Essays on Climatic Disruptions and Monetary Policy

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Declaration

Chapter 2, co-authored with Professor Warwick McKibbin, was published as a chapter in the Reserve Bank of Australia's 2018 Conference volume, *Central Bank Frameworks: Evolution or Revolution*? Working Paper versions of the material were also published by the Brookings Institution's *Hutchins Center on Fiscal and Monetary Policy* and the ANU Centre for Applied Macroeconomic Analysis (CAMA). My contribution is 70 percent.
Chapters 3 and 4 are solely authored by me. Chapter 5, which is co-authored with Warwick McKibbin, Adele Morris and Peter Wilcoxen, is forthcoming in the *Oxford Review of Economic Policy*. My contribution is 65 percent.

Otherwise, this thesis is my own work and has not been previously submitted for a degree at any institution.

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To my late Mother!

Abstract

This thesis consists of four research papers that examine the macroeconomic effects of climate change and the implications for the conduct and design of optimal monetary policy.

The first paper (joint with Warwick McKibbin) examines alternative monetary regimes and evaluates the performance of the conventional inflation targeting framework from the standpoint of Australia. Specifically, the paper examines (i) how well each monetary regime can handle supply shocks; (ii) the challenges associated with the measurement and communication of target variables under alternative monetary regimes, particularly for indicators whose real-time measurements are subject to relatively larger errors in a climatically disrupted world; (iii) the forecastability of the target variables under each monetary regime; and (iv) the ability of the conventional inflation targeting regime to credibly anchor price expectations under conditions of persistent supply-side disruptions.

The second and third papers build on the arguments from the first paper by revisiting the measurement and forecastability problems facing inflation-targeting central banks in a carbon-constrained and climatically disrupted macroeconomy. The second paper tests the hypothesis that the inclusion of climate effects in the estimation of potential output can improve real-time estimates of the output gap, with Australia as a case study. Using variations in temperature and precipitation 'anomalies' as proxies for climatic conditions over time, the paper employs an unobserved component model estimated by the data-driven Maximum Likelihood technique in the state-space context to derive *climate-neutral* measures of potential output and the output gaps. The results show that potential output and output gap measures that are adjusted for climatic disruptions are relatively more accurate in real time than those obtained from conventional approaches that do not take climate effects into consideration

The third paper employs a Bayesian-estimated structural multivariate filtering model calibrated to data for Australia and the United States, innovatively incorporating climate hysteresis into the estimation of potential output and the output and unemployment gaps. The results suggest non-trivial implications for monetary policy in a climatically disrupted world, with different implications for inflation signals during the upturn or downturn of the business cycle. Specifically, macroeconomic slacks are smaller when both actual conditions and potential supply capacity are modelled to change simultaneously, with recessions that may be less disinflationary, and booms that may be less inflationary.

The final paper, forthcoming in the *Oxford Review of Economic Policy* (joint with Warwick McKibbin, Adele Morris and Peter Wilcoxen) explores the interaction of climate change and monetary policy as they jointly influence macroeconomic outcomes, employing a general equilibrium model with full sectoral disaggregation of the energy generation sectors and strong global linkages in capital and trade. The results show that a central bank that targets the growth in nominal income outperforms one that is focused on flexibly balancing price and output stability goals in a carbon-constrained environment. Overall, the interaction between climate policy and monetary policy strongly suggests that the two policy frameworks should be jointly evaluated. Managing each regime separately can easily lead to policies that seem optimal in isolation, but that perform very poorly in practice.

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Chapter 1

1. Introduction

> *The combination of the weight of scientific evidence and the dynamics of the financial system suggest that, in the fullness of time, climate change will threaten financial resilience and longer-term prosperity. While there is still time to act, the window of opportunity is finite and shrinking* (Mark Carney, 2015).

1.1 Context and Aim of the Thesis

There is strong scientific evidence on the existential threat posed by climate change. Largely anthropogenic in nature, climate-induced natural disasters will become prevalent and unpredictable over time, with increased risks for environmental sustainability and macroeconomic stability (IMF, 2017; IPCC, 2018). On the macroeconomic front, climate risks are classified to be either *physical*—catastrophic economic damages and uncertainty caused by unpredictable climate-induced natural disasters— or *transitional*—the effects and uncertainty associated with climate policy actions (or inaction) in the transition to a low-carbon economy.

While agriculture remains the key channel through which the short-term effects of climate change are felt, especially in the developing world, physical climate risks affect macroeconomic stability via several other channels. For example, following natural disasters, the destruction of capital and livelihoods may depress households' balance sheets, negatively affecting consumption and investment (Batten, 2018). For regions or economies that are highly susceptible to frequent and extreme natural disasters, the effects of climate-related physical risks may include the disruptions to manufacturing value chains (Kingwell and Farré, 2009) and recreation and tourism (Scott et al., 2012) as well as reduction in effective labor supply (Stapleton et al., 2017). Via the financial sector, the macroeconomic effects of physical climate risks are also enormous.

Frequent, extreme natural disasters pose huge payout burdens on the insurance sector, with severe ramifications for the stability of the financial system in the event of widespread insurance defaults (Bank of England, 2015; NGFS, 2018). Sudden devaluation of assets in disaster-prone regions (Bunten and Khan, 2014) and the increased risk-aversion tendencies following persistent exposures to natural disasters (Bernstein et al., 2019) are other associated risk factors that may undermine financial and overall macroeconomic stability in a climatically disrupted world.

Emissions reduction via carbon pricing has been identified as the most effective approach to addressing the global climate emergency. While bold and ambitious emissions reduction targets are required, the larger the carbon price, the larger the stagflationary effects—falling output and rising prices, especially for carbon-intensive goods and services—in the short-to-medium term. An abrupt, disorderly transition to a low-carbon economy has large macroeconomic costs as well, ranging from substantial stranded assets (McGlade and Elkins, 2015) to the financial stability implications from rapid asset repricing and risk reallocations in financial markets (Bolton et al.,2020). Although the debate on the optimal approach to carbon pricing remains unresolved, three broad climate policy regimes are advanced in the literature: a direct tax on carbon emissions, a market-based tradable permit system or a hybrid policy of both regimes (McKibbin and Wilcoxen, 2002; Hepburn, 2006). Regardless of which climate policy regime a country adopts, the transition to a low-carbon economy is likely to be stagflationary with attendant financial stability risks, although the magnitudes of the effects differ across regimes (McKibbin et al., 2017). Therefore, the effectiveness of existing macroeconomic stabilization policies must be carefully re-examined regarding their goals of promoting broad macroeconomic stability in a carbon-constrained world.

Evidence in the literature strongly suggests that climate policy can serve as a tool for fiscal reform, especially under a carbon tax regime with the associated revenues recycled (McKibbin et al., 2012). However, the growing climate-monetary policy literature has been largely focused on the financial stability implications of climate change, with very scant research evidence on how alternative climate regimes will affect the ability of central banks to stabilize the economy under conditions of extreme physical climate risks and the price-output trade-off associated with transitional climate risks. The goal of this thesis is to bridge this gap. The key questions underpinning the thesis and summaries of the associated research findings are discussed next.

1.2 Key Research Questions and Findings

1.2.1 Does climate change matter for monetary policy?

Apart from the severe financial stability risks posed by climate change, the monetary policy implications of climatic disruption come from two sources: the increased frequency and severity of negative supply shocks and the transition risks posed by a carbon-pricing policy.

The effectiveness of monetary policy crucially hinges on the nature of macroeconomic shocks to which the economy is frequently exposed or susceptible. In the face of demand shocks, the conventional flexible inflation targeting monetary policy framework can be effective in stabilizing prices and output. However, as prices and output take divergent paths following climate-induced supply shocks, the standard monetary policy response seeking to tame near-term inflationary pressure by tightening the policy stance may accentuate the negative effects on output. Conversely, attempts at restoring output growth by easing the policy stance may be more inflationary, all else equal. The central bank must distinguish between temporary supply shocks (for which the optimal policy stance may be neutral) and permanent supply shocks for which a change in the policy stance is required. While the conventional flexible inflation targeting framework is not suitable for macroeconomic stabilization under conditions of persistent supply shocks in general, the high unpredictability and heterogeneity in expectation formation regarding the evolution of climate risks further exacerbate the challenge for monetary policy.

Even for small-scale natural disasters whose effects may be temporary, the frequency of disasters means the central bank faces an ongoing policy dilemma in maintaining macroeconomic stability (Debelle, 2019; Brainard, 2019). Therefore, in a climatically disrupted world with frequent disaster episodes, the central bank faces the constant, error-prone burden of distinguishing permanent shocks from those it deems to be temporary.

In addition to the stark price-output stability trade-off created by climate-induced supply shocks, climate shocks also negatively affect the real-time measurement of key policy variables. Whether in the form of physical or transitional climate risks, climatic disruptions induce structural macroeconomic changes that weaken or distort the relationship between price and output dynamics, further complicating the real-time forecasting of key policy variables like potential output and the output gap.

The output gap—the deviation of actual output from potential—is a key input into macroeconomic policy decisions, from examining fiscal sustainability to determining the monetary policy stance. For a flexible inflation-targeting central bank, the policy signal for accommodating output stability depends on the output gap and the evolution of inflation. The measurement and real-time unreliability issues associated with potential output and output gap estimates are not new. As Hayek (1945) puts it, the information required for macroeconomic policy formulation is not centrally available for a coordinating authority, like the central bank. On account of this knowledge problem, real-time estimates of potential output and the output gap are inaccurate either due to constant revisions as new information becomes available or due to the constantly changing state of the macroeconomy, with strong evidence suggesting that the latter is the primary factor (Orphanides and van Norden, 2002; Marcellino and Musso, 2011). That is, the constantly changing nature of the business cycle makes it difficult to accurately model how far the current state of the economy is away from its long-term potential. This also makes it extremely difficult to accurately distinguish between temporary and permanent shocks (Coibion et al., 2018). Therefore, persistent climate-induced macroeconomic volatility and uncertainty may further exacerbate the measurement problem.

On account of the above issues, the case for incorporating climate-related shocks into the monetary policy toolkit cannot be overemphasized. The key challenge, however, remains the selection of appropriate climate-modelling techniques suitable for the policy horizon facing monetary policy. While long-term scenario-modelling techniques like the integrated assessment Models (IAMs) (see Nordhaus, (1973, 2011)) may be informative in providing forecasts of long-term policy variables, like the natural rate of interest, the lack of real financial frictions and full sectoral disaggregation as well as the use of arbitrary assumptions make the IAMs less suitable for monetary policy purposes (Pindyck, 2017; NGFS, 2020).

In addressing these issues, the first paper begins with a survey of the literature on alternative monetary policy regimes and evaluates the performance of the conventional inflation targeting framework from the Australian context. Specifically, the paper examines how well each monetary regime can accommodate supply shocks, the challenges associated with the measurement and communication of the target variables under alternative monetary regimes and how the real-time measurement, particularly for indicators whose real-time measurements are subject to relatively larger errors in a climatically disrupted world. The paper also evaluates the forecastability of the target variables under each monetary regime and the ability of the conventional inflation targeting regime to credibly anchor price expectations under conditions of persistent supply-side disruptions. While the inflation targeting regime has improved the anchoring of inflation expectations, the results suggest that the nature of future shocks to the Australian economy, especially due to increasing physical or transitional climate risks, requires a serious rethinking of the monetary regime, with nominal income targeting as the preferred alternative.

The second and third papers build on the arguments from the first paper by revisiting the measurement and forecastability problems facing inflation-targeting central banks in a carbon-constrained and climatically disrupted macroeconomy. The second paper tests the hypothesis that the inclusion of climate effects in the estimation of potential output can improve real-time estimates of the output gap, with Australia as a case study.

Using variations in temperature and precipitation ‘anomalies’ as proxies for climatic conditions over time, the paper employs an unobserved component model estimated by the data-driven Maximum Likelihood technique in the state-space context to derive *climate-neutral* measures of potential output and the output gaps. The results show that potential output and output gap measures that are adjusted for climatic disruptions are relatively more accurate in real time than those obtained from conventional approaches that do not take climate effects into consideration.

In a macroeconomic environment characterized by persistent climatic disruptions, climate risks will affect both short-term demand conditions and the underlying long-term supply capacity (potential output) via a *hysteresis* mechanism. The third paper employs a Bayesian-estimated structural multivariate filtering model calibrated to data for Australia and the United States, innovatively incorporating *climate hysteresis* into the estimation of potential output and the output and unemployment gaps. The results suggest non-trivial implications for monetary policy in a climatically disrupted world, with different implications for inflation signals during the upturn or downturn of the business cycle. Specifically, macroeconomic slacks are smaller when both actual conditions and potential supply capacity are modelled to change simultaneously, with recessions that may be less disinflationary, and booms that may be less inflationary.

1.2.2 Does the joint design of climate and monetary policies matter for optimal macroeconomic outcomes?

The choice of a climate policy instrument matters for monetary policy from the standpoint of how the price on carbon affects the forecasting and the anchoring of inflation expectations as well as the attendant price-output stability trade-off. While no monetary policy regime may be ex ante more effective at maintaining macroeconomic stability under persistent climatic disruptions, this thesis investigates whether there is an optimal combination of climate and monetary regimes better suited at promoting strong macroeconomic stability in a carbon-constrained world.

The fourth paper, forthcoming in the *Oxford Review of Economic Policy* (joint with Warwick McKibbin, Adele Morris and Peter Wilcoxen) explores the interaction of climate change and monetary policy as they jointly influence macroeconomic outcomes, employing a general equilibrium model with financial frictions, full sectoral disaggregation of the energy generation sectors and strong global linkages in capital and trade. The results show that a central bank that targets the growth in nominal income outperforms one that is focused on flexibly balancing price and output stability goals in a carbon-constrained environment. Overall, the interaction between climate policy and monetary policy strongly suggests that the two policy frameworks should be jointly evaluated. Managing each regime separately can easily lead to policies that seem optimal in isolation, but that perform very poorly in practice.

1.3 Organization of the thesis

This thesis is organized as follows. Chapter 2 provides a survey of the literature on alternative monetary policy regimes and evaluates the performance of the conventional inflation targeting framework from the Australian context. Chapter 3 employs a data-driven approach in examining how the inclusion of climate effects in the estimation of potential output can improve real-time estimates of the output gap, using Australia as a case study. Chapter 4 employs a Bayesian-estimated structural multivariate filtering model calibrated to data for Australia and the United States to innovatively incorporate *climate hysteresis* effects into the estimation of potential output and the output and unemployment gaps. Chapter 5 explores the interaction of climate change and monetary policies as they jointly influence macroeconomic outcomes, using a general equilibrium model with financial frictions, full sectoral disaggregation of the energy generation sectors and strong global linkages in capital and trade. The final chapter provides a concluding summary and the direction for future research.

Chapter 2

2. Twenty-five Years of Inflation Targeting in Australia: Are There Better Alternatives for the next Twenty-five Years?

Note: This is an updated manuscript of the published paper 'Mckibbin and Panton (2018)' to which my contribution was 70 percent. All results are the same. However, I have updated the references of previously cited working papers that are now published.

Abstract

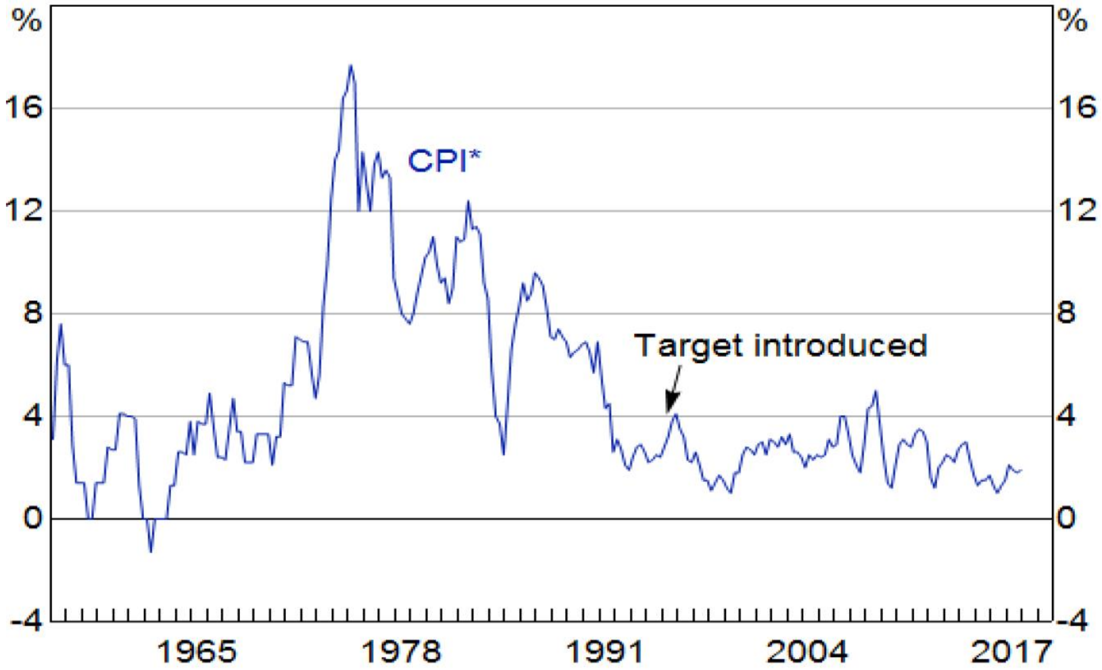
This paper provides a survey of the literature on alternative monetary policy frameworks and evaluates whether the current inflation-targeting framework, followed by the Reserve Bank of Australia (RBA) for the past 25 years, is likely to be the most appropriate framework for the next 25 years. While flexible inflation targeting has appeared to work well in Australia in the past decades, the nature of future shocks suggests that some form of nominal income targeting is worth considering as an evolutionary change to Australia's framework for monetary policy.

2.1 Introduction

The core mandates of the Reserve Bank of Australia (RBA hereafter) are promoting price stability, employment, economic prosperity, and the welfare of the Australian people. However, the way in which monetary policy has been conducted, in order to achieve these goals, has undergone evolutionary changes over the past 35 years. Most notable was the switching from money targeting that prevailed throughout the 1980s, to a "checklist" approach and finally to inflation targeting beginning around 1993. Under the inflation targeting framework, the RBA's price stability objective is defined as achieving a *medium-term average inflation rate* of 2 to 3 percent over the cycle – which allows some policy space for short-run considerations of output and employment fluctuations. While the introduction of inflation targeting has witnessed a substantial containment in inflationary pressure, with year-ended inflation averaging under 3 percent since 1993 (Figure 2.1), the theoretical debate about the desirability of inflation targeting as an optimal monetary policy regime remains active.

The debate has been less focused on whether inflation targeting has tamed inflation, but more focused on whether its side effects (e.g. sacrificing output stability for price stability, weak anchoring of expectations, etc.) are more pronounced compared to outcomes under alternative monetary policy regimes.

Figure 2.1. Evolution of CPI Inflation



* Excludes interest charges prior to September quarter 1998 and adjusted for the tax changes of 1999–2000

Sources: ABS; RBA

In discussing the possible future role for inflation targeting in Australia, this paper begins with a summary of the alternative monetary frameworks that have been proposed in the economics literature over many decades. The third section addresses the major issues that are important for the relevance of each monetary framework with a particular focus on the Australian context. The fourth section explores the nature of historical shocks experienced during the inflation targeting period in Australia and then conjectures the likely nature of future shocks in the domestic and global economies over the coming decades. A summary and policy implications are outlined in section five.

2.2 Alternative Monetary Frameworks

Stanley Fischer (1995) observed that the search for an optimal monetary policy framework is an unending one. This is reflected in the RBA's monetary policy framework undergoing evolutionary changes over the years. From the failure of money targeting in the 1980s to the introduction of inflation targeting in the early 1990s, changes to the conduct of monetary policy have been mostly dictated by the prevailing macroeconomic fundamentals.

In this section, we place the current inflation targeting regime in the broader context of alternative monetary regimes in the literature. The goal is to provide a summary analysis on how changing macroeconomic fundamentals can require rethinking the monetary policy framework over time.

2.2.1 Inflation targeting

In its strictest form, an inflation targeting regime is concerned with achieving and maintaining *low* and *stable inflation*, with a base drift, without consideration for controlling deviations in the output level. That is, all shocks that affect price stability— whether temporarily or permanently—are accommodated by changes to the policy rates as summarized by equation (2.1).

$$i_t = i_{t-1} + \alpha \left(\pi_{t,t+n} - \bar{\pi}\right) \qquad (2.1)$$

where the nominal interest rate i set in period t is a function of the rate from $t-1$ and α measures how the central bank responds to shocks that cause forecast inflation ($\pi_{t,t+n}$) to deviate from the inflation target ($\bar{\pi}$). However, in practice, as per the mandate of most central banks, some considerations are given to output stabilization in the conduct of monetary policy, under what is termed *flexible inflation targeting*. Under such a regime, the central bank has an objective function given in (2.2)

$$L_t = \frac{1}{2}[(\pi_t - \bar{\pi})^2 + \lambda y_t^2] \qquad (2.2)$$

where π_t is inflation in period t, $\bar{\pi}$ is the central bank's inflation target and $\lambda \geq 0$ is the weight on the central bank attaches to stabilizing the output gap (y_t).

That is, instead of responding to all shocks that affect inflation, a flexible-inflation targeting central bank distinguishes between temporary and permanent shocks in balancing the price stabilization objective with the output stabilization goal (Fischer, 1995; King, 1997; Bernanke 2015). Equations (2.1) and (2.2) imply that the accuracy of the forecasts of inflation and potential output are critical in achieving optimal monetary policy outcomes—in the form of strongly anchored expectations and policy credibility. Indeed, most central bank forecasting models include an estimate of the output gap as a critical element in the forecast of future inflation. However, there is strong evidence that central banks' forecasts, particularly in measuring the output gap, are subject to large errors. The less well central banks can forecast the output gap, the more policy credibility is undermined (Orphanides, 2001; Beckworth and Hendrickson, 2020). A variant of the flexible inflation target regime is the set of rules proposed by Henderson and McKibbin (1993) and applied to the U.S. Fed policy behavior by Taylor (1993). As indicated by equation (2.3), the monetary policy reaction function under a Henderson-McKibbin-Taylor (HMT) type rule is expressed as:

$$i_t = i_{t-1} + \alpha\,(\pi_t - \bar{\pi}) + \gamma(Y_t - \bar{Y}_t) \qquad (2.3)$$

where α and γ represent the respective weights on price stability and output stability and Y_t is output[1]. Under the assumption of sticky nominal wages, these parameters can be derived, as was the case in Taylor (1993) for the U.S. Fed covering the period 1984-1992. In addition to price and output stability, other macroeconomic indicators such as exchange rates can be included in the HMT-type rules using a general equilibrium modelling framework. An example is the approach in the G-Cubed model (McKibbin and Wilcoxen, 2013).

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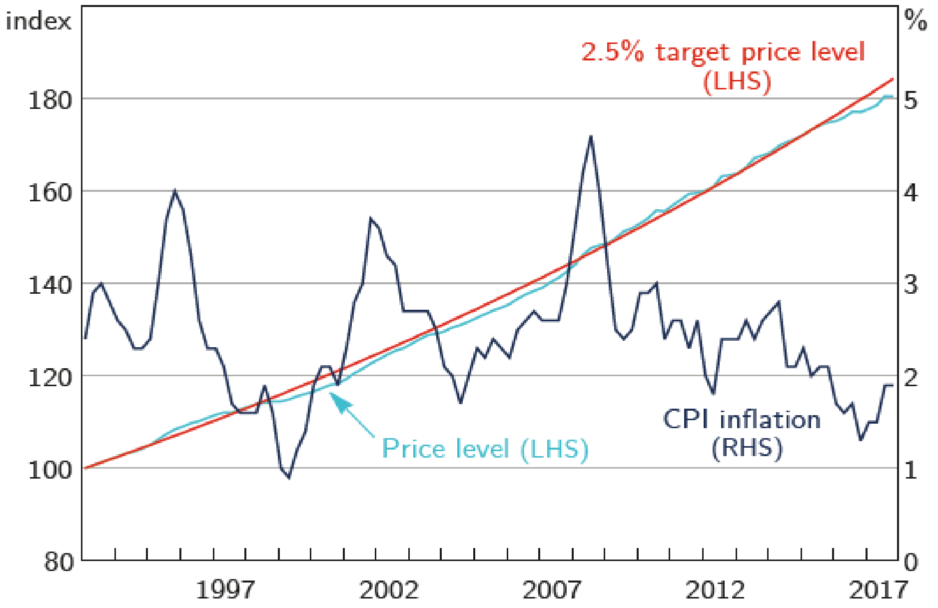
[1] The output term can also be written in terms of output growth relative to target. This alternative is the specification used in the G-Cubed model because average trend output growth is easier to measure than the level of potential output at each point in the future. McKibbin and Wilcoxen (2013)

2.2.2 Price level targeting

The foremost objective of monetary policy, achieving and maintaining price stability, is usually interpreted as maintaining low and stable rate of inflation (Svensson, 1999). For the RBA, 'low and sta*ble*' is defined as maintaining an average CPI inflation rate of 2 to 3 percent over the cycle. But it could also mean maintaining a *stable price level*, instead of its rate of increase—the inflation rate.

Under price level targeting, the goal of monetary policy is to maintain stability in the *price level*, with the price level maintained along a desired path by compensating lower past inflation with higher current inflation and vice versa. That is, under price level targeting, bygones are *not* bygones, making it an effective regime in anchoring expectations. However, the effectiveness of a price level target as a monetary policy anchor is crucially dependent upon whether economic agents are rational—that is, they fully understand the history-dependent nature of a central bank's policy response (Amano, Engle-Warnick and Shukayev 2011). However, recent findings by Woodford (2013) and Honkapohja and Mitra (2019) show that under the assumption that agents are not fully rational or have imperfect knowledge about the history-dependent nature of policy, price level targeting is still superior to inflation targeting. As illustrated in Figure 2.2, the core CPI inflation rate has largely averaged below 2.5 per cent– the midpoint of the RBA's 2 to 3 per cent target range – since the introduction of inflation targeting in 1993.

Figure 2.2. Quarterly CPI and CPI Inflation 1993Q1-2017Q4



Notes: The 2.5 % target price level is the price level had inflation (excluding volatiles) been targeted at exactly 2.5 % throughout the entire period; levels are indexed at March 1993 = 100

Sources: ABS; Authors' calculations; RBA

As periods of below-target inflation are not offset by above-target inflation under inflation targeting, the core price level remains slightly lower during most of the inflation-targeting era than it would have been had inflation been targeted at 2.5 per cent per annum with no bygones being bygones. By letting bygones be bygones—as is the case under inflation targeting—the price level becomes non-trend stationary with a base drift, potentially increasing the variance of output indefinitely. As Svensson (1999) has shown, assuming agents are rational, and the central bank has perfect control over inflation, then the monetary policy loss function under price level targeting can be written as

$$L_t = \frac{1}{2}[(P_t - P_t^{\cdot})^2 + \lambda(y_t - y_t^{\cdot})^2] \qquad (2.4)$$

where P_t and P_t^* are the price level and socially optimal price level respectively, while y_t and y_t^* are output and potential output and $\lambda \geq 0$ is the weight placed on output stabilization. Contrary to the argument that a price level targeting regime creates high output variability by not letting *some* (temporary) bygones be bygones, the strong anchoring of expectations and promotion of policy credibility cannot be overemphasized.

Similar to arguments by Evans (2012) and Williams (2017), Bernanke (2017) points out that with the strong anchoring of expectations that can be achieved under price level targeting, monetary policy can be effective under a *binding* zero lower bound (ZLB) on interest rates by introducing a *temporary* price level target. According to the temporary price-level target argument, instead of creating policy space by increasing the inflation target—which is inefficient (Eggertsson and Woodford, 2003)—or making a complete regime change to price level targeting—which could create high policy uncertainty—the optimal approach is the introduction of a *temporary* price level target evoked during periods of binding ZLB and communicated with clear Odyssean-type forward guidance.

2.2.3 Nominal income targeting

Nominal income targeting has long been advanced in the literature as a suitable policy rule[2]. Indeed, before the widespread adoption of inflation targeting by central banks in the 1990s, various forms of nominal income targeting were seen to be a better alternative than inflation targeting under a range of assumptions.

Unlike flexible inflation targeting (or price level targeting), that addresses the symptoms (price stability) of output volatility, the objective of monetary policy under nominal income targeting is the stabilization of some measure of total nominal income. A policy rule targeting a specific *level* of nominal income can be expressed as:

$$i_t = i_{t-1} + \alpha \left(PY_{t,t+n} - \overline{PY}_{t+n} \right) \tag{2.5}$$

with $PY_{t,t+n}$ representing nominal income level in period $t+n$, forecast in period t, and $\overline{PY}_t$ the targeted level. McCallum (2015) argues that in order to overcome the time-inconsistency problem, nominal income targeting should be based on the growth rate of nominal income (g_t) instead of its level as expressed in equation (2.6):

$$i_t = i_{t-1} + \alpha \left(g_{t,t+n} - \bar{g}_{t+n} \right) \tag{2.6}$$

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[2] See Henderson & McKibbin (1993), Sumner (2014), Woodford (2012), Beckworth & Hendrickson (2020)

Apart from the fact that there need not be a *divine coincidence* to simultaneously achieve price and output stability (Blanchard and Gali, 2007) under nominal income targeting, a central bank following the nominal income targeting regime does not need to have real-time knowledge of potential output—a source of serious policy errors under inflation targeting. A nominal income target can be achieved with a range of outcomes for inflation and real output. For example, inflation could be above that desired by equation (2.3) and real output growth below that desired in equation (2.3) but the nominal income target could still be achieved *ex post*.

A second advantage of nominal income targeting is that productivity shocks that create divergent paths for price and output need not be accommodated by sacrificing output stability for price stability (Rogoff, 1985; Henderson and McKibbin, 1993). Third, in the event of extreme crisis when real interest rates may need to fall sharply to stabilize falling output, a nominal income target automatically allows expected inflation to rise well above the long run inflation goal. The sharper the fall in expected output, the larger the capacity for the central bank to drive higher expected inflation without abandoning the nominal income target. With falling real output, the inflation upper bound is automatically relaxed.

In a very transparent way, the extent to which inflation can rise is restricted to a band that is determined by the amount real GDP changes for a given shock. Thus, there is still a credible band for expected inflation, but the upper and lower inflation rates vary with the extent of economic shocks. This can be interpreted as a transparent rule that implements the idea of "inflation targeting over the cycle". This can be contrasted with a central bank following an inflation target. With a hard upper bound of 3%, a well anchored expected inflation rate is unlikely to rise above 3% unless a central bank announced a special circumstance. In the case of extreme negative supply shocks, nominal income targeting enables the real interest rate to fall more quickly (if expected inflation can rise) and further than under a flexible inflation target. A further consideration is that in a time of large private and public debts, a key part of financial stability is to ensure nominal GDP grows at a reasonable rate. Sustainable growth of nominal GDP is more important than low inflation in a highly leveraged world.

There are a number of additional considerations regarding the form of nominal income rules. Apart from level versus growth rate issues, a key question is whether a nominal gross domestic product (GDP) rather than a nominal gross national product (GNP) rule is more appropriate. In a closed economy the two would be the same. However, in an open economy, GDP is a measure of production location whereas GNP is a measure of what income is generated. In countries with large swings in terms of trade, GNP varies far more than GDP over time.

2.2.4 Financial stability

Besides the conventional goals of promoting price stability and output stability as required by the mandates of most central banks, there has been an active debate on whether central banks should also worry about financial stability. An early contribution to this was Borio and Lowe (2002) and the global financial crisis (GFC) accentuated the debate. By 2010 it was a key issue in the debate about the role of monetary policy in Australia[3]. Evidence in the literature remains mixed on which policy rule can optimally incorporate financial stability as an objective of monetary policy, with Woodford (2012) arguing for a Taylor-type rule and Sheedy (2014) recommending a nominal income rule. Using the weighted sum of asset prices and household debt in relation to an equilibrium level as proxy for financial stability risks (Disyatat, 2010; Woodford, 2012), an additional mandate incorporating financial stability can be described by a loss function of the form[4]:

$$L_t = \frac{1}{2} \mathrm{E}_0 \sum_{t}^{\infty} \beta^t \left[\pi_t^2 + \lambda_y y_t^2 + \lambda_\Omega \Omega_t^2\right] \qquad (2.7)$$

where $\lambda_y \geq 0$ and $\lambda_\Omega \geq 0$ are the weights on output stability and financial stability, Ω_t is a measure of financial risks and $0 < \beta < 1$ is a discount factor. In this ternary framework, flexible inflation targeting is still the standard rule with an invariant long-run price level but addressing financial stability risks are included as a mandate of monetary policy, not to be only tackled through regulatory policies.

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[3] This was a major focus in the paper by Cagliarini, Kent and Stevens (2010) on fifty years of inflation targeting.

[4] In the monetary literature this is referred to as a "ternary" mandate

2.2.5 Other monetary regimes

In addition to the above policy rules, there are a number of alternative proposals for monetary regimes. A fixed exchange rate regime is popular in countries with central banks that do not have sufficient credibility to follow independent monetary policies. The fixed exchange rate regime effectively imposes on the domestic central bank the monetary regime of the country to which the exchange rate is pegged. Other variations include pegging the commodity price index or other definitions of the inflation or price level targets. These have been comprehensively evaluated by Frankel & Catão (2011) in the context of the specific problems faced by emerging economies, and economies subject to large variations in their terms of trade due to commodity price fluctuations.

In the Australian context, with the apparent success of inflation targeting over the past 25 years, the debate in 2018 is between the continuation of flexible inflation targeting or switching to a more clearly identified nominal income target. The key issues to be carefully considered in making such a switch are analysed in the next section.

