK, from 1968Q1 to 2015Q1 for Australia, from 1974Q2 to 2015Q1 for New Zealand, while for Norway and Sweden, the sample runs from 1982Q1 to 2015Q1. Eventually we will test robustness to starting the analysis in 1982 for all countries.

6.1. Time invariant rational expectation benchmark

The estimation results for the posterior mode, along with the prior distribution using a time invariant (constant) model are reported in Table 2. For ease of exposition, we report here only the parameters in the policy rule, other parameters can be obtained at request.

The table suggests policy rules that have a high weight on output and a small weight on inflation. With regard to the exchange rate, the central bank in Norway responds strongly to the exchange rate, whereas in the other countries, the response is small or negligible. Hence, from these results we would conclude that only the central bank in Norway responds strongly to the exchange rate.

Are these estimates reasonable? First, we note that when including the exchange rate in the interest rate reaction function, the response to inflation becomes lower than in a standard Taylor rule. This is as expected, as the response goes via the exchange rate also. More importantly, given our long sample, and the many known policy changes, estimating constant parameter models over the sample may seem very restrictive. In fact, we would argue that if the data are generated by different distributions reflected by different regimes, forcing a time invariant distribution to the data should potentially yield different results depending on the sample analysed. Thus, we can anticipate that there will be a more nuanced picture when we allow the parameters to switch between different regimes. We turn to this now.

6.2. A model with switching policy rule and volatility

The used procedure allows the likelihood to be evaluated at each point in time under the different regimes. This information, through a Bayesian filtering scheme, is used to update the probabilities of being in different states. So even if there was only one outlying observation (perhaps a switch to inflation targeting), the estimation procedure would still pick it up. But we do not just have one outlying observation, we have at least a decade of inflation targeting after periods of fixed exchange rates. This allows us to better evaluate both the switch in regimes and the duration of the regimes.

Economic reasoning suggests that it may be useful to allow both the parameters and the volatility to switch over time. Still, we could use a statistical criteria to evaluate if such a regime switching model gives an accurate description of the data. Table 4 in Appendix B provides such

Table 2
Priors and Posterior mode of policy rule.

Params	P.distr	P.prob	low	high	AU	CA	NO	NZ	SW	UK
ρ_i	beta	0.90	0.40	0.75	0.79	0.84	0.93	0.88	0.78	0.80
γ_π	gamma	0.90	0.90	3.00	0.13	0.17	0.50	0.54	0.09	0.19
γ_y	gamma	0.90	0.10	3.00	2.49	3.35	1.14	0.36	1.31	2.88
γ_e	gamma	0.90	0.05	3.00	0.01	0.04	2.18	0.50	0.00	0.01

[19] To specify the priors we use quantiles. It is customary in the literature to set priors in terms of means and standard deviations. This does not necessarily work the other way around. That is for given quantiles, we do not necessarily have corresponding means and standard deviations. This is because many distributions do not have first and second moments, e.g. the Cauchy distribution.

[20] This optimization technique is inspired from the intelligent behavior of honey bees. Artificial bees fly around a potentially multidimensional search space and adjust their position in the landscape according to the amount of food (likelihood) that is found in various locations.

[21] In our experience, the algorithm is easily capable of improving the solutions found by Newton-based optimization techniques such as e.g. Matlab's fmincon or Christopher Sims' csminwell.

[22] We apply twelve levels of tempering that progressively transform an almost uniform distribution into the posterior kernel.

Table 3
Priors and posterior mode.

