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in emerging and developing economies**

Channing Arndt, Christopher Loewald and Konstantin Makrelov

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Enquiries

Head: Economic Research and Statistics Department
South African Reserve Bank
P O Box 427
Pretoria 0001

Tel. no.: +27 12 313-3911
0861 12 SARB (0861 12 7272)

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Climate change and its implications for central banks in emerging and developing economies

Channing Arndt, Christopher Loewald and Konstantin Makrelov¹

Abstract

Climate change mitigation and adaptation will prove to be sources of significant structural change. The impacts will be far-reaching and often irreversible, with particularly large effects on emerging and developing economies. This paper assesses the implications of these changes for central banks in developing countries. They can best support adaptation and mitigation efforts by maintaining macroeconomic stability, lowering the cost of borrowing to support green investment, facilitating the development of green assets, and improving the sharing of information in the financial system, especially with respect to risks. Yet, emerging market central banks currently have limited capacity to assess climate risks and their effects on financial stability, growth, and inflation. As such, the paper also provides options for central banks to develop analytical frameworks useful for that purpose.

JEL Classification: Q54, E52, E58, E17

Keywords: climate change, monetary policy, central banking, climate change models

Corresponding author's email address: konstantin.makrelov@resbank.co.za

¹ Channing Arndt is the Director, Environment and Production Technology Division, IFPRI, Christopher Loewald is the Chief Economist of the South African Reserve Bank, and Konstantin Makrelov is a Lead Economist at the South African Reserve Bank. The views expressed in this paper are those of the authors and do not necessarily represent those of the South African Reserve Bank or Reserve Bank policy. While every precaution is taken to ensure the accuracy of information, the South African Reserve Bank shall not be liable to any person for inaccurate information or opinions contained herein.

1 Introduction²

Climate change mitigation and adaptation will prove to be sources of significant structural change. The impacts will be farther-reaching than many other structural drivers, and frequently irreversible. Mean projected warming is expected to increase by 3 to 4 °C by 2100 in the absence of mitigation (IEA 2014; IPCC 2014, 2018), an outcome to be avoided. Currently, the implications of the warming that has already occurred are manifesting themselves more rapidly and more forcefully than previously thought likely (IPCC 2018).

At a macroeconomic level, relative price adjustments of various kinds – energy costs, pricing of externalities, growing demand for more energy-efficient products and services, among others – will be far-reaching. Bolton et al. (2020) argue that climate change will generate “green swan events”, similar to the low-probability, high-impact “black swan” events. These are likely to be highly disruptive and characterized by complex transmission mechanisms, primarily through financial systems. Balance sheets and risk profiles of some households, financial and non-financial firms are likely to experience significant stress as a result of climate change, affecting financial stability and the insurance sector (Carney 2015).

The breadth of policy risks faced by central banks in dealing with climate change and its consequences is becoming increasingly apparent. This paper explores how emerging market and developing country central banks might develop policy responses to climate change. Importantly, emerging and developing economies are almost invariably more exposed to climate change events because of the relatively large size of weather-dependent sectors (e.g., agriculture and food-processing). They also are typically less resilient to climate change events, accentuating vulnerability to shocks (Farid et al. 2016). Adaptation and mitigation need to be economically and financially manageable in the sense of minimizing damage and maximizing opportunity.

The literature is reviewed, and three channels that seem especially important to guide central banks in facilitating adaptation are identified. These include how the economic effects of climate change affect monetary policy; how to minimize financial sector risk and facilitate the flow of funds to better encourage green investment; and how to analyse financial risks arising from climate change.

At the core of each of these channels is the role of risk and uncertainty. As a physical phenomenon, climate change renders *past* information progressively less useful, destroying its value for understanding potential future trajectories. Global emissions paths are probably reasonably forecastable, but the ability of (atomistic) economic actors to adapt to new circumstances, and the behaviour of larger (non-atomistic) actors, notably nation-states, as events unfold, are much less certain. This complicates the intermediation task, which in a broad sense is about allowing relative prices to adjust, responding to the incentives they create, and facilitating the flow of savings to the most efficient allocations.

That task of efficiently intermediating savings for use in adaptation and mitigation will be done primarily by governments, central banks and financial sectors, requiring development of appropriate risk assessment and management tools. Until this is well advanced, climate change will tend to augment economic costs and threats to financial stability.

² We are grateful to Dr Witness Simbanegavi and Professor Finn Tarp for useful comments and suggestions.