2.3 Key Issues in the choice of the monetary regime

On the debate regarding the appropriate monetary regime for Australia, there are a number of critical issues that need to be considered. Included are several critical questions such as:

1) How well does each regime handle shocks?
2) Can the target of monetary policy be credibly measured and clearly understood?
3) How transparent is the regime when exceptions to the basic policy rule are required?
4) Are price expectations anchored by the monetary regime?

Each of these issues are considered in turn below.

2.3.1 How does the monetary regime handle shocks?

One of the more important issues in the choice of a monetary regime is how well each regime handles different types of shocks. This question goes back to the work of Poole (1970) on money demand versus goods demand shocks and supply shocks and extended by Henderson and McKibbin (1993) to consider: money demand shocks; aggregate demand shocks; supply shocks; and changes in country risk. The standard result in the theoretical literature and the large modelling literature (summarised in Bryant, Hooper and Mann (1993)) is that inflation targeting and nominal income targeting handle money demand shocks well because both would neutralise the monetary shocks before they emanate from the money market. Both regimes handle demand shocks equally well, since a rise in demand implies a rise in inflation as well as a rise in nominal income. Under both regimes, a rise in the interest rate would automatically dampen the effects of demand shocks on output and inflation.

The exact extent of policy change, and therefore the trade-off between output and inflation, would be different under each regime and which regime performs best depends on the parameters of the particular model. Thus, in practice, the relative performance is an empirical question. Because of the constantly changing nature of money velocity, a fixed money rule does not handle demand shocks well, causing many countries to abandon monetary targeting during the 1970s.

The type of shocks that are not handled well by strict inflation targeting are aggregate supply shocks, such as a surprise fall in productivity or the occurrence of an earthquake. In the face of a negative supply shock, an inflation-targeting central bank would see prices rising and output falling. In response to rising prices, monetary policy would be tightened and therefore the output fall would be accentuated. A flexible inflation-targeting central bank, if it knew the nature of the supply shock, could argue that policy did not need to be tightened and therefore the response would be tempered. A nominal income-targeting central bank would see prices rising and output falling and nominal income approximately unchanged (the outcome would depend on output and price elasticities).

To the extent that some supply shocks are unobserved, there is an advantage of nominal income targeting over inflation targeting, and even over flexible inflation targeting in the form of weakened policy credibility. While a flexible inflation-targeting central bank may have to signal special circumstances under which certain supply shocks would not be accommodated (if they are considered temporary), a nominal income-targeting central bank on the other hand does not have to make such a distinction. To the extent that the distinction between shocks that can be accommodated and those that cannot be accommodated is not correctly made due to the lack of real-time knowledge by the central bank, a nominal income target can be argued to promote stronger policy credibility than a flexible inflation target.

2.3.2 Can the target be credibly measured and clearly understood?

Whatever target a central bank adopts as the anchor for monetary policy, effective communication is crucial for the formation of expectations by private agents. Crucial to such communication are two key issues. First, can the selected target be *credibly* measured by the central bank? Second, is the target *clearly* understood by economic agents?

2.3.2.1 Measurement

For all monetary policy rules, the question of how credibly the central bank can measure the target is a key concern, particularly for indicators whose measurement in real time cannot be done with precision. There is strong empirical evidence that there is unlikely to be a *divine coincidence* in the conduct of monetary policy, especially when there are real wage rigidities (Blanchard and Gali, 2007) or supply shocks (Kim, 2016)[5]. That is, when there are divergent paths for price and output, central banks that aim to achieve both price and output stability—via *flexible* inflation targeting or price level targeting—are faced with a strong trade off. A key input into such flexible monetary policy reaction or loss functions is an estimate of the output gap. However, as the economy's potential output is not observed in real time, the use of preliminary estimates of the output gap is the norm.

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[5] achievement and maintenance of price stability does not guarantee output stability, with a strong trade-off in achieving both objectives

Apart from the lack of uniformity in measurement and large *ex post* revisions of preliminary estimates, the unreliability of output gap data for policy purposes is largely underpinned by the constant changes in the end-point in trend output as the true nature of the economy changes with hindsight (Orphanides and Norden, 2002). The lack of a reliable output gap measure is the "Achilles heel" of inflation targeting as currently practiced.

As no publicly available historical output gap series is available for Australia, most empirical analyzes on the issue follow an econometric approach (see Gruen and Stone, 2005). For nominal income targeting on the other hand, such real-time knowledge burden from output gap measurement is not placed on the central bank. That is, for a monetary policy regime based on nominal income target (as opposed to inflation or price level target), the real-time knowledge problem on the central bank is for forecasting nominal income, instead of the output gap.

2.3.2.2 Understanding

Monetary policy is considered credible if the expectations of economic agents are firmly anchored. But such anchoring of expectations depends on how clearly and easily the policy or target can be understood. A nominal income target outperforms other policy rules on this count. First, unlike a flexible inflation target for which both price stability and output stability goals are communicated, only a nominal growth target is communicated for a nominal income targeting regime (McCallum 2011; Sumner, 2011)[6]. Second, with volatile items, particularly oil and food prices, excluded in measuring *underlying inflation*—the measure of inflation accommodated by most inflation-targeting central banks, including the RBA, persistent disconnect between headline and underlying inflation may weaken policy credibility, particularly in an environment characterized by persistent supply shocks that drive a wedge between underlying and headline inflation. Such distinction between underlying and headline inflation that affects policy credibility needs not be made under nominal income targeting.

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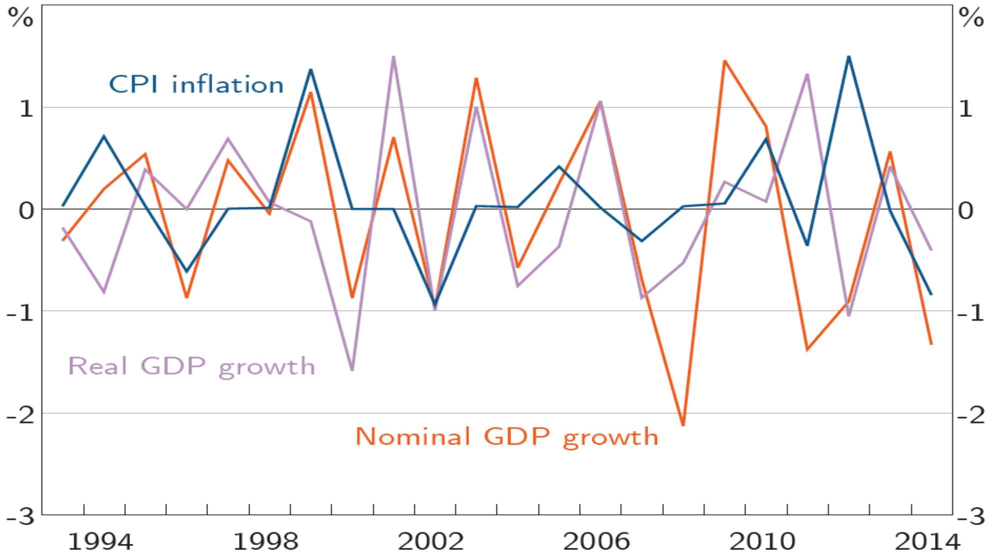
[6] Nothing prevents the central bank from announcing the underlying inflation and real growth goals – indeed this would enhance understanding the of the policy.

Another issue relating to measurement is the extent of revision of data over time. Compared with inflation statistics, nominal GDP statistics are published with long time lags and subject to revisions over time. However, as there is evidence that errors from nominal income growth forecast are stationary, the impact of growth data revisions on target credibility may not a major concern compared with errors in measuring the output gap. However, it may be feasible, by using big data, to generate daily information on a large part of nominal expenditure. Whether good proxies for nominal income growth in real time may be developed is an area where future research could focus.

2.3.3 How forecastable are the Different Targets?

Figure 2.3 shows the forecast errors made by the OECD in forecasting annual nominal GDP growth, real GDP growth and CPI inflation for Australia from 1993 until 2014. The forecast errors are also stationary when tested for a unit root. They also appear to be of a similar magnitude. The results are similar for errors made by the Australian Treasury in forecasting nominal GDP and inflation over the decade 2007-2017 (Table 2.1). For the period 2007-2012, the errors made in the May forecasts for 1-year nominal GDP and inflation are of similar magnitude as measured by the root mean square error (RMSE). For the succeeding period (2012-2017), the RMSE for the May 1-year ahead nominal GDP forecast is almost twice that of inflation for the same period, although the December 1-year forecast for nominal GDP performance is better than the inflation forecast performance. However, over the entire 10-year period, there appears to be little difference between the Treasury's forecast performance for both CPI inflation and nominal GDP.

Figure 2.3. OECD's Forecast Errors



Source: OECD and authors' calculations

Table 2.1. Root-Mean Squared Errors of Australian Treasury's Forecasts of Nominal GDP and CPI Inflation

(Forecast for next financial year)

	Nominal GDP		CPI Inflation	
Period	May	December	May	December
2007/08—2011/12	1.38	0.89	1.18	1.10
2012/13—2016/17	1.52	0.74	0.87	0.70
20070/8—2016/17	1.45	0.82	1.04	0.92

Note: The root mean squared error (RMSE) is calculated by squaring the forecast errors, averaging them over the indicated periods and taking the square root of the result. Forecast error at each horizon is computed as actual (outturn) less forecast.

Source: Australian Treasury; Authors' calculations

2.3.4 Are Inflation Expectations Firmly Anchored in Australia?

It is often argued that a focus on inflation by central banks is the best way to anchor inflation expectations. It is worth exploring if this is correct. The key measure of how credibly a central bank has performed under inflation targeting is to test for any decoupling between the inflation expectations of private agents and the central bank's inflation target or forecast (King 2005). The best explanation of this concept is the statement by Blinder (2000, p 1422) that '[a] central bank is credible if people believe it will do what it says'. Under a credible flexible inflation-targeting regime, short-term deviations from the target are allowed without fear of weakening policy credibility, provided economic agents are confident that the target will be achieved over the cycle. That is, while the goal is the firm anchoring of long-term inflation expectations, short and medium-term expectations can be anchored through forward guidance—more likely so if the forward guidance is 'Odyssean', rather than 'Delphic', in nature (see Bernanke (2017)). However, as wage and price-setting behaviours are more contingent on short and medium-term expectations than longer-term ones, persistent flexibility in postponing target achievement may drive de-anchoring of inflation expectations.

We explore several aspects of the anchoring of inflation expectations in Australia. We follow the work by Demertzis et al (2008) on the U.S. economy and Łyziak and Paloviita (2017) on the inflation expectations in the Eurozone. First, we test how long-term expectations are influenced by actual inflation. Second, we examine the dependence of long-term expectations on short-term expectations. We base these inflation expectations on a mix of financial market data and different surveys of expectations. An alternative approach using survey data is proposed by Carvalho et al (2017) using data for a range of countries but not including Australia. Further work could use this approach to test the conclusion from our analysis.

An inflation targeting central bank minimizes the following loss function (2.8) subject to the Lucas supply function (2.9)

$$L_t = \frac{1}{2}\mathbb{E}[(\pi_t - \bar{\pi})^2 + \lambda y_t^2] \tag{2.8}$$

$$y_t = \pi_t - \pi_t^e + \xi_t \tag{2.9}$$

where ξ_t is a zero-mean and constant variance supply shock. The optimization of (2.8) can be written as

$$\pi_t|\xi_t = \frac{1}{2}[\bar{\pi} + \pi^e - \xi_t] \tag{2.10}$$

where π_t is period's t inflation outcome that is conditional on ξ_t and π_t^e is private agents' expectations. Under a credible monetary policy regime, private agents' expectations are firmly anchored ($\pi^* = \pi^e$). This means that from equation (2.10):

$$\pi_t|\xi_t = \bar{\pi} - \frac{1}{2}\xi_t \tag{2.11}$$

$$\mathbb{E}(\pi) = \bar{\pi} \tag{2.12}$$

Assuming that long-run inflation expectation, π_t^e, at any given time is a function of the weighted average of the inflation target (π^*) and one period lagged inflation rate (π_{t-1}) as in (2.13):

$$\pi_t^e = \rho_t\bar{\pi} + (1 - \rho_t)\pi_{t-1} \tag{2.13}$$

then, ρ_t ($\in [0,1]$) denotes how firmly inflation expectations are anchored. Therefore, at one extreme is full credibility ($\rho_t = 1$) where expectations are exactly anchored at target. At the other extreme is the case of no policy credibility ($\rho_t = 0$) with complete de-anchoring of expectations. Therefore, if the argument that inflation targeting has successfully tamed inflation in a credible manner is true, then there must be a disconnect between inflation and inflation expectations in the historical data.

To test this hypothesis, we follow the approach by Demertzis et al (2008) as summarized by the vector autoregressive (VAR) model below

$$\begin{pmatrix} \pi_t \\ \\ \pi_t^e \end{pmatrix} = \begin{pmatrix} c_1 \\ \\ c_2 \end{pmatrix} + \begin{pmatrix} a(L) & b(L) \\ \\ c(L) & d(L) \end{pmatrix} \begin{pmatrix} \pi_{t-1} \\ \\ \pi_{t-1}^e \end{pmatrix} + \begin{pmatrix} \varepsilon_{1t} \\ \\ \varepsilon_{2t} \end{pmatrix} \tag{2.14}$$

$$\begin{pmatrix} \varepsilon_{1t} \\ \\ \varepsilon_{2t} \end{pmatrix} \sim iid\left(\begin{pmatrix} 0 \\ \\ 0 \end{pmatrix}, \begin{pmatrix} \sigma_{11} & \sigma_{21} \\ \\ \sigma_{12} & \sigma_{22} \end{pmatrix} \right)$$

where π_t and π_{t-1} are the actual CPI and one quarter lagged CPI rates respectively and π_t^e is expected (medium or long-term) expected inflations. Under the conditions that actual lagged inflation has no effect on inflation expectations (medium- and long-term) and vice versa, as well the lack of any contemporaneous shock transmission from actual inflation to expected inflation (and vice versa), then impulse response functions (IRFs) generated from Equation (2.14) must show no reaction dynamics.

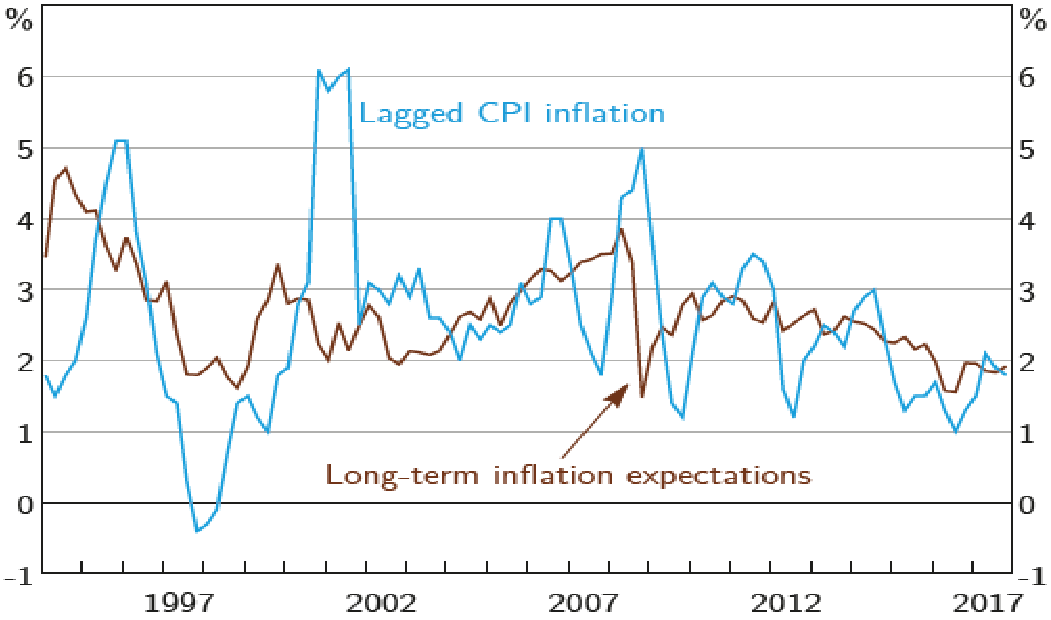
Similar to Gillitzer and Simon (2015), we split the sample into two regimes with different inflation dynamics: the era before inflation targeting (1986:Q3–1993:Q4) and the inflation-targeting era (1994:Q1–2017:Q4). Inflation expectations data are those based on the RBA's statistical tables. Short-term expectations are represented by the business inflation expectations 3-months ahead data series (1989:Q3–2017:Q4), while medium-term expectations are represented by the union officials' 2-year ahead data series (1997:Q2–2017:Q4). We use the break-even 10-year inflation rate as a proxy for longer-term inflation expectations (1989:Q3–2017:Q4).

2.3.4.1 Pre-Inflation Targeting Era: Was Monetary Policy Credibility Low?

The primary goal of adopting inflation targeting was to improve the credibility of monetary policy. As shown in Figure 2.4, both CPI inflation and long-term inflation expectations have been on a downward trend throughout the decades leading to inflation targeting. To test monetary policy credibility during the pre-inflation-targeting era, we examine the sensitivity of long-term inflation expectations to actual inflation dynamics (lagged one quarter) using the VAR model in Equation (2.14) with two lags (determined by information criteria).

Empirical diagnostic checks show, among other things, that the model was correctly specified, with serially uncorrelated and homoskedastic errors. The impulse responses are provided in Figure 2.5. The results show that the formation of long-term expectations was sensitive to actual inflation dynamics during the period, indicating weak anchoring and poor credibility.

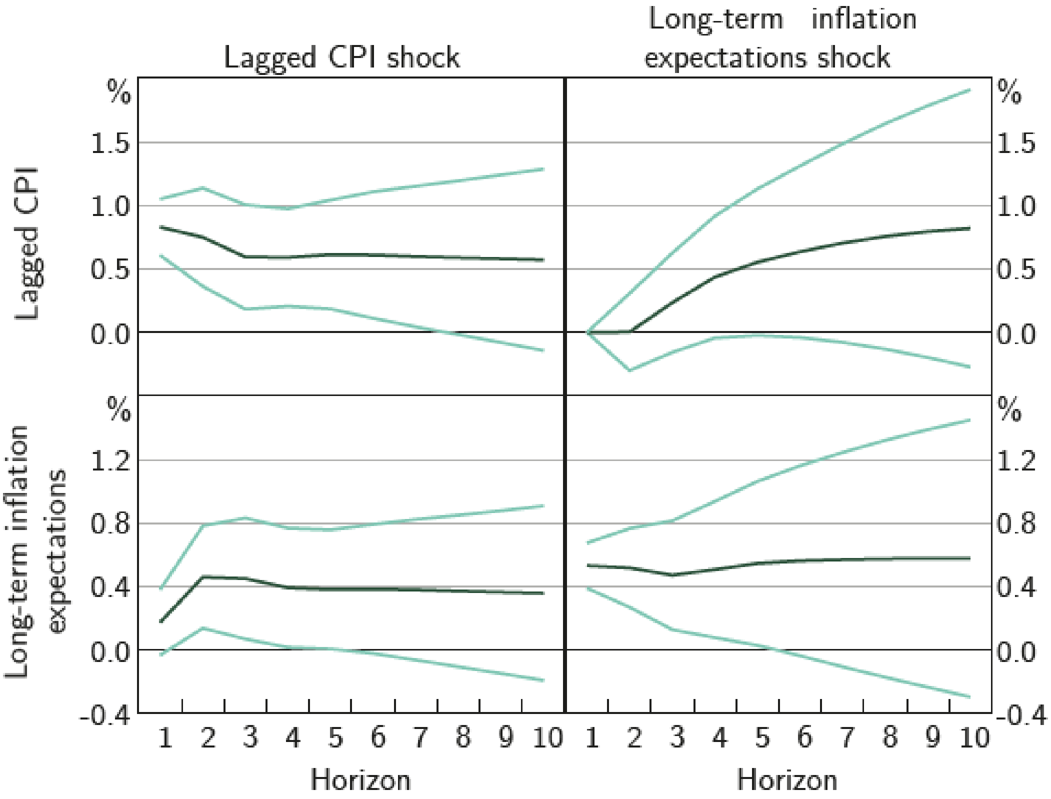
Figure 2.4. Inflation and Long-term Inflation Expectations



Note: Long-term inflation expectations are represented by the average annual inflation rate implied by the difference between the 10-year nominal bond yield and the 10-year inflation-indexed bond yield, as compiled by the RBA

Sources: RBA; Yieldbrok

Figure 2.5. IRFs—CPI and Long-term Inflation Expectations: 1986Q3-1993Q4



Note: Response to Cholesky one standard deviation (degrees of freedom adjusted) innovations with ±2 standard errors

Sources: Authors' calculations; RBA

2.3.4.2 Inflation Targeting Era: Have Expectations Been Credibly Anchored?

Figure 2.6 shows inflation and expectations dynamics during the inflation targeting era. As more data on expectations are available for the inflation-targeting era, we examine not just how actual inflation affects long-term inflation and vice versa, but also how long-term expectations are influenced by short-term expectations. Under strong anchoring, both actual inflation and short-term inflation expectations[7] should not influence long-term expectations and vice versa.

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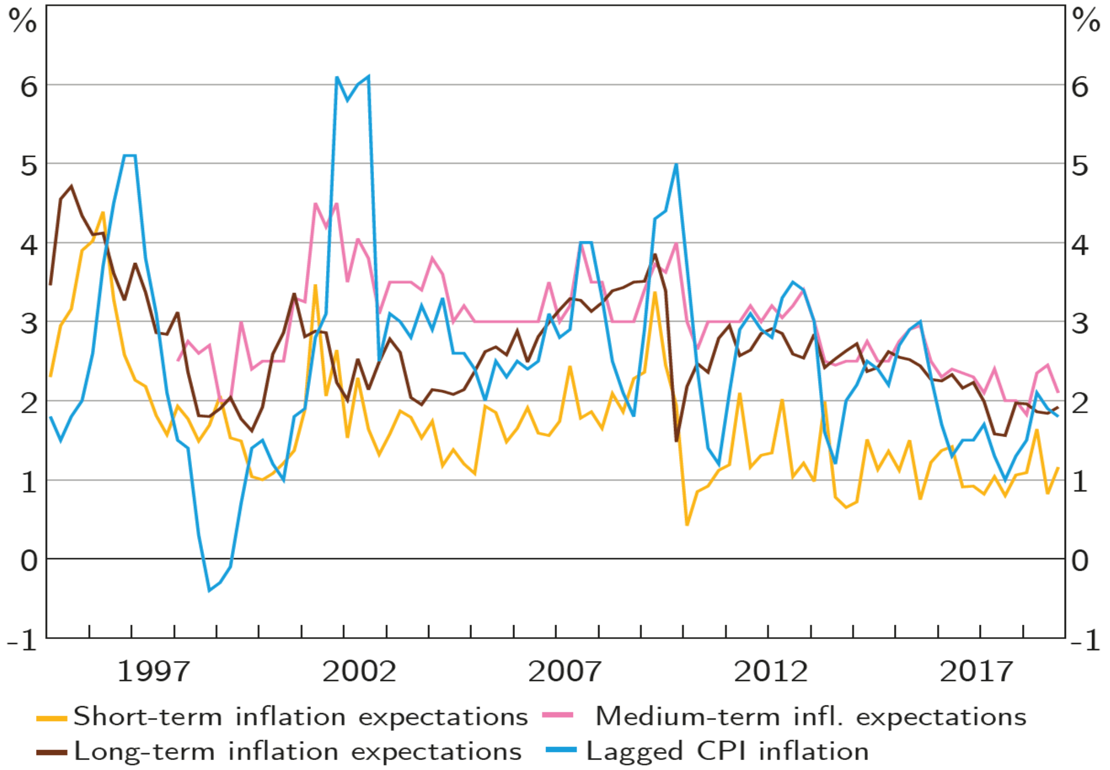
[7] Survey of Business inflation expectations – 3-months ahead as compiled by the National Australian Bank

Figure 2.6. Inflation and Inflation Expectations: 1994Q1-2017Q4

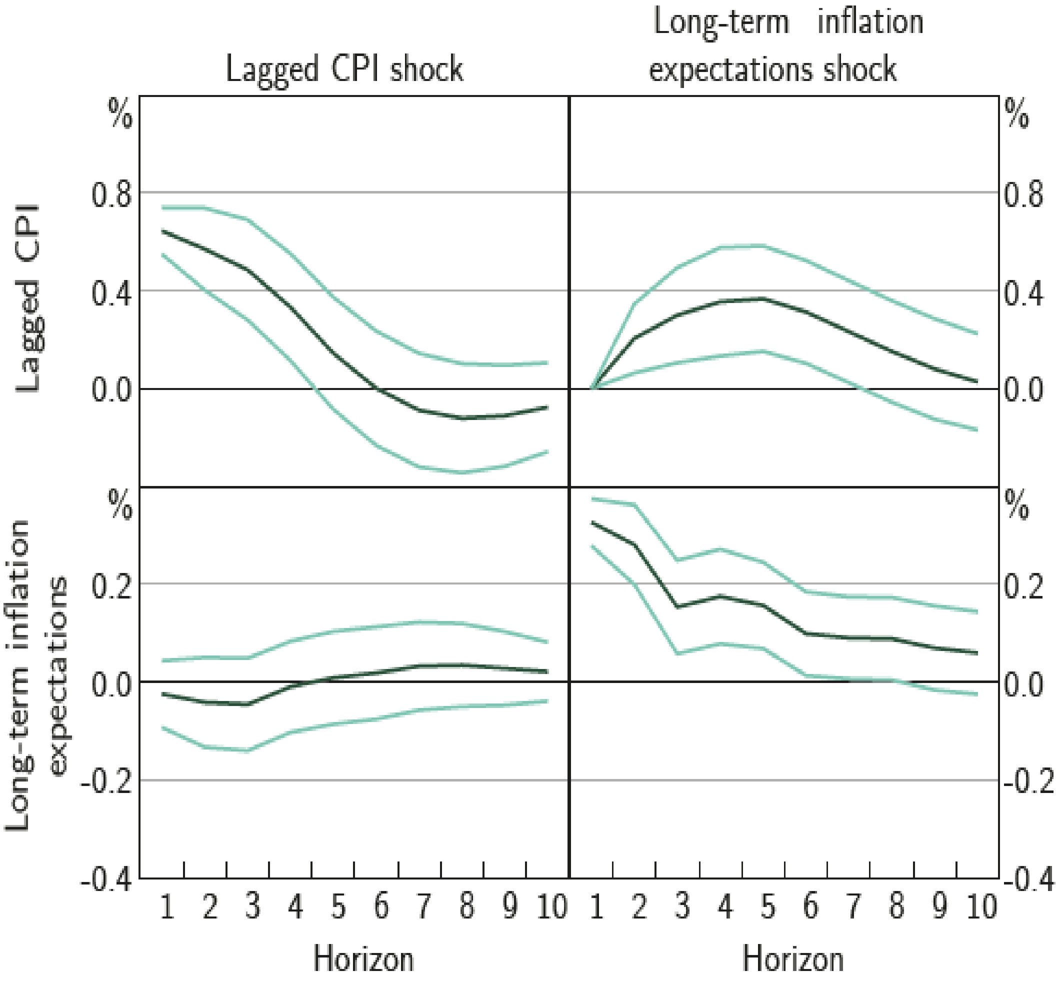


Notes: Short-term inflation expectations are represented by business inflation expectations – 3-months ahead as compiled by the National Australia Bank (NAB); medium-term inflation expectations are represented by union officials' inflation expectations – 2-years ahead, long-term inflation expectations, see notes to Figure 2.4

Sources: ABS; Australian Council of Trade Unions; Employment Research Australia; NAB; RBA; Workplace Research Centre; Yieldbroker

As shown in Figure 2.7, actual inflation and long-term inflation expectations exhibit strong level of contemporaneous response to shocks emanating from either directions, indicative of incomplete anchoring of expectations. However, there is a return of inflation expectations to baseline after 4 quarters which indicates stronger anchoring over time. Figure 2.8 also shows similar dynamics between CPI and medium-term expectations.

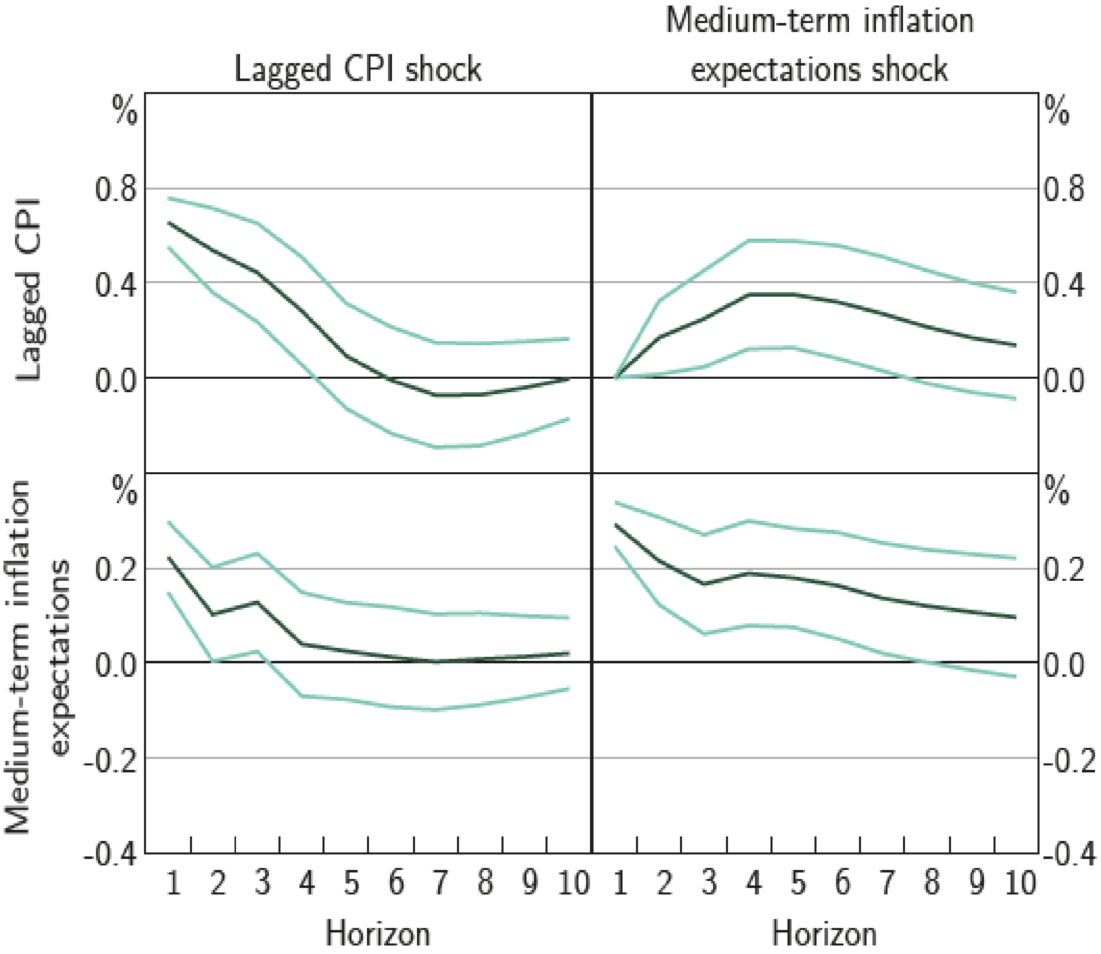
Figure 2.7. IRFs – CPI and Long-term Inflation Expectations: 1994:Q1–2017:Q4



Note: Response to Cholesky one standard deviation (degrees of freedom adjusted) Innovations with ±2 standard errors

Sources: Authors' calculations; RBA

Figure 2.8. IRFs – CPI and Medium-term Inflation Expectations: 1994:Q1–2017:Q4



Note: Response to Cholesky one standard deviation (degrees of freedom adjusted) Innovations with ±2 standard errors

Sources: Authors' calculations; RBA

2.3.4.3 Did the Global Financial Crisis Affect the Anchoring of Expectations?

To account for the possibility of changes in de-anchoring risks over time during the global financial crisis[8] (GFC), we split the sample into two: before the GFC (data available for 1989Q3 to 2008Q2) and after the GFC (2008Q3 to 2017Q4) using a crisis dummy, d^{fc}, which equals 0 for the period before the GFC and 1 otherwise.

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[8] We consider September 2008 (2008Q3) onwards as the post-GFC period.

We estimate the following equation, similar to Ehrmann (2015):

$$\pi^e_{t|t+n} = (1 - d^{GFC})[\phi_{pre-GFC} + \psi_{pre-GFC}\pi_{t-1}] + d^{GFC}[\phi_{post-GFC} + \psi_{post-GFC}\pi_{t-1}] + \varepsilon_t \quad (2.15)$$

where $\pi^e_{t|t+n}$ denotes the average medium-term inflation expectations or long-term inflation expectations. π_{t-1} is one quarter lagged inflation rate and ε_t is white noise. From the results provided in Table 2.2 below, there is further evidence that inflation expectations are not strongly anchored in the short term, with the GFC having no real noticeable effects on such dynamics. While both pre-GFC and post-GFC coefficients are statistically significant, the pre-GFC coefficients are slightly larger.

Table 2.2. Pre-GFC and Post-GFC Inflation and Expectations Dynamics

Dependent Variable	$\psi_{\text{pre-GFC}}$	$\psi_{\text{post-GFC}}$	Adj. R^2
Dependence of Medium Expectations on $\boldsymbol{\pi_{t-1}}$			
Medium-Term Expectations	0.36*** (7.22)	0.24*** (4.70)	0.66
Dependence of Long and Medium Expectations on Short-term Expectations			
Long-term Expectations	1.16*** (3.61)	1.04*** (2.64)	0.56
Medium-Term Expectations	0.57*** (5.23)	0.42*** (3.31)	0.37

Notes: π_{t-1} refers to actual CPI inflation rate lagged one quarter; OLS estimates with Newey-West heteroskedasticity autocorrelation consistent standard errors; *** indicates statistical significance at 1 percent; *t*-statistics are indicated in parentheses

Sources: Authors' calculations; RBA

2.4 Empirical Evidence on Shocks

2.4.1 Nature of Historical Shocks

As outlined in Section 2.3, the various monetary regimes handle shocks to the economy in different ways. Faced with demand shocks, an inflation-targeting central bank can appropriately tighten the monetary policy stance, simultaneously containing inflationary pressure and slowing down output growth. Therefore, with demand shocks, there can be a divine coincidence, such that an inflation-targeting central bank faces no trade-off between achieving the price and output stability objectives. However, in the case of supply shocks that create divergent paths for price and output, such divine coincidence disappears, creating a stark trade-off between achieving price stability and output stability (see Blanchard and Galí (2007) and Kim (2016)). There are a number of studies of the Australian economy that have attempted to evaluate whether shocks historically have been demand or supply shocks. A brief overview of empirical evidence on the nature of shocks (demand versus supply) that characterised Australia's business cycle over the years is provided below.