Params	P.distr	P.prob	low	high	AU	CA	NO	NZ	SW	UK
τ	beta	0.90	0.17	0.83	0.19	0.17	0.51	0.15	0.37	0.17
κ	gamma	0.90	0.12	0.87	0.05	1.23	3.94	2.37	2.88	1.68
α	beta	0.90	0.12	0.28	0.16	0.05	0.41	0.12	0.17	0.07
ρ_q	beta	0.90	0.10	0.80	0.27	0.30	0.57	0.36	0.23	0.07
ρ_{y^*}	beta	0.90	0.40	0.80	0.93	0.97	0.83	0.96	0.97	0.96
ρ_{π^*}	beta	0.90	0.10	0.80	0.97	0.81	0.97	0.81	0.85	0.93
ρ_z	beta	0.90	0.40	0.80	0.38	0.33	0.85	0.59	0.56	0.29
coef_tp_L_H	beta	0.90	0.00	0.10	0.03	0.00	0.00	0.00	0.01	0.00
coef_tp_H_L	beta	0.90	0.00	0.10	0.12	0.01	0.01	0.01	0.06	0.04
$\rho_i(S_t^{Pol} = Low)$	beta	0.90	0.40	0.75	0.94	0.91	0.96	0.93	0.90	0.91
$\rho_i(S_t^{Pol} = High)$	beta	0.90	0.40	0.75	0.47	0.82	0.92	0.84	0.73	0.72
$\gamma_\pi(S_t^{Pol} = Low)$	gamma	0.90	0.90	3.00	0.17	0.77	0.57	0.65	0.96	0.82
$\gamma_\pi(S_t^{Pol} = High)$	gamma	0.90	0.90	3.00	0.16	0.58	0.57	0.49	0.95	0.82
$\gamma_y(S_t^{Pol} = Low)$	gamma	0.90	0.10	3.00	2.58	0.22	0.06	0.22	0.23	0.28
$\gamma_y(S_t^{Pol} = High)$	gamma	0.90	0.10	3.00	2.60	0.04	0.21	0.09	0.04	0.16
$\gamma_e(S_t^{Pol} = Low)$	gamma	0.90	0.05	3.00	0.00	0.07	2.03	0.24	0.00	0.07
$\gamma_e(S_t^{Pol} = High)$	gamma	0.90	0.05	3.00	0.30	0.27	2.49	0.35	0.91	0.71
vol_tp_L_H	beta	0.90	0.00	0.10	0.01	0.02	0.04	0.01	0.03	0.06
vol_tp_H_L	beta	0.90	0.00	0.10	0.02	0.05	0.13	0.06	0.12	0.09
$\sigma_i(S_t^{Vol} = Low)$	inv_gamma	0.90	0.01	1.00	0.00	0.00	0.00	0.00	0.00	0.00
$\sigma_i(S_t^{Vol} = High)$	inv_gamma	0.90	0.01	1.00	0.00	0.00	0.01	0.01	0.01	0.00
$\sigma_q(S_t^{Vol} = Low)$	inv_gamma	0.90	0.01	1.00	0.02	0.01	0.05	0.02	0.01	0.01
$\sigma_q(S_t^{Vol} = High)$	inv_gamma	0.90	0.01	1.00	0.04	0.03	0.07	0.04	0.03	0.02
$\sigma_z(S_t^{Vol} = Low)$	inv_gamma	0.90	0.01	1.00	0.00	0.01	0.00	0.00	0.00	0.00
$\sigma_z(S_t^{Vol} = High)$	inv_gamma	0.90	0.01	1.00	0.01	0.01	0.00	0.01	0.01	0.01
$\sigma_{y^*}(S_t^{Vol} = Low)$	inv_gamma	0.90	0.01	1.00	0.00	0.00	0.00	0.00	0.00	0.00
$\sigma_{y^*}(S_t^{Vol} = High)$	inv_gamma	0.90	0.01	1.00	0.00	0.01	0.01	0.01	0.01	0.00
$\sigma_{\pi^*}(S_t^{Vol} = Low)$	inv_gamma	0.90	0.01	1.00	0.00	0.01	0.00	0.01	0.01	0.00
$\sigma_{\pi^*}(S_t^{Vol} = High)$	inv_gamma	0.90	0.01	1.00	0.02	0.03	0.00	0.02	0.02	0.01
$\sigma_y(S_t^{Vol} = Low)$	inv_gamma	0.90	0.01	1.00	0.00	0.00	0.00	0.00	0.00	0.00
$\sigma_y(S_t^{Vol} = High)$	inv_gamma	0.90	0.01	1.00	0.01	0.00	0.01	0.00	0.01	0.01
$\sigma_\pi(S_t^{Vol} = Low)$	inv_gamma	0.90	0.01	1.00	0.03	0.01	0.01	0.01	0.01	0.01
$\sigma_\pi(S_t^{Vol} = High)$	inv_gamma	0.90	0.01	1.00	0.05	0.01	0.07	0.01	0.01	0.05
stderr_DCPI	inv_gamma	0.90	0.01	0.10	0.01	0.01	0.01	0.01	0.01	0.01
stderr_DFCPI	inv_gamma	0.90	0.01	0.10	0.00	0.00	0.00	0.00	0.00	0.00
stderr_DGDP	inv_gamma	0.90	0.01	0.10	0.00	0.01	0.01	0.01	0.01	0.00
stderr_DFGDP	inv_gamma	0.90	0.01	0.10	0.01	0.01	0.01	0.01	0.01	0.01

an evaluation by comparing the log Marginal Data Density (MDD) Laplace approximation for the constant model with three alternative regime switching models; a model with switches in the parameters only, a model with switches in volatility only and our preferred model with both switches in volatility and parameters.[23] The results confirm that models that allow for switches in either policy parameters and/or volatility are preferred to a constant parameter model in all countries.

Still, the most preferred model is the model that allows for switches in both parameters and volatility, such as the one we estimate here. In the robustness section, however, we will discuss robustness to some other alternative model specifications.

Table 3 displays the posterior mode of the estimated parameters in our preferred model with switches in both policy responses and volatility of the structural shocks. We find that the size of the policy responses, and the volatility of structural shocks, have not remained constant during the different sample periods. First, for all countries, interest rate smoothing is more pronounced in the low exchange rate response regime. The exchange rate regime is normalised taking also into account the interest rate smoothing parameter. We find that in the high response regime, Norway has by far the strongest response to the exchange rate, followed by Sweden and the UK. In fact, for Norway the response is substantial also in the low response regime, followed by New Zealand.[24] We note here that Lubik and Schorfheide (2007) did not find that New Zealand responds to the exchange rate. We believe that the added observables in our setup, combined with realistic flexibilty that regime switching provides, allows for better identification of parameters.

For the other countries, the response is close to zero in the low response regime. Hence, the picture is nuanced relative to the constant parameter model. Interestingly, it is the three European countries that respond the most, that also have the most stable exchange rate in the inflation targeting period, c.f. the stylized facts in Table 1.

With regard to the other policy parameters, for most countries the interest rate responds more strongly to inflation and output in the low response regime. Exceptions are Australia and Norway, where the interest rate responds more strongly to output in the high response regime. However, given that the interest rate smoothing is also more pronounced in the low response regime, the low response regime can be characterized by an interest rate rule that emphasizes interest rate smoothing and strong inflation and output response, while the high response regime is characterized by strong exchange rate response, and for Norway, also substantial output response. Interestingly, with regard to the size of the estimated parameters, the responses to output in the low response regime have now declined substantially relative to the constant parameter model, while the responses to inflation and the exchange have increased.

Regarding the Markov state processes for volatility, most shocks display the highest volatility in regime $\left(\mathcal{S}_t^{Vol} = High\right)$. For all countries, the probability of moving from a high to a low volatility regime is greater than moving from a low to a high volatility regime. Note that Norway stands out from the other countries in that volatility of terms of trade is 2–3 times higher than in the other countries (in both the low and

[23] Because the likelihood we work with is only approximate, we use the laplace approximation to the posterior distribution, see Christiano et al. (2011) for details on computation.

[24] Note that the exchange rate behavior may be affected by fiscal policy in commodity exporting countries, via public commodity export revenues being invested abroad (in effect amounting to scheduled or non-discretionary foreign exchange interventions, with reserves being held by the government rather than the central bank).