Climate risks, moreover, do not follow historical distributions (Bolton et al. 2020; Schlosser and Strzepek 2015). This suggests that modelling needs to improve, and central banks will need macro-models that extend into financial sector dynamics, supply-side shocks, and risk-modelling. Building capacity to use and develop models presents challenges in emerging and developing economies, and thus some suggestions are provided as to how these challenges can be addressed.

The next section identifies the economic transmission channels of climate change of particular relevance to central banks. Section 3 describes some of the differences between advanced and emerging and developing economies and why these require somewhat different approach to policy. In section 4, the role of central banks in managing climate change risks and facilitating the transition to a less carbon intensive economy is discussed. Options to develop central banks modelling tools to take account for climate related risks are discussed in section 5.

2 The impact of climate change on the economy: physical and transition risks

There are two distinct elements in the transmission mechanism linked to mitigation and adaptation. The first element relates to physical risks, defined as risk associated with the materialization of climate change events. The second element is linked to risks associated with the transition to a low-carbon economy.

2.1 Physical risk

Climate change has affected and will continue to affect economies through multiple supply and demand channels. And, unlike other supply-side shocks, those from climate change are expected to be persistent, with frequently irreversible effects (Bolton et al, 2020).

2.1.1 Impacts on production

Climate change will affect labour supply, capital accumulation and productivity. For example, extreme heating is expected to increase mortality and morbidity, reducing the skill base. It will also decrease productivity in locations that are already warm (Deryugina and Hsiang 2014; Fankhauser and Tol 2005). Human capital more generally is likely to be affected by mass migration, crime and social unrest as a result of climate change (Dell, Jones, and Olken 2014).

Climate change and associated natural disasters are, on balance, likely to damage capital and land and increase the depreciation rate of capital with long-term impacts on income and output (Fankhauser and Tol 2005; Stern 2013). One estimate suggests a 7 per cent decline in GDP per capita by 2100 for every 0.04 °C increase in temperatures (Kahn et al. 2019). Natural disasters also disrupt transportation and distribution networks and impact negatively on productivity and global trade.³

Climate change will affect all sectors of the economy, with water, agriculture, transport and infrastructure particularly vulnerable. Agriculture is most obviously vulnerable due to the sector's dependence on precipitation, water availability for irrigation, and maintenance of historical temperature ranges. The impacts are expected to be large and negative. For example, Lesk, Rowhani and Ramankutty (2016), in a cross-country study, find that droughts and

³ Gassebner, Keck, and Teh (2010) find that an additional natural disaster reduces exports by 0.2 per cent and imports by 0.1 per cent. The impact depends on level of economic development and political risk. Countries with lower levels of development and higher political risk experience the largest impacts (Oh and Reuveny 2010).

extreme heat decrease cereal production by 9 to 10 per cent. In many developing economies, the agricultural sector has strong links with other sectors of the economy, such as agro-processing, leading to large spill-over effects.

These large impacts on the agricultural sector are a main channel for climate change to affect African developing economies. In these countries a large part of the population depends on subsistence farming. Less than 3 per cent of smallholder farmers have crop insurance in Sub-Saharan Africa, which makes the sector very vulnerable to extreme climate events such as drought conditions (IFS 2018). In the absence of effective mitigation, losses of between 4 and 8 per cent of GDP by about 2050 are projected as a result of climate change for the region (Mekonnen 2014; Simbanegavi and Arndt 2014; Arndt et al. 2019).

2.1.2 Impact on prices

Negative shocks to agricultural production also cause higher and more volatile food inflation. For emerging market and developing economies, food inflation has a higher weight in the consumer price index, leading to higher and more volatile headline inflation. Poverty and inequality levels will increase as poorer households are more vulnerable to food inflation than other types of inflation (Arndt, McKay, and Tarp 2016; Kelly et al. 2018). Some of these effects can be offset if higher food prices translate into increased investment, productivity, and wages in rural areas (Headey 2014; Headey and Martin 2016).

Higher frequency of natural disaster and gradual climate change will increase the volatility of other prices in the economy as well as generate short and long-term changes in relative prices. Central banks will face more volatile output and inflation, hindering their ability to maintain price stability and growth.