Empirical evidence on the nature of shocks (demand versus supply) underpinning Australia's business cycle is mixed. Using a structural VAR model developed for the Australian economy covering the period 1980–98, Dungey and Pagan (2000) provide evidence that demand shocks are the dominant driver of business cycle activities over the period, with limited influence from monetary policy. Buncic and Melecky (2008) reach similar conclusions. According to their findings, domestic demand shocks were the key driver of variations in Australia's potential output during the period 1981–2005, with limited influence from supply shocks. But the opposite is true for inflation, with aggregate supply shocks being the major determining factor. In a study analysing key features of Australia's business cycles covering the period 1959–2000, Cashin and Ouliaris (2001) find strong empirical evidence demonstrating a persistent countercyclical relationship between output and prices over the entire period, indicative of the dominance of supply shocks in explaining fluctuations in output.

Similar findings, that supply shocks were the dominant drivers of Australia's macroeconomic fluctuations, were reached by Backus and Kehoe (1992) covering different periods spanning 1861–1985 and Fisher, Otto and Voss (1996) for the period 1959–95. Recent evidence also remains mixed, although demand shocks are largely believed to be the major driver of the fluctuations in output relative to supply shocks. Using quarterly data covering 1992 to 2013, Rees, Smith and Hall (2016) find that, while demand shocks (consumption preferences and expenditures) are relatively more pronounced in influencing output fluctuations and particularly strong in driving variations in consumption, aggregate supply shocks (mark-up shocks in the non-traded, non-resource and import sectors) are the major driver of the fluctuations in inflation.

2.4.2 Likely Future Shocks

While the debate on the performance of monetary policy regimes usually focuses on how regimes would have performed historically, it is also useful to be forward thinking about the likely nature of future shocks to the global and Australian economies.[9] There are three main areas where future shocks can be anticipated. The first is climate change and climate policy responses. The second is the emergence of a fourth industrial revolution or a new Renaissance due to the rapid adoption of new technologies such as artificial intelligence. The third is the growth of larger emerging economies into the world economy following the experience of China.

2.4.2.1 Climate Change and Policy Responses

McKibbin *et al* (2017) explored the interdependence between the choice of climate policy regimes and the choice of monetary regimes. They argue that, while climate policy and monetary policy have been considered and pursued separately as two distinct policy regimes, the joint interaction of both policies in influencing macroeconomic fluctuations must be the concern for future macroeconomic stabilisation policy.

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[9] Such a historical review of performance was the basis of the Brookings model comparison project (see Bryant *et al* (1993)).

That is, while optimal monetary policy outcomes can be achieved when the traditional goals (price stability and output stability) are met, the climate policy objective of promoting low carbon emissions cannot be achieved without consequences for price and output stability under alternative monetary policy and climate policy regimes.

There are several issues raised by McKibbin *et al.* The first is that increasing climate shocks will likely imply greater output volatility from supply side shocks due to climate-related disruption. This greater volatility in the real economy also implies that estimating the output gap is likely to become increasingly difficult. Thus, an inflation-targeting regime based on output gap forecasting is likely to be more difficult to implement. As mentioned above, a nominal income-targeting regime does not rely on output gap estimation and may be better at anchoring inflation expectations within a band.

The second problem is related to the nature of the likely climate policy response. A cap-and-trade carbon emissions trading framework targets the level of emissions over time through a market-determined carbon price that stabilises or reduces emissions. The more ambitious the carbon target, the higher and more volatile the carbon price will be. The carbon price feeds directly into the price of energy and therefore into the inflation rate. Over time, the carbon price is likely to have a trend increase given the nature of the carbon reduction targets adopted by countries, including Australia, under the Paris Agreement. Thus, an inflation-targeting regime would need to adjust for both a change in trend inflation due to the carbon price as well as volatility in inflation due to volatility in carbon prices. The second effect is less problematic if the climate policy is implemented as a carbon tax because the carbon price (equal to the tax) is known. There would, however, still be a trend change in the underlying inflation rate which needs to be considered in the monetary regime.

The extent to which the issues raised by climate change are important will depend on a number of highly uncertain events: the nature of future climate disruption; the extent to which Australia takes on a deep cut in its emissions target; and the nature of the actual climate policy that is eventually implemented in Australia.

McKibbin et al. (2017) conclude that considering climate change should be thought of as an increasing importance of supply side shocks, which are better handled by nominal income targeting than inflation targeting.

2.4.2.2 The rise of artificial intelligence

There is a large and growing literature on the impact of artificial intelligence on economic activity.[10] While some analysts and policymakers are more optimistic about the potential benefits from artificial intelligence, ranging from enhanced real-time forecasting capabilities, spotting bubbles, and uncovering complex macro-financial links (Lagarde 2017), some are more concerned about how such changes to the nature of the economy could make real-time forecasting and understanding of macroeconomic fundamentals more complicated than ever before. Saniee *et al* (2017) suggest that the world could be on the verge of a fourth industrial revolution underpinned by the rapid advancement in technology. This would make forecasts of potential growth and the output gap highly uncertain. Currently, there is a huge mismatch between low growth and productivity statistics on one hand and high expectations of improvement in productivity due to rapid advancement in technology on another.

The real problem could be due to two issues. Either there is a problem with how the effects of new technologies on economic growth and productivity are measured by economists (Feldstein 2017), or we are yet to clearly understand the lag from the introduction of new technologies to the realisation of their impacts on output and productivity (Brynjolfsson, Rock and Syverson 2017). In either case, as new technologies make the structure of the economy more complex, measuring the underlying fundamentals, particularly concepts like ‘potential output’ will become even more challenging. An alternative view is offered by Gordon (2016) who argues that productivity growth will remain weak for many years. Such uncertainty over productivity growth will make projection of potential growth very difficult.

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[10] For example, see Bostrom (2014), Brynjolfsson and McAfee (2014), Benzell *et al.* (2015), Acemoglu and Restrepo (2018), Kavuri and McKibbin (2017) and Kavuri (2018).

In such an environment where central banks cannot account for surprise increases in productivity, then inflation would be surprisingly low for long periods. The credibility and effectiveness of monetary policy in such an environment will be contingent upon the nature of the monetary policy framework in place. Suppose productivity growth rises more sharply than expected. Inflation-targeting central banks would continue to see inflation below their inflation target because monetary policy would be too tight relative to that possible in a strongly growing economy. They would need to continually relax monetary policy to attempt to raise inflation to the target. Over time, failure to achieve this would undermine the credibility of the inflation target.

Under a nominal income target, suppose the target of the RBA is 6 per cent per year calculated assuming 3 per cent potential growth and 3 per cent inflation. If growth was surprisingly strong because of higher-than-expected productivity growth, output growth may turn out to be 4 per cent with inflation at 2 per cent. The nominal income target can still be met without affecting the credibility of the central bank. The difference would be that inflation would be lower than desired. If this is sustained then the central bank could announce a higher future nominal income target, adjusting to the new reality of higher real growth.

2.4.2.3 Continued emergence of developing countries into the global economy

The accession to the World Trade Organization in 2000 and the implementation of structural reforms by Chinese authorities since then have positioned China as a major economy, transforming the global economy through millions of workers, producers and consumers entering global production and consumption networks. The importance of the China boom for the Australian economy from 2001 to 2016 is explored in Dungey, Fry-McKibbin and Linehan (2014) and Dungey *et al* (2017).

An emerging country boom would affect Australia in a similar way to the China boom of the 2000s – strong external demand, high Australian nominal income growth and an appreciating exchange rate, which would lower import prices. It might also lead to a lowering of Australian country risk, as investment in Australia is seen as a high return activity given Australia's production structure and trade links into emerging economies. This would raise domestic prices but reduce import prices. It would also increase asset prices in Australia. An inflation-targeting central bank would face what the RBA faced from 2000. Thus, a flexible inflation target and a nominal income growth target would both perform well as long as the shock was clearly understood and enunciated within the inflation-targeting framework.

2.5 Summary and Implications

The past 25 years of inflation targeting has coincided with an impressive performance of the Australian economy. The flexible inflation-targeting regime followed by the RBA has clearly outperformed the alternative monetary frameworks (fixed exchange rates; a fixed monetary rule; a checklist of intermediate targets) that had been implemented in earlier decades. However, as Australia positions itself as a competitive economy in a rapidly changing global economy, it is worth asking whether there is likely to be a better approach for monetary policy in the future.

There has certainly been a long and rigorous debate that other monetary regimes can outperform inflation targeting in theory. Both flexible inflation targeting and the nominal income targeting have appealing characteristics in theory. Flexible inflation targeting has worked well, although it could be argued that this is mostly because of the nature of the shocks in the Australian economy, which have largely been domestic and foreign demand shocks. The key issue is what will be the nature of future shocks hitting the Australian economy. In recent years, productivity shocks have become more important globally. This has seen central banks, including the RBA, become less successful at forecasting inflation and achieving the inflation target. We show in this paper that inflationary expectations appear not to be as well anchored in the Australian economy, as would be expected given the existence of the inflation-targeting framework.

Looking to the future, the importance of supply shocks being driven by climate policy, climate shocks and other productivity shocks generated by technological disruption as well as a structural transformation of the global economy appear likely to be increasingly important. This suggests an important evolution of the monetary framework may be to shift from the current flexible inflation-targeting regime to a more explicit nominal income growth-targeting framework. The key research questions that need further analysis are: (1) how forecastable is nominal income growth relative to inflation? and (2) what precise definition of nominal income is most appropriate given the ultimate objectives of policy (e.g. nominal GDP, nominal GNP, domestic demand netting out terms of trade shocks – or some other measure that is available at high frequency)? Also, whether the target should be specified in growth rates or levels is an open research question analogous to the choice between inflation targeting and price level targeting.

It would be a mistake to argue that there is no need to change the monetary policy regime because the existing monetary policy regime in Australia has been successful. Monetary regimes have evolved for centuries and when they have changed it has usually been because of a crisis – the collapse of Bretton Woods or the recession that Australia didn't need to have in 1991. It is better to have a policy regime change in an evolutionary way backed by theoretical and empirical research (as has been the case with flexible inflation targeting in Australia since 1993) than to wait for a breakdown in the existing regime. The difference between inflation targeting over the cycle and a nominal growth target is an incremental move from a less transparent to a more transparent policy rule that has a number of attractive features, particularly under the type of supply side shocks that are likely over coming decades.

Chapter 3

3. Climatic Disruptions and Output Gaps: Should Central Banks Incorporate Climate Effects into Policy?

Abstract

The goal in this paper is to test the hypothesis that the inclusion of climate effects in the estimation of the sustainable component of output (potential output) can improve real-time estimates of the output gap—the deviation of actual output from potential. Using variations in temperature and precipitation 'anomalies' as proxies for changing climatic conditions over time, the paper employs an unobserved component model estimated by the data-driven Maximum Likelihood technique to derive *climate-neutral* measures of potential output and the output gaps for Australia. The results show that potential output and output gap measures that are adjusted for climatic disruptions are relatively more accurate in real time than those obtained from conventional approaches that do not take climate shocks into consideration.

3.1 Introduction

The emergence of rules-based monetary policy is premised on promoting strong policy credibility (Kydland and Prescott, 1977; Henderson and McKibbin, 1993; Taylor, 1993). By remaining committed to announced policy targets and providing forward guidance as to how policy actions will evolve, the central bank can promote policy credibility and firmly anchor the expectations of economic agents. To this end, a key requirement for rules-based monetary policy is that a nominal anchor selected as target must be one that can be reliably measured in real-time. However, the real-time measurement problem is complicated in practice (Orphanides, 2001, 2002; Panton and McKibbin, 2018), thus undermining the credibility of monetary policy.

The output gap—the deviation of actual output from potential—is an unobservable but key input into macroeconomic policy decisions, from examining fiscal sustainability to determining the monetary policy stance. For a flexible inflation-targeting central bank, the policy signal for accommodating output stability depends on the output gap and the evolution of inflation. When the output gap is negative, a loose monetary policy stance may be warranted. Similarly, for a positive output gap, a tight monetary policy stance aimed at taming inflation may be optimal, all else equal. However, real-time output gap estimates are grossly inaccurate and unreliable (Orphanides, 2001; Orphanides and van Norden, 2002). With climatic disruptions found to have stronger and more persistent negative effects on output than previously thought (Hsiang and Jina, 2014), frequent episodes of climate-induced disasters may induce structural changes in the economy that weaken the relationship between inflation and output dynamics, further complicating the task of distinguishing accurate policy signals from noise based on potential output and output gap estimates (Coeuré, 2018).

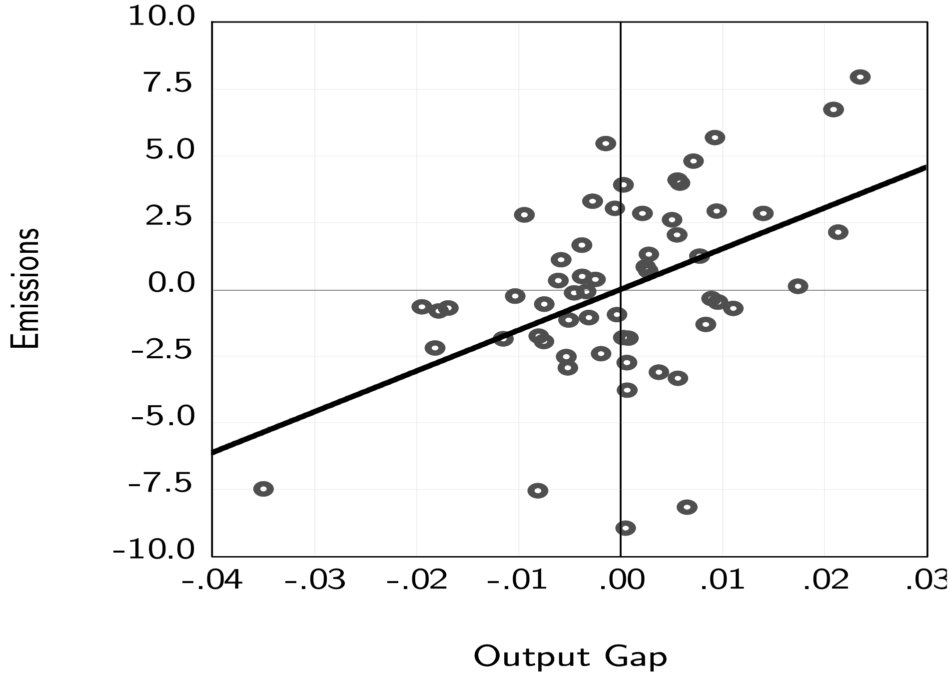
Since monetary policy affects the real economy with a lag, the reaction function usually includes the forecasts of the output gap in setting the future path of the policy rate (Svensson and Woodford, 2003; Laubach and Williams, 2002), requiring the flexible inflation-targeting central bank to have some knowledge about the future path of the economy. That is, in addition to catching up with potential policy errors due to mismeasurement of past macroeconomic trends, the inflation-targeting central bank faces an additional burden of predicting the future path of the economy. As Hayek (1945) brilliantly puts it, the key challenge confronting the design of optimal economic policy is that the information required for real-time policy formulation is not centrally available. When applied to the real-time formulation of monetary policy, the knowledge problem relating to the estimation of potential output and the output gap exposes monetary policymakers to severe policy mistakes (Orphanides, 2001, 2004). For instance, Beckworth and Hendrikson (2020) provide empirical evidence that output gap mismeasurement by the U.S. Federal Reserve over the period 1987-2007 was a serious problem for monetary policy credibility.

That is, unanticipated changes in the short-term interest rates driven by output gap forecast errors can lead to policy-induced shocks, in addition to the actual shocks facing the economy. Earlier works by Orphanides and van Norden (2002) for the United States, Nelson and Nikolo (2003) for the United Kingdom and Cayen and van Norden (2004) for Canada reached similar conclusions.

The knowledge problem is further complicated when the macroeconomy is buffeted by structural disruptions and heightened uncertainty (Heal, 2017; Coeuré, 2018), making the task of finding accurate policy signals more challenging (Mishkin, 2007; Alberola et al. 2014, NGFS, 2018). For example, rising temperature or drought conditions weaken output (Dell et al. 2012; Fomby et al. 2013; Kamber et al. 2013; Burke et al. 2015) or cyclones persistently disrupt output and energy supply (Hsiang and Jina, 2014), the associated fluctuations in food and energy prices have significant effects on consumption, investment and the anchoring of inflation expectations (De Winne and Peersman, 2016; Coeuré, 2018) and the stability of the financial system (Cameron and Shah, 2013; Bank of England, 2015; NGFS, 2018). There is strong scientific evidence that unabated global warming will accelerate the frequency and severity of climatic disruptions (IPCC, 2018). That is, as anthropogenic carbon emissions remain unchecked, so will global warming and the attendant climate-induced weather anomalies, further amplifying the variability in the business cycle (Doda, 2014).

Figure 3.1 shows a statistically significant association between output fluctuations and cyclicality in Australian carbon emissions at the business cycle frequency, consistent with the evidence that climate shocks do contain useful information in understanding the position of the economy in the business cycle (Buckle et al. 2007; Gallic and Vermandel 2020). Hence, the need to incorporate climate-induced weather shocks in the estimation of potential output and the output gap.

Figure 3.1. Cyclical Fluctuations in Output and Emissions



Note: The figure plots the cyclical components of output and Carbon (CO_2) emissions obtained using the HP filter on annual real GDP and emissions data for Australia covering the period 1980-2017. λ is set to 6.25 as per Ravn and Uhlig (2002). *Correlation coefficient = 0.59, P-value < 1%*

Source: Author's calculations; Our World in Data and RBA data

Despite the serious challenges that climate shocks pose for the real-time conduct of monetary policy, there is little research evidence on how the knowledge problem facing central banks in terms of the real-time estimation of key policy variables like potential output and the output gap is complicated with rapidly changing climatic conditions. The growing climate-monetary policy literature has been focused largely on the financial stability implications of physical and transitional climate risks (Carney, 2015; McGlade and Elkins, 2015; Cortés and Strahan, 2017; Dafermos et al. 2018), with scant evidence on the structural disruptions caused by climate risks affect the real-time forecast accuracy of key policy variables. A notable exception is the work by Boldin and Wright (2015) who provide statistical evidence on why mere seasonal adjustment of macroeconomic variables is not sufficient in accounting for the effects of climate-induced weather anomalies.

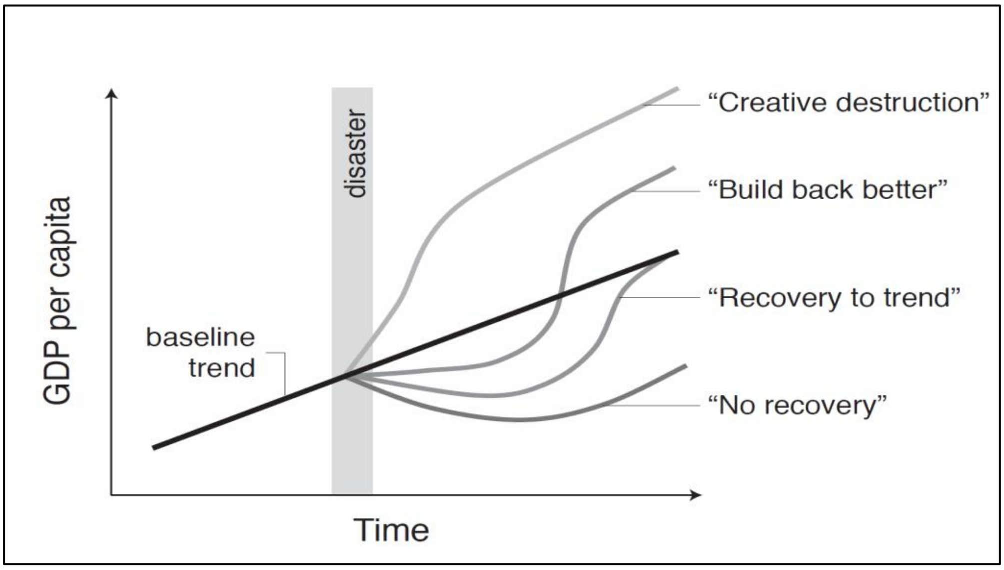
Building on the arguments by McKibbin et al (2017) that the joint interaction of climate and monetary policies is crucial in promoting sustained macroeconomic stability, this paper seeks to examine how climate shocks affect a key input into the monetary policy framework—the output gap. Using a parsimonious unobserved component model that decomposes output into trend and cycle and estimated via Maximum Likelihood â la Clark (1989), this paper seeks to evaluate the effects of climate shocks in measuring potential output and the output gap. The results show that the inclusion of climate effects in the estimation of the output gap produces statistically significant improvements in real-time accuracy compared with conventional estimates that do not take climate effects into account.

The rest of the paper is organized as follows. The next section provides a summary of the relevant literature on climate change and economic growth and builds a conceptual bridge that links arguments in the climate-economy realm with the monetary policy literature. The third section outlines the empirical strategy. The results are analyzed in section four. The final section contains policy implications and concluding remarks.

3.2 Review of the climate change and output growth literature

The impact of climate change on human society is a well-researched theme (Cavallo and Noy, 2010; Dell et al, 2014), with strong evidence on the negative effects of climatic disruptions on macroeconomic stability. As rising temperature increases the risks posed by extreme climate events in an unpredictable fashion over time, disruptions of agricultural activity (Gandhi & Cuervo, 1998), reduction in effective labour supply (Frankhauser and Tol, 2005; Kjellstrom et al., 2019) and the increasing rate of capital depreciation (Stern, 2013) as well as weakening financial stability (Carney, 2015) strongly affect macroeconomic stability. However, the evidence on the longer-run output effects of climate-induced shocks remains contentiously mixed, with four alternative hypotheses advanced in the literature.
On one hand are the 'creative destruction' and 'build-back-better' hypotheses, while on the other is the 'no recovery' hypothesis. A mid-way narrative is the 'recovery-to-trend' hypothesis. Figure 3.2 summarizes the output effects of climate change under the various hypotheses.

Figure 3.2. Competing Climate Shocks and Output Growth Hypotheses



Source: Hsiang and Jina (2014).

3.2.1 Creative destruction and build back better hypotheses

Following narratives from the earlier climate-economy literature (see Tol and Leek (1999)), Skidmore and Toya (2002) argue that frequent episodes of natural disasters can promote the introduction of new technologies, thus positively affecting investments, total factor productivity and growth. Similar arguments are made by Okuyama (2003) and Benson and Clay (2004). While output may be negatively affected in the immediate aftermath of disasters, the introduction of new technologies, coupled with employment creation via reconstruction programs, can have positive effects on long-run output (Cuaresma et al, 2008). Another associated narrative is the argument 'build-back better' argument. That is, post-disaster reconstruction and investment will lead to the replacement of outdated infrastructure with modern and more climate-resilient units, with net positive long-run output effects (Hallegatte and Dumas, 2009).

However, the creative destruction and build-back-better hypotheses fail to account for several other factors, including the adverse health outcomes and destruction of natural resource stock and the attendant negative effects on potential output. That is, if the post-disaster capital upgrading does not exceed the productivity losses incurred as a result of natural disasters, then the net effect on long-run output growth may be negative (Hsiang and Jina, 2014).

3.2.2 Recovery-to-trend hypothesis

According to this narrative, while output may fall in the immediate aftermath of a natural disaster, the economy will eventually converge to the pre-disaster trend. The key underpinning argument is that as the physical capital stock is destroyed following a natural disaster, the increased marginal product of capital in the post-disaster environment will trigger increased cross-border inflows of capital, thus stimulating output until the pre-disaster trend can be reached (Yang, 2008; Strobl, 2011). Similar conclusions are reached by Stromberg (2007). However, how susceptible a region or economy is to extreme and unpredictable natural disasters may affect the pace or magnitude of capital replacement, with evidence that high insurance claims (Bank of England, 2015) and falling housing prices (Bunten and Kahn, 2017) following natural disasters pose serious risks to financial stability. Declines in private financial flows (Yan, 2008), increased permanent risk-aversion tendencies following exposures to persistent natural disasters (Cameron and Shah 2013), and outmigration from affected regions (Strobl, 2011; Bohra-Mishra et al, 2014; Boustan et al, 2020) have also been identified to have negative long-run output growth effects. Thus, the evidence remains unclear whether the economy will return to the pre-disaster state following natural disasters.

3.2.3 No-recovery hypothesis

Proponents of the no-recovery hypothesis maintain that by damaging physical capital stock that cannot be fully replaced without sacrificing resources that would have otherwise created more productive investments, natural disasters permanently lower long-run output below the pre-disaster trend (Hornbeck, 2012; Cole et al., 2014). Using an innovative dataset on the physical exposure of countries to all known cyclones over the period 1950-2008, Hsiang and Jina (2014) compare a country's output growth rate to itself in the years immediately before and after exposure to cyclones in a difference-in-difference framework. They find robust evidence that output falls strongly after cyclones, remaining below pre-disaster trend for up to two decades, strongly rejecting the creative destruction and recovery-to-trend hypotheses. While these negative effects may be relatively less pronounced in advanced economies compared to emerging markets and developing countries (Dell et al 2012), they are also found to be nonlinear (Burke et al 2015).

3.3 The output gap and climatic disruption: a conceptual connection

Based on evidence summarized above on the growth effects of climate shocks, there is clearly a strong link between the climate-economy literature and the monetary policy literature, with the attempt at connecting these two realms another innovative contribution of the current paper. The goal in this section is to provide a conceptual analysis of the connection from the standpoint of the conventional flexible inflation targeting framework. Just as the findings on the growth effects of climatic disruption remain mixed, the concept of output gap has been variously defined in the literature[11] (see literature in Kiley (2013)), although the original definition popularized by Okun (1962) remains common in practice. According to Okun, potential output denotes the rate of output growth that can be achieved without giving rise to inflationary pressure, with the output gap defined as the deviation of actual from potential output.

In the case of an inflation-targeting central bank that seeks to flexibly balance the price stability and output stability objectives, the policy signal for accommodating output stability depends on the output gap and the evolution of inflation. When the output gap is negative, then there must be low inflationary pressure for which a loose monetary policy stance may be warranted. Similarly, for a positive output gap, a tight monetary policy stance aimed at taming inflation is optimal, all else equal. However, when the underlying dynamics between inflation and output are distorted due to macroeconomic imbalances such as those created by frequent episodes of natural disasters, then monetary policy reaction based on the evolution of the output gap may be inefficient on two fronts.

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[11] In the DSGE literature, potential output is defined as the rate of output would prevail if there were no nominal rigidities, but all other (real) frictions and shocks were unchanged (Woodford, 2003; Basu and Fernald, 2009). According to the U.S. Congressional Budget Office (CBO, 2001), the output gap is the deviation of output from the level consistent with current technologies and capital and labor utilization rates—the production function approach. This approach is widely followed across policy institutions, including the Organization for Economic Cooperation and Development (based on the work by (Giorno et al. 1995)

First, if the creative destruction hypothesis is the true description of the effects of climate-induced weather shocks on output, then the central bank is faced with the task of determining whether to accommodate or condition the policy stance on the short-term adverse output effects or the positive effects due to increased investments. Under the scenario that the central bank considers near-term inflationary pressure resulting from a natural disaster to be only *temporary* and therefore not accommodated by tightening the policy stance, then rising productivity and output growth will be happening alongside lower interest rates, thus driving an unsustainable surge in output. This point is well emphasized by Borio et al (2014) in terms of the effects of omitting financial variables in measuring potential output. That is, contrary to the restrictive assumption that high inflation is always indicative of a positive output gap (Okun, 1962), low and stable inflation can also co-exist alongside an unsustainably positive output gap when there are macroeconomic imbalances driving growth, but whose effects are not captured in measuring the economy's output potential. Using a growth-accounting approach in which the various components of output are adjusted for macroeconomic imbalances, Alberola et al. (2014) reach similar conclusion.

Second, under the assumption that the no-recovery hypothesis is taken to be the true explanation of the growth effects of climatic disruptions, the flexible-inflation targeting central bank faces a much tougher challenge. As prices and output take divergent paths following climate-induced supply shocks, the standard monetary policy response seeking to tame near-term inflationary pressure may accentuate the negative effects on output. Attempts at restoring output growth by easing the policy stance may drive up inflation pressure, all else equal. The central bank must distinguish between temporary shocks (for which the optimal policy stance may be neutral) and permanent shocks for which a change in the policy stance is required. As Keen and Pakko (2007) point out, despite the massive damages experienced by the U.S. Gulf coast in the wake of Hurricane Katrina in 2005, the U.S. Federal Reserve tightened the policy stance, working under the assumption that the growth-effects of Katrina were only temporary, but quickly acted to tame inflationary pressure. However, in a climatically disrupted world with frequent disaster episodes, the central bank faces the constant, error-prone burden of distinguishing permanent shocks from those it deems to be temporary.

Even for small-scale natural disasters whose effects may be temporary, the frequency of disasters means the central bank faces an ongoing dilemma. Therefore, regardless of whether climate shocks are creative destruction mechanisms or events that adversely affect the level or trend growth rate of output, how central banks address the effects of climate change may affect the effectiveness of monetary policy toward achieving macroeconomic stability in a climatically-disrupted and carbon-constrained world (McKibbin et al., 2017).

3.4 Empirical Strategy

This section provides a summary review of the output-gap estimation literature followed by the modelling framework.

3.4.1 Traditional Approaches to Output Gap Estimation

Since the seminal contribution by Beveridge and Nelson (1981) on decomposing a macroeconomic variable into its sustainable trend and cyclical components, there has been an explosion in research efforts on the subject, especially in estimating potential output and the output gap. The traditional methods employed in measuring potential output vary broadly on two extremes in the literature: univariate and structural approaches.

On the univariate extreme where simplicity is valued over structural relationships and economic priors, the overall slack in the economy is estimated by decomposing output (y_t) into trend (μ_t) and cyclical (z_t) components:

$$y_t = \mu_t + z_t \tag{3.1}$$

The simple Hodrick-Prescott [HP hereafter] filter (Hodrick and Prescott, 1997), Beveridge-Nelson decomposition (Beveridge and Nelson, 1981) and the unobserved components model of Watson (1986) are the popular candidates in this category, with the HP filter remaining the most popular approach in practice. The artificially determined noise-to-signal ratio in the HP filter is found to be usually at odds with the actual data, with the potential for producing spurious relationships that are not related to the actual data-generating process (Nelson and Kang, 1981; Harvey and Jaeger, 1993; Marcellino and Musso, 2011; Hamilton, 2018).

On the other extreme where the need for strong presumed theoretical relationships dominates over simplicity, the widely used production function approach (Giorno et al 1995; Shackleton, 2018) as well as the structural vector autoregressive (SVAR) technique (Blanchard and Quah, 1989) and DSGE-based approaches (Smets and Wouters, 2003) are commonly employed. By using detailed information and carefully exploiting economic priors, estimates derived from these approaches are more suitable for direct interpretation of the changes in cyclical output. However, as Borio et al (2014) and Chan and Grant (2017) argue, results from these structural models are very sensitive to specification issues, with the estimates just as relatively accurate as the several underpinning assumptions. Another shortcoming of the structural approaches is the use of the simple techniques in deriving some key relationships as inputs (see Alberola et al., 2014), with the potential for exposing the estimates to the problems of their univariate counterparts. On the fully structural spectrum with DSGE models, what constitutes potential output is even much more complicated, with such output level defined to exist only absent certain model-based distortions (e.g., nominal rigidities) and what the modeler may consider to be 'inefficient' shocks (Woodford, 2003; Basu and Fernald, 2009; Kiley, 2013). Estimates of potential output and other key monetary policy variables derived from long-term climate scenario-modelling techniques, like the integrated assessment Models (IAMs) (see Nordhaus, (1973, 2011)), may be even less suitable for monetary policy purposes, especially given the use of several arbitrary assumptions regarding the climate damage function (Pindyck, 2017) and the lack of real financial frictions (NGFS, 2020).

Aimed at overcoming the simplicity and lack of economic priors in the univariate models and the over complexity of the structural approaches, mid-way multivariate techniques that add structural relationships to the univariate approaches are common in the literature (see Laxton and Tetlow, 1992; Kuttner, 1994; Benes et al 2010; Blagrave et al 2015). However, like the DSGE or SVAR approachs, these multivariate filtering techniques have drawbacks of their own, especially in terms of distinguishing permanent (supply) shocks from temporary (demand) shocks (Coibion et al., 2018).

Aimed at further investigating the measurement and monetary policy credibility issues raised by McKibbin and Panton (2018) and NGFS (2020), a parsimonious, data-driven approach is employed in this paper. The empirical framework specified below follows the intuitions of the multivariate approaches, but with a more data-driven focus.