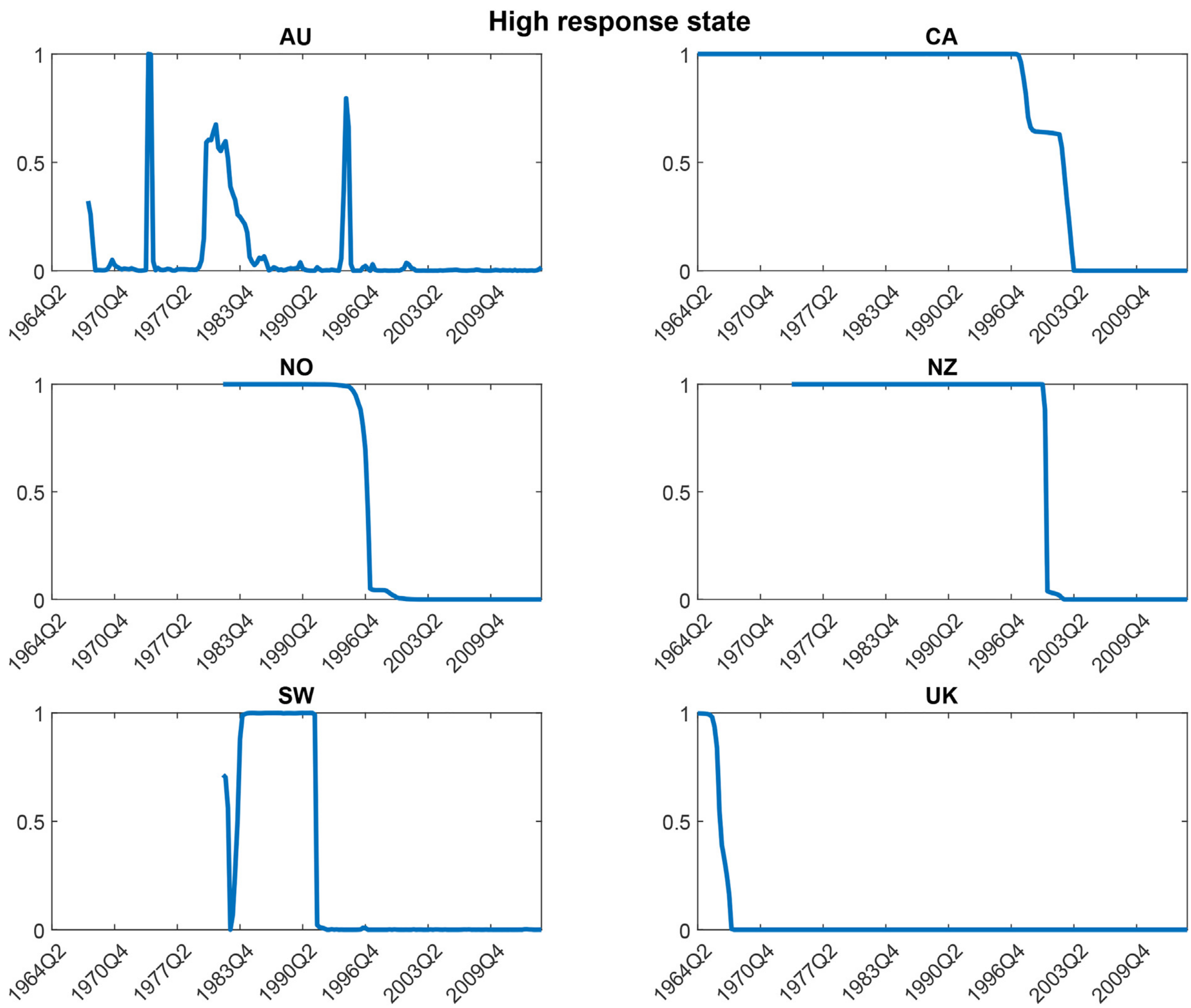

Fig. 1. Smoothed Probabilities of high response ($S_t^{Pol} = High$).

high volatility regime), see Table 3. This is most likely due to the relative size of the petroleum sector in that country. Still, despite this high volatility in the terms of trade, output and inflation do not display much higher volatility in Norway than in the other countries. This may suggest that by responding strongly to the implied exchange rate volatility, they are also able to partly shelter the domestic economy from the volatile terms of trade shocks, as emphasized first when we discussed stylized facts. We turn to this in more detail below.

Finally, with respect to the other structural parameters (that are not switching), most parameters seem to be within reasonable values. We note that the parameter α that measures the degree of openness, is estimated to be the largest in Norway, followed by Sweden, Canada and the UK. Hence, by that measure Norway is the most open country. Interestingly, these four countries are also those that observe the most pronounced response to the exchange rate in the high response regime.

Fig. 1 displays the smoothed probabilities of being in the high policy response regime, $\left(\mathcal{S}_t^{Pol} = High\right)$ while Fig. 2 displays the probability of being in a high volatility regime $\left(\mathcal{S}_t^{Vol} = High\right)$. The figures emphasize that all the central banks but Australia switched from a high to a low response regime at some point in the sample. Australia stands out in the sense that they have responded on-off to the exchange rate during certain brief periods, ending around 1996. UK also stands out, in the sense that they only responded strongly early in the sample; around 1971/1972. This period corresponds well with the end of the Bretton Woods system, an exchange rate arrangement where the US dollar was tied to gold.[25] After the US dollar's convertibility into gold was suspended in August 1971, several countries that had pegged their currencies to the US dollar changed their arrangements. UK abandoned the peg in June 1972 and adopted instead a moving band around the Deutchmark (DM).[26] The observed switch to the low response regime is characterized by an increased smoothing parameter (ρ_i), see Table 3 for details, implying an overall decline in the response to the exchange rate.