2.1.3 Fiscal and financial impacts

Financial and fiscal risks can increase in response to higher frequency and greater severity of natural disasters. Government expenditure in response to disasters will put pressure on the fiscus, at times when revenue may also be under pressure. For emerging markets with large foreign currency liabilities and current account deficits, the combination of falling exports and rising government debt can cause significant economic and financial instability, as foreign currency receipts slow down, and external funding constraints tighten. The current Covid-19 crisis provides some indication of how large natural disasters may also unfold.

The financial stability channel is particularly important for central banks. Batten, Sowerbutts, and Tanaka (2016) and Batten (2018) identify several financial stability channels. Figure 1 provides a diagrammatic representation of these channels. Weather events translate into adverse economic shocks. These translate into asset price and balance sheet effects generating credit and financial market losses and increasing operational and liability risks.

An adverse shock to the capital of a bank leads to an increase in lending spreads and reduction in lending. The interaction between bank capital and economic activity, in turn, affects the risk-taking behaviour of the financial sector and generates financial accelerator effects. This mechanism can significantly amplify the economic impacts of climate-related events.⁴

Climate change can also generate significant liability risks. These risks are related to claims from parties who have suffered climate related losses against those that they hold responsible.

⁴ See Borio and Zhu (2012) and Woodford (2010) for a theoretical explanation of how shocks to the capital of banks amplify economic shocks.

These risks can affect insurers directly, and also affect overall financial stability through their impact on company valuations (Carney 2015).

The impact on insurance companies is expected to be large and to generate significant financial stability risks. Large insurance losses due to a climate event can lead to distress or failure of insurance companies.⁵ This could result in financial instability if critical insurance services or systematically important financial markets are not provisioned. Insurance companies can also reduce coverage in response to rising climate risks, which in turn can decrease collateral value and tighten credit constraints for households and firms (Batten, Sowerbutts, and Tanaka 2016). In the absence of insurance cover, some of the climate related losses are transferred onto the balance sheets of firms and households (Klomp 2014).⁶

Lower levels of financial development in many emerging and developing economies may reduce the strength of these channels and the financial stability risks. But less sophisticated financial markets and institutions will also make it more difficult to source funding and intermediate savings required to deal with climate change impacts (Crespo Cuaresma, Hlouskova, and Obersteiner 2008; Hsiang and Jina 2014; Raddatz 2009).

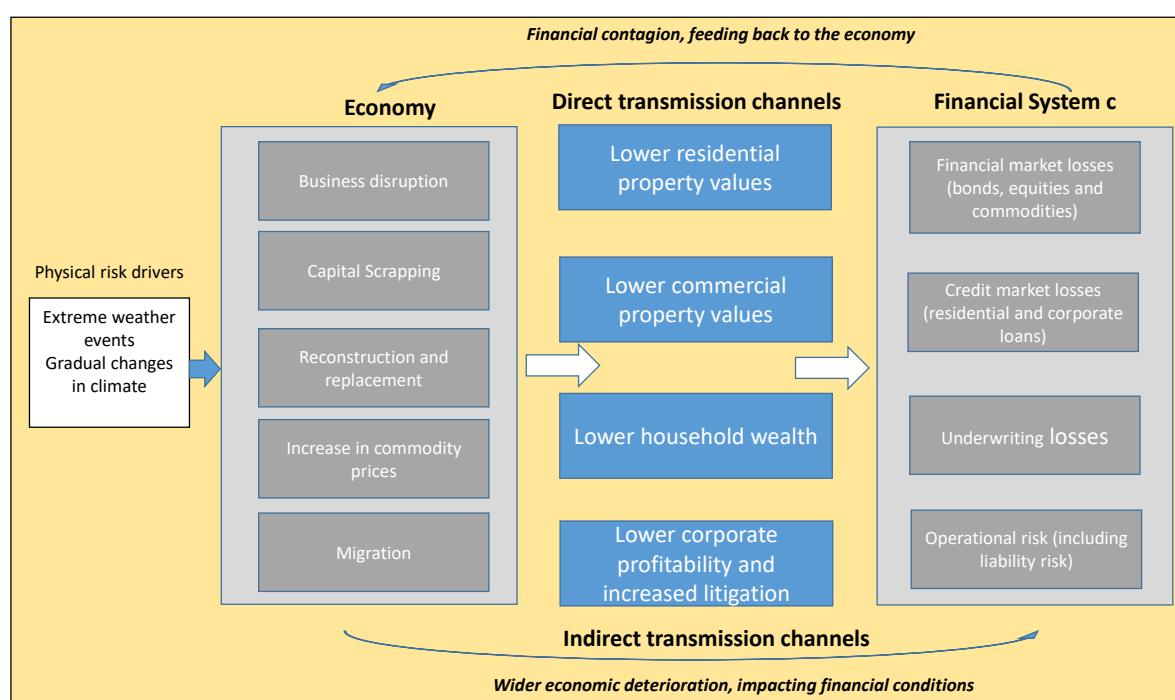


Figure 1: From physical to financial risks

Source: NGFS (2019)