3.4.2 Empirical Framework

In the spirit of Clark (1989) and the recent literature (Borio et al. 2017), the following state-space model is employed to decompose output into its sustainable (T_t) and climatically adjusted cyclical (C_t) components:

$$Y_t = T_t + C_t \tag{3.2}$$

$$T_t = T_{t-1} + \psi_{t-1} + \eta_t \tag{3.3}$$

$$\psi_t = \psi_{t-1} + v_t \tag{3.4}$$

$$C_t = \rho C_{t-1} + \gamma' Z_t + \zeta_t \tag{3.5}$$

Where Y_t is log of seasonally adjusted real output, T_t represents the trend (sustainable) component of output, ψ_t represents the stochastic slope of trend output and cyclical component of output (the output gap) is represented by C_t. The vector Z_t contains a set of conditioning climate and macroeconomic variables. η_t, v_t and ζ_t are independent, normally distributed error terms with zero means and variances of σ_η^2, σ_v^2 and σ_ζ^2 respectively.

The measurement equation as specified in (3.2) decomposes output into two unobserved components—a non-stationary trend component (T_t) and a stationary cycle (C_t) component. The first transition equation (3.3) models the trend component (potential output) as an integrated random walk with drift. The higher the lag order of the trend in the model, the smoother the estimated trend but the more volatile the cycle (output gap). Therefore, the inclusion of a single lag is an empirical compromise between smooth trend output versus less volatile output gap.

The output gap is dependent on its own lag and a set of conditioning climate and macroeconomic variables à la Clark (1989) and Borio et al. (2017). To the extent that the conditioning variables in Z_t contain information about cyclicality in output, potential endogeneity issues with γ' are of no sequence as long as causal inferences are not drawn.

Although the effects of the conditioning variables are directly applied on the cycle, short-term adverse climate effects may be elevated into long-term output trends over time (Hsiang and Jina, 2014). Therefore, when these output effects persist via hysteresis (Blanchard and Summers, 1989), both short-term demand conditions and the underlying long-term supply capacity (potential output) may be simultaneously affected. It is worth noting that the modelling of the simultaneous effects of climate shocks on both short-term and long-term output dynamics is out of the scope of the current paper.

As a starting point for comparison with model results, a dynamic HP is estimated as in (3.6) below, with solutions (for T_t and β) that minimize (3.7) derived via the Kalman filter,

$$Y_t = T_t + \beta(Y_{t-1} - T_{t-1}) + \varepsilon_{2,t} \tag{3.6}$$

$$\sum_{t=1}^{T} \left[\frac{1}{\sigma_1^2}(Y_t - T_t)^2 + \frac{1}{\sigma_0^2}(\Delta T_{t+1} - \Delta T_t)^2 \right] \tag{3.7}$$

where Y_t is the log of seasonally adjusted real output, T_t is the trend (sustainable) component of output, and $\varepsilon_{2,t}$ is assumed to be normally distributed with mean zero and variance σ_0^2. The inclusion of the lagged output gap term in (3.6) means the dynamics of the estimated gap do not just depend on the noise-to-signal ratio $\left(\lambda = {\sigma_1^2}/{\sigma_0^2}\right)$, but also on β. The setup here is similar to Borio et al. (2017) who use the dynamic HP model as a baseline comparison with their estimates of finance-neutral output gaps.

3.4.2.1 Informative Climate Variables

The debate on the environmental and economic effects of climate change has been contentious in part because of the use of different proxy indicators when measuring climate effects. Ranging from the use of natural disaster casualties (Skidmore and Toya, 2002) to tropical cyclones (Hsiang and Jina, 2014) to temperature and rainfall (Dell et al, 2012; Burke et al, 2015), the evidence remains strong on how unabated global warming will increase the frequency and severity of extreme natural disasters (IPCC, 2014; 2018) and the volatility in the business cycle (Buckle et al. 2007; Doda, 2014). Given the short-to-medium term policy horizon facing the central bank, it is worth noting that the appropriate climate proxy variables must be those whose macroeconomic effects match such frequency. Growing scientific evidence suggests that rapidly changing climatic conditions will drive severe variability in weather conditions over time, with variations in temperature and precipitation anomalies serving as key channels through which the short-term effects of climate change can be examined (Boldin and Wright, 2015). To measure how deviations in climatic conditions affect output fluctuations, temperature and precipitation anomalies—deviations of average temperatures from the 1961-1990 averages— are used as proxies in this paper for climatic variations over time.

In order to isolate short-term weather phenomena from long-term climatic variations, *variations* of the anomalies are used instead of the mere periodic anomalies. Therefore, in addition to inflation and a survey-based measure of capacity utilization, temperature and precipitation anomalies are included in the vector Z_t in equation (5). The model is calibrated to Australian data. Summary descriptions of the variables and data sources are provided in Table 3.3A in the Appendix. The dataset covers the period 1998Q2-2017Q4.

3.5 Estimation and Results

3.5.1 Estimation

The Maximum Likelihood Estimation (MLE) technique is employed in estimating the model specified in equations (3.2) to (3.5) in the state-space framework with the Kalman filter algorithm to estimate the output gap persistence parameter, ρ, and the climate shock coefficient, γ.

With the use of the Kalman filter, both the observed and the state (unobserved) variables of interest (potential output and the output gap) are estimated via a recursive process. The Kalman filter recursively computes the likelihood function with new parameters of the model estimated via MLE, with the process repeated until the parameters are stable across iterations (see Commandeur and Koopman (2007); Durbin and Koopman (2012)). Given the initial values of the observed parameters, the Kalman filtering process produces two separate estimates of the state parameters: the filtered estimates (real-time estimates sequentially updated up to the current period) and the smoothed estimates (final estimates based on full data sample). Given that the evidence on how climate shocks affect the state of the business cycle remains mixed, no prior knowledge about the effects of such shocks is assumed in the estimation process.

The process of *diffuse initialization*[12] à la Harvey (1989) and Hamilton (1994) is followed in estimating the filtered estimates of the state vector. By employing diffuse initialization, the use of HP-filtered estimates as initial values for the state vector (as in Berger et al. (2015)) or the use of tight Bayesian priors (as in Borio et al. (2017)) is avoided in this paper. The estimation process follows a step-by-step procedure, with the climate-related variables (temperature and precipitation anomalies) separately modelled to determine their individual effects on the evolution of the output gap. The estimated coefficients from the various models are provided in Table 3.1. The first model (Model 1) is based only inflation and capacity utilization. The second model (Model 2) adds temperature anomalies to Model 1. Model 3 replaces temperature with precipitation. The final model (Model 4) tests the possibility of non-linear output effects of climate-related shocks as per the findings by Burke et al. (2015). This is achieved by including the squared values of temperature and precipitation anomalies along with inflation and capacity utilization in the estimation.

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[12] Diffuse initialization is the approach through which unknown initial values of state variables are endogenously estimated within the state-space context (Hamilton, 1994)

3.5.2 Results

The result of Model 1 (excluding climate variables) shows that while capacity utilization is a statistically significant driver of the business cycle, inflation contains no real information content about the business cycle, consistent with the recent literature (Borio et al. 2017). The inclusion of climate variables provides more reasonable estimates, especially when temperature is combined with inflation and capacity utilization (Model 2 and Model 4).

While the estimated coefficients for climate variables are relatively smaller (compared to inflation), their inclusion greatly improves the statistical significance of the estimated output gaps. The results based on precipitation anomalies (both in Model 3 and Model 4) are not statistically significant, largely consistent with the findings that for developed economies with mechanized and technology-driven agriculture, variations in precipitation patterns may have relatively minor effects on growth compared with less developed societies that are dependent on rainfall for food production (Barrios et al., 2010; Sadoff et al., 2016; Damania and Zaveri, 2020).

Table 3.1. Maximum Likelihood Estimated Coefficients

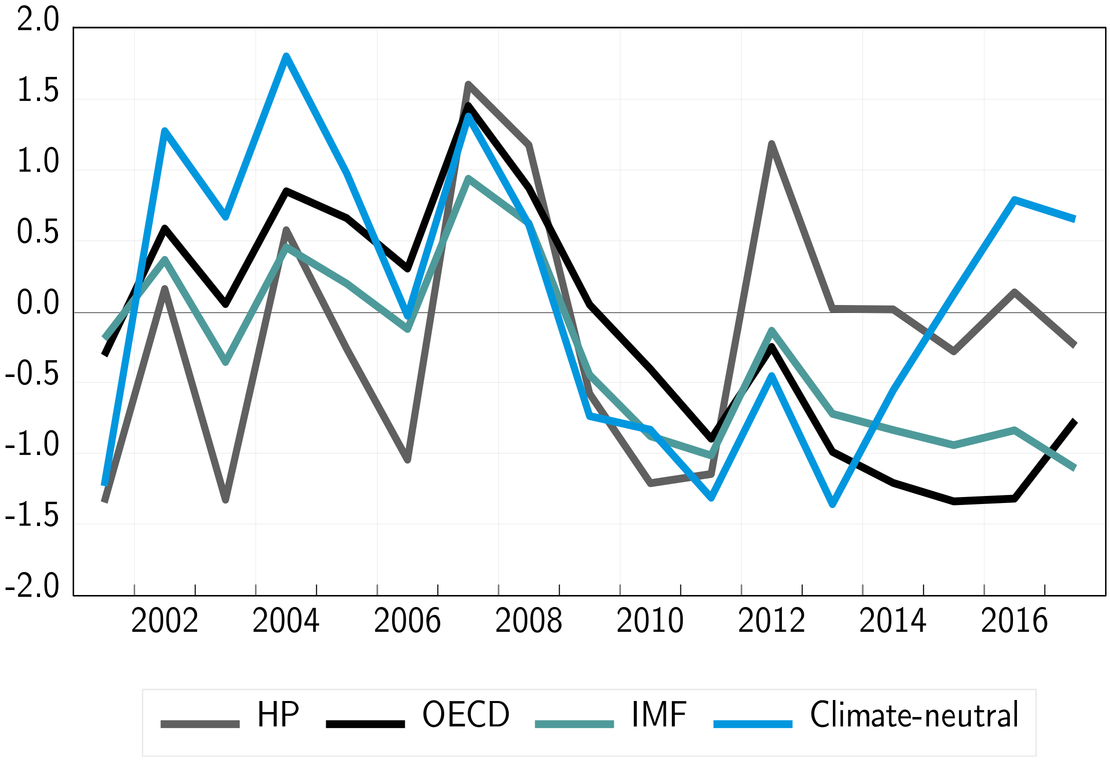
	δ_ζ^2	δ_η^2	ρ	ΔTemp	ΔPrep.	ΔCUR	ΔINF
Model 1	-14.27***	-11.27***	0.106***	-	-	0.000***	-0.08
	(2.419)	(0.374)	(0.001)			(0.000)	(0.098)
Model 2	-14.52***	-11.54***	0.10***	-0.0039*	-	0.001***	-0.176***
	(1.195)	(0.133)	(0.00)	(0.002)	-	(0.000)	(0.053)
Model 3	-14.07***	-11.57***	0.10***	-	0.000	0.001***	-0.160
	(0.61)	(0.19)	(0.00)		(0.00)	(0.000)	(0.058)
Model 4	-14.54***	-11.53***	0.10***	-0.004**	0.000	0.0005***	-0.176***
	(0.126)	(0.115)	(0.0002)	(0.002)	(0.00)	(0.000)	(0.054)

Source: Author's calculations
Note: ***$p < 0.01$; **$p < 0.05$; *$p < 0.1$. Standard errors are in parentheses.
Temp, Prep, CUR and INF represent temperature, precipitation, Capacity utilization rate and Inflation, respectively.

For the rest of the analysis, the temperature anomaly variable is used as the proxy for climate-induced weather shocks, with the output gap estimates from Model 2 (based on variations in temperature anomaly, capacity utilization and inflation) termed as 'climate-neutral' output gaps. In addition to the dynamic HP model estimates (equations 3.6—3.7), the climate-neutral output gap estimates are also compared with 'official' estimates for Australia—based on data from the International Monetary Fund's (IMF) World Economic Outlook (WEO) database and the Organization for Economic Cooperation and Development's (OECD) Economic Outlook database. To reduce the noise in the data and also match the reporting frequencies for the official estimates, the climate-neutral and HP output gap estimates are analyzed at the annual frequency. The various output gap measures are presented in Figure 3.3.

On the overall, the various output gap measures seem to point to excess demand pressure during Australia's mining boom, especially in the years leading to the GFC. However, while the climate-neutral and the HP gaps point to a sharper post-GFC recovery, the official estimates suggest much lower demand pressure relative to supply capacity in the Australian economy. Further analyses are undertaken below to examine how the inclusion of temperature anomaly shocks improves the real-time accuracy of the estimated output gaps for Australia compared with conventional estimates.

Figure 3.3. Output Gap Estimates (Percent of Potential Output)



Source: Author's calculations; OECD and IMF

3.5.2.1 Evaluating Real-time Performance

The policy relevance of output gap estimates is crucially tied to how accurate and reliable these estimates are when used in real-time. While there has been a contentious empirical search for an optimal approach in unmasking the ghosts—potential output and the associated output gap—real-time estimates of these variables remain notoriously unreliable, with model uncertainty and parameter instability in estimating potential output for a constantly changing macroeconomy identified to be the key factors (Marcellino and Musso, 2011). Earlier findings by Orphanides and van Norden (2002) provide an extensive account regarding the real-time output gap measurement problem, concluding that while data revisions may be critical, but how well the estimation framework fits the economy is the most crucial factor.

A summary of the classification of real-time versus ex post (final) estimates is provided below:

i. HP Filter

- For each year (T), the real-time estimates are based on the data sample up to that point time and the corresponding real-time output gap estimate is what would have been produced using a given method. The *ex post* (final) estimates are based on the full data sample.

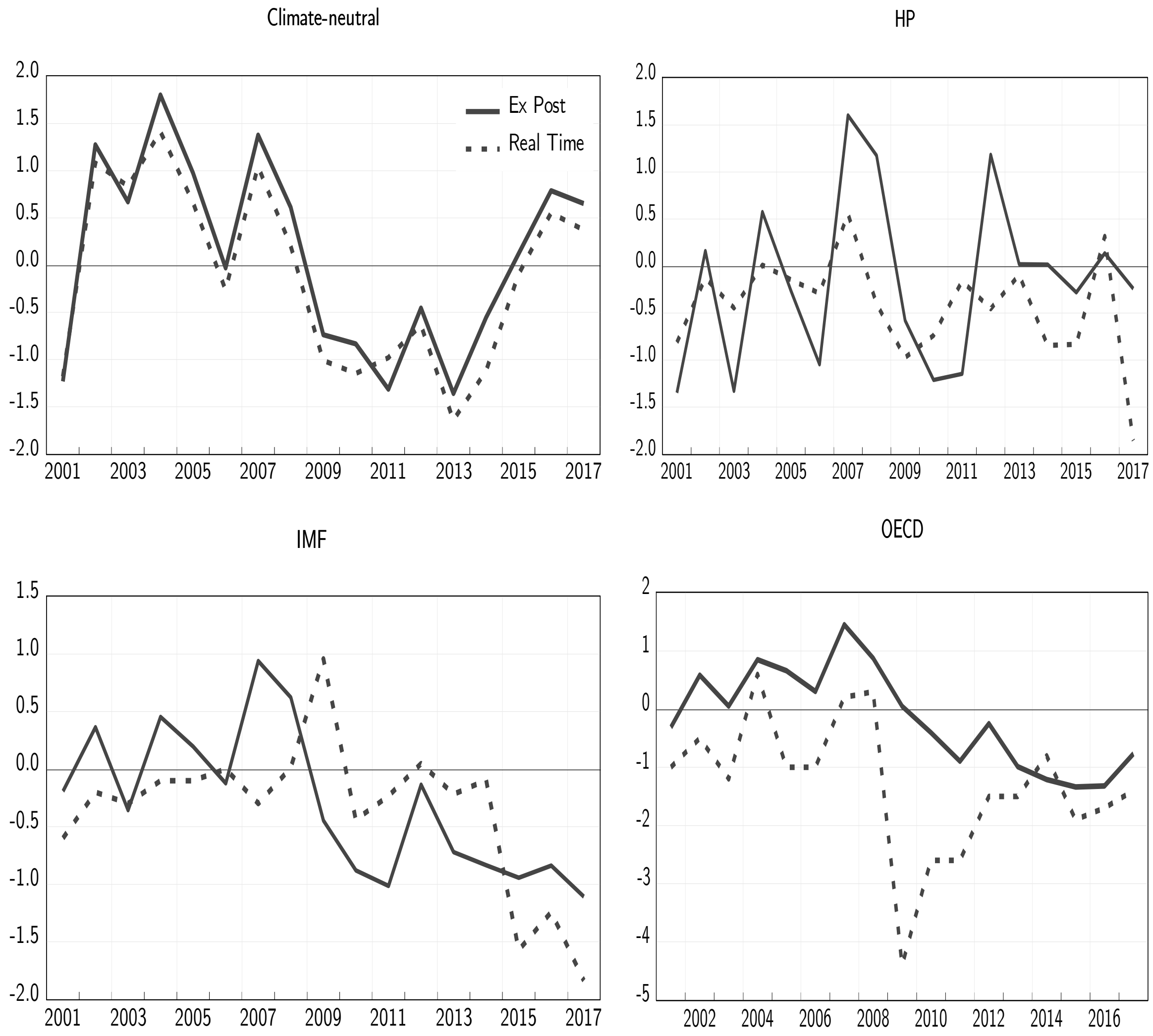
ii. IMF and OECD

- OECD: For each year (T), the December vintage of the OECD Economic Outlook constitutes the real-time estimates for that year, while the ex post (final) estimates are based on the June vintage released in year $T+1$ for year T.
- IMF: For each year (T), the October vintage of the IMF World Economic Outlook (WEO) constitutes the real-time estimates for that year, while the ex post (final) estimates are based on the April vintage of the WEO released in year $T+1$ for year T.

iii. Unobserved Component State-Space (Climate-neutral) Model

- For state-space unobserved component models (as employed in this paper), the maximum likelihood estimation via Kalman filter produces two main estimates: filtered estimates and smoothed estimates. The estimation of the filtered estimates uses past observations up to time t, where $1 \leq t \leq T$, while the smoothed estimates are based on the full sample, T. Therefore, the filtered estimates are the real-time values while the smoothed estimates are the final values, with any large, considerable difference between the two estimates indicative of the degree of parameter instability in the model (Orphanides and van Norden (2002).

Figure 3.4. Real-time versus Ex Post Output Gaps (Percent of Potential Output)



Source: Author's calculations; IMF and OECD.

Figure 3.4 shows that the climate-neutral gaps appear to be relatively more consistent in both the direction and magnitude between the *ex post* and real time estimates, providing strong indication that climate variables contain useful information about the changing dynamics of the Australian economy. However, for the official estimates, there are considerable differences between the real-time and ex post pictures painted. In the pre-GFC environment, both the IMF and OECD provided contrasting estimates for the state of the Australian economy. While the IMF's projections were largely indicative of an overheating economy, the OECD projected an underperforming economy relative to potential.

However, ex post, estimates from both institutions appear much more consistent in pointing toward an Australian economy with a growing slack in the post-GFC environment. There is a considerable difference between the real-time and ex post HP-filtered gaps as well, especially in the post-GFC era.

In addition to the root-mean squared error (RMSE) of the difference between the final and the real-time estimates of the various output gap measures, the last three columns of Table 3.2 provide some useful indicators. Scaled measures of the revisions (SMR) and correlation (COR) between the ex-post and real-time estimates are also provided to gauge the extent to which each measure is reliable. The lower the scaled measures of revisions (SMR1 and SMR2), the more reliably the output gap estimates are measured. The higher the correlation between the ex-post and the final estimates, the less the difference between model estimates in real time versus ex post. The climate-neutral estimates outperform the rest of the methods on these fronts.

Table 3.2. Summary Output Gap Revision Statistics

Method	RMSE	SMR1	SMR2	COR
OECD	1.53	1.24	1.79	0.51
IMF	0.66	1.08	1.05	0.44
HP	1.01	0.94	1.01	0.39
Climate-neutral	0.30	0.22	0.30	0.98

Source: Author's calculations. *SMR1 is the ratio of the standard deviation of the total revisions (final estimate less real-time estimate) to the standard deviation of the final output gap series. *SMR2 is the ratio of the root-mean squared error (RMSE) of the total revisions to the standard deviation of the final output gap series. COR is the correlation between the ex-post (final) estimates and the real-time estimates.

3.5.2.2 Robustness

A series of robustness checks are performed to examine whether the results for the climate-neutral model analyzed so far are driven by specification issues or may be considerably different with the use of alternative proxy variables for climate-induced weather shocks.

On the specification question, different specifications of the model in equations 3.2 to 3.5 are examined. Alternative specifications of the model, including an integrated random walk and a constant random walk with drift (by changing the noise-to-signal ratio), do not provide any considerable difference in the results. To check whether the results are sensitive to the choice of climate shock indicator, the Aridity Index (AI) due to Oury (1965), a commonly used climate index in the literature to capture the effect of heat and drought, particularly on agricultural productivity (see Zhang and Carter, 1997; Wang et al, 2018) is employed as an alternative climate shock variable. The AI is computed as:

$$AI_t = \frac{1}{(1.07)^{T_t}} P_t \tag{3.8}$$

where P_t is the total precipitation for period t in millimeters and T_t is the mean temperature for period t in degrees Celsius. Simply put, the AI is precipitation normalized with respect to temperature. To capture the persistent variations in the AI caused by ongoing anomalies in precipitation and temperature patterns, shocks to the index are computed as:

$$AI_{Shock} = \frac{1}{\sigma^{AI^m}} (AI_t - AI^m) \tag{3.9}$$

where σ^{AI^m} is the standard deviation of the long-term AI mean over the period 1961-1990. The results based on AI shocks as proxy for climatic variations are similar to the model with variations in temperature anomalies, with no considerable difference from the results presented above (see Appendix Table 3.4B and Figure 3.5A).

3.6 Conclusions

The output gap is a key input into macroeconomic policy decisions, from examining fiscal sustainability to informing the monetary policy stance. However, as an unobserved variable, obtaining accurate real-time estimates of the output gap is a major challenge in practice, especially when an economy is experiencing macroeconomic imbalances that distort the relationship between aggregate supply and demand. Under such conditions, the extraction of signal from noise becomes a more challenging task. Using a simple unobserved component model calibrated to Australian data, the effects of climate-induced weather shocks—proxied by variations in temperature and precipitation anomalies—on potential output and the output gap were tested. The results show that climate-induced weather shocks contain useful information in explaining the transitory movements in output, with the estimated climate-neutral output gaps found to be relatively more reliable compared to conventional measures that do not take climate effects into consideration.

3.7 Appendix

Table 3.3A Data Description and Sources

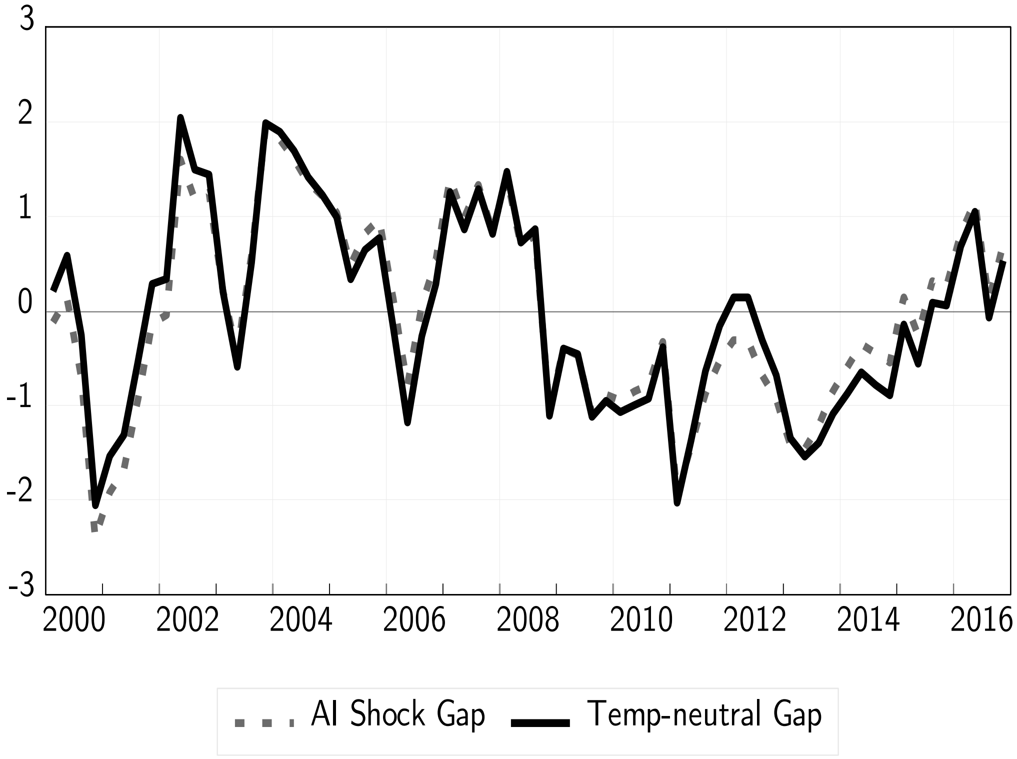
Variable	Description	Data Source
Mean Temperature Anomaly	Deviation of Mean surface air temperature from long-term (1961-1990) average	Australian Bureau of Meteorology (BoM)
Rain (Precipitation) Anomaly	Deviation of rainfall from long-term (1961-1990) average	Australian Bureau of Meteorology (BoM)
Inflation Rate	The inflation rate is computed as the first difference of the log of CPI	RBA
Survey-based measure of Capacity Utilization	Rate computed as first difference of log of capacity utilization net balance	OECD
GDP	Log of Seasonally-adjusted real GDP	RBA
Official Output Gap Statistics	Published data Vintages	World Economic Outlook Database [IMF]; Economic Outlook Database [OECD]

Table 3.4B Robustness Checks: Summary Output Gap Revision Statistics

Method	RMSE	SMR1	SMR2	COR
OECD	1.53	1.24	1.79	0.51
IMF	0.66	1.08	1.05	0.44
HP	1.01	0.94	1.01	0.39
Temperature-neutral	*0.30*	*0.22*	*0.30*	*0.98*
Aridity-Index Gap	*0.33*	*0.32*	*0.32*	*0.95*

Source: Author's calculations. *SMR1 is the ratio of the standard deviation of the total revisions (final estimate less real-time estimate) to the standard deviation of the final output gap series. *SMR2 is the ratio of the root-mean squared error (RMSE) of the total revisions to the standard deviation of the final output gap series. COR is the correlation between the ex post (final) estimates and the real-time estimates.

Figure 3.5A. Robustness Checks: Aridity Index Shock vs Temp-neutral Output Gap



Chapter 4

4. Climate Hysteresis and Monetary Policy

Abstract

Since the birth of the natural rate hypothesis, the conventional notion that short-term output simply fluctuates around a relatively stable long-term trend became the norm in modern macroeconomics, including in the standard New Keynesian DSGE model. However, the global financial crisis (GFC) led to a serious rethinking of this norm, giving rise to the re-emergence of the Blanchard-Summers' hysteresis debate and a new business cycle paradigm in which the short-term output effects of financial crises permanently feed into long-term growth trends. This paper employs a Bayesian-estimated structural multivariate filtering model calibrated to data for Australia and the United States, innovatively incorporating *climate hysteresis* into the estimation of potential output and the output and unemployment gaps. The results suggest non-trivial implications for monetary policy in a climatically disrupted world, with different implications for inflation signals during the upturn or downturn of the business cycle. Specifically, macroeconomic slacks are smaller when both actual conditions and potential supply capacity are modelled to change simultaneously, with recessions that may be less disinflationary, and booms that may be less inflationary.

4.1 Introduction

Climate risks—whether physical in the form of increased frequency and severity of climate-induced weather anomalies or transitional in the form of the macroeconomic impacts from putting a price on carbon—create negative supply shocks to the macroeconomy. Evidence suggest that the effects of physical climate risks affect not only current macroeconomic conditions, but such negative effects also feed into long-term macroeconomic trends (Hsiang & Jina, 2014). Similarly, even a well calibrated carbon tax policy may create long-lasting stagflationary effects on the macroeconomy, although the magnitude of such effects is contingent upon the nature of the monetary regime (McKibbin, Morris, Panton, & Wilcoxen, 2017; McKibbin, Morris, Wilcoxen, & Panton, forthcoming). Simply put, in a structurally disrupted world that is continuously buffeted by climate shocks, conditioning macroeconomic stabilization policy on underlying trends that are constantly changing is extremely complicated, particularly in terms of the real-time calibration of forward-looking monetary policy.

Under the conventional inflation targeting regime, the optimal policy stance is typically conditioned on forecasts of the output gap (the deviation of current output from potential) or the unemployment gap (the deviation of current unemployment rate from the natural level or the non-accelerating inflation rate of unemployment—NAIRU[13]). With the forecasts of these unobservable variables already notoriously subject to errors under normal conditions (Orphanides & Norden, 2002), the task of distinguishing actual policy signals from noise is even more complicated in a climatically disrupted world. Apart from the measurement problem, the conventional inflation targeting framework is better suited at macroeconomic stabilization in a world characterized by demand shocks, not supply shocks.

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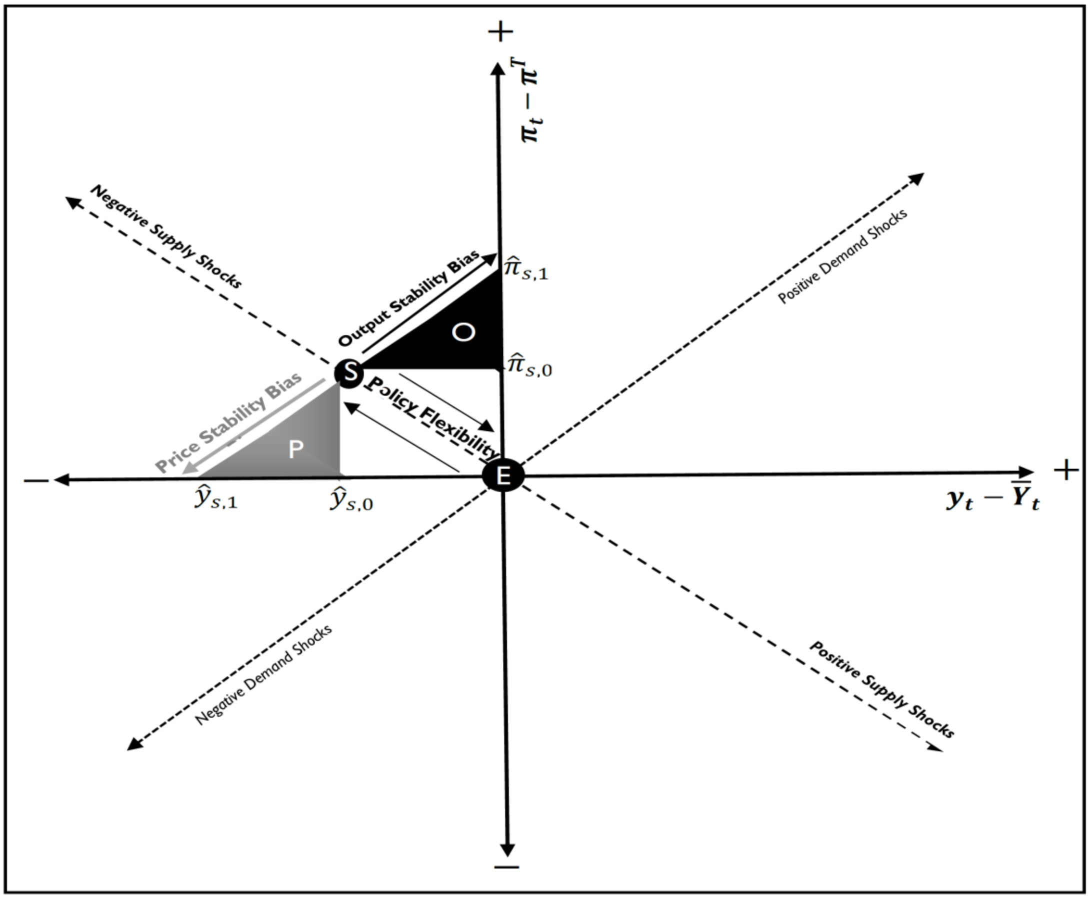
[13] Although interchangeably used in practice, NAIRU differs from the related concept of the natural rate of unemployment. As originally defined by Modigliani and Papademos (1978), NAIRU refers to the level of unemployment consistent with stable inflation in the short to medium term. The natural rate on the other hand is the rate at which inflation would gravitate to its long run expected steady state value, after all transitory shocks have fully worked through labour and product markets (Friedman, 1968).

In a *divinely coincidental* world where the welfare-relevant employment conditions remain invariant to adverse supply shocks, maintaining price stability is mechanically equivalent to maintaining stable output and employment conditions (Blanchard & Gali, 2007). Absent such divine coincidence, however, monetary policy faces a stark trade-off, especially in an environment with ongoing adverse supply shocks. The classic problem of inflation-output stability trade-off under adverse supply shocks is illustrated in the second quadrant of Figure 4.1. Imagine an economy initially in equilibrium (at E) before being hit by an adverse supply shock, resulting into stagflation (negative output gap at $\hat{y}_{s,0}$ and an above-target inflation at $\hat{\pi}_{s,0}$). A flexible inflation targeting central bank that seeks to biasedly '*look through*' the output effect as only temporary and only reacts to tame inflationary pressure may further weaken output (as indicated by the move from $\hat{y}_{s,0}$ to $\hat{y}_{s,1}$).

Figure 4.1. Price-Output Stability Trade-off Under Adverse Supply Shocks



Despite the significant hit to industrial production and overall U.S. output from the 2005 Hurricane Katrina disaster, the U.S. Federal Reserve responded by tightening the policy stance by up to 25 basis points[14], working under the assumption that the growth effects of the disaster were only temporary, but near-term inflationary pressure must be tamed. Conversely, attempts at stimulating output via a loose policy stance may create further upward pressure on inflation (from $\pi_{s,0}$ to $\pi_{s,1}$).