For Sweden, the switch to the low response regime corresponds well with the adoption of an inflation targeting regime for monetary policy.[27] For the three resource rich countries, Canada, New Zealand and Norway, the switch from a high to low response regime came some time in the 1990s, and after they adopted inflation targeting. In particular, although Canada adopted the inflation targeting framework already in 1991, our results suggest that the switch did not occur before 1997/1998, corresponding to the time when the Bank of Canada stopped intervening systematically in the foreign exchange market, see the discussion in

[25] The Bretton Woods system dissolved between 1968 and 1973. In August 1971, the dollar's convertibility into gold was suspended. The dollar had struggled throughout most of the 1960s within the parity established at Bretton Woods, and this crisis marked the breakdown of the system. By March 1973 most of the major currencies had begun to float against each other.

[26] The moving band was subsequently replaced by a managed floating in 1992.

[27] By 1993, Sweden had been through a turbulent period trying to defend the exchange rate against the DM (crawling peg). Eventually they gave up defending the currency and adopted instead a managed float for the exchange rate and an inflation targeting framework for monetary policy, see the discussion in Section 2.

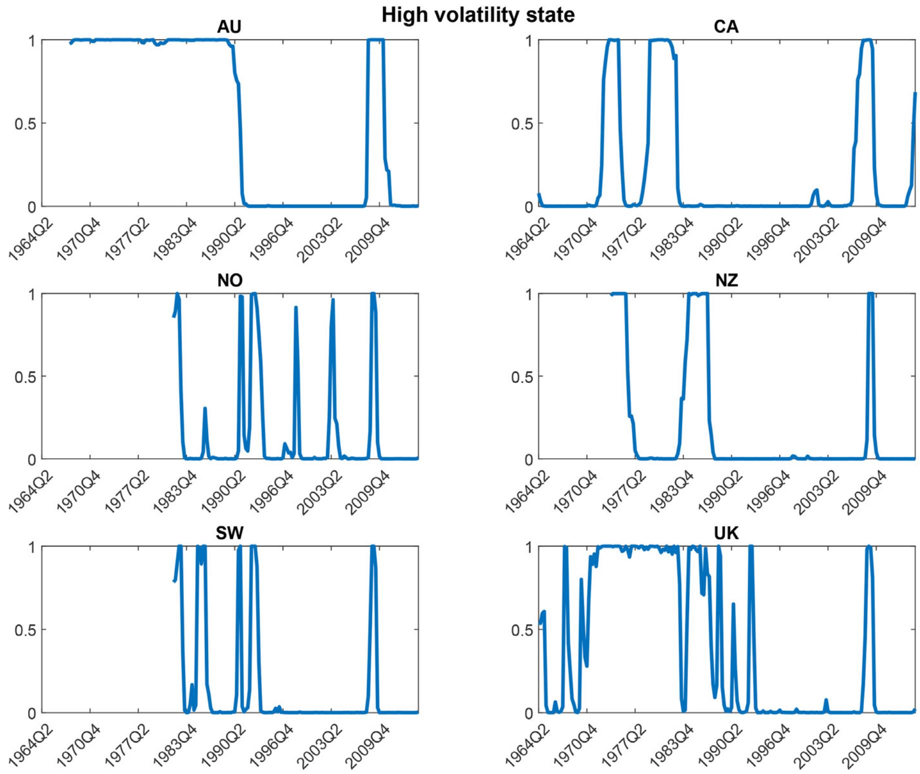

Fig. 2. Smoothed Probabilities of high volatility (S_t^{Vol}=High).

Section 2 and in Lama and Medina (2012). Interestingly, these results are also consistent with Dybowski et al. (2018), which using a Time Varying Parameter Bayesian VAR (TVP-BVAR) model, find the importance of the exchange rate as a determinant of the policy rate to decline throughout the 1990s and 2000s.

Finally, Norway, switches to a low response regime in 1999, around the time of adopting inflation targeting (2001). This is consistent with what was explicitly announced at that time, c.f. the discussion in Section 2. However, the switch does not involve a much lower response to the exchange rate. In fact, monetary policy in Norway continues to respond strongly to the exchange rate after the switch, (see the parameters in Table 3). Hence, the central bank in Norway responds strongly to the exchange rate both prior and post implementing inflation targeting (informally in 1999 and more formally in 2001). The main change, though, comes in the form of a more gradual interest setting (through an increase in the smoothing parameter, as for the other countries), and a reduction in the response to output (in contrast to the other countries).

Thus, our results give a more nuanced picture of the weight that central banks give to stabilizing the nominal exchange rate. In particular, the central bank in resource rich countries Canada, New Zealand and Norway respond to the exchange rate long after adopting inflation targeting, and for Norway, the response is high in all periods. These are new findings in the literature. Australia stands out from the other resource rich countries, as the interest rate responds to the exchange rate only at certain brief periods early in the sample. However, as the Australia Dollar is the fifth most traded currency in the world, responding to the exchange rate would be challenging, and could be the reason for the lack of response. We emphasize, however, that we can not rule out that the central banks that respond strongly to the exchange rate do so to achieve the inflation target and overall macroeconomic stability. This may differ from country to country, based on different preferences and concerns, see also Kam et al. (2009).

Our results stand in contrast to Lubik and Schorfheide (2007) and Dong (2013), who analyse interest rate response in Australia, Canada, New Zealand and the U.K. In particular, Lubik and Schorfheide (2007) found only Canada and UK to respond to the exchange rate, while Dong (2013) found no evidence that the central Banks adjusted the interest rate in response to the exchange rate. We believe that the added observables in our setup, combined with realistic flexibilty that regime switching provides, allows for better identification of parameters in more countries.