2.2 Impact of transition risks

Transition to a low-carbon economy and the associated mitigation costs are expected to carry risk of heightened economic and financial costs and, at the same time, generate opportunities.

⁵ Munich Re estimates that in real terms annual average weather-related insurance losses have increased from USD 10bn in the 1980s to about USD 50bn in 2015 (NatCatSERVICE 2015). The number of extreme weather events has tripled since the 1980s (NatCatSERVICE 2018).

⁶ For many developing economies, the level of financial development is very low. In this case the climate change impacts will be mainly through impacts on key sectors such as agriculture and prices.

2.2.1 Costs

Reducing carbon emissions requires a decline in the production and consumption of high-carbon products such as fossil fuels, a fall in energy intensity, and a move to low-carbon energy production (Batten 2018). The transition requires a combination of policies, which can lead to large structural changes, affecting negatively many mining communities as well as firms and workers employed in energy-intensive sectors (IMF 2019a). Over time, successful mitigation will require transition to low-emissions modes of transport, with implications ranging from vehicle manufacture to fuel production and from distribution to maintenance.

Price-based instruments push transition (and transition costs) in the economy by reducing firm profitability for carbon-intensive firms and increasing prices to consumers and firms for carbon-intensive commodities. This also changes relative returns in the economy, guiding investment in new technologies. IMF (2019a) argues that limiting climate change impacts to 2°C requires a carbon tax of USD 75 per ton of CO₂. The current aggregate global carbon tax is only USD 2 per ton of CO₂. A carbon tax of US\$75 is likely to increase coal prices on average by 200 per cent compared to the baseline price in 2030, natural gas by 70 per cent and petrol prices by 5 to 15 per cent.

The impacts are different across countries depending on energy intensity. Similarly, within-country effects depend on the energy consumption of different firms, the sources of energy and the composition of household consumption. Energy intensive firms in China and India can see increases in their costs of between 6 and 11 per cent (IMF 2019a).

There are some offsets, however, as pricing of carbon could yield significant revenue, underscoring the point that adequate pricing of carbon ultimately redistributes economic activity across sectors and firms. In China and Russia, revenues can exceed 6 per cent of GDP, while in India and Indonesia the revenue gains are closer to 2 per cent of GDP (IMF 2019a; Parry, Veung, and Heine 2014). Effective recycling of revenue can reduce mitigation costs and accelerate the transition process. Recycling options vary and include reduction in different taxes, border carbon adjustment, rebates, environmental investment, deficit reduction and others.⁷

Alternatives to price mechanisms are also available but are likely to be less efficient, as the literature shows.⁸ Regulatory arbitrage is also likely to be a source of economic cost, not least because it lengthens the time to achieve significant positive externalities as transition gathers pace and scale. To minimize negative effects on emerging and developing economies from

⁷ Alton et al. (2014) evaluate the cost of introducing carbon taxes in South Africa. The introduction of a phased-in carbon tax of USD 30 per ton of CO₂ reduces national welfare and employment by about 1.2 and 0.6 percent, respectively. Unilateral imposition of a carbon tax on South African exports has more negative impacts than imposing a domestic tax. Recycling through corporate taxes reduces the impact on GDP growth, while recycling through social grants offsets the negative impact on consumption of the bottom deciles. The inflationary impacts can be reduced by recycling through sales taxes. Similar results are produced for China by Liu and Lu (2015). They find small impacts on the Chinese economy. Production taxes reduce the impact on GDP. In the absence of effective recycling, a carbon tax, which causes a large emitter to decrease emission by 25 per cent, can cost 1 per cent of GDP (Farid et al. 2016).