As indicated by the *policy flexibility zone* in the diagram, the price-output stability trade-off is addressed in practice by *"flexibly"* conditioning policy reactions on shocks that are judged to be *non-transitory* and to the extent that they affect underlying macroeconomic conditions (Bernanke and Gertler, 1999). However, in an economy characterised by a sequence of ongoing climate-induced disruptions, making any accurate distinctions between transitory and permanent shocks is a faulty exercise (Brainard, 2019), rendering the flexible inflation targeting regime sub-optimal in a carbon-constrained world (McKibbin et al., 2017; McKibbin & Panton, 2018; McKibbin et al., forthcoming). The effects of the adverse supply shock illustrated in Figure 1 would be more complex, if instead of only affecting current output, the shock also affects the long-term growth trend. For example, a typical natural disaster that weakens households' balance sheets and depresses private consumption today may also negatively affect firms' current investment decisions (Batten, Sowerbutts, & Tanaka, 2016), potentially lowering future capital stock and weakening advancement in technical progress (Fankhauser & Tol, 2005).

Unlike relatively rare financial crises whose onset might be foreseen (Kamisky & Reinhart, 1999; Rajan, 2005; Reinhart & Rogoff, 2009), the climate crisis creates series of ongoing shocks that structurally disrupts the macroeconomy in an unpredictable fashion (Fomby, Ikeda, & Loayza, 2013; Hsiang & Jina, 2014). Although a large literature is emerging on the monetary policy effects of climate risks, research effort has been largely focused on the financial stability implications of physical and transition risks (Bolton et al., 2020; England, 2015; NGFS, 2019) with scant findings on how these risks affect the

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[14] *See minutes of the September 20, 2005 Federal Open Market Committee (FOMC)*

overall nature of the monetary regime, with few notable exceptions (McKibbin et al., 2017; McKibbin et al., forthcoming).

Consistent with recent evidence on the long-term output effects of short-term shocks (L. M. Ball, 2009; Blanchard, 2018; Bluedorn & Leigh, 2018; Borio, Disyatat, & Juselius, 2014, 2017; Cerra & Saxena, 2008, 2017), the type of structural disruptions posed by climate-induced persistent weather anomalies may feed into both transitory and long-term growth dynamics, through what may be termed as *climate hysteresis*. Usual seasonal adjustments techniques that simply remove "normal" seasonal weather variations from macroeconomic data seriously falls short of capturing the "abnormal" climate-induced weather patterns (Boldin & Wright 2015), least to mention their long-term hysteresis effects. Although there is a strong literature on the effects of climate shocks on the macroeconomy (Buckle, Kim, Kirkham, McLellan, & Sharma, 2007; van de Ven & Fouquet, 2017), the current paper is the first attempt at incorporating climate hysteresis into the estimation of potential output and the output and unemployment gaps, to the best of my knowledge.

Apart from carefully creating a nexus between the literature on the macroeconomic effects of climate change and the monetary policy literature, this paper contributes to the literature by incorporating climate hysteresis effects into the estimation of potential output and the output and unemployment gaps, key unobservable variables that are crucial in the conduct of forward-looking macroeconomic stabilization policy, especially monetary policy. The core message of the paper is for an economic environment in which the short-term effects of persistent climate shocks are elevated into long-term economic trends, macroeconomic slacks are smaller when both actual conditions and potential supply capacity are modelled to change simultaneously, with recessions that may be less disinflationary, and booms that may be less inflationary. The remainder of the paper proceeds as follows. The next section provides a summary of the relevant literature on climate change and economic growth. The third section outlines the model. The results are analyzed in section four. The section six contains the concluding remarks.

4.2 Related Literature

The unpredictable onset and frequency of physical climate risks have devastating effects on the environment and the macroeconomy (Cavallo & Noy, 2010; Dell, Jones, & Olken, 2014), with competing hypotheses on how such risks affect long-term output growth trends. Some findings suggest that while output may be negatively affected in the immediate aftermath of disasters, the introduction of new technologies following disasters may have positive effects on long-run growth (Crespo Cuaresma, Hlouskova, & Obersteiner, 2008; Hallegatte & Dumas, 2009; Skidmore & Toya, 2002). Related research findings, including Stromberg (2007), Yang (2008) and Strobl (2011), show that economies are likely to simply return to their pre-disaster growth trends provided the increased marginal product of capital in the post-disaster environment triggers increased capital inflows that stimulate economic activity.

Recent findings largely argue against the creative destruction or 'return-to-trend' arguments pushed in the earlier literature, with increased macroeconomic risks in the post-disaster environment identified as the main factor undermining growth. For example, for regions exposed to frequent episodes of severe physical climate shocks, uncertainty from high insurance claims (Bank of England, 2015), falling housing prices (Boustan, Kahn, Rhode, & Yanguas, 2020), increased permanent risk-aversion tendencies following exposures to natural disasters (Cameron and Shah 2013), and outmigration from affected regions (Strobl, 2011; Boustan et al., 2020) are some of the increased risks factor that may affect current and future macroeconomic outcomes for such regions. Hsiang and Jina (2014) provide evidence that for economies that are frequently exposed to cyclones, the short-term growth effects may be small, but those negative effects strongly persist over time, gradually lowering the long-term growth and development trajectories of the affected economies. Earlier findings by Fomby et al. (2013) also suggest that the growth effects in the aftermath of climate-induced disasters may persist for longer, especially in the case of drought.

Apart from the measured effects of large and severe natural disasters that may be relatively infrequent, the short-term impact of climate change is felt in the form of ongoing abnormal variations in weather patterns. Although a summer of extreme heatwaves or an incident of flooding may be small in and of itself, scientific evidence (IPCC, 2018) suggests that such events will become more severe and frequent over time with changing climatic conditions, subjecting the economy to an ongoing cycle of adverse supply shocks and structural disruptions. As temperature rises, the associated elevated level of heat stress negatively affects labor supply and productivity (Dell, Jones, & Olken, 2012; Heal & Park, 2015; Kjellstrom, Maître, Saget, Otto, & Karimova, 2019; Zander, Botzen, Oppermann, Kjellstrom, & Garnett, 2015) and accelerates the depreciation of capital (Stern, 2013) resulting in costly capital adjustment and reallocation (Zhang, Deschenes, Meng, & Zhang, 2018). Therefore, whether in the form of large natural disasters or gradual worsening of weather anomalies, physical climate risks pose a serious challenge to macroeconomic stabilization.

On the macroeconomics front, the current paper is closely related to Alichi et al. (2019) who introduce partial labor market hysteresis in a multivariate model applied to the United States. They show that when short-term shock persistence is embedded in the model via hysteresis, the estimated output gaps are much smaller and NAIRU more volatile than conventional estimates that consider output cyclicality to fluctuate around a rather relatively smooth potential growth path. Closely related earlier findings include Bluedorn and Leigh (2018) who document empirical evidence on output shocks persistence and Cerra and Saxena (2008, 2017) who argue that the output gap can be poorly measured and inconsistent with macroeconomic fundamentals when the frequency and depth of economic crises are the key drivers of the path of potential growth. These findings are consistent with earlier modelling by Pagan (1997) and Harding and Pagan (2002) who provide evidence on the persistence of short-term output shocks.

4.3 Model

From the literature, climate-induced weather anomalies affect the macroeconomy from many angles, including weakening labour productivity, fast depreciation of capital and increased macroeconomic risks and uncertainty. In order to incorporate the persistence of these climate-induced shocks into the estimation of potential output and the output and unemployment gaps, it is useful to start with a simple simulation experiment, with New Keynesian micro-foundations in the spirit of Alichi et al. (2019). Assume standard Cobb-Douglas production function with constant returns to scale:

$$\overline{Y}_t = A_t K_t^{\alpha} L_t^{1-\alpha} \tag{4.1}$$

where potential output, capital and potential employment are represented by $\overline{Y}_t$, K_t and L_t respectively, and α the share of capital in production, with firms minimizing their labor costs $(W_t L_t)$, the rental costs of capital $(r_t^k K_t)$ and the capital adjustment costs (c)—the cost associated changing investment and capital stock to match existing labor supply and productivity. Consistent with the literature (Benes, Kumhof, & Laxton, 2014; Hayashi, 1982; Sargent, 1978), the adjustment costs follow a quadratic process:

$$r_t^k K_t \frac{1}{2} c \left(\frac{K_t}{K_{t-1}} - 1\right)^2 \tag{4.2}$$

Assuming perfectly competitive labor and capital markets, with firms taking wages and rental costs as given, the cost minimization problem takes the form:

$$\min_{L_{t+i}, K_{t+i}} E_{\mathrm{t}} \sum_{i=0}^{\infty} \beta^i \left(W_{t+i} L_{t+i} + r_{t+i}^k K_{t+i} \left[1 + \frac{1}{2} c \left(\frac{K_{t+i}}{K_{t+i-1}} - 1 \right)^2 \right] + \lambda_{t+i} \left(\overline{Y}_{t+i} - A_{t+i} K_{t+i}^{\alpha} L_{t+i}^{1-\alpha} \right) \right) \tag{4.3}$$

where β is the discount factor and λ_t and E_{t} are the Lagrange multiplier and expectation operator respectively.

For the above optimization problem, the first order conditions (FOCs) become:

$$Labor\text{:} \qquad W_t - \lambda_t(1-\alpha)\frac{\overline{Y}_t}{L_t} = 0 \tag{4.4}$$

$$\begin{aligned} Capital\text{: } r_t^k\left[1+\frac{1}{2}c\left(\frac{K_t}{K_{t-1}}-1\right)^2\right] + r_t^k K_t C\left(\frac{K_t}{K_{t-1}}-1\right)\frac{1}{K_{t-1}} \\ + \beta c E_t\left[r_{t+1}^k K_{t+1}\left(\frac{K_{t+1}}{K_t}-1\right)\left(-\frac{K_{t+1}}{K_t^2}\right)\right] - \lambda_t \alpha \frac{\overline{Y}_t}{K_t} = 0 \end{aligned} \tag{4.5}$$

When compactly expressed as in (4.6), the FOCs show that the evolution of capital is contingent upon labor supply and the costs associated with adjusting capital investment to match labor supply or productivity.

$$\frac{r_t^k K_t\left[1+\frac{1}{2}c\left(\frac{K_t}{K_{t-1}}-1\right)^2\right] + r_t^k K_t c\left(\frac{K_t}{K_{t-1}}-1\right)\frac{K_t}{K_{t-1}} - \beta c E_t\left[r_{t+1}^k K_{t+1}\left(\frac{K_{t+1}}{K_t}-1\right)\frac{K_{t+1}}{K_t}\right]}{\alpha} - \frac{W_t L_t}{1-\alpha} = 0 \tag{4.6}$$

Absent capital-adjustment costs, the capital-labor ratio can simply be expressed as:

$$\frac{r_k^k K_t}{w_{L_t}} = \frac{\alpha}{1-\alpha} \tag{4.7}$$

Under more realistic assumptions where firms make costly (rather than costless) capital adjustments, the constant capital-labor ratio in (4.7) can only be achieved over a relatively longer time horizon. That is, in the short term, the optimal amount of capital that firms hold, relative to available labor supply or productivity, may be largely a function of the level of uncertainty in their operating environment (Bernanke, 1983; Bloom, 2009). For example, Bernanke (1983) argues that apart from the potentially high costs require to revise or adjust current investments in the face of macroeconomic uncertainties, optimizing behaviour requires that long-term investment decisions are informed by an understanding of uncertainties over the longer-term horizon. For firms with investments in regions or sectors that are highly susceptible to unpredictable and extreme aggregate shocks (like those due to rapidly changing climatic conditions), the assumption of high adjustment costs is a reasonable one.

To evaluate how capital adjusts to a change in potential employment, say due to weakening labor productivity because of rising temperature and heat stress (Chavaillaz et al., 2019; Kjellstrom et al., 2019), the linearized version of equation (4.6) becomes:

$$\hat{k}_t = \frac{c}{c + \beta c + 1}\hat{k}_{t-1} + \frac{\beta c}{c + \beta c + 1}E_t\hat{k}_{t+1} + \frac{1}{c + \beta c + 1}\hat{l}_t \tag{4.8}$$

where $\hat{k}_t$ and $\hat{l}_t$ represent the deviations of labour and capital from their initial steady states. By applying the method of undetermined coefficients à la Campbell (1998) and Christiano (2002), equation (4.8) collapses to much straightforward solution regarding the law of motion for capital when potential employment deviates from steady state:

$$\hat{k}_t = \rho\hat{k}_{t-1} + \eta\hat{l}_t \tag{4.9}$$

where $\eta = 1 - \rho$ represents labor share of output. By substituting (4.9) into (4.8) (and restricting the coefficients in front of $\hat{k}_{t-1}$ to zero) and omitting explosive solutions, equation (4.10) reveals that the higher the adjustment costs, the slower firms will take to adjust their investments, further amplifying the potential losses for firms in sectors exposed to persistent macroeconomic risks affecting employment, including physical and transition climate risks.

$$\rho = \frac{c + \beta c + 1 \pm \sqrt{(c + \beta c + 1)^2 - 4\beta c^2}}{2\beta c} \tag{4.10}$$

More importantly, in the face of persistent shocks to the economy that drive potential employment away from its steady state level (e.g., say persistent decline in labor productivity due to heat stress with rising temperature), the effect on potential output will be in the form of direct and contemporaneous fall due to falling labor supply or productivity, and indirect (gradual) decline due to costly capital adjustments to match available level of employment or productivity.

To measure output elasticity with respect to these two effects, equation (4.9) is rewritten as:

$$K_t = \rho K_{t-1} + (1-\rho)\frac{K}{L}L_t = \sum_{i=0}^{\infty} \rho^i (1-\rho)\frac{K}{L}L_{t-i} \tag{4.11}$$

with the production function in (4.1) rewritten as

$$\overline{Y}_t = A_t[K(L_t, L_{t-1}, \dots)]^{\alpha} L_t^{1-\alpha} \tag{4.12}$$

By differentiating (4.12) with respect to L_t and compactly rearranging, the elasticity of output with respect to labor are presented below, with the contemporaneous (direct) effect captured in (4.13) and the gradual (indirect) capital adjustment effect represented by (4.14).

$$\frac{\frac{\partial \overline{Y}_t}{\overline{Y}_t}}{\frac{\partial L_t}{L_t}} = (1-\alpha) + \alpha(1-\rho) \tag{4.13}$$

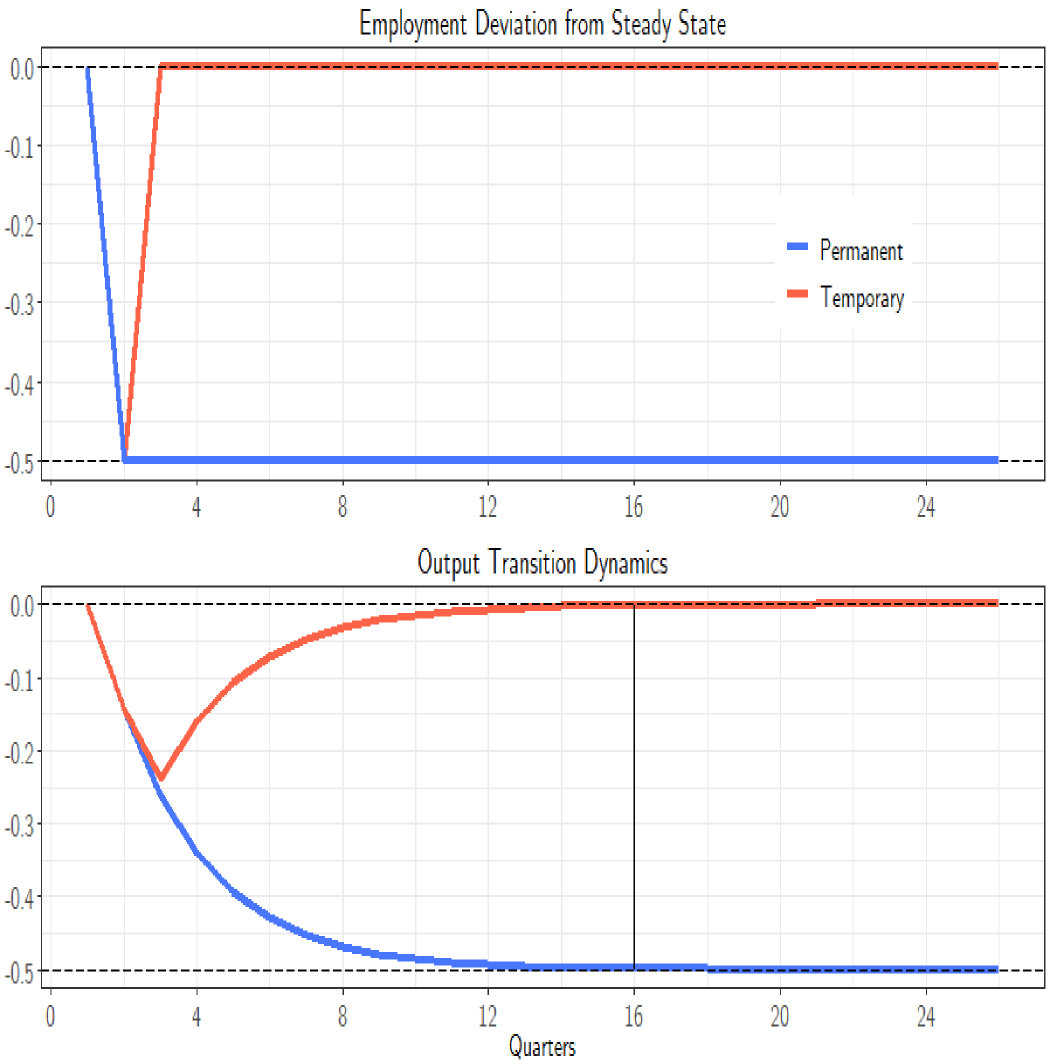
$$\frac{\frac{\partial \overline{Y}_{t+i}}{\overline{Y}_{t+i}}}{\frac{\partial L_t}{L_t}} = \alpha\rho^i(1-\rho) \quad \text{for } i = 1,2,\dots \tag{4.14}$$

Based on (4.13) and (4.14), it can be seen that in the long run, persistent changes in NAIRU will translate one-for-one into potential output, with the labor productivity effects of climate shocks (Zander et al., 2015; Strobl, 2011; Boustan et al., 2020) serving as one of the several channels through which climate change affects potential output. The labor market effects of climate change may also result from climate-related emigration (Cattaneo & Peri, 2016). For regions with harsher and persistent weather anomalies, out-migration of the labor force may weaken long-term potential employment (Strobl, 2011; Boustan et al., 2020). As people emigrate to regions with relatively better climate conditions within or across countries, there may be more unemployment or underemployment, with the associated reduction in income, savings and or investment translating into lower potential output (Fankhauser &Tol, 2005).

To assess these arguments, a simulation experiment based on equations (4.13) and (4.14) is performed. Consider a 0.5 percentage point decline in potential labour supply or labor productivity, say due to extreme and persistent heatwaves and other harsh climate-induced weather conditions, to examine the effects on output and capital. Consistent with the New Keynesian DSGE literature (Smets & Wouters, 2003), the calibrated values for β, α and the adjustment costs parameter, c, are set at 0.99, 2/3 and 20 respectively. Figure 2 presents the effect on output and the transition path back to steady state following the shock.

In the first scenario, the decline is assumed to be permanent while in the second scenario, a one-time temporary decline (say due to once-in-a decade heatwave or bushfire) is assumed. In either scenario, the fall in output is deeper in the first year of the shock, followed by a gradual decline towards the initial steady state (temporary shock) or a lower, permanent steady state (permanent shock). Beyond the year of impact of the shock, the gradual output transition dynamics can be explained by the pace of capital adjustments by firms. Whether permanent or temporary, the simulation results suggest that output returns to steady state within four years. This is consistent with recent arguments that although the natural rate hypothesis may have passed its time (Farmer, 2013), a more plausible working null hypothesis would be that there exists labor market hysteresis, with the magnitude of the effects on long-term growth less than unity (Blanchard, 2018b) and gradually fading over time (up to 4 years as per Figure 4.2). That is, while the effects of climate-induced weather shocks may not be permanent, the disruptions caused by these shocks may have relatively longer stagflationary effects (i.e., rising inflation combined with falling output), distinguishing them from typical demand shocks.

Figure 4.2. Simulated Output Effects from Steady-state Deviation of Potential Employment



Source: Author's calculations

Using data on real GDP, inflation, the unemployment rate, capacity utilization and a measure of climate-induced weather shocks for Australia and the United States, the goal in this paper is to derive estimates of potential output and the output and unemployment gaps that embody the persistence of short-term climate shocks. Based on the simulation results above, some anecdotal inference can be made that for climate shocks that affect labor productivity, their output effects may persist for up to at least four years.

In the spirit of Borio, Disyatat, & Juselius (2017) and Alichi et al. (2019), the modelling approach follows two steps. First, climate-induced weather shocks are embedded into the estimation of *climate-neutral* output gaps. Second, the climate-neutral output gaps are then incorporated in the estimation of NAIRU, with climate shocks and their hysteresis effects allow to persist for up to four years. The full procedure is demonstrated below.

4.3.1 The Stochastic Process for Output

Although variously defined in the literature (Kiley, 2013), in this paper, the output gap ($\hat{y}_t$) is defined consistent with Okun's Law as the deviation of real output y_t from potential ($\overline{y}_t$) in log terms:

$$\hat{y}_t = \ln y_t - \ln \overline{y}_t \tag{4.15}$$

The law of motion underpinning output stochasticity consists of three equations, beginning with the structural micro-foundations derived above (equations 4.13 and 4.14) and as anecdotally evidenced by the simulation experiment (Figure 4.2) that changes in NAIRU affect potential output, with the output effects lasting for up to four years as in equation (4.16).

$$\overline{y}_t = \overline{y}_{t-1} + G_t^{\overline{y}} - \eta\left(\overline{U}_t - \overline{U}_{t-1}\right) - \rho\frac{\left(\overline{U}_{t-1} - \overline{U}_{t-5}\right)}{4} + \varepsilon_t^{\overline{y}} \tag{4.16}$$

$$G_t^{\overline{y}} = \theta G_t^{ss\overline{y}} + (1-\theta)G_{t-1}^{\overline{y}} + \varepsilon_t^{G\overline{y}} \tag{4.17}$$

Changes in NAIRU ($\Delta\overline{U}_t$) are modelled to have direct impact on potential output through hysteresis, with the direct contemporaneous effect from persistent deviation of employment from steady state captured by the term $\eta(\overline{U}_t - \overline{U}_{t-1})$—the share of labor in a Cobb-Douglas production function (equation 9). When potential employment falls from its steady state due to climate-induced shocks, this will result in higher NAIRU, causing capital to gradually adjust to match available employment or labor productivity.

This is captured by the last term $\left(\rho\frac{(\overline{U}_{t-1}-\overline{U}_{t-5})}{4}\right)$ in (4.16). Potential output also evolves according to a level shock ($\varepsilon_t^{\overline{y}}$) and a non-constant trend growth ($G_t^{\overline{y}}$) that is a function of steady state trend growth (G_t^{ssy}) as in (4.17).

$$\hat{y}_t = \phi_1\hat{y}_{t-1} + \phi_2 CI_t + \phi_3\varepsilon_t^{G\overline{y}} - \phi_4\varepsilon_t^{\overline{y}} + \varepsilon_t^{\hat{y}} \tag{4.18}$$

A climate index (CI), capturing persistent weather anomalies, is directly embedded in the output gap equation (4.18), similar to the treatment of financial imbalances in the estimation of finance-neutral output gaps in Borio et al. (2017). Note that since climate shocks can affect both actual and potential output, the sign of the effect on the output gap is endogenously determined in the model by way of diffuse initialization (Commandeur & Koopman, 2007)[15]. Apart from shocks that may temporarily create excess demand relative to potential ($\varepsilon_t^{\hat{y}}$), the output gap equation also accounts for plausible forward-looking behavior by consumers regarding future productivity and income that may bring forward excess consumption. This is captured by including the shock to trend output growth ($\varepsilon_t^{G\overline{y}}$), while level shocks to potential growth that may create excess supply relative to demand are captured by $\varepsilon_t^{\overline{y}}$.

4.3.2 Phillips Curve

$$\pi_t = \lambda_1 E_t\pi_{t+1} + (1-\lambda_1)\gamma_{t-1} + \lambda_2\hat{y}_t + \varepsilon_t^{\pi} + \lambda_3\varepsilon_t^{\overline{y}} \tag{4.19}$$

$$\text{where } \gamma_{t-1} = (\pi_{t-1} \times \hat{y}_{t-1})$$

A Phillips curve is added to the model to aid in identifying shocks to output and provide additional information in the estimation of potential output and the output gap. A special feature of the Phillips curve specified here is the inclusion of a lagged rescaled output gap $\pi_{t-1} \times y_{t-1}$ to capture full underlying inflation pressure in the economy.

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[15] In state space modelling, when nothing is known about the initial value of a state variable, diffuse initialization is the approach through which that initial value is endogenously estimated within the state-space context (Hamilton, 1994)

This is consistent with macroeconomic theory that facing higher adjustment costs, firms are more prone to upward nominal price adjustments during period of high inflation, causing the Phillips curve to be steeper during such periods compared with periods of lower inflation dynamics (Laurence Ball, Mankiw, & Romer, 1988; Lawrence Ball & Mazumder, 2011). Therefore, an interaction variable constructed as the product of inflation and the output gap is a good way to capture the full nature of underlying pressure in the economy (Lansing, 2019).

Also note the inclusion of the term ($\varepsilon_t^{\overline{y}}$) to capture shocks to productivity that may reduce marginal costs and inflation, consistent with the DSGE literature (see Woodford, 2003). However, in a climatically disrupted environment where constant weather shocks create price volatility with plausible negative effects on productivity, such shocks may result in higher inflation. To account for this possibility, the parameter λ_3 is estimated via diffuse initialization.

4.3.3 NAIRU Estimation with Climate Hysteresis Embedded

Equations (4.20) to (4.23) describe the evolution of unemployment, with u_t denoting the unemployment gap–the deviation of the unemployment rate (U_t) from NAIRU ($\overline{U}_t$).

$$\hat{u}_t = \overline{U}_t - U_t \tag{4.20}$$

$$\overline{U}_t = \tau_4 \overline{U}_t^{\,ss} + (1-\tau_4)\overline{U}_{t-1} + G_t^{\overline{U}} - \frac{1}{2}\varpi(\hat{y}_t + \hat{y}_{t-1}) + \varepsilon_t^{\overline{U}} \tag{4.21}$$

$$G_t^{\overline{U}} = \tau_3 G_{t-1}^{\overline{U}} + \varepsilon_t^{G^{\overline{U}}} \tag{4.22}$$

$$\hat{u}_t = \tau_2 \hat{u}_{t-1} + \tau_1 \hat{y}_t + \varepsilon_t^{\hat{u}} \tag{4.23}$$

Based on Benes et al. (2014) and in the spirit of Alichi et al. (2019) who incorporate labor market hysteresis in the estimation of potential output and output gap for the United States, climate hysteresis is embedded in the NAIRU equation (4.21) through the inclusion of the 2-year moving average of the climate-neutral output gap in (4.18).

As it is unclear how expectations are affected by projected climatic variations, climate-induced changes embedded in the NAIRU are modelled to be adaptive—depending on abnormal weather variations in the previous and current periods as captured by the inclusion of the two-year moving average of the climate-neutral output gap $\left(\frac{1}{2}\varpi(\hat{y}_t+\hat{y}_{t-1})\right)$. Under conditions of climate-induced weather anomalies that persistently distort both demand and supply conditions in the economy, the output gap may never close, implying a persistently changing NAIRU. This time-varying specification also includes non-climate shocks to NAIRU $(\varepsilon_t^{\overline{U}})$ and variation in the trend $(\varepsilon_t^{G^{\overline{U}}})$. Note also the dependence of the unemployment gap on the output gap in (4.23), consistent with Okun's law.

4.3.4 Capacity Utilization Gap

Measures of capacity utilization are incorporated into the model to provide more information on the overall level of slack in the economy.

$$\hat{c}_t = C_t - \overline{C}_t \tag{4.24}$$

$$\overline{C}_t = \delta_2 \bar{C}^{ss} + (1-\delta_2)\overline{C}_{t-1} + G_t^{\overline{C}} + \varepsilon_t^{\bar{C}} \tag{4.25}$$

$$G_t^{\overline{C}} = (1-\delta_1)G_{t-1}^{\overline{C}} + \varepsilon_t^{G\bar{C}} \tag{4.26}$$

$$\hat{c}_t = \kappa\hat{y}_t + \varepsilon_t^{\hat{c}} \tag{4.27}$$

The equilibrium capacity utilization rate $(\overline{C}_t)$ is time-varying, with a growth rate of $G_t^{\overline{C}}$ and subject to shocks $(\varepsilon_t^{\bar{C}})$ whose effects gradually fade over time, contingent on the value of the parameter δ_2. Ranging from unstable and costly energy supply (van de Ven & Fouquet, 2017) and weakened labor productivity (Kjellstrom et al., 2019; Chavaillaz et al., 2019) to costly adaptation to rapidly changing working conditions (Chambwera et al., 2014), the effects of changing climatic conditions on industrial capacity and production cannot be overemphasized.

To keep things simple, the capacity utilization effects of climate change are captured in equation (4.27) via the inclusion of the climate-neutral output gap in the estimation of the capacity utilization gap—the deviation of current capacity (C_t) utilization rate from the equilibrium rate $\left(\overline{C}_t\right)$.

4.4 Data and Estimation

4.4.1 Data

Measuring climate hysteresis effects requires the crucial task of identifying climate-induced weather shocks whose effects are not merely transitory, but relatively permanent and persistently feed into long-term macroeconomic trends. To this end, the Standardized Precipitation Evapotranspiration Index (SPEI) by Vicente-Serrano et al. (2010) is employed as a proxy for climate-induced persistent weather anomalies. The SPEI captures current weather conditions (represented by current temperature and precipitation patterns[16]) relative to cumulative patterns from previous periods, statistically standardized to enable uniform comparisons across space, time, and different climate regimes, within and across countries.

Therefore, unless a distinctive pattern of climate-induced weather anomalies is taking place over time, the SPEI measured at a time scale of 12 months or longer would gravitate towards zero due to averaging over shorter time periods. This feature is important in the current paper as it allows only climate-induced persistent weather shocks to be incorporated in examining *climate hysteresis* effects. A summary of the computation methodology of the SPEI is provided in Appendix 4A.3 (see detailed technical treatment in Vicente-Serrano et al., 2010). In addition to weather shocks, the macroeconomic dataset used in estimating the model include real GDP, inflation, unemployment rate and measure of capacity utilization for Australia and the United States (see Table 4A.2 in the Appendix).

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[16] the SPEI can be computed using only temperature and precipitation data with a simple method (Thornthwaite, 1948), although the results are more accurate based on modern approaches that include data on wind speed, surface humidity and solar radiation.

4.4.2 Bayesian Estimation

The model is estimated using Bayesian techniques, specifically the regularized maximum likelihood approach in the spirit of Ljung (1999), with the Kalman filter employed in estimating the latent variables in the model (Hamilton, 1994). Consistent with the literature, tight priors are utilized as in Alichi et al. (2019), except for selected climate variables for which diffuse initialization is followed, as indicated in the text. For the United States, the priors for the steady state output growth and NAIRU are calibrated as 1.8 percent and 4.3 percent respectively as per the projections in the CBO's *Budget and Economic Outlook: 2020 to 2030*. For Australia, the steady state potential output growth rate of 2.7 percent is calibrated, consistent with the average from the OECD's long-term projections over the four decades ending in 2060, while NAIRU is calibrated at 4.6 based on the OECD's historical average over the two decades ending in 2021. The Bayesian priors and posterior estimates for both Australia and the United States are summarized in Appendix Table 4A.1.

4.5 Results

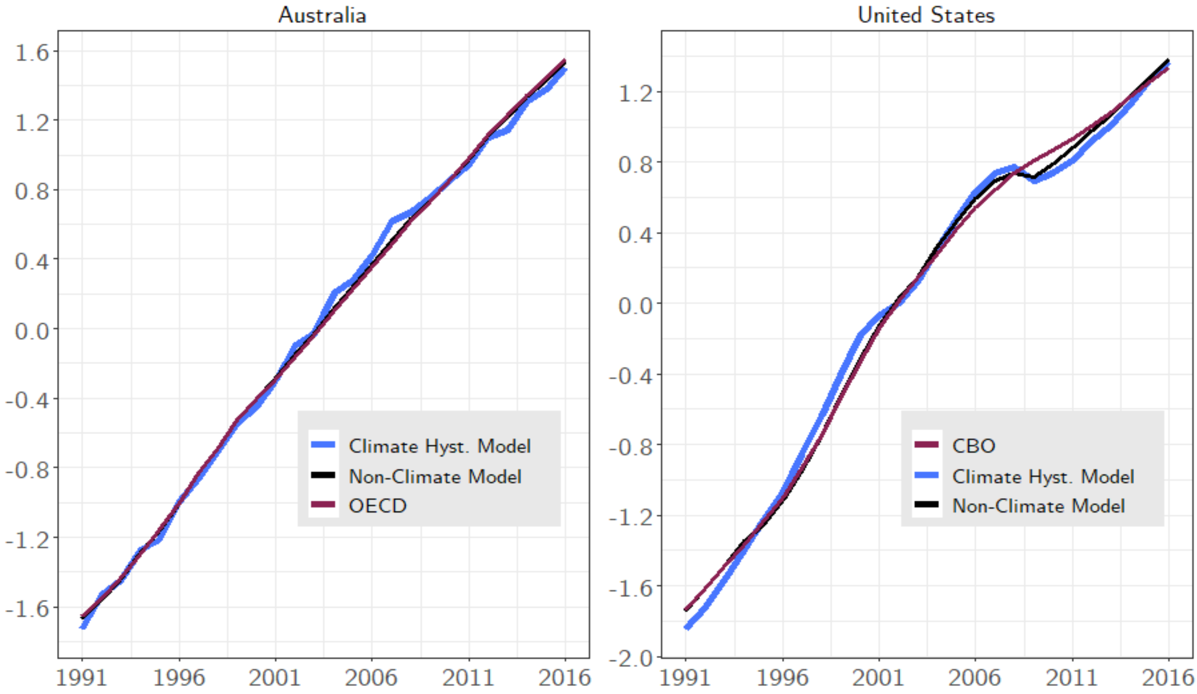
4.5.1 Potential Growth, Output Gaps and NAIRU

To examine potential hysteresis effects, two models are estimated: the model as described by equations (4.15)-(4.27), with a climate index included in the output gap equation (18) which is termed as the '*climate hysteresis model*', and a version of the model that omits the climate index from (4.18), termed as the '*non-climate model*'. In this section, model-based estimates of potential growth trends, output gaps and NAIRU are analyzed and compared with official estimates—OECD estimates for Australia and CBO estimates for the United States.