Turning to volatility in Fig. 2, there is a striking similarity in the timing of the switch between the high and low volatility regimes across countries, with the possible exception of Norway. In particular, independently of the chosen policy rules, the probability of being in a regime of low volatility was high from the middle 1990s until the middle 2000s (the period referred to as 'the Great Moderation'). Following this, there is a high probability of being in a high volatility regime during the period of the financial crisis in all countries. For Australia, Canada and the UK for which we observe a longer sample, there is an additional prolonged period of high volatility in the 1970s, whereas Norway and Sweden experience a period of high volatility during the Nordic banking crisis in the early 1990s. Norway also experience pronounced volatility in 2002/2003.

Hence, it seems that the switches in volatility indeed pick up well known episodes of changes in exogenous volatility that many countries have in common, and independent of the chosen regime.

6.3. Impulse responses

Having observed the different responses to the exchange rate, an interesting question to discuss is the extent to which policy rules with a high response to the exchange rate amplify or reduce the effects of terms of trade shocks on the domestic variables. To address this, Fig. 3 displays the generalized impulse responses to the terms-of-trade shock (which increases export prices relative to import prices). The impulse responses emphasize that responding strongly to the exchange rate will exacerbate the effects of a terms-of-trade shock on both output and domestic

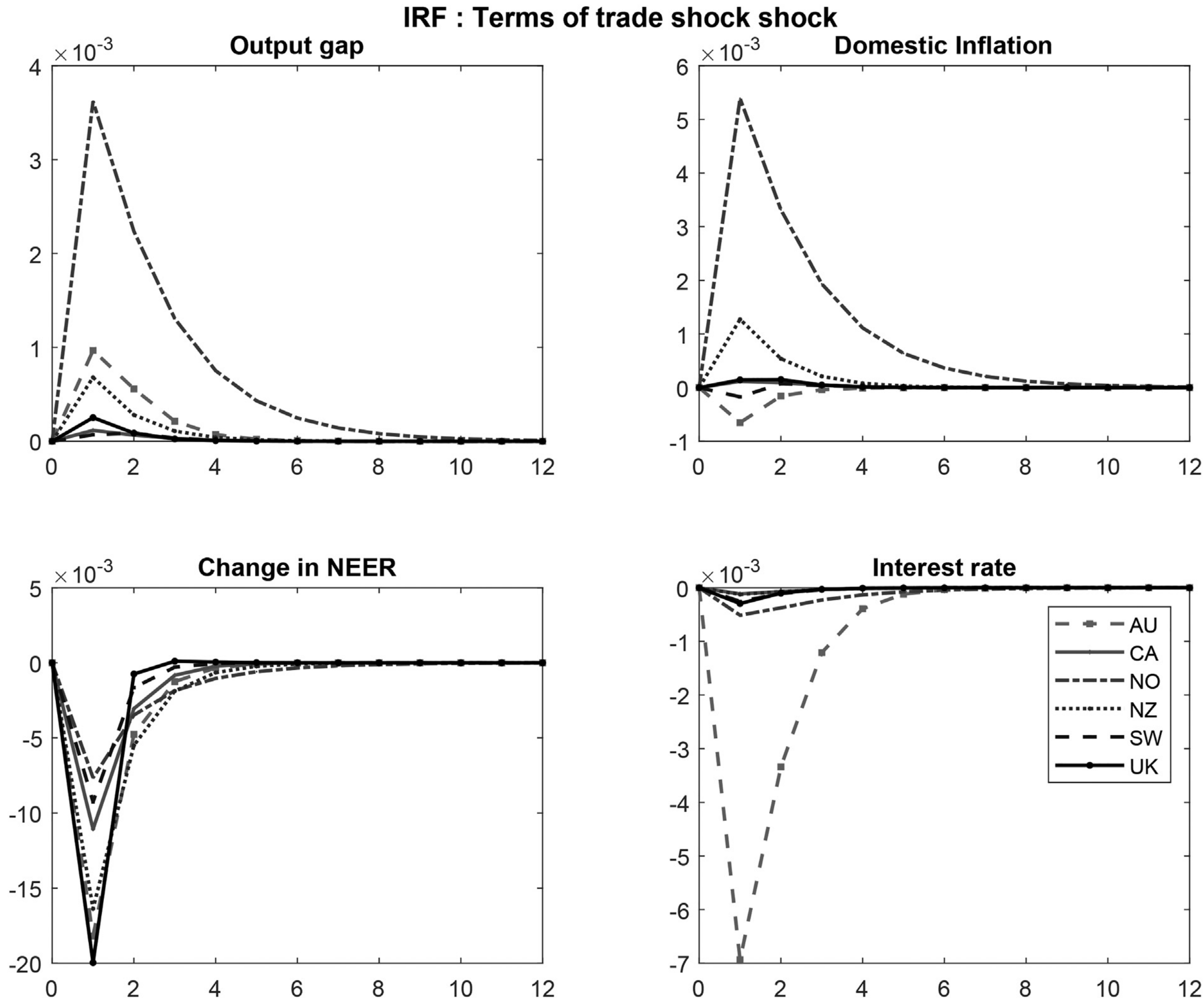

Fig. 3. Generalized IRFs to a Terms of trade shock.

inflation. In particular, a favorable terms-of-trade shock appreciates the exchange rate on impact. The effect on output (and inflation) will depend on the expected interest rate response. If the central bank is in a policy regime of high exchange rate response, then the exchange rate will appreciate by much less, as the interest rate will also take into account the fact that the exchange rate has appreciated. This will reverse the initial exchange rate response and push up output and inflation relative to a regime of no exchange rate response. This is clearly seen in Fig. 3. Norway has been in a regime of high exchange rate response in most of the sample, and the effect of the terms-of-trade shocks on output and inflation are therefore clearly amplified relative to the other countries.