⁸ Regulatory interventions such as emission rates or renewables standards can be less effective and more distortionary (Farid et al. 2016). However, they can have lower impact on prices. Regulation and standards can also increase prices by encouraging the purchase of more expensive but environmentally friendly products. Instruments such as feebates, which impose fees on emissions above some reference rate and provide rebates when emissions are below, have smaller impact on prices but are also less effective in curbing emissions (IMF 2019a). In emerging markets, which have less capacity to monitor and enforce, some regulatory interventions are likely to be ineffective in reducing carbon emissions.

efforts to reduce arbitrage and carbon leakage, it is important for those countries to opt-in to international coordination early in the process.⁹

Delayed or abrupt introduction of these policies to reduce carbon emissions or insufficient investment can generate large declines in asset prices, increases in stranded assets¹⁰ and cause financial instability, resembling a Minsky moment (Batten, Sowerbutts, and Tanaka 2016; Carney 2015). At the same time, higher energy prices are likely to increase inflationary pressures in the economy. These impacts fall directly within the remit of central bank policy.

2.2.2 Opportunities

The transition to a less carbon-intensive economy also presents opportunities. In addition to the future climate change avoided by reducing greenhouse gas emissions, climate change mitigation policies help to deliver positive externalities that increase output and reduce inflation. Potential benefits include technological spillovers, reduced dependence on natural resource sectors, enhanced energy security, and increased health through reduced air pollution (Krogstrup and Oman 2019). These co-benefits can create new jobs and new industries, increasing the medium-to-long-run benefits of mitigation (Groosman, Muller, and O'Neill-Toy 2011).

Policy can encourage the development of new technologies and these new technologies can reduce the transition costs. Better technologies increase the attractiveness of low or zero emissions options. For example, in electricity generation, rapid and largely unforeseen advances in wind and solar generation technologies have transformed power generation (Arndt et al. 2019). In South Africa, wind and solar have displaced coal as the least-cost source of power generation and should provide two thirds or more of total power by 2050 under least-cost power planning and ignoring all externalities (McCall et al. 2019). In transport, rapid advances in battery technology has been improving the cost-competitiveness of electric vehicles. Essentially all major vehicle manufacturers are rapidly introducing new electric vehicle models. As noted in the preceding section, a shift to these technologies entails substantial disruption, potentially requiring government interventions to deal with the closure of firms (Volz 2017).

On the mitigation side, the long-maintained assumption that the developed world would pilot new technologies and the developing world would then adopt those technologies with at least some lessons of experience learned may not hold. Developing countries are often well endowed with solar and wind resources and relatively less burdened with legacy investments in carbon-intensive industries, opening possibilities for a more leading role (Arndt et al. 2019).

In summary, climate change mitigation and adaptation will impact central bank policy through several financial and real economy channels. Central banks will likely face multiple climate change effects at particular times, often falling under the same policy mandate but requiring different policy responses. For example, relative price changes are key to driving a transition to a low-emissions economy, but they can also be inflationary. Addressing financial stability

⁹ Carbon leakage can worsen the short-term impacts as companies choose to leave and set their operations in countries with less stringent mitigation policies. Current leakage rates are not substantial (Fischer, Morgenstern and Richardson 2015). Some leakage can be addressed through border tax adjustment, which will increase inflationary pressures in the short to medium term. These adjustments are a particular threat for emerging and developing markets, which are not committed to mitigation, and may see the cost of their exports rise. In 2016, only 12 per cent of global carbon emissions were priced (Farid et al. 2016).

¹⁰ The estimated losses through stranded assets are between USD 1 trillion to USD 4 trillion for fossil fuel sectors and close to USD 20 trillion for other sectors (NGFS 2019).

risks can exacerbate the impact of climate change supply-side shocks, by, for example, limiting credit. These trade-offs are similar to what central banks deal with on a daily basis. Climate change, however, has the potential to increase the frequency and size of them, opening space for large policy errors. Central banks will have to be more effective in executing their mandates but also more flexible in their policy approach. At the same time, relative price signals need to be clear. A positive but low and stable inflation rate will clarify relative price signals and help to guide investment decisions.

3 Advanced versus developing economies

Climate change mitigation in emerging economies can have large positive benefits, not least because sunk costs in old technologies are low, but also because of demographic booms, especially in Africa, implying that the positive externalities and returns to investment in climate change could be significantly larger than in advanced economies. Ensuring sustainable flows of capital to emerging and developing economies, however, will require countries to maintain macroeconomic stability, use fiscal space well, and enable clear pricing of positive and negative climate change externalities.