Figure 4.3 presents potential output trends (in log deviations from 1990) for Australia and the United States. When the standard assumption of smooth trend growth in developed economies is removed by incorporating climate hysteresis into the model, potential growth follows a more cyclical pattern, with climate shocks seem to generate more volatility in the trends in both countries.

Volatilities in trend growth imply serious complication for generating any accurate signals for real-time macroeconomic policymaking, particularly in a structurally disrupted environment where short-term output is even more volatile.

Figure 4.3. Model-based versus Official estimates of Potential Growth Trends (Log Deviations from 1990)



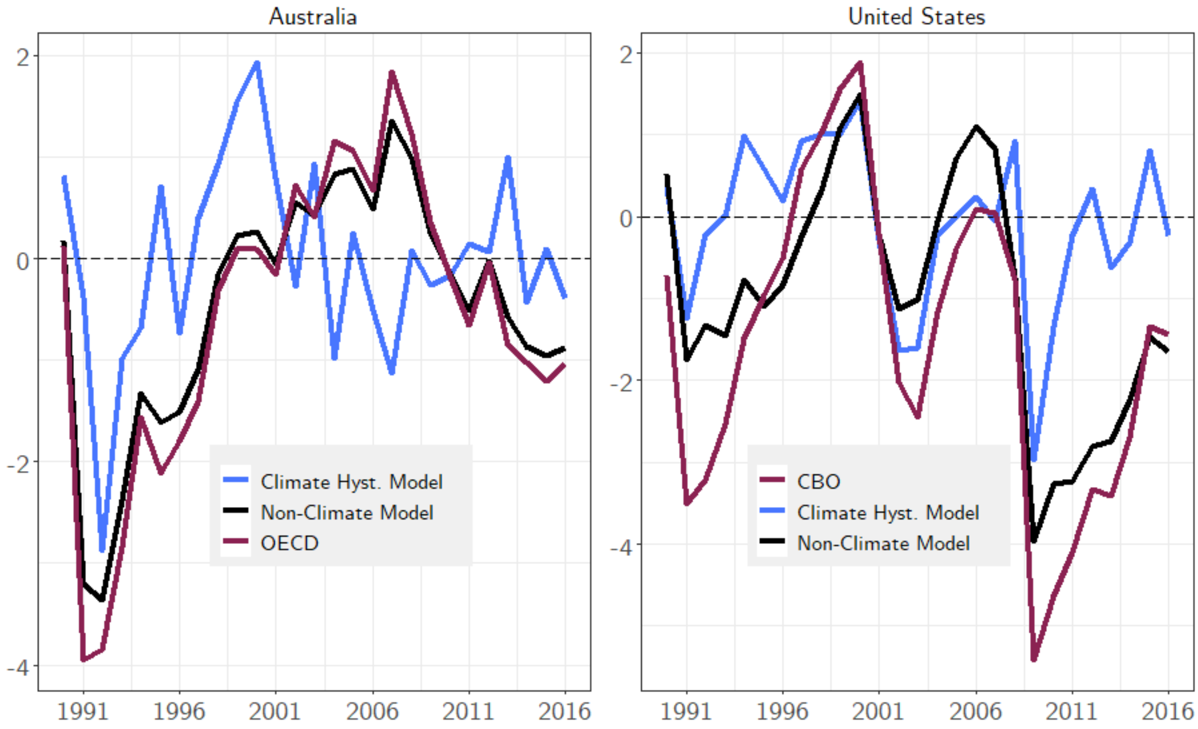
Source: Author's estimates; OECD and CBO data.

Note: The log deviations of potential growth from 1990 series are normalized with zero mean and variance one

These complications can be better examined by analyzing the trends in the model-based output gap estimates against the official estimates as presented in Figure 4.4. Throughout the 1990s for example, the model with climate hysteresis suggested less potential supply capacity relative to demand, indicative of a much slower or weaker potential growth compared with conventional measures of potential output. That is, given the same current demand condition but less potential growth, the output gap is much smaller compared with estimates that assume more (stable) excess supply capacity. In the years following the global financial crisis (GFC), model-based estimates of the output gap in both Australia and the United States suggested less potential supply capacity (although more pronounced for the climate-based model estimates).

As economies become more subjected to frequent disruptions, both actual and potential output will be constantly changing as key drivers of potential output become more volatile (Debelle, 2019). Therefore, measures of potential output and the output gap that do not account for these structural disruptions will create two problems for maintaining macroeconomic stability.

Figure 4.4. Model-based versus Official Output Gaps Estimates

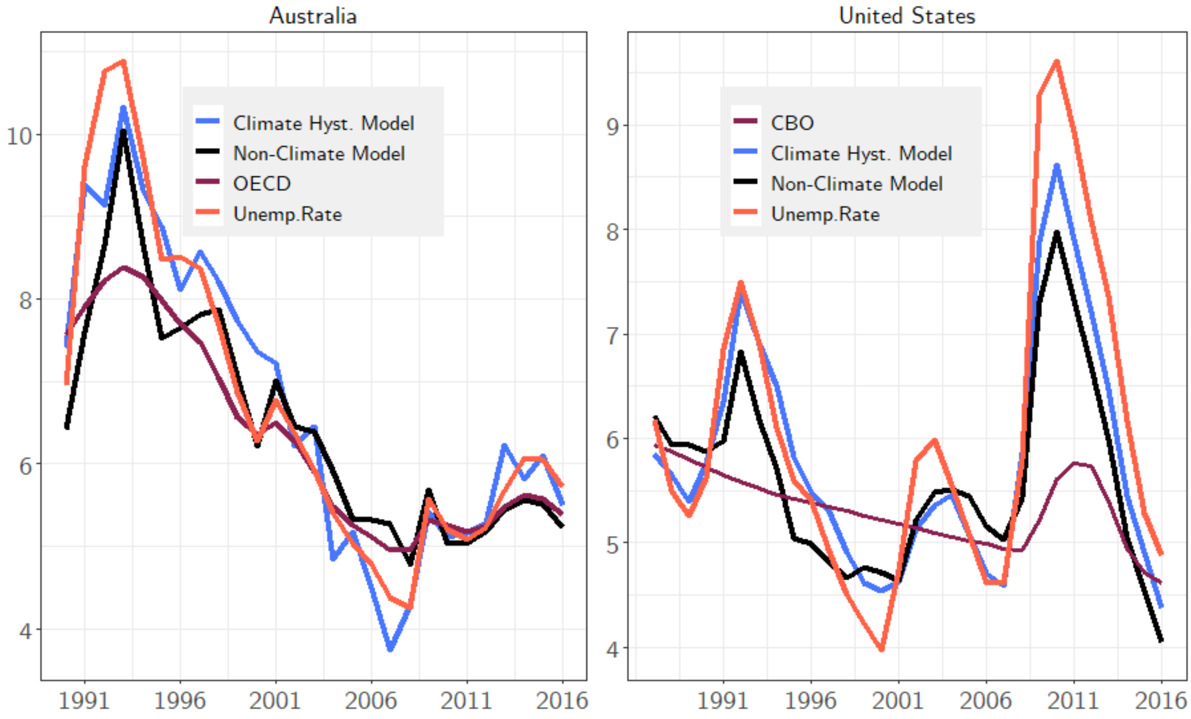


Source: Author's estimates; OECD and CBO data.

First, the size of the business cycle would be repeatedly overstated under the assumption that rapidly changing demand conditions fluctuate around a relatively stable trend growth. During a downturn for example, there would be much larger negative output gap than would otherwise be if potential growth is modelled with hysteresis from persistent structural disruptions embedded. Second, as a result of maintaining relatively stable goal posts regarding potential growth in a structurally disrupted environment, the mistaken signals from demand pressure may create policy-induced shocks to the economy.

All else equal, a large negative output gap would imply a more accommodative monetary policy stance, a move that may create excess demand pressure and financial stability risks if the output gap was much smaller due to structural disruptions that are persistently weakening potential supply capacity but whose effects are not engendered into policymaking (Borio et al., 2017). This is consistent with arguments by Friedman and Schwartz (1965) that the U.S. Federal Reserve mistakenly pursued an overly tightened policy stance during the Great Depression, and arguments by Coibion et al. (2018) about the Fed's mistaken loose policy stance in the 1970s. In the wake of the GFC, similar policy mistakes were lamented (Bean et al., 2010).

Figure 4.5. Estimates of NAIRU (Percent)



Source: Author's estimates; OECD and CBO data.

Figure 4.5 presents a comparison of the trends for model-based estimates of NAIRU against the OECD estimates (for Australia) and the CBO estimates (for the United States). Like potential output estimates, the model-based estimates of NAIRU are more volatile than official estimates, with larger magnitude when climate shocks and related hysteresis effects are embedded into the modelling.

Slacks in the labor market are also consistent with the trends in potential output and output gaps (Appendix Figure 4A), with the results largely supportive of the evidence that short-term (demand) shocks that drive the cyclicality in output also affect long-run unemployment dynamics—via hysteresis. While the modelling of the structural determinants of NAIRU are out of the scope of the current paper, the NAIRU trends are largely reflective of the relative levels of spare capacity estimated from each model. In the case of Australia, the climate model-based NAIRU estimates for the decade leading to 2000 are higher than the non-climate and official estimates, but consistently lower throughout the years leading to the GFC. This may be due to the fact that during the period 1990-2000, the climate-neutral estimates of potential output were relatively lower. The climate model estimates are similar to recent NAIRU estimates by Cusbert (2017) for Australia, although the magnitude and volatility of the estimates in the current paper are higher due to the inclusion of climate effects.

For the United States, the model-based NAIRU estimates are also volatile compared with CBO estimates, especially so in the aftermath of the GFC, consistent with evidence by Alichi et al. (2019). The output gaps along with the respective model-based estimates of unemployment gap are plotted in Appendix Figure A. While the unemployment gap, when estimated using the NAIRU concept without consideration of the Beveridge curve relationship, may be at odds with efficient labor market outcomes (Rogerson, 1997), the closed matching of the output and unemployment gaps shows a strong coherence regarding the signals on how far the current state of the economy is away from the model-based potential.

The different unemployment and output gap magnitudes suggest different underlying inflation dynamics. For example, given the same level of high unemployment during a recession, the climate hysteresis model with smaller output and unemployment gaps (due to lower potential output and higher NAIRU estimates) would be associated with less disinflationary pressure compared with conventional model estimates. These differences in measures of economic slack imply different forward-looking monetary policy decisions, particularly in terms of inflation forecasting. The next section explores relative inflation forecast performance.

4.5.2 Inflation Forecasts Evaluation Experiment

Based on the results above, climate shocks appear to contain useful content for understanding the nature of underlying trends in the economy. Whether or not climate shocks, or more precisely climate-neutral output gaps, have predictive power in improving the forecasts of macroeconomic activity and whether such predictive ability is robust over time is the question explored in this section through a simple forecasting experiment. The goal here is to compare the predictive contents of the three output gap measures discussed above in terms of forecasting headline inflation.

Following the literature (Orphanides & Norden, 2005; Pichette, Robitaille, Salameh, & St-Amant, 2019), consider a simple linear forecasting models of the form:

$$\pi_t^h = \delta + \sum_{i=1}^{m} \lambda_i \, \pi_{t-i}^1 + \sum_{i=1}^{n} \psi_i \, \hat{y}_{t-i} + \varepsilon_{t+h} \tag{4.28}$$

where δ is a constant, $\pi_t^h = \log P_t - \log P_{t-h}$ is inflation over *h* periods ending in t and P is the consumer price index[17]. Due to the very small sample size[18], the model is estimated with a single lag (m). An extended version of (4.28) that includes a rescaled output gap instead of the standard measure is also estimated. This is consistent with the Phillips curve in equation (4.18). The rescaled output gap constructed as the product of inflation and the output gap. To serve as a benchmark for comparison with the model-based output gaps, an autoregressive (AR1) model that omits the output gap or the rescaled output gap is estimated:

$$\pi_t^h = \delta + \sum_{i=1}^{m} \lambda_i \, \pi_{t-i}^1 + \varepsilon_{t+h} \tag{4.29}$$

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[17] The headline personal consumption expenditure (PCE) is used in the case of the United States and headline CPI (excluding the 1999-2000 interest and tax changes) for Australia.

[18] Statistical reference drawn from small samples can be improved with the use of Bootstrapped standard errors (Gonçalves and White, 2005). The standard errors were bootstrapped with 10,000 repetitions on the OLS estimation of equations (28) and (29).

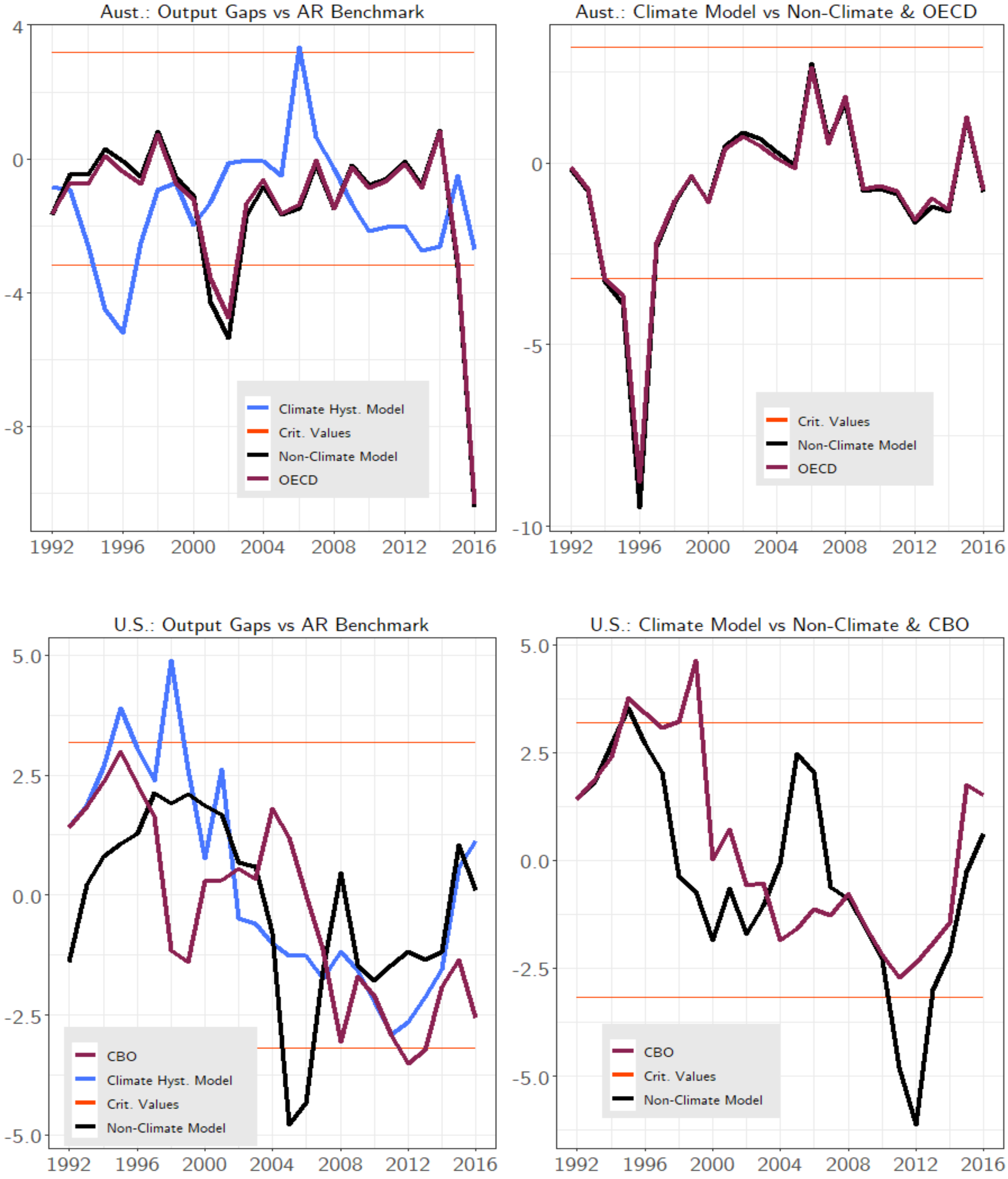
Standard conventional forecast comparison tests, including the Diebold-Mariano test (Diebold & Mariano, 1995), are not appropriate here since the AR benchmark is nested within the output gap models. Also, considering that standard tests for nested models, including the Clark-McCracken's tests (Clark & McCracken, 2001, 2009), are based on global forecast performance over a given sample period without accounting for any possibility of change in the relative forecasting performance of two models over time as evidence suggests (Stock & Watson, 2003a), the Fluctuation Test by Giacomini and Rossi (2010) is employed in this paper. The Giacomini- Rossi's Fluctuation Test was designed to specifically account for time-varying instability in relative forecast performance (See Appendix A.4 for summary details of the Fluctuation Test). This is particularly useful for relative forecasts evaluations in the current paper since the competing output gap measures seem to follow divergent paths over some time period, before converging again over another time period. In this context, the relative underlying demand pressures and the associated inflation dynamics may differ across the competing output gap models over time. Hence, the need for forecast comparisons based on a test that account for such instability and fluctuations, for models that are nested or otherwise.

As a common practice in the literature, the Mean Squared Forecast Error (MSFE) is used as the loss function in comparing the predictive performance of the models for the Fluctuation Test. Using inflation and output gap data over the period 1985-2016, the models are estimated and used for one-year-ahead out-of-sample forecasting beginning in 1992, with a window size of six years. Note that considering the very small sample size, this exercise is largely illustrative, and these results must be interpreted with caution. Another shortcoming of the forecasting exercise is the fact that only final data is used without comparing the outcomes when real-time data is used to inform policy. The use of final data means that forecast errors due to data revisions are not evaluated here.

Figure 4.6 plots the 2-sided Fluctuation Test results comparing the relative forecast performance of the output gap model and the naïve AR benchmark (the left graph for each country) as well as relative forecast performance of the climate model against the non-climate output gaps (the right graph for each country). In the case of Australia, the null hypothesis of equal forecast performance is rejected against the alternative that the output gap models produce statistically significant and better inflation forecast than the AR benchmark since the values of the test statistic fall below the negative critical value lines. For the climate hysteresis output gap, this is especially so during the period 1996-95, and during 2001-2002 for the non-climate output gaps. Climate shocks seem to contain predictive contents for forecasting inflation in the case of Australia, largely indicative of the fact that compared with the non-climate output gaps, the climate hysteresis output gap also shows better and statistically significant forecast performance, especially during 1994-1996.

In the case of the United States, the forecast performances of the respective output gap estimates relative to the AR benchmark are mixed. While the non-climate output gap estimates prove to be more predictive and statistically outperform the naïve AR benchmark in terms of forecasting PCE inflation (especially during 2005-2013), the AR benchmark statistically outperforms the climate model, especially during 1995-1998. Similarly, the forecast performance of the climate hysteresis output gap compared with the other gap estimates is mixed. While the climate model shows better and statistically significant forecast performance during 2011-2012, the opposite is true during 1995-1999.

Figure 4.6. Evaluation: Output Gaps vs AR Benchmark Inflation Forecasts



Source: Author's calculations.

Note: The figure reports the 2-sided Giacomini-Rossi (2010) rolling-window fluctuation test statistic for the output gap models (28) against the AR benchmark at 5% level of significance. For each country, the first graph (Left) compares the output gap models with the AR benchmark while the second (Right) compares the Climate-hysteresis model output gap inflation forecast with forecasts based on the non-climate model and official estimates. When the estimated test statistic is below the negative critical value line, then the respective output gap measure forecasts significantly better than the benchmark. When it is above the positive critical value line, then the AR benchmark significantly outperforms the output gap model's forecast. The climate hysteresis model performs significantly better than the other output gap estimates when the test statistic falls below the negative critical value line for graphs on the right, and vice versa.

The introduction of the rescaled output gaps produces similar relative inflation forecast performance for with marked improvement in the climate model's inflation forecast performance in the case of the United States, especially during the GFC (see Appendix Figure 4B). The unstable and changing nature of the relative information forecast performances of the various output gap measures largely relate to the different unemployment and output gap magnitudes estimated under each model. For example, the climate hysteresis model with smaller output and unemployment gaps is associated with less disinflationary pressure during a downturn, since the gap between current demand conditions and the potential supply capacity is less.

4.6 Conclusion

This paper has examined the effects of persistent climate-induced weather shocks on potential output and NAIRU as well as the associated output and unemployment gaps. To inform the incorporation of climate hysteresis effects into the model, the modelling began with a simulation experiment based on a standard Cobb-Douglas production function with firms facing quadratic adjustment costs in responding to deviation of potential labor supply from steady state. Consistent with the recent literature, the modelling approach followed two steps. First, climate-induced weather shocks were embedded into the estimation of *climate-neutral* output gaps. Second, the climate-neutral output gaps were then incorporated in the estimation of NAIRU, with climate shocks and their hysteresis effects modelled to persist for up to four years.

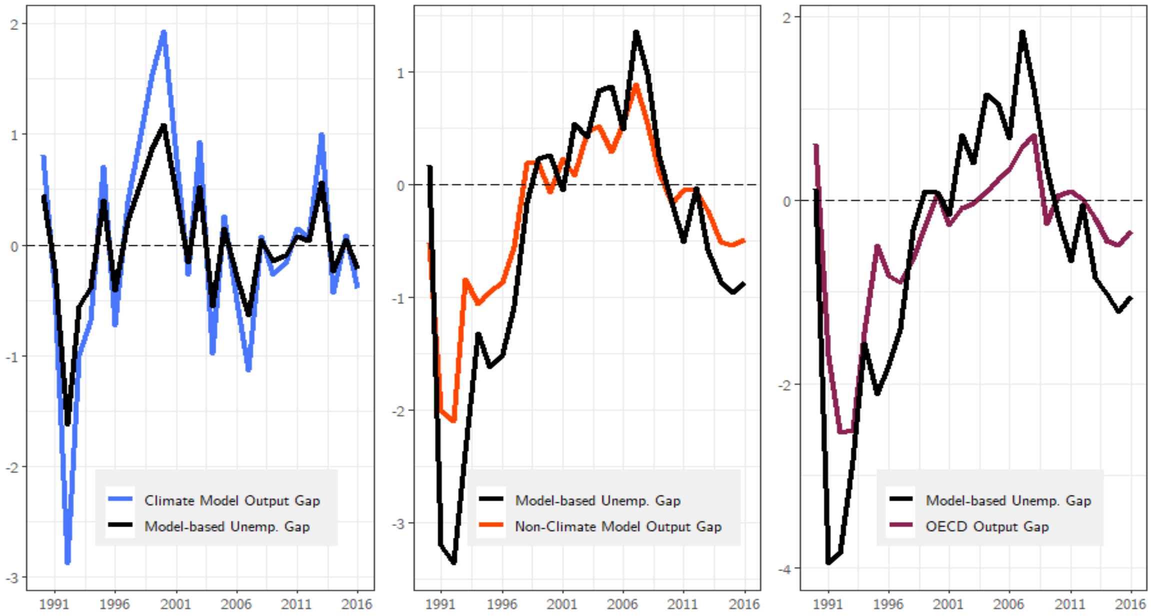
The results suggest that macroeconomic slacks are smaller when both actual conditions and potential supply capacity are modelled to change simultaneously, with recessions that may be less disinflationary, and booms that may be less inflationary. In a world characterized by persistent climatic disruptions, measures of potential output and the output gap that do not account for these structural disruptions would create problems for maintaining macroeconomic stability.

First, the size of the business cycle would be repeatedly overstated under the assumption that rapidly changing demand conditions fluctuate around a relatively stable trend growth. Second, because of maintaining relatively stable goal posts regarding potential growth in a structurally disrupted environment, the mistaken signals from demand pressure may create policy-induced shocks to the economy. All else equal, a large negative output gap would imply a more accommodative monetary policy stance, a move that may create excess demand pressure and financial stability risks if the output gap was much smaller due to structural disruptions that are persistently weakening potential supply capacity but whose effects are not engendered into policymaking.

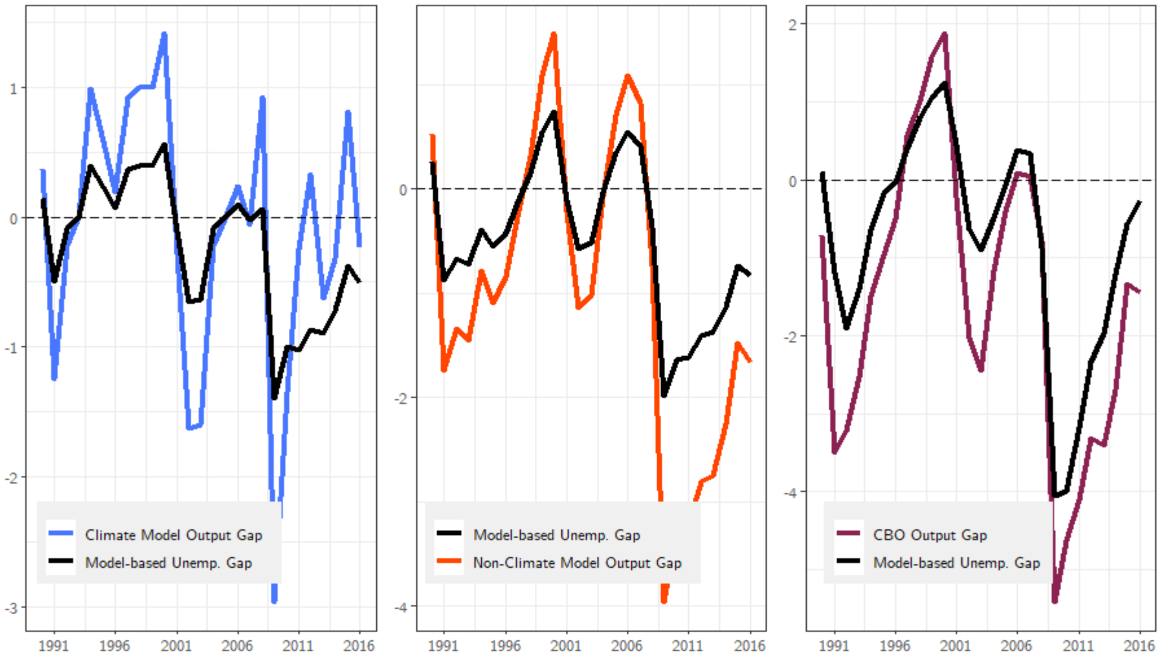
4.7 Appendix

Figure 4.7A. Model-based Output and Unemployment Gaps Estimates (Percent)

Australia

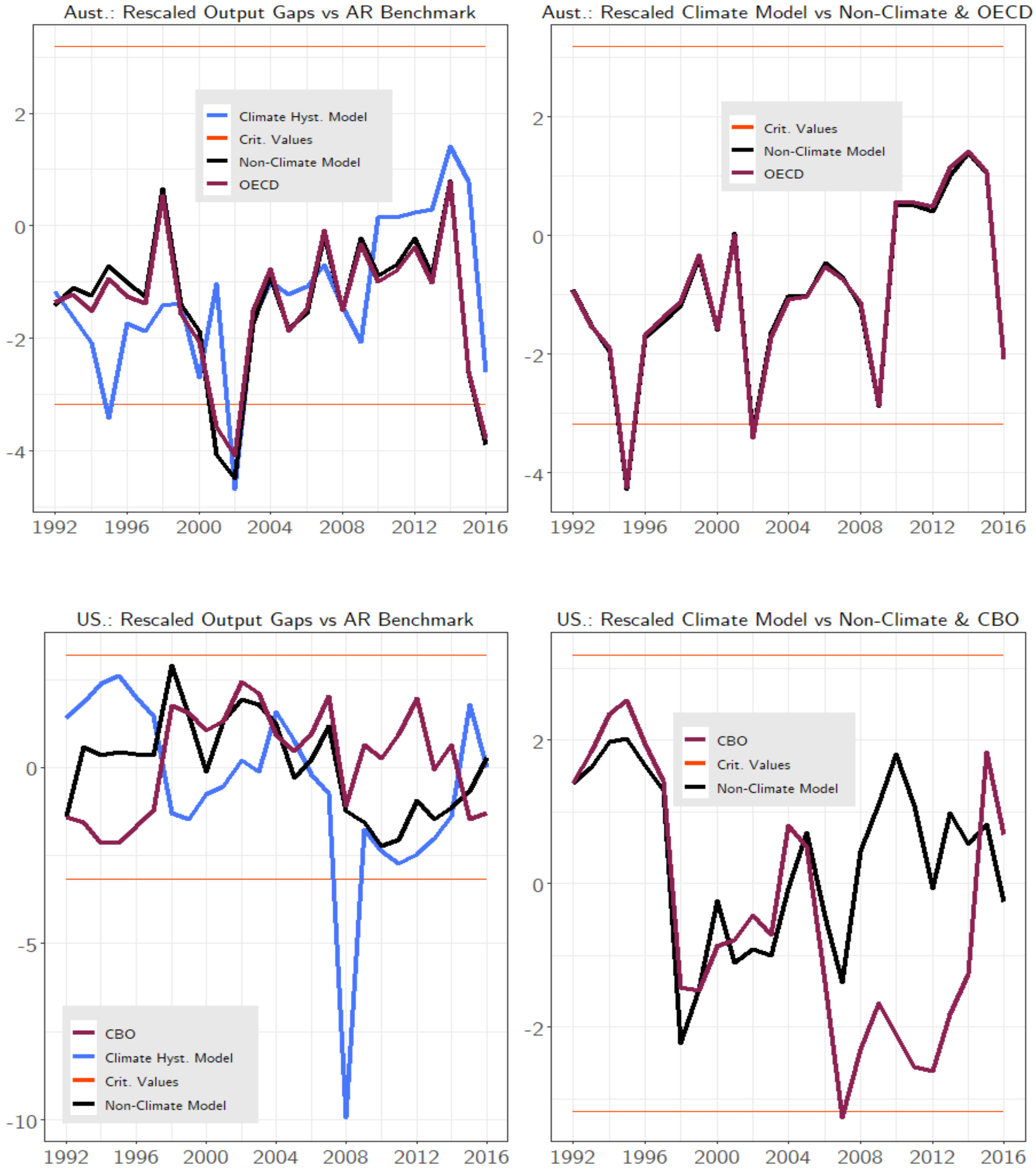


United States



Source: Author's calculations; OECD and CBO data.
Note: Each figure plots the model-based output gap and the unemployment gap computed based on that model's estimated NAIRU.

Figure 4.8B. Evaluation: Rescaled Output Gaps vs AR Benchmark Inflation Forecasts



Source: Author's calculations.
Note: The figure reports the 2-sided Giacomini-Rossi's rolling-window fluctuation test statistic for the rescaled output gap models against the AR(1) benchmark at 5% level of significance. For each country, the first graph (Left) compares the rescaled output gap models with the AR benchmark while the second (Right) compares the rescaled Climate-hysteresis model output gap inflation forecast with forecasts based on the other rescaled output gap estimates. When the estimated test statistic is below the negative critical value line, then the respective output gap measure forecasts significantly better than the benchmark. When it is above the positive critical value line, then the AR(1) benchmark significantly outperforms that output gap model's forecast. The climate hysteresis model performs significantly better than the other output gap estimates when the test statistic falls below the negative critical value line for graphs on the right, and vice versa.

Table 4.1A. Bayesian Priors

	Australia				United States			
	Mode		Standard Error		Mode		Standard Error	
	Prior	Posterior	Prior	Posterior	Prior	Posterior	Prior	Posterior
$\boldsymbol{\eta}$	0.700	0.712	0.210	0.027	0.700	0.651	0.210	0.018
$\boldsymbol{\theta}$	0.153	0.141	0.007	0.058	0.290	0.311	0.007	0.067
$\boldsymbol{\phi_1}$	0.600	0.570	0.020	0.017	0.671	0.635	0.020	0.016
$\boldsymbol{\phi_3}$	0.300	0.323	0.091	0.027	0.300	0.319	0.091	0.022
$\boldsymbol{\phi_4}$	0.800	0.822	0.241	0.025	0.800	0.812	0.240	0.021
$\boldsymbol{\varpi}$	--	0.463	--	0.033	--	0.455	--	0.030
$\boldsymbol{\lambda_1}$	0.250	0.377	0.003	0.003	0.410	0.409	0.001	0.001
$\boldsymbol{\lambda_2}$	0.082	0.093	0.002	0.001	0.082	0.088	0.002	0.001
$\boldsymbol{\tau_4}$	0.100	0.131	0.030	0.017	0.120	0.126	0.036	0.016
$\boldsymbol{\tau_3}$	0.880	0.890	0.004	0.003	0.880	0.875	0.004	0.004
$\boldsymbol{\tau_2}$	0.400	0.435	0.120	0.03	0.407	0.418	0.122	0.025
$\boldsymbol{\tau_1}$	0.350	0.451	0.150	0.03	0.521	0.507	0.156	0.028
$\boldsymbol{\delta_1}$	0.100	0.109	0.025	0.017	0.100	0.105	0.104	0.017
$\boldsymbol{\delta_2}$	0.200	0.210	0.060	0.018	0.200	0.199	0.060	0.016
$\boldsymbol{\kappa_1}$	2.167	2.153	0.585	0.053	2.167	2.147	0.585	0.048

Source: Author's estimates

Note: The use of (--) for parameters that were diffusedly initialized within the Kalman filter.