On a final note, recall from the discussion above that volatility of the terms of trade is much higher in Australia, Canada, New Zealand, and in particular, Norway, than in Sweden and the UK. This is most likely due to the fact that these are resource rich countries, facing volatile commodity markets. Given this volatility, and a formal regime of inflation targeting, it may seem surprising that the terms of trade shocks do not explain even more of the variance in the nominal exchange rate than they do. The fact that the central banks have stabilized the exchange rate substantially more may have contributed to this. As pointed out in Section 2, despite large differences in the terms of trade, the exchange rate has about the same volatility across the countries in the recent period, but with Australia at the higher end. Hence, we believe this suggests that monetary policy has had a role to play in the stabilization of the exchange rate (and subsequently inflation), eventhough they have adopted inflation targeting.[28]

We conclude by noting that applying the same analysis across countries and yet getting different results for the resource rich countries, is a strong indication that we are picking up relevant information about changing regimes in open commodity exporting economies.

7. Extensions and robustness

In the figures above, we displayed the smoothed probabilities of being in various regimes based on the mode. We believe our regime switching model suggests a reasonable picture of policy switches and spurs of volatility consistent with historical experience and information available from speeches and publication from the relevant Central Banks. From Table 4, we saw that such a model was also preferred to a constant parameter or volatility model. Still it is interesting to know what the results would have been if we had entertained different regime switching models, say allowing for switches in volatility only or parameter only.

Table 5 in Appendix B displays the coefficients in the policy rule for all countries assuming a model that only allows for switches in volatility (only), while Fig. 4 displays the probability of being in a high volatility

[28] Finally, the contributions to net capital outflows from high public sector foreign savings during high oil-tax income periods, may also have helped contain nominal exchange rate appreciation, in particular in Norway. This mechanism has allowed the policymakers to respond to the exchange rate.

regime. The table confirms again that Norway responds by far the most to the exchange rate, followed by New Zealand, while there is virtually no response to the exchange rate in the other countries. This is very similar to the constant parameter case. Also, as in the constant parameter model, there is very little response to inflation and a high response to output (except Norway). Smoothing is also high in all countries. This could suggest that the model now interprets some of the periods of known policy changes as spurs of high volatility instead, as seen in Figure 4.

Table 6 in Appendix B displays the coefficients in the policy rule for all countries assuming a model that only allows for switches in parameters (only). Compared to the constant parameter and volatility only model, now also Canada and the UK respond, in addition to Norway and New Zealand. We also see that the interest rate generally responds more to inflation and output when we also allow parameters to change.

The sample start used in the estimation varies, with data going back to the 1960s for all countries but Norway and Sweden, that have data only available from the 1980s. To examine the results starting in more recent time for all countries, we start the sample in 1980 also for Australia, Canada, New Zealand and the UK. *Re*-estimating the model from 1980, we find the overall conclusion to be robust. In particular, Canada switches between high and low response as before, although for some countries, Canada and the UK in particular, the switches have moved a few quarters relative to the baseline model, see the Fig. 5 in the Appendix.

8. Conclusion

We analyse whether inflation targeting central banks in advanced small open economies respond to the exchange rate changes. Using a Markov switching DSGE model that explicitly allows for parameter changes, we observe that the size of policy responses and the volatility of structural shocks, have not remained constant during the sample period analyzed.

Our results give a more nuanced picture of the weight that central banks give to stabilizing the nominal exchange rate. In particular, while the central banks in Sweden and the UK switch to a low exchange rate response regime shortly after severe periods of currency crisis and the collapse of their fixed exchange rate regime, the central banks in Canada, New Zealand and Norway continue to respond to the exchange rate even after adopting inflation targeting framework, and for Norway, throughout the whole sample. Australia stands out from the other resource rich countries, by responding to the exchange rate only at certain brief periods early in the sample.

Through our Markov Switching mechanism we are able to compare the estimated effect of shocks, across different types of monetary policy regimes, and across countries where exports are important to a varying degree. Thus, the fact that we are applying the same analysis across small open economies and yet get different results for the various countries, is a strong indication that we are picking up relevant information about changing regimes in open economies.

Appendix A. Data and sources

We use *nominal effective exchange rates* from the BIS for all countries, based on their time-varying narrow weight set. The data set is monthly and is downloaded from the FRED database.[29] From this we calculate quarterly averages. We invert the indexes so that a higher index value indicates a weaker local currency.

Seasonally adjusted *CPI series* are collected from national sources (Australian Bureau of Statistics, Statistics Canada, Statistics New Zealand, Statistics Norway, Statistics Sweden and Statistics UK) for all countries. We use standard series that are long enough for our sample: For Australia and Canada we use Consumer Prices, All Items, for Sweden we use the Consumer Price Index, Standardized, for New Zealand we use Consumer Prices All Groups, for Norway we use Consumer Prices, All Items, Total and for the UK, we use the All Items Retail Price Index. The data series are monthly. From this we calculate quarterly averages.[30]

For *real GDP*, we use data from national sources, except for Canada, where we use data from the IMF IFS and for New Zealand where we use data from OECD in order to get long enough series.[31] The data series are seasonally adjusted by their national sources, except for Canada and Sweden, where we have to seasonally adjust the data.

For *interest rates*, we collect three-month interbank rates for Australia, Canada, Sweden, New Zealand and the UK from the FRED database. The interest rate for Norway was downloaded from national sources via Datastream.[32] National sources did not provide long enough series for the other three countries.

For the *terms of trade*, we use data from national sources for Australia, Canada, New Zealand and Norway,[33] while we use IMF-data for the UK and Sweden, in order to obtain long enough data series for those countries.[34]

We construct series for *foreign inflation and foreign GDP* for each country, based on time-varying weights from the BIS (the same set that was used to construct the effective exchange rates). We select the three largest trading partners for each country from the weight-set in the year 1993, and apply the time-varying weights to those three countries (rescaled to make up 100% in total for each year). Weights are fixed back in time from 1991, since the time-varying weights are available only from 1991. For most of the sample, the three largest trading partners are, for Australia: the US, Japan and the Euro Area, for New Zealand Australia, Japan and the US, for Norway: the Euro Area, Sweden and the UK, for Canada: the US, Japan and the Euro area, for Sweden: the Euro area, the US and the UK and for the UK: the Euro area, the US and Japan.[35]

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[29] We use the following FRED data series Australia: NNAUBIS, New Zealand: NNNZBIS, Canada: NNCABIS, UK: NNGBBIS, Norway: NNNOBIS and Sweden: NNSEBIS.