Table 4.2B. Data Sources

Indicator	Sources
SPEI	Global SPEI database (based on monthly climate data from the Climatic Research Unit of the University of East Anglia)
Inflation Rate	CPI: Reserve Bank of Australia. PCE: US Bureau of Economic Analysis
Unemployment Rate	Australian Bureau of Statistics U.S Bureau of Labor Statistics
Capacity Utilization *Australia: Manuf. Production Index* *US: Manuf. Cap. Utilization Index*	OECD (for Australia) U.S. Federal Reserve
Real Gross Domestic Product	Australian Bureau of Statistics US Bureau of Economic Analysis
Official Output Gap Statistics	OECD; CBO

4.7.1 Climate Index

4.7.1.1 The Standardized Precipitation Evapotranspiration Index (SPEI)

Despite its multitemporal nature, the lack of temperature and changes in evapotranspiration in determining drought conditions is a key weakness of the widely used standardized precipitation index (SPI). Developed by Vicente-Serrano et al (2010), the SPEI improves on the SPI with the inclusion of evapotranspiration. For a given month i, the SPEI is computed, based on the Thornthwaite method (Thornthwaite, 1948) as the difference precipitation (P_i) and potential evapotranspiration (PET_i)

$$D_i = P_i - PET_i \tag{4.30}$$

where the difference, D_i, captures the water balance (deficit or surplus) for month i. At a given time scale k (3, 6 or 12 months), the aggregated water balance, D_n^k is the sum of D_i before the current month, n^{th}

$$D_n^k = \sum_{i=0}^{k-1} (P_{n-i} - PET_{n-i}), \quad n \geq k \tag{4.31}$$

To ensure comparability across space and time according to the heterogeneity in climatic conditions between and within countries, the D_n^k series at different time scales are fitted to a probability distribution. Extremity in weather conditions is accounted for by adjusting the distribution of the D_n^k using a density function of log-logistic probability:

$$f(x) = \frac{\omega}{\theta}\left(\frac{x-\mu}{\theta}\right)^{\omega-1}\left(1+\left(\frac{x-\mu}{\theta}\right)^{\omega}\right)^{-2} \tag{4.32}$$

where the parameters θ, ω and μ represent the scale, shape, and origin for the D_n^k series in the range $(\mu > D < \infty)$. With $f(x)$ transformed into a normalized random variable, the value of the SPEI is bounded between -3 and 3. Annual SPEI values are obtained by averaging the 12-monthly series of each year over the period 1980-2016. To capture climatic conditions specific to a particular country (Australia and United States in this paper), the 12-month SPI and SPEI averaging is done across grid cells that overlap a country's cropland areas, following the literature (see Couharde et al, 2019).

Note that since the 12-month SPEI values are obtained by averaging values over shorter time periods, non-zero SPEI values at the 12-month scale (or longer) will indicate persistent underlying weather anomalies over time.

Table 4.3C. SPEI Drought Classification

SPEI > 2	Exceptionally moist
1.60 < SPEI < 1.99	Extremely moist
1.30 < SPEI < 1.59	Very moist
0.80 < SPEI < 1.29	Moderately moist
0.51 < SPEI < 0.79	Slightly moist
0.50 < SPEI < 0.50	Near normal conditions
0.79 < SPEI < 0.51	Slightly dry
1.29 < SPEI < 0.80	Moderately dry
1.59 < SPEI < 1.30	Very dry
1.99 < SPEI < 1.60	Extremely dry
SPEI < 2	Exceptionally dry

Source: NOAA's National Centres for Environmental Information

Note that while the SPEI is primarily a drought classification index, the two key components—temperature and precipitation—and the multi-scalar nature of the SPEI values make the index ideal for examining the broader effects of global warming beyond the effects of drought. For example, an extreme drought may be due to a combination of persistent rise in temperature and acutely low precipitation (rainfall) over a prolong period, two phenomena that are found in the climate-economy literature to have devastating effects on economic growth. Apart from the temperature effects of labour productivity and capital depreciation, droughts are found to have more persistent growth effects than other climate-induced natural disasters (Fomby et al., 2013).

4.7.2 Giacomini-Rossi Fluctuation Test

Based on a chosen general loss function, $L(.)$, (like the standard Mean Square Forecast Error—MSFE), the Giacomini-Rossi's (Giacomini and Rossi, 2010) Fluctuation Test compares the relative forecasting performance of two competing models over time for sequences of R in-sample and P out-of-sample loss differences computed over the rolling windows of size *m* as:

$$m^{-1} \sum_{j=t-\frac{m}{2}}^{t+\frac{m}{2}-1} \Delta L_j\left(\theta_{j-h,R}, \gamma_{j-h,R}\right), t = R+h+\frac{m}{2}, \ldots, T-\frac{m}{2}+1 \qquad (4.30)$$

Provided the following assumptions hold,

i. $\left\{P^{-\frac{1}{2}} \sum_{t=R+h}^{R+h+[\tau P]} \Delta L_t\left(\theta_{t-h,R}, \gamma_{t-h,R}\right)\right\}$ follows the Central Limit Theorem

ii. $\sigma^2 = \lim_{P \to \infty} E\left(P^{-\frac{1}{2}} \sum_{t=R+h}^{T} \Delta L_t\left(\theta_{t-h,R}, \gamma_{t-h,R}\right)\right)^2 > 0$

iii. $\frac{m}{P} \to \mu \in \ 0, \infty$ as $m \to \infty$, $P \to \infty$, whereas $R < \infty, h < \infty$

then the null hypothesis of equal predictive forecast performance at each point in time (not over the global sample period as in conventional tests) becomes:

$$H_0 \colon E\left[\Delta L_t\left(\theta_{j-h,R}, \gamma_{j-h,R}\right)\right] = 0$$

where the two-sided alternative is

$$E\left[\Delta L_t\left(\theta_{j-h,R}, \gamma_{j-h,R}\right)\right] \neq 0$$

Under the two-sided alternative, the Fluctuation Test Statistic is the largest value over the sequence of the relative forecast error losses is

$$F_{t,m}^{\mathrm{OOS}} = \sigma^{-1} m^{-\frac{1}{2}} \sum_{j=t-\frac{m}{2}}^{t+\frac{m}{2}-1} \Delta L_j\left(\theta_{j-h,R}, \gamma_{j-h,R}\right)$$

where $\hat{\sigma}$ is a heteroskedasticity- and autocorrelation-consistent (HAC) estimator (Newey and West, 1987) of the long-run variance of the loss differences.

The null hypothesis is rejected against the two-sided alternative,

$$E\Big[\Delta L_t\Big(\theta_{j-h,R}, \gamma_{j-h,R}\Big)\Big] \neq 0,$$

when

$$\max\left|F_{t,m}^{\mathrm{OOS}}\right| > k_\alpha$$

where the critical value, k_α is contingent upon the choice of the size of the rolling window relative to the number of out-of-sample loss differences *P*, or formally, *m* = *[μP].*

Chapter 5

5. Climate Change and Monetary Policy: Issues for Policy Design and Modelling

Abstract

This paper explores the interaction of monetary policy and climate change as they jointly influence macroeconomic outcomes, connecting policy and outcomes in each realm to the implications of the other. It also explores the nature of the macroeconomic model that would be required to explore the links between monetary policy and climate policy. The paper has four parts. First, it reviews the relevant macroeconomic outcomes of emissions mitigation policy and climatic disruption, exploring how negative supply shocks can affect central banks' ability to forecast and manage inflation. Second, the paper reviews basic approaches to monetary policy, including inflation and output targeting, and other responsibilities that may fall to central bankers. Third, we bring together the two sets of issues to consider the appropriate monetary framework in a carbon-constrained and climatically disrupted world and to highlight the climate policy frameworks that can make monetary policies more efficient and effective. We then summarize the nature of the macroeconomic modelling framework that is needed to better analyze climate and monetary policy interactions. We conclude that policy responses to climate change can have important implications for monetary policy and vice versa and that, in light of the urgency of ambitious climate action, these policy spheres should be brought together more explicitly and more appropriate macroeconomic modelling frameworks developed.

5.1 Introduction

This paper explores the interaction of climate change and monetary policy as they jointly influence macroeconomic outcomes (McKibbin *et al.*, 2017). It also outlines the features of macroeconomic models that policymakers will need to evaluate climate and monetary policies and their interaction. In bringing together the literature on climate change and monetary policy, we seek to alert policymakers in each realm to the implications of the other. The challenge that closely connects climate change and monetary policy is the potential for and response to economic 'shocks'. These are abrupt events that increase or decrease the demands for goods and services (demand shocks) or increase or decrease the supply or cost of goods and services (supply shocks).

Aggregate shocks—those that apply to goods and services generally rather than any specific sector—can be temporary or involve more permanent changes in the economy. One can think of the impacts of climatic disruption and ambitious climate policy as both demand and supply shocks, some aspects of which would be transitory and some of which would be permanent. For example, extreme weather events and sea-level rise can result in damages to crops, flooding of major cities and industrial areas, coastal erosion that destroys property and physical plant, extensive power outages, infrastructure damage, and the dislocation of workers. These are all negative supply shocks. Spikes in crop prices might be temporary, but sea level rise may permanently destroy productive coastal land. An abrupt and stringent constraint on greenhouse gas (GHG) emissions can permanently increase the prices of fossil fuels, but the degree to which it makes existing capital uneconomic is transitory. Climate events whose effects may appear to be only temporary may affect long-term output as the destruction of capital may affect the growth rate of potential output via hysteresis channels.

Most research on the links between climate change and monetary policy has focused on the financial stability implications of climate change and the transition risks associated with climate policy actions. There is a distinction made between climate-induced physical risks (increased frequency and severity of climate-induced natural disasters) and transition risks (negative supply shocks from climate policy) (Carney, 2015; Batten *et al.*, 2016).

Increased frequency and severity of climate-induced catastrophic events may affect the pace or magnitude of capital replacement, with evidence that high insurance claims (Bank of England, 2015) and falling housing prices (Boustan *et al.*, 2020) following natural disasters pose serious risks to financial stability. Some of the serious risk factors for stability of the financial system following severe or persistent climatic disruptions include declines in private financial flows (Yan, 2008); weak households and firms' balance sheets (Batten *et al.*, 2019); increased permanent risk-aversion tendencies following exposures to natural disasters or climatic variations (Cameron and Shah, 2013) and increased legal risks (NGFS, 2019).

The transition to a low-carbon economy also poses risks to the financial system, particularly in the form of losses associated with stranded capital and lower future profit prospects from carbon-intensive investments (NGFS, 2019). The magnitude of such losses is a function of the extent to which the policy is orderly and efficient, along with the market characteristics of different industries and the relevant demand and supply elasticities. Our focus is on the interaction between climate policy and the design of monetary frameworks in the face of different climate policies.

We proceed in six parts. First, the paper reviews basic emissions-mitigation policy options and the different ways in which they can impact output, relative prices of particular goods, and overall price levels. It also reflects on how the manifestations of climatic disruption can impact prices and output levels. Such outcomes can affect central banks' ability to forecast and manage inflation. Second, we briefly review the basic approaches to monetary policy, including various types of inflation and output targeting rules. We also outline some other responsibilities that may fall to central bankers related to legal differences across jurisdictions. Third, we bring together the two sets of issues to consider the optimal monetary framework in a carbon-constrained and climatically disrupted world and to highlight the climate policy frameworks that can make monetary policies more efficient and effective.

A core message of this paper is that policy responses to climate change can have important implications for monetary policy and vice versa. Different approaches to imposing a price on carbon will impact energy and other prices differently; some would provide stable and predictable price outcomes, and others could be more volatile. All else equal, more volatile prices pose greater challenges to central bank authorities than more predictable prices, in part because they complicate the forecasting of inflation and other economic variables that central banks use to benchmark their policies. Similarly, ambitious climate policy can affect output, both in aggregate and disproportionately in select emissions-intensive sectors. Policies that are the least costly and most predictable can minimize the extent to which monetary policymakers must anticipate their effects in their overall stewardship of the macroeconomy.

Likewise, monetary policy could have important impacts on the macroeconomic outcomes of emissions abatement policy and extreme weather events. For instance, if continuously rising prices from carbon policy induce the central bank to raise interest rates to slow inflation, this would exacerbate the fall in overall economic activity from the carbon policy—thus lowering gross domestic production (GDP), employment, and welfare relative to other ways a central bank could react. The political backlash from such macroeconomic outcomes may create fewer incentives for political actions on emissions reduction. Second, a sustained rise in the relative price of carbon could enter into wage negotiations, for example, if workers anticipate a decline in the buying power of their earnings, even if carbon-tax revenues are recycled. In this case, an inappropriate monetary policy response could lead to a wage–price spiral as people find it harder to forecast inflation and therefore lose an important anchor for inflation expectations. Untethered inflation expectations could lead to a costly long-lived inflationary process. Thus, in light of the urgency of ambitious climate action and the clear conceptual relationship between the policy frameworks, we argue that monetary and climate policy should be considered jointly.

From a monetary perspective, climate change and climate policy are both supply and demand shocks, and the monetary policy literature has long emphasized the importance of supply shocks versus demand shocks in the choice of a monetary regime. Thus, the insights from this large historical literature can inform the climate/monetary policy discussion of today. In a world characterized by continual climatic disruptions, especially on the supply side, the need for rethinking the monetary policy framework in the context of how to price carbon is high.

Given the theoretical discussion, we then outline the key features needed in economy-wide macroeconomic models for policymakers, that would enable an analysis of climate and monetary regimes and their interaction. We then present an overview of G-Cubed, a model that has these features. Finally, in section VI we present results from G-Cubed to show how three different monetary regimes lead to different inflation, output, and emission outcomes under a carbon tax.

5.2 Climate policy

In this section, we discuss basic options for GHG emissions mitigation policy, which fall broadly into two categories: (1) establishing an explicit, economy-wide price for emitting carbon dioxide (CO_2), or (2) adopting a suite of regulatory measures and subsidies. Any of these approaches can impose burdens on the economy, but they also provide environmental benefits that can justify their costs. Although we focus here on the economic costs of climate policy, we emphasize that important positive net benefits can accrue from efficiently controlling GHG emissions and reducing the risks of climatic disruption and ocean acidification. Hepburn (2006) provides a complete discussion of the choice of climate policy instruments. Here we focus on the design details of these approaches that have different implications for monetary policy.

5.2.1 Carbon pricing

Economists widely agree that the most efficient approach to reducing GHG emissions is to establish a price on those emissions. Policymakers can set the price directly on fossil-fuel-related CO_2, the largest constituent of overall GHG emissions, and several other GHG emissions via a tax. For fossil CO_2, the tax could fall on the carbon content of fossil fuels or the CO_2 emitted from burning fuels. Alternatively, policymakers can impose a price indirectly through a tradable permit system, or through a hybrid policy that has a mix of the characteristics of tax and permit programmes.

5.2.1.1 Carbon taxes

A carbon tax is the most direct and transparent approach for establishing a price on carbon emissions. Policymakers have many options for the design of a carbon tax trajectory and the related provisions of the policy, including the use of the revenue. For example, the tax could be set equal to an estimate of the marginal social cost of carbon (SCC) which would internalize the externalities associated with climate change. The tax could be designed to achieve particular emissions or revenue goals. A typical proposal would set a starting value for the tax and specify a rate at which the tax should rise over time in real terms. The magnitude of the carbon tax can depend on the emissions goal and, importantly, when the policy starts.

A carbon tax has three key features that matter for the monetary authority: (i) the trajectory of the tax is known in advance; (ii) there will be a significant initial impact on the price level when the tax is first established; and (iii) the growth of the tax in real terms over time will introduce an upward trend in prices and, other things equal, push the economy toward a higher overall rate of inflation—at least through the medium run. Also, although a carbon tax establishes a predictable price, its impact on emissions will vary from year to year with economic conditions, technological change, and other factors.

Research has shown that the ultimate economic impact of a carbon tax depends on the use of the revenue that it raises.

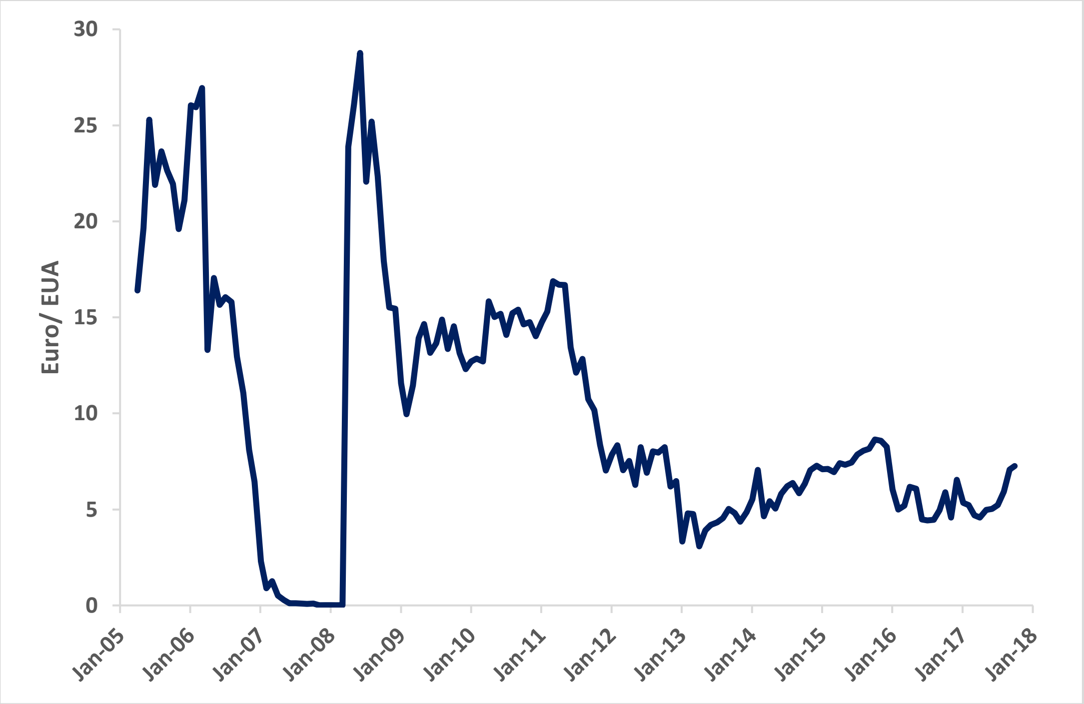
For example, reducing marginal rates on other taxes, such as those on labour and capital, can reduce the existing distortions in those markets and thus offset some of the macroeconomic burdens of the carbon tax (Pearce, 1991; Metcalf, 2007). McKibbin *et al.* (2012) find that using carbon-tax generated revenue to offset capital income tax burdens leads to a more pro-growth effect of a carbon tax on the US economy. In contrast, Metcalf (2007) and Perry and Williams (2011) find that using the revenues to reduce labour taxes generates higher welfare gains than when used to reduce capital taxes. Although there is no empirical consensus on the optimal use of the tax revenues, there is a strong consensus that carbon tax policies whose revenues are recycled efficiently can promote emissions abatement at lowest cost. (McKibbin *et al.* 2015; Liu *et al.* 2020). The policies can also have importantly different distributional consequences.

5.2.1.2 Tradable permits

An alternative way to limit GHG emissions would be to establish a system of tradable emissions permits. For example, a regulator could require fossil fuel producers or users to have a permit for each metric ton of CO_2 emissions that would be associated with those fuels. The regulator would then choose a target level of emissions for each year, issue that number of permits (a range of mechanisms for distributing permits are discussed in the literature) and allow trading. To emit a ton of CO_2, a fuel user would need to buy a permit at the market price (or would have to forgo selling a permit at that price), so the market price would become the *de facto* price of emitting CO_2. This approach establishes a predictable level of emissions. With a fixed supply of permits (assuming no banking or borrowing across compliance periods), any change in the demand for permits, such as fluctuations in economic conditions, will cause the carbon price to vary from year to year along a vertical supply curve for permits. Thus, from the perspective of the monetary authority, this approach is quite different from a carbon tax because the number of permits (and hence the level of emissions) in each future year may be known in advance. The initial price would not be known in advance and would be determined by market forces after the implementation of the policy. Finally, the rate of growth of the price would be determined by market forces as well.

Both the implementation of the policy and business-cycle shifts can greatly influence the level and volatility of permit prices in a cap-and-trade system. For example, the programme can allow banking and borrowing of emissions allowances across compliance periods or establish a floor and ceiling on permit prices (Fell *et al.*, 2012). To illustrate the potential volatility of emissions permit prices in practice, Figure 5.1 reports the history of the futures prices of the emissions allowances in the European Union's Emissions Trading System (ETS). Some of the factors that contributed to the volatility included an inadvertent oversupply of allowances in the early phases of the programme and a major financial and economic crisis in 2008 that dramatically reduced demand for allowances.

Figure 5.1. The futures price of allowances in the EU ETS from January 2005 to October 2017



Notes: Unit of trading: one lot of 1,000 Emission Allowances. Each Emission Allowance is an entitlement to emit one metric ton of CO_2 equivalent gas. Contract series: consecutive contract months to March 2008, and then December contract months only from December 2008 to December 2012.

Source: Bloomberg.

5.2.1.3 Hybrid policies

A third approach would be a hybrid of the tax and permit policies. McKibbin and Wilcoxen (2002) develop such a policy. This approach is analogous to how the US Federal Reserve (the Fed) sets short-term interest rates while the bond market sets the long-term interest rate through market transactions (McKibbin, 2012). In this policy, the cumulative emissions target for a country is used to determine a declining annual flow of emissions which achieves the target at a specified date in the future. Each year's desired annual emissions level is used to determine a matching annual quantity of emission permits. These annual permits are then combined to create a long-term emissions bond, where the annual coupons on the bond are the annual emission permits. The allocation of these long-term bonds to current individuals and firms should be undertaken at the beginning of the programme. An agency that might be called a 'central bank of carbon' then announces a short-term maximum carbon price, or price ceiling for the current year or several years into the future. Fixing the short-term carbon price is much like the approach of the Fed which announces a short-term interest rate. In the current year, the central bank of carbon makes available as many annual permits as demanded at the ceiling price, effectively capping the price of carbon in that year. If a small number of long-term permits are made available in the early years of the policy, then the short-term carbon price cap will always be binding unless there is a substantial reduction in emission at low cost.

The long-term price of carbon, however, will be determined in the futures market for carbon emission rights available in future years (much like the long-term bond market determines long-term interest rates). In the market for future emission rights, the carbon targets are balanced against expectations of future short-term prices, where each year's expectation is either the market equilibrium price in that year or the ceiling price set by the agency, whichever is lower. Thus, the short-term price is equivalent to a carbon tax (when the cap is binding, which is likely if few long-term permits are issued), but the long-term price is determined by future cap and trade markets.

In terms of its impact on monetary policy, a hybrid policy would be midway between standard tax or permit policies. It would: (i) establish a ceiling price trajectory known in advance; but (ii) allow actual prices to be lower than the ceiling when market conditions warrant; and (iii) allow variation in emissions from year to year.

5.2.2 Non-price emissions abatement policies

Although pricing carbon and other GHGs has many attractive features, a number of other climate policies have been proposed. For example, the US Environmental Protection Agency (EPA) drafted the Clean Power Plan as a regulatory approach to reducing emissions from the electric sector. Under that regulation, states were required to achieve specified targets for average CO_2 emissions per kilowatt-hour of electricity generated from existing power plants (they could also opt instead to achieve a target having an equivalent mass of CO_2). Other policies aimed at reducing emissions include tighter fuel efficiency standards for vehicles; production and investment tax credits for renewable electricity; renewable portfolio standards for electric utilities; and tax credits for a range of goods such as residential solar systems, electric vehicles, and home and business weatherization.

At their core, these policies impose implicit prices on the use of fossil fuels because they impose a cost or monetary incentive on incremental emissions-reducing activities. However, unlike the explicit carbon pricing policies discussed above, the prices are not directly observable, differ from one sector and state to the next, and do not have clear predictable trajectories. They are also likely to yield higher carbon abatement costs because of the nature of the policy. As a result, accounting for them in setting monetary policy is far more difficult. For example, a regulatory approach like the Clean Power Plan can raise electricity prices by amounts that are hard to predict and differ significantly across the country owing to regional variations in stringency and implementation strategy.

5.2.3 Policy impacts

Whether implemented as a broad-based emissions price or as a suite of narrower actions, a carbon abatement policy affects the economy in two ways. First, it increases production costs and the relative prices of carbon-intensive goods and services, negatively affecting real wages, consumption, investment, and, ultimately, output. Second, the policy may exacerbate the distortionary effects of existing taxes in the economy, particularly in the labour market. This occurs because existing taxes on labour income reduce the incentive to work by reducing the returns to labour. A carbon tax raises price levels, thereby lowering the real wage, further decreasing the incentive to work and exacerbating the existing distortions in the labour market. This 'tax interaction effect' is potentially quite large, suggesting the benefits of using the carbon tax revenue to reduce other tax rates may be significant. Indeed, modelling has supported this finding (McKibbin *et al.*, 2012).

Although each climate regime can be designed to achieve the same emissions target at the same point in time, the various climate policy frameworks can produce different inflation and output dynamics. In particular, it is this that matters for the short-run response of monetary policy.

5.3 Monetary policy

How the objectives of monetary policy—price stability and employment expansion—are achieved for any economy depends on many factors, notably the structure of the economy and the nature of macroeconomic shocks to which the economy is susceptible. While the broad macroeconomic stability experienced throughout the 'Great Moderation' may have partly been explained by the introduction of inflation targeting across much of the developed world, the global financial crisis (GFC) and the ensuing Great Recession have reignited the longstanding debate (see Meade, 1978; Henderson and McKibbin, 1993; Taylor, 1993) on the optimal monetary policy framework. Among the leading central banks, the search for the optimal framework suitable for the rapidly changing economy is ongoing (Bernanke, 2017; Clarida, 2019).

Towards such an end, the recent literature has compared macroeconomic performance under inflation targeting with counterfactual outcomes under two main rules: price-level targeting and nominal income targeting. In this section, we provide a summary of these rules (see McKibbin and Panton (2018); Svensson, (2020)).

5.3.1 Inflation targeting

Typically, inflation targeting involves making discretionary decisions on how to respond *flexibly* to the deviations of inflation from target and output (or employment) from the long-term target. Implementation of this framework requires the forecasting of the values of the relevant policy values (Svensson, 2020). This process is complicated by rapidly changing macroeconomic conditions in a climatically disrupted world.

In practice, inflation-targeting central banks must anticipate how the economy will adjust over future periods to a change in policy today (Bernanke *et al.*, 1999; Bernanke, 2007). An example appears in equation 5.1 below, used for setting the interest rate, where $\pi_{t,t+1}$ is the bank's forecast at time t of the inflation rate at time $t+1$ and $\bar{\pi}_t$ is its inflation target:

$$i_t = i_{t-1} + \alpha\,(\pi_{t,t+1} - \bar{\pi}_t) \tag{5.1}$$

This approach makes clear that an accurate forecast of inflation is critical to the central bank's success and credibility. And the key to that forecast is the measurement of the output gap: the difference between the actual and potential output[19] of the economy. For example, a forecasting rule might be that inflation will be the target rate adjusted by an increasing function f of the difference between real output of the economy, Y_t, and the central bank's assessment of the economy's maximum potential output, $\bar{Y}_t$:

$$\pi_{t,t+1} = \bar{\pi}_t + f(Y_t - \bar{Y}_t) \tag{5.2}$$

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[19] Potential output is the maximum sustainable output the economy could produce given: (i) optimal use of the economy's supplies of labour, capital, and other primary factors; and (ii) the levels of total and factor-specific productivity.

If the actual output is equal to potential output, the bank will expect inflation to be at its target rate $\bar{\pi}_t$. In contrast, if actual output is below potential output, then it will expect inflation to be lower than $\bar{\pi}_t$, and if the output is above potential output, then it will expect inflation above $\bar{\pi}_t$. However, both Y_t and $\bar{Y}_t$ are estimates and are inherently uncertain. Thus, the central bank may make errors in forecasting the output gap and thus use a poor forecast of inflation in its targeting strategy.

5.3.2 Price level targeting

Price level targeting (PLT) is similar to inflation targeting, but the target is the price level itself rather than the inflation rate. If there is a rise in inflation above target, the central bank not only acts to eliminate the excess inflation but induces a period of below-target inflation in order to return the price level to its target trajectory. In this sense, the initial price level casts a long shadow over the future path of prices. An example of setting central bank interest rates with PLT appears in equation 5.2, where the actual price level is P_t and the target level is $\bar{P}_t$:

$$i_t = i_{t-1} + \alpha\,(P_t - \bar{P}_t) \qquad (5.3)$$

With the core objective of maintaining the price level along the desired path by compensating for lower past inflation with higher current inflation, PLT is an effective policy rule for anchoring expectations as long as private agents correctly account for its implicit history dependence (Svensson, 1996). This requires that monetary policy is credible enough to be the main anchor of price expectations (Amano *et al.*, 2011). Under a binding zero lower bound (ZLB) constraint, Bernanke (2017) proposes a state-contingent temporary PLT framework that involves combining inflation targeting with price-level targeting. That is, via forward guidance, the central bank can commit to maintaining an accommodative policy stance following a deep recession until achieving average inflation, and employment targets. However, during normal times, monetary policy is conducted using inflation targeting, although switching the policy stance during recessions may render monetary policy less effective in anchoring expectations (Bodenstein *et al.*, 2019).

5.3.3 Henderson–McKibbin–Taylor Rules

In contrast to rules focused only on inflation or the price level, Henderson–McKibbin–Taylor (HMT) rules include an explicit balancing of a central bank's goals of price and output stability. Henderson and McKibbin (1993) outlined a general set of rules that specified the way in which interest rates could respond to both inflation and the output gap. This is shown in equation (5.4).

$$i_t = i_{t-1} + \alpha\,(\pi_t - \overline{\pi}_t) + \beta(Y_t - \bar{Y}_t) \qquad (5.4)$$

Parameters α and β govern how the central bank balances its goals for inflation and output. They can either reflect the preferences of policy-makers or could be calculated optimally given the structure of the economy.[20] They showed that these parameters are especially dependent on the stickiness of nominal wages, meaning the tendency of wages to respond slowly to changes in the performance of a company or the broader economy. Taylor (1993) used this general form of the rule and selected specific values of α and β to replicate the historical behaviour of the Fed between 1984 and 1992. Others have since econometrically estimated the parameters of the HMT rule for the Fed and found results close to Taylor's original calibration.

A more general HMT rule is implemented in the G-Cubed multi-country model (McKibbin and Wilcoxen, 2013). G-Cubed allows the modelling of a wide variety of central bank policy rules, including exchange rate targeting, money supply targeting, or a variety of explicit trade-offs between variables that reflect policies adopted by central banks in different countries. Equation (5.5), for example, is a generalization of equation (5.4) that includes potential weights on the exchange rate (e_t with target $\bar{e}_t$) and the money supply (M_t with target $\overline{M}_t$).

$$i_t = i_{t-1} + \alpha\,(\pi_t - \bar{\pi}_t) + \beta(Y_t - \bar{Y}_t) + \delta(e_t - \bar{e}_t) + \sigma(M_t - \overline{M}_t) \qquad (5.5)$$

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[20] Typically, the latter would be done by representing the central bank's objective via a loss function that is quadratic in deviations in inflation and output. The parameters of the rule would then be chosen to minimize the expected loss.

These additional terms allow the equation to represent a wide variety of rules. For example, a central bank in a small country that aims to peg its currency to the US dollar would have $\alpha = \beta = \sigma = 0$ and a very large value for δ. The Bank of China, on the other hand, might be represented by a rule with roughly equal values for α, β, and δ (that is, assigning equal importance to the first three objectives) and set $\sigma = 0$.

5.3.4 Nominal income and nominal GDP targeting

Monetary policymakers can target a measure of nominal economic activity instead of inflation or price levels. Targeting nominal economic activity means that policymakers try to avoid recessions (in nominal terms) to maintain a steady increase in economic activity or a particular rate of growth. There are several different measures of economic activity that central banks could target. Nominal GDP is a measure of the value-added in an economy at current prices. Nominal income is a measure of the value of income generated by economic activities, including by individuals and businesses, measured at current prices. Nominal gross output is the value of final plus intermediate goods produced in an economy. In a single good model, such as most macroeconomic models, nominal GDP and nominal output would be equivalent.

In a multi-sector model, intermediate goods production would imply a difference between total gross production and value-added. In the US economy, the concepts of nominal GDP and nominal income are similar. In a small open economy with a large amount of foreign capital, the two measures diverge due to payments of dividends to foreign capital owners. In the following discussion, we will use nominal income targeting (NIT) as shorthand for each type of rule. Equation 5.6 represents a nominal income rule where nominal income is represented by PY_t and the bank's target for it is $\overline{PY_t}$:

$$i_t = i_{t-1} + \alpha \left(PY_t - \overline{PY}_{\mathrm{t}}\right) \tag{5.6}$$

The rule can also be written in terms of the rate of change in nominal income, where g_t is the growth rate of nominal income rather than its level, and $\bar{g}_t$ is the bank's target:

$$i_t = i_{t-1} + \alpha\,(g_t - \bar{g}_t) \tag{5.7}$$

There is a large and long literature supporting NIT rules (see Meade, 1978; Bean, 1983; Henderson and McKibbin, 1993; McCallum, 2011 and 2015; Frankel, 2012; Woodford, 2012; Sumner, 2014; Beckworth and Hendrickson, 2020). The advantage of an NIT rule is that it has implicit weighting on both prices and output. Moreover, in its growth rate form, it applies equal weights to inflation and output growth. Both can be shown to be equal to α. NIT rules respond to demand shocks in the same direction as inflation targeting: i.e. raising interest rates in the face of a positive demand shock. However, the magnitude of the change may be different from inflation targeting since the rule includes implicit weighting of output changes as well as inflation. Under the NIT approach, there is no need for the existence of 'divine coincidence' (Blanchard and Galí, 2007) for the output and price stability objectives to be achieved in the face of demand shocks (Bean, 1983; Rogoff, 1985; Ball and Mankiw, 1995; Frankel, 2012; McKibbin, 2015).