[30] Datastream series ID AUCONPRCF for Australia, UKCHAW for the UK, CNCONPRCF for Canada, SDCCPI..E for Sweden, NZCONPRCF for New Zealand and NWCONPRCE for Norway.

[31] EcoWin codes *gbr01020* for the UK, *swe01850* for Sweden and *nor01005* for Norway, and Datastream series AUGDP…D for Australia. The series for Canada collected from the IMF IFS is denoted 15699BVRZF…, and the OECD EO series for New Zealand is Q.NZL.GDPV

[32] FRED data series are denoted Australia: IRTIBO1AUQ156N, Canada: IR3TIB01CAQ156N, Sweden: IR3TIB01SEQ156N, New Zealand: IRTIBO1NZQ156N and the UK: IR3TTS01GBQ156N. For Norway, we find the series in Datastream denoted: NWIBK3M.

[33] For Australia from Australian Bureau of Statistics via Datastream: AUTERMTDE, For Canada from Statistics Canada via Datastream: CNTRMTRDG. The series from Statistics Canada is available back to Q1 1981, and we use data from the OECD MEI before that. The two series track each other closely after 1981. For New Zealand we use NZTOTPRCF from Datastream. For Norwegian terms of trade, we use the series QUA PXM from Statistics Norway.

[34] We calculate the terms of trade from IMF-data as the quarterly export price index divided by the quarterly import price index (both unadjusted). The series IDs in the IMF IFS data base are, for e.g. UK export prices, Q11276ZF. National series and IMF-series track each other closely for the UK and Sweden.

[35] Note that Euro area GDP/CPI series are only available from 1995/1996. To construct Euro area data prior to 1995/1996, we construct time series based on data from Germany and France (weights 0.5 on each in 1960). Inflation data for France, Germany, the Euro Area, the US and Japan are collected from Datastream (local sources, corresponding to those for our six home countries under study). GDP data for France, the Euro Area and the US are Ecowin-series, local sources (fra01980, emu01718, usa01006), while GDP data for Germany (Q13499BURZF…) and Japan (Q15899BURZF…) are from IMF-IFS. Note also that in calculating the foreign series for Australia and New Zealand, Japan has a more significant weight than in the case of the other countries (where the weight is small or zero). The IMF IFS-series for Japan, for the period before 1979:q3, is replaced with OECD EO-series QJPN.GDPV because the IMF IFS-series seems to have a break and be non SA for the earlier period. This matters for Australia and New Zealand where the weight for Japan is significant.

Appendix B. Extra tables and figures

Table 4
Model comparison - Log MDD (Laplace).

	AU	CA	NO	NZ	SW	UK
Constant	3683.5	4469.7	2616.0	3194.1	2796.0	4253.1
Parameter only	3506.7	4384.9	2536.4	3207.4	2850.5	4285.9
Volatility only	NaN	4443.4	2612.2	3237.1	2899.5	4385.7
Parameter and volatility	3773.9	4513.8	2793.0	3247.1	2942.6	4571.6

Table 5
Prior and poster mode, volatility only.

Params	P.distr	P.prob	low	high	AU	CA	NO	NZ	SW	UK
ρ_i	beta	0.90	0.40	0.75	0.89	0.89	0.95	0.92	0.87	0.92
γ_π	gamma	0.90	0.90	3.00	0.14	0.28	0.49	0.57	0.09	0.28
γ_y	gamma	0.90	0.10	3.00	2.93	4.87	0.08	0.59	1.25	4.70
γ_e	gamma	0.90	0.05	3.00	0.01	0.08	2.71	0.64	0.00	0.01

Table 6
Priors and Posterior mode, parameter only.

Params	P.distr	P.prob	low	high	AU	CA	NO	NZ	SW	UK
$\rho_i(S_t^{Pol} = Low)$	beta	0.90	0.40	0.75	0.66	0.93	0.92	0.86	0.92	0.88
$\rho_i(S_t^{Pol} = High)$	beta	0.90	0.40	0.75	0.78	0.85	0.87	0.91	0.48	0.67
$\gamma_\pi(S_t^{Pol} = Low)$	gamma	0.90	0.90	3.00	1.11	0.97	0.52	0.58	1.09	0.57
$\gamma_\pi(S_t^{Pol} = High)$	gamma	0.90	0.90	3.00	0.15	0.56	0.52	0.58	1.09	0.57
$\gamma_y(S_t^{Pol} = Low)$	gamma	0.90	0.10	3.00	0.30	0.54	0.65	0.19	1.12	0.20
$\gamma_y(S_t^{Pol} = High)$	gamma	0.90	0.10	3.00	2.91	0.25	0.35	0.04	0.58	0.23
$\gamma_e(S_t^{Pol} = Low)$	gamma	0.90	0.05	3.00	0.00	0.06	1.26	0.00	0.00	0.10
$\gamma_e(S_t^{Pol} = High)$	gamma	0.90	0.05	3.00	0.02	0.43	2.39	1.45	0.00	1.22

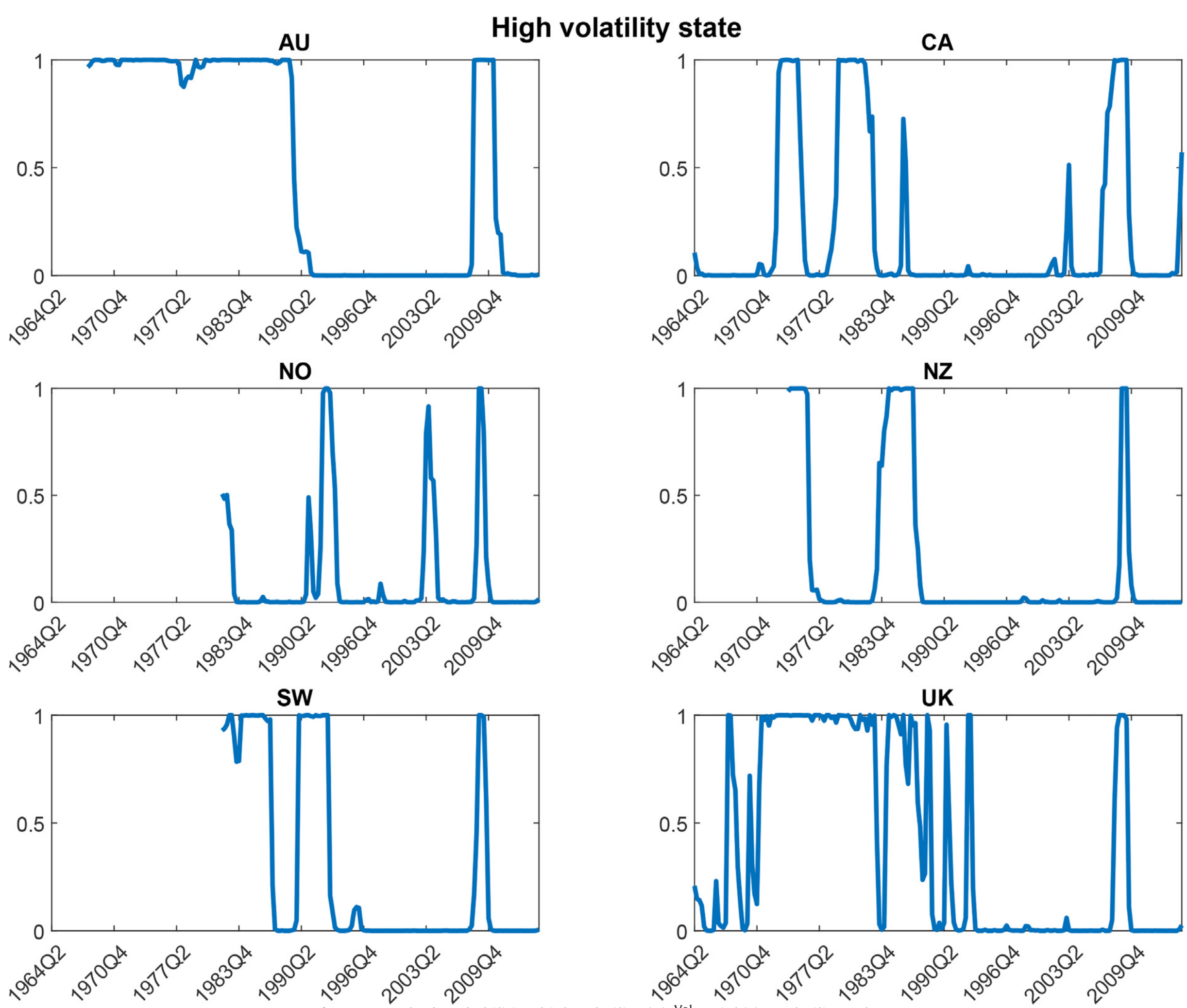

Fig. 4. Smoothed probabilities, high volatility ((S_t^{Vol}=High).) - volatility only.

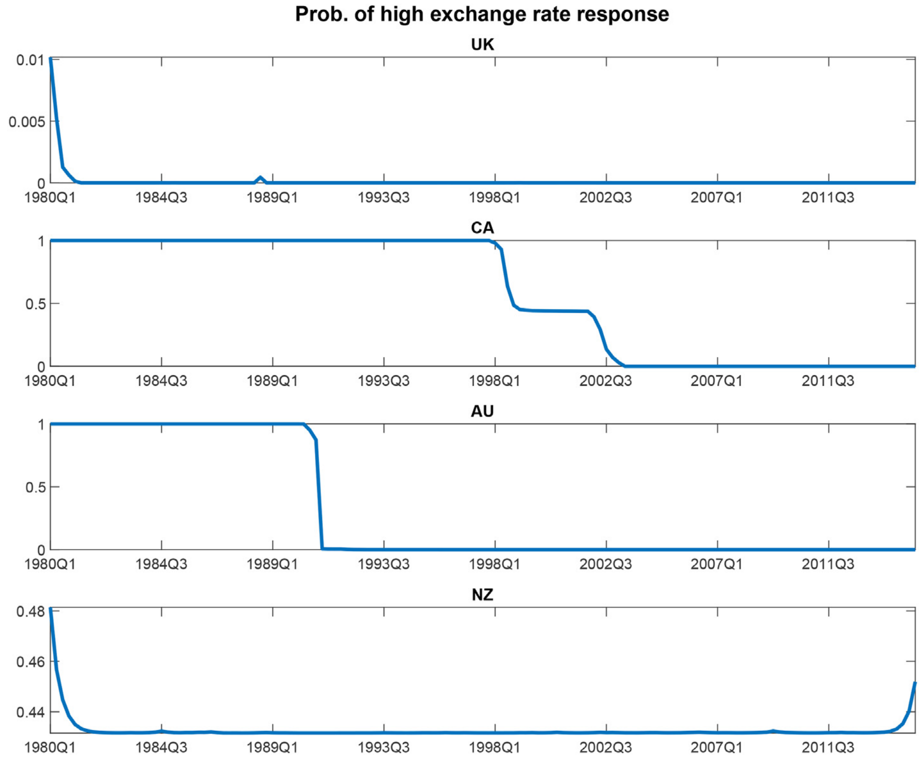

Fig. 5. High response: Smoothed probabilities - short sample (post 1980).

Appendix C. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.eneco.2021.105138.

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