The main difference between nominal income and inflation targeting is the rule's response to a shock to aggregate supply. As inflation rises and output falls under an aggregate supply shock, an NIT rule weights the changes equally. For example, a central bank facing a shock that raised the price level and reduced output by equal percentages, thus leaving nominal GDP unchanged, would leave the interest rate unchanged. Thus, the major advantage of nominal GDP targeting highlighted in the literature is that it gives the central bank the ability to handle permanent supply shocks with close to optimal monetary policy outcomes (Rogoff, 1985; Henderson and McKibbin, 1993; Frankel, 2012; Garin *et al.*, 2015). In the case of a persistent change in real trend growth, the implication of not changing the nominal GDP target would be a permanent change in the rate of inflation.

5.4 Jointly optimizing climate and monetary policies

Having reviewed the basics of both climate policy and monetary policy, we now consider the interactions between the two. Following that, we discuss the implications of extreme weather events and other climatic disruptions for joint management of climate and monetary policy.

5.4.1 Climate policies

This section examines each climate policy regime to consider the implications of each major monetary policy regime for that particular climate policy regime.

5.4.1.1 Carbon taxes

From a monetary perspective, a carbon tax is a complex aggregate supply shock. On the one hand, the tax increases cost in the fossil energy sector and thus reduces the total output that can be produced for a given set of primary factors. On the other hand, if revenue from the tax is used to lower other distortionary taxes, that component of the policy would be a supply shock in the other direction, lowering costs and increasing potential output. To keep things simple, in the discussion below we assume that the net macroeconomic impact, not accounting for the environmental benefits of the policy, is negative; that is, that any positive supply impacts from reductions in other taxes are not sufficient to fully offset the negative impact of the carbon tax itself. Thus, real output may return to its baseline rate of growth, but the level of output would be lower at each point in time relative to what it would have been.

First, consider a simple scenario. Suppose a central bank has set a target rate of inflation at 3 per cent per year and has been achieving it for several years. The government then imposes a carbon tax that takes effect immediately (at $t = 0$), has not been anticipated by private agents, and once established is held constant indefinitely. Overall economic output would decline, and inflation would spike up. With no response by the central bank, and assuming that private agents recognize that the policy is effectively a one-time change in relative prices and thus do not expect subsequent changes in the underlying inflation rate, the inflation rate would quickly return to its original level.

The price level would step up to a higher level overall. The relative price of carbon-intensive goods would be permanently higher. The level of real output would be permanently lower but the rate of growth of real output would return to baseline.

Now consider various ways a central bank might respond to this 1-year spike in inflation. A central bank using strict inflation targeting would see the inflation spike at $t = 0$ and respond by raising the interest rate. That would slow the economy further than the carbon tax did on its own, and it would also cause the exchange rate to appreciate, making imported goods cheaper but exports uncompetitive. Both impacts would reduce the underlying inflation rate in the economy, partially offsetting the increase in overall inflation caused by the tax. However, the decline in output would be worse than if the central bank had not responded. Moreover, lags in the propagation of interest rate changes through the economy could easily cause the impact of the rate increase to occur at $t = 1$ or later when inflation would otherwise have returned to baseline.

A central bank using *flexible inflation targeting* (FIT) might avoid exacerbating the output effect of the tax if it recognized that the carbon tax was a one-time step in the price trajectory and did not change interest rates. In practice, however, fluctuations in the economy from year to year will mean that the bank may have difficulty separating the impact of the carbon tax from that of other events that may have caused it to miss its target for year 0. A central bank that was aware of the tax and was using FIT would want to raise interest rates slightly in year 0 and somewhat more in year 1 to offset the baseline component of the inflation rate. However, it would be challenging in practice to separate the baseline component from the portion due to the carbon tax. Without understanding the interaction of monetary and climate policies, the bank may mistake all of the inflation in year 0 for a baseline deviation and thus raise interest rates far more than would be desirable. Understanding the nature of the climate policy response would be even more critical for a central bank using PLT. Without an appropriate rule, the bank would not only offset the inflation shock but would tighten monetary policy even further to return the price level to the original trajectory.

If the bank does not understand the nature of the carbon abatement policy, both HMT and NIT (as automatic rules) will perform better than inflation targeting because both rules would lead to less tightening of monetary policy. A central bank using an HMT rule would weigh the rise in inflation against the fall in output, and it would thus raise interest rates less than a bank using inflation targeting. The bank might even lower interest rates if the rule's weight on output or the output decline itself were sufficiently large. Similarly, a central bank using an NIT rule would implicitly account for the fall in output: although P would rise, the decline in Y would mean that PY would rise less than P alone would suggest.

In practice, a critical element in determining how a central bank would react would be the bank's assessment of inflationary expectations. This is particularly important because the most likely carbon tax policy is not a single once-and-for-all step, but rather an initial step followed by a rise in the carbon tax rate in real terms over time. This is more complicated for the central bank because the shock potentially changes the rate of inflation as well as the price level, and possibly changes the rate of growth of actual and potential output as well. Accommodating the carbon tax policy would thus require that the bank raise its target inflation rate. However, doing so is relatively straightforward since the carbon tax is known in advance. The bank could anticipate the impact it would have on the inflation rate and adjust its target accordingly.

5.4.1.2 Tradable emission permits

The issues discussed for the interaction of the carbon tax with the monetary regime would also apply under a tradable permit policy. However, the main difference is that the future trajectory of permit prices would be less certain than the carbon tax (which would be set explicitly in the policy). Permit prices would be uncertain for at least two reasons: (i) uncertainties in the marginal cost of abatement at the emissions limit; and (ii) variations in economic conditions that affect the demand and supply of fossil energy. As a result, the impact of the policy on prices would be uncertain, and it would thus be more difficult for the central bank to adjust monetary policy to deal with the volatility of prices generated by the permit trading system.

5.4.1.3 Hybrid policy

The advantage of a hybrid policy over a permit trading system would be that the carbon price in the short term would have the same predictability as does the carbon tax as long as the ceiling price was binding (which it would be designed to be in practice). The long-term expected carbon price would be clear from the long-term permit market. Depending on the length of time of the fixed price on a hybrid policy, the problems for the central bank would be smaller than in a more volatile trading system.

5.4.1.4 Regulatory and other responses

Relative to a carbon pricing policy, regulations, subsidies, and standards to control GHG emissions would be more difficult for a central bank to anticipate and respond to since the effects on output and prices would be opaque and hard to predict. This would be true under each monetary rule because of the challenge in assessing the consequences of such policies on current and potential output and current and expected inflation.

5.4.2 Climatic disruption and output volatility

There is strong empirical evidence that extreme weather events reduce economic growth (Cavallo and Noy, 2010) in the short run. For example, droughts and floods can disrupt agricultural activity and damage crops (Gandhi and Cuervo, 1998). Extreme weather can also reduce the effective labour supply due to climate-induced health impacts (Fankhauser and Tol, 2005), and it can increase the rate of capital depreciation (Stern, 2013). In short, as climate disruption leads to more frequent (or more damaging) extreme weather events, monetary policymakers will need to respond to more frequent (or larger) negative supply shocks.

A central bank following strict inflation targeting would react to an extreme weather event by tightening monetary policy to stem the rise in inflation. A bank following PLT would react even more strongly, raising interest rates enough to reduce the price level back down to its target. In both cases, the bank would worsen the impact of the shock on economic activity.

A central bank using FIT might avoid exacerbating the fall in output if it accounted for the transitory nature of the event and chose to use its discretion to adjust the timing of policy adjustment. However, its task would be made difficult by imperfect real-time measurement of the output gap. There is substantial evidence indicating that the Fed's estimates of the output gap under normal economic conditions have been prone to large errors (Orphanides, 2004; Sumner, 2014). For example, using a New Keynesian model with imperfect information, Beckworth and Hendrickson (2020) show that the Fed's output gap forecasts over 1987–2007 explain only 13 per cent of the fluctuations in the actual output gap. Estimates during periods of unusually persistent and unpredictable productivity shocks, as would be the case with increased climatic disruption, could be even worse, although the output may be adjusted to account for such shocks (Panton, 2020). In general, more frequent or intense shocks make inflation forecasting more difficult for both the central bank and private actors, which erodes the rationale for basing monetary policy primarily on inflation forecasts.

In contrast, a central bank using an HMT or NIT rule would respond to extreme weather shocks by balancing the rise in prices against the drop in economic output caused by the event. As with the onset of a carbon tax, such a central bank would be less likely than an inflation-targeting bank to exacerbate the damage to the economy. However, implementing an HMT rule in a changing climate would be challenging for a reason mentioned above. An increase in the frequency of extreme weather events raises the difficulty of forecasting potential output and therefore the output gap.

An advantage of NIT is that the central bank using NIT does not need to have a precise estimate of the output gap because only the nominal income target is announced. As a concrete example, suppose the growth rate of potential output is estimated by the central bank to be 3 per cent per year, and the desired inflation rate is 3 per cent. The nominal income target growth rate for a central bank with an NIT rule would, therefore, be the sum of the two: 6 per cent.

Now suppose that an extreme weather event causes potential output growth to fall to 2.5 per cent over the forecast period, meaning that the event reduces potential output by 0.5 per cent. If the NIT central bank achieves its 6 per cent nominal income target, output growth would be 2.5 per cent and the inflation rate would be 3.5 per cent. Inflation would have exceeded the bank's preferred value of 3 per cent. However, the discrepancy is too small to undermine the expectation of private agents and financial markets that the bank is committed to a clear rule. That means that with NIT, the bank limits the rise in expectations of higher inflation, preventing a wage–price spiral. Indeed, the central bank does not even need to observe or account for the precise nature of the shock: simple adherence to the policy rule gives a reasonable policy response. Thus, rules like NIT that do not rest on output gap calculations are better for promoting macroeconomic stability than those that do, especially during periods with an unusual number of supply-side macroeconomic shocks.

5.4.3 Climatic disruption and financial stability

Some analysts are also concerned that climatic disruption, and the policy responses to it, can weaken financial stability (Carney, 2015; NGFS, 2019), which some authors argue should be an additional responsibility of central banks. Stability of the financial system in the short run may differ significantly from the stability of output and employment. For example, when debt contracts are secured by assets priced in nominal terms, sharp changes in the price level can trigger widespread cascades of asset sales. These sales would temporarily drive asset prices down much further than the initial changes in output and employment would warrant. Although the empirical evidence on how extreme weather events affect financial stability remains mixed, some believe severe and persistent climate-induced natural disasters pose serious risks to the stability of the financial system. According to the Bank of England (2015), apart from the climate-induced physical risks ranging from severe weather events like flooding, droughts, and disruption of agricultural productivity, insurance firms face losses from climate damages that they may not be able to diversify fully.

The potential for abrupt constraints on GHG emissions can also pose risks to financial assets and the balance sheets of fossil energy companies. Highly ambitious climate policy could strand capital and weaken the profitability of firms (Dafermos *et al.*, 2018). Still, policymakers will take such outcomes into account in their decisions about which policies to adopt. Research is emerging on how monetary policy could foster climate-related financial stability, with some advocates arguing for 'green' quantitative easing (QE) arrangements by many central banks (Campiglio, 2016). Some argue that central banks can address credit market failures that impede low carbon investments by expanding their balance sheets with securities of entities engaged in low-carbon activities (e.g. renewable energy) (Campiglio, 2016). Apart from the use of QE programmes, some argue for the inclusion of financial stability as a permanent monetary policy objective, particularly in an economy prone to persistent supply shocks that endanger financial stability (Cecchetti *et al.*, 2000; Woodford, 2012). However, a long-standing argument remains that monetary policy should focus on the traditional goals of price and output stability, with financial stability concerns best handled by regulatory tools such as macroprudential policies (Bernanke and Gertler, 1999, 2001; Bank of England, 2015).

Sheedy (2014) provides strong empirical evidence that when debt contracts are written in nominal terms, NIT outperforms FIT. The results arise from improving financial market risk allocation mechanisms, particularly by insulating households' nominal income from shocks even when there is short-run price stickiness. Sheedy argues that since the ability of borrowers to meet their obligations is more related to their income, a monetary policy rule that puts more weight on nominal income than price stability is most suitable in addressing asset price bubbles. Examples include those that could result from the short-run consequences of a carbon tax (i.e. stranded asset risks). Using a model with default probabilities and bankruptcy costs, Koenig (2013) also reached a similar conclusion, strongly upholding the view that in an economy with adverse supply shocks and nominal debt contracts, targeting nominal income is the optimal monetary policy approach to containing asset price risks.

5.5 Features needed in macroeconomic models for policymakers

The discussion above makes it clear that macroeconomic models that are needed to analyse climate shocks, climate policy, and the interaction with monetary policy would need to be more complex than most well-known existing dynamic stochastic general equilibrium (DSGE) models. A model needs several features to be able to analyse climate shocks and climate policy.

First, there needs to be a consistent macroeconomic framework. Second, there needs to be disaggregation of the energy generation sectors, since different energy-producing sectors have different carbon intensities and carbon policies impact on fuel types differently due to the variation in the carbon content of alternative energy sources and the characteristics of the markets they serve. Third, and more importantly, models need sufficient sectoral disaggregation to account for how climate shocks and changes in energy prices impact sectors differently. For example, transportation and manufacturing would be affected differently by changes in carbon prices. These changes across sectors can have macroeconomic implications. Fourth, there needs to be a financial sector with different types of assets and different capital stocks across sectors, so the issue of stranded assets and changes in return to capital from carbon reduction policies can be taken into account. Finally, the model should be global since climate shocks, climate policies, and monetary policies all have impacts that are propagated across countries.

5.6 The G-Cubed model and some applications

The G-Cubed multi-country model is an intertemporal general equilibrium model which the original authors describe as a hybrid of DSGE and computable general equilibrium (CGE) models. The model is documented in McKibbin and Wilcoxen (2009, 2013). Some of the key features, particularly the interaction of sectoral relative prices and macroeconomic outcomes, have been highlighted in McKibbin and Stoeckel (2018). The model is global with the world economy disaggregated into the countries and regions in Table 5.1.

Table 5.1. Regions in the G-Cubed model

Region	Region description
Australia	Australia
China	China
Europe	Europe
India	India
Japan	Japan
OPEC	Oil-exporting developing countries
ROECD	Rest of the OECD, i.e. Canada, New Zealand, and Iceland
ROW	Rest of the world
Russia	Russian Federation
USA	United States

Table 5.2. Sectors in the G-Cubed model

No.	Sector Name	Notes
1	Electricity delivery	Energy sectors other than generation
2	Gas utilities	
3	Petroleum refining	
4	Coal mining	
5	Crude oil extraction	
6	Natural gas extraction	
7	Other mining	Goods and services
8	Agriculture and forestry	
9	Durable goods	
10	Nondurables	
11	Transportation	
12	Services	
13	Coal generation	Electricity generation sectors
14	Natural gas generation	
15	Petroleum generation	
16	Nuclear generation	
17	Wind generation	
18	Solar generation	
19	Hydroelectric generation	
20	Other generation	

Within each region, there are multiple firms as well as household and government sectors which all interact in markets for goods, services, and primary inputs. There are also markets for equities, bonds, household capital, and foreign exchange. Production is represented by an explicit set of heterogeneous firms, one for each sector. Table 5.2 summarizes the 20 sectors in each economy.

G-Cubed is a 'hybrid' model, in the sense used in the papers published in the Rebuilding Macroeconomic Theory Project, in the January 2018 edition of the *Oxford Review of Economic Policy* (see Vines and Wills (2018), Blanchard (2018a), and Wren-Lewis (2018)). The term 'hybrid' means that the model has both features of a micro-founded DSGE model and features of a 'policy model' or 'structural economic model'. The G-Cubed model includes all of the features of a micro-founded DSGE model: there are optimizing agents who are subject to two important frictions. In this sense the model is like the Smets–Wouters (2007) model or the Christiano *et al*. (2005) model. The first friction can be found in the process capital accumulation in each sector of each economy. This is driven by investment function that is subject to quadratic adjustment costs. As a result of this friction, investment leads to a gradual adjustment of the capital stock over time; what happens is that investment responds to the value of Tobin's q, with 30 per cent of firms responding to a forward-looking q which evolves in a model-consistent manner with the remaining 70 per cent of firms having a backward-looking q.

The second major friction is in the wage-setting process. Nominal wages are driven by a Calvo–Rotemberg-style Philips curve (in which some workers are backward looking) while prices are set by profit-maximizing firms in each sector. The firms hire labour up to the point at which the marginal product of labour equals the real wage defined in terms of the output price level of that sector. As a result of these assumptions, nominal wages are sticky and adjust over time in a way which depends on labour-contracting assumptions, something which is allowed to differ from country to country. Any excess supply of labour enters the unemployed pool of workers. Unemployment, or the presence of excess demand for labour, causes the nominal wage to adjust over time in a way which—taken in conjunction with the monetary rule and the behaviour of the nominal exchange rate—will ensure that the labour market clears in the long run.

In the short run, unemployment can arise both because of structural supply shocks and because of changes to aggregate demand in the economy. The behaviour of some consumers (30 per cent) is driven by an Euler equation in which consumption in any period responds both to the contemporaneous real interest rate and to a forward-looking expectation of future consumption (one which evolves in a model consistent manner). The remaining 70 per cent of consumers follow a simple rule of thumb where they consume their entire income each period. This can also be interpreted as if they are liquidity constrained.

As noted, like in the Smets–Wouters model and in the Christiano *et al*. model, there are two fundamental frictions in the model. One is in the process of capital accumulation (because of adjustment costs in the investment function), and the other is in the inflationary process (because of the overlapping nature of the wage-setting process). Together these two features mean that the model has new-Keynesian features and does not behave, in the short run, like a real business cycle (RBC) model. But crucially, in the long run the model does have RBC properties.

The model is much closer than most DSGE models to what Blanchard (2018a) calls a policy model, or what Wren-Lewis (2018) calls a structural economic model. There are several aspects to this resemblance. First, the model pays attention to the need to disaggregate output into a number of different sectors, whose relative prices may move during simulation. In addition, the model captures inter-industry linkages (in that some of the output of some industries serves as inputs into other industries), and it treats the price of energy and mining as determined in a different manner from that of manufactured goods or services.[21] Because of this there are many features of the model's behaviour which will be familiar to those who have experience with using computable general equilibrium (CGE) models.

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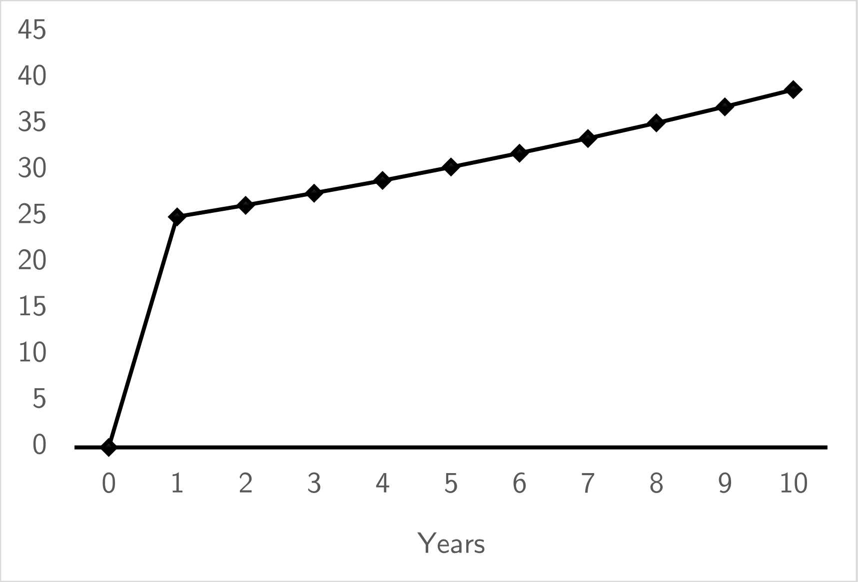
[21] Allowing for changes in the relative prices of the goods produced in the 12 core sectors and energy subsectors is fundamental to modelling the impact of climate policy. It is important to capture the change in relative price of different electricity generation technologies, the relative prices of primary energy sources and the change in the relative price of energy intensive and non-intensive goods and services, These have macroeconomic implications.

Being global, the model needs to capture the effects of international trade and of international capital flows. Trade balances are determined by carefully modelled export functions and import functions for each country, which map consistently into the equations for imports and exports in other countries; changes in real exchange rates between countries have significant and important influences on trade flows between countries within the model. The model supposes perfect international mobility of capital between countries, and the exchange rate is determined, *à la* Dornbusch, by the uncovered interest parity (UIP) condition, except for countries having pegged exchange rates and for those countries within the European Monetary Union. But there is explicit allowance for risk premia in these UIP equations.

McKibbin and Stoeckel (2018) summarize a large number of applications of this model. Using the G-Cubed model, we performed simulations that show how the joint optimization of climate and monetary policies may lead to far superior macroeconomic outcomes than when each policy framework is considered separately. To keep things simple, we consider a scenario in which the United States alone adopts a tax of $25 per ton of carbon, growing at 5 per cent per year, with the carbon tax revenue recycled to households via lump-sum rebate. Figure 5.2 displays the tax.

Figure 5.2: Annual US Carbon Tax (U.S. Dollars Per Ton)



We considered three alternate monetary policy frameworks based on the discussion in section 5.3. Under the first regime, the central bank follows a pure inflation target (equation 5.1).[22] Under the second regime, the central bank follows a nominal income target (equation 5.7).[23] Under the third regime, the central bank follows a more conventional flexible inflation targeting regime as typified by the Henderson–McKibbin–Taylor rule (equation 5.5).[24] Results are shown below for output, inflation, CO_2 emissions, and the path of the interest rate for the first decade of the carbon tax shock under the alternate monetary regimes.

While the imposition of a price on carbon leads to output decline and a rise in inflation, the magnitudes of the macroeconomic outcomes depend on the monetary policy framework of the central bank. Pure inflation targeting is associated with the deepest decline in gross output, with nominal income targeting outperforming flexible inflation targeting. However, over the decade, the various regimes converge. Although carbon-price-induced inflationary pressure is much sharper in the immediate aftermath of the policy under nominal income targeting than flexible inflation targeting, the nominal-income-targeting central bank seeks to stabilize price faster. Both regimes achieve price stability at the end of the decade. Therefore, while the long-run policy stance and macroeconomic outcomes appear similar under both monetary regimes, a central bank that targets the growth in nominal income outperforms one that is focused on flexibly balancing price and output stability goals in a carbon-constrained environment.

These findings reflect the fact that under nominal income targeting, households' balance sheets can be insulated from macroeconomic shocks when the monetary policy stance seeks to stabilize nominal income or spending. While pure inflation is associated with greater emissions reductions, this is achieved through a substantial costly reduction in output induced by the central bank itself when the bank's sole objective is to maintain its inflation target.

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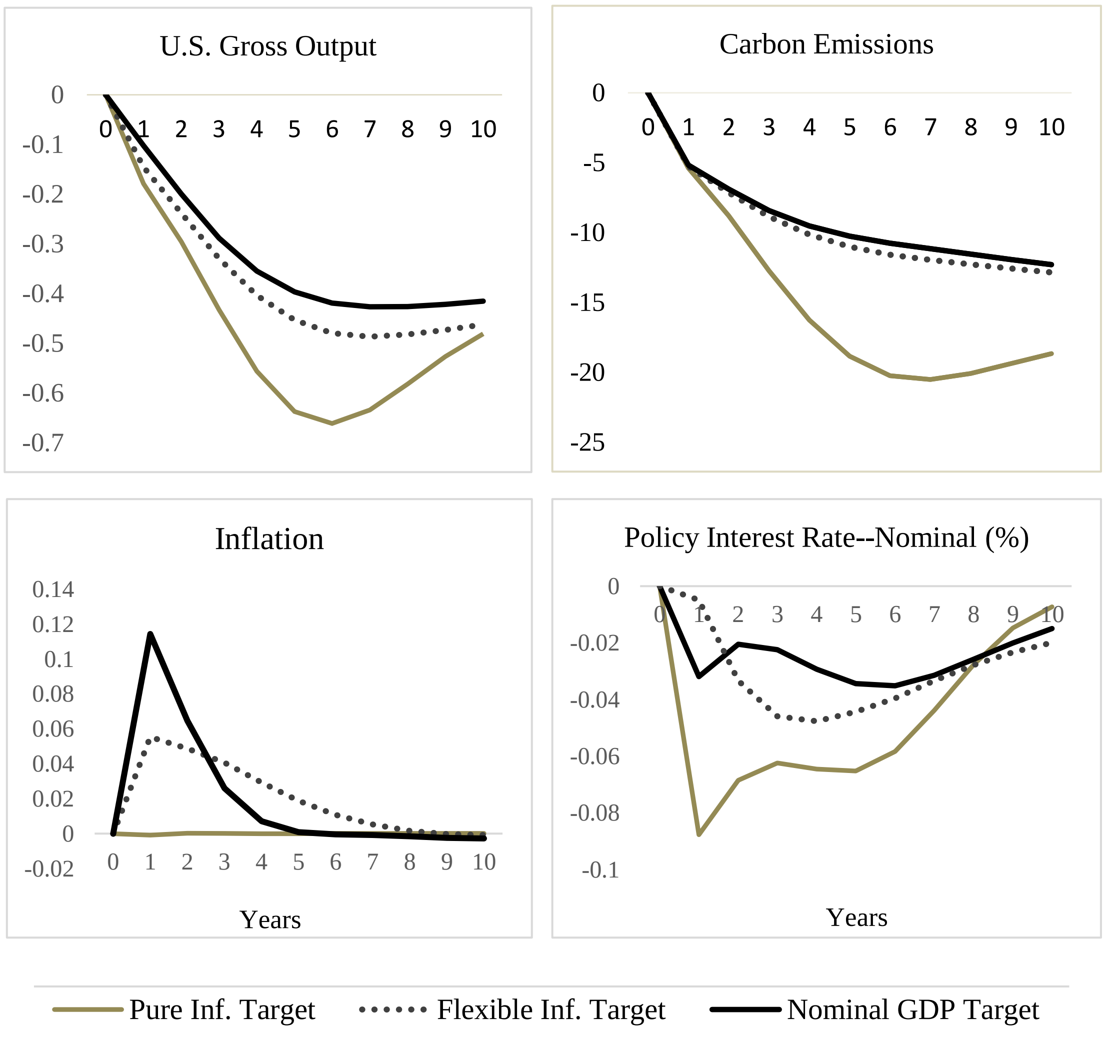
[22] By setting the weight on price stability, α, to 100 in the rule, the central bank seeks to accommodate any deviation of inflation from target.

[23] The nominal income rule is calibrated in growth rates, with α set to 20.

[24] Calibrated with the assumption that the central bank puts more weight on price ($\alpha = 2$) stability and less on output stability ($\beta = 1$)

Flexible inflation targeting and nominal income targeting are similar to one another in terms of their emissions reductions, but the output and employment outcomes are better under a nominal income target regime. This feature of nominal income targeting—better output performance for similar environmental outcome compared with the conventional flexible-inflation targeting regime—is crucial when considering the political economy of climate policy. Therefore, while the transition to a low-carbon economy may be associated with divergent paths for price and output, subject to the stringency of the price on carbon, jointly optimizing climate and monetary policies may lead to superior outcomes. There is vastly more research needed on these issues

Figure 5.3: U.S. Carbon Tax Effects Under Alternate Monetary Regimes—Percent Deviation from Pre-carbon Tax Baseline



Source: Authors' calculations

5.7 Conclusions

This paper has argued that, in a carbon-constrained and climatically disrupted world, there are important linkages between climate change and monetary policy regimes. First, the question arises how central banks should anticipate and respond to inflation increases and output decreases that result from climate policy. Responding solely to the inflationary component would lead to larger output losses than using a monetary policy rule that also aims to keep output and employment high. In particular, we argue that nominal income targeting is an attractive approach. It avoids creating public expectations of higher future inflation, and it does not require the central bank to understand the precise nature of the climate policy shock. Simple adherence to the policy rule gives a reasonable policy response. Moreover, nominal income targeting is less vulnerable to imprecise information about the current state of the economy than many other monetary policy rules.

Second, the design of climate policy can significantly affect how hard it is for central bankers to respond to the climate policy itself, as well as to respond to ordinary economic shocks that cause increased economic volatility, as a result of the carbon policy. Fluctuating carbon prices under a cap-and-trade policy would make inflation forecasting more difficult for central banks than a policy such as a carbon tax or a hybrid approach in which carbon prices are more stable and more predictable. Thus, a climate regime based on a carbon tax, or a hybrid policy with stable short-term prices, would simplify the response of a central bank to economic shocks.

A third challenge is that climatic disruption will increase the frequency and severity of negative supply shocks, making it more difficult for central banks to forecast output gaps, and therefore to forecast inflation (see Panton, 2020), a key part of some monetary policy frameworks. We conclude that nominal income targeting, which does not rely on such forecasts, may be better suited to a climatically disrupted world than other monetary rules. Overall, the interaction between climate policy and monetary policy strongly suggests that the two policy frameworks should be evaluated jointly. Managing each regime separately can easily lead to policies that seem fine in isolation but that perform very poorly in practice.

Finally, we have discussed the type of model needed by policymakers for analysing climate and monetary policy interactions. Small DSGE models that are currently popular in the macroeconomics literature and used by major central banks are inadequate for this purpose and many other more complex questions. There are other models already available in associated literatures, such as G-Cubed, that have the structure and complexity needed to add considerable understanding of the interdependence of monetary and climate policies.

Chapter 6

6. Conclusions

6.1 Summary of Key Findings

This thesis began with three objectives in mind. The first objective was to examine the interlinkages between the key findings and ideas in the climate-economy literature one hand, and the monetary policy literature on the other. The second objective was to evaluate the key channels through which the macroeconomic effects of climate change affect the conduct and design of monetary policy, and finally, to determine whether there is an optimal combination of the two policy regimes.

Chapter 2 began with a survey of the monetary policy literature, identifying the key features of the main policy regimes advanced over the years. In comparing the alternative monetary regimes, the focus was on four main questions: (i) how well does each regime handle supply shocks? (ii) can the target of monetary policy be credibly measured and clearly understood? (iii) how transparent is the regime when exceptions to the basic policy rule are required? (iv) are price expectations anchored by the monetary regime? The results suggest that while the flexible inflation targeting regime has improved the anchoring of inflation expectations in Australia, the nature of future shocks to the Australian economy requires a serious rethinking of the monetary policy framework, with nominal income targeting advanced as a suitable alternative.

Chapter 3 began with a review of the climate-economy literature before building a conceptual bridge connecting the key ideas with the monetary policy literature. Expanding the arguments in the preceding chapter, Chapter 3 then examined how climate-induced weather shocks further complicate the real-time measurement problem facing central banks, especially regarding the estimation of potential output and the output gap. Using a simple unobserved component model calibrated to Australian data, the effects of climate-induced weather shocks—proxied by variations in temperature and precipitation anomalies—on potential output and the output gap were tested.

The results show that climate-induced weather shocks contain useful information in explaining the transitory movements in output, with the estimated climate-neutral output gaps found to be relatively more reliable compared to conventional measures that exclude climate effects.

Chapter 4 further examined the measurement question by investigating how the simultaneous effects of climate shocks on both actual and potential output affect the understanding of business cycle dynamics by innovatively incorporating climate hysteresis effects into a Bayesian-estimated multivariate filtering model calibrated to Australian and U.S. data. Not only do persistent climate shocks affect the measurement of potential output and NAIRU as well as the associated output and unemployment gaps, but by also including such shocks in the estimation of these latent variables, a special feature of the business cycle is revealed: macroeconomic slacks are smaller when both actual conditions and potential supply capacity are modelled to change simultaneously, with recessions that may be less disinflationary, and booms that may be less inflationary.

Finally, Chapter 5 explored the interaction of climate change and monetary policy as they jointly influence macroeconomic outcomes, employing a general equilibrium model with full sectoral disaggregation of the energy generation sectors and strong global linkages in capital and trade. The results show that a central bank that targets the growth in nominal income outperforms one that is focused on flexibly balancing price and output stability goals in a carbon-constrained environment. Overall, the interaction between climate policy and monetary policy strongly suggests that the two policy frameworks should be jointly evaluated. Managing each regime separately can easily lead to policies that seem optimal in isolation, but that perform very poorly in practice. There are strong policy implications of these findings.

Depending on how climate policy is designed and interacted with existing macroeconomic policies, the transition to a low-carbon economy may involve declines in output and employment. The nature of the monetary policy framework may be crucial in that transition. Under the conventional inflation-targeting framework, maintaining price stability in the face climate-policy induced surge in inflation cannot be achieved without further dampening output and employment.

Maintaining strong output and employment outcomes may be crucial for the political success of a climate policy, especially in the post-COVID-19 era where there are no strong political incentives to flatten the climate curve. On this front, a monetary policy framework based on targeting the growth nominal income does not only provide more relative macroeconomic stability, but it also reduces the economic losses associated with climate policy and makes climate policy more politically viable.

6.2 Direction of Future Research

Several questions on the climate-monetary policy nexus remain unexplored, especially how the post-COVID-19 policy agenda and the political economy complexities will affect the flattening of the climate curve. While the global policy response to the pandemic has been very different across economies, all countries have responded with some combinations of health, fiscal and monetary policies. In a similar way, the response to climate change over the coming decades will involve a combination of climate, fiscal and monetary policies. Such an interesting interaction of the three policy regimes, which is currently missing in the literature, will be a key focus of my next research agenda. While the thematic focus in this thesis is on the macro level effects of climate change, the examination of the firm-level effects of climate risks, especially in the cross-border context, is another important area for further research.

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