Compared to advanced economies, many emerging and all developing countries have relatively less fiscal and monetary space or the domestic savings to fund the climate change transition and to manage adaptation costs. Emerging and developing economies have higher inflationary rates than developed economies. Average inflation rate in advanced economies was 1.7 per cent over the period 2001 to 2019, compared to 6 per cent for emerging and developing economies.

Despite lower debt-to-GDP ratios, emerging and developing economies face higher borrowing costs and lower credit ratings (Table 1). This requires stricter fiscal and macro discipline to avoid macroeconomic volatility and to keep non-resident savings invested locally.

Financing space is required for economies to build infrastructure to facilitate stronger economic growth and to reasonably deal with mitigation and adaptation. Infrastructure, institutional and financial development gaps all suggest that capacity to develop and implement policies to channel investment is limited, and indeed the risk is high of failing to match capital to mitigation and adaptation needs. Limited financial sector development is also likely to increase vulnerability and impair capital allocation.¹¹ Emerging markets do not feature in the top 20 most financially developed economies according to the IMF financial development index.¹² Liquidity constraints are tighter and banks are less able to deal with shocks to their balance sheets or to provide funding to insurance companies in need.

Most emerging and developing economies have shifted in recent times to prudent, sustainable macroeconomic policies. Climate change will test those settings as climate shocks place stress on relative prices, as adaptation requires more investment and adjustment, and as the increasingly global view of climate raises the prospect of larger capital flows.

¹¹ There are, however, significant differences across emerging and developing economies. Countries such as South Africa are more financially developed than other emerging markets and even some advanced economies. On balance, the level of financial development is lower in emerging than advanced economies.

¹² For more information on the IMF's Financial Development Index see <https://data.imf.org/?sk=F8032E80-B36C-43B1-AC26-493C5B1CD33B>.

Table 1: Credit ratings for selected countries (as of May 2020)

Country	MOODY'S		S&P	
	Foreign	Domestic	Foreign	Domestic
UK	Aa2	Aa2	AA	AA
USA	Aaa	Aaa	AA+	AA+
Japan	A1	A1	A+	A+
Finland	Aa1	Aa1	AA+	AA+
France	Aa2	Aa2	AA	AA
Germany	Aaa	Aaa	AAA	AAA
Brazil	Ba2	Ba2	BB-	BB-
Chile	A1	A1	A+	AA-
Colombia	Baa2	Baa2	BBB-	BBB
Mexico	Baa1	Baa1	BBB	BBB+
Peru	A3	A3	BBB+	A-
Czech Republic	Aa3	Aa3	AA-	AA
Egypt	B2	B2	B	B
Hungary	Baa3	Baa3	BBB	BBB
Israel	A1	A1	AA-	AA-
Poland	A2	A2	A-	A
Russia	Baa3	Baa3	BBB-	BBB
Saudi Arabia	A1	A1	A-	A-
South Africa	Ba1	Ba1	BB	BB+
Turkey	B1	B1	B+	BB-

Source: Bloomberg

4 Policy goals and levers

This section discusses several central bank interventions that have been raised in the emerging literature. Central banks, particularly those in advanced economies, are encouraged to change their monetary policy frameworks to tolerate higher inflation rates, support the development and use of green assets through changes in macro prudential regulation and green quantitative

easing (QE), provide funding for green investment and ensure greater climate change disclosure by financial and non-financial firms.¹³

4.1 Monetary policy

4.1.1 Monetary policy framework

A stable and moderate inflation rate is sometimes thought of as ‘grease in the wheels’ where real rigidities in price determination exist, facilitating a positive relationship between inflation and growth. In this conception, relative price adjustments are facilitated, creating some useful money illusion. Along these lines, some economists have made the case for more inflationary approaches to monetary policy to help prevent large relative price shocks from reducing growth. McKibbin et al. (2017), for example, argues that nominal GDP- and income-targeting would better protect economic activity, given expected price volatility associated with mitigation interventions and output gap uncertainty.

Nominal GDP-targeting, an approach that has gained favour in advanced economies with sticky deflation, seems especially unhelpful in emerging market contexts, where clarity of pricing will help to guide investment.¹⁴ The view behind this paper is that where inflation tends to be high, alternatives to inflation-targeting are unlikely to be helpful.

For many emerging and developing economies, low and stable inflation creates wide-ranging benefits that go far beyond any gains that might occur from obscuring relative price movements. These include having clear nominal anchors, lower inflation premia and interest rates, better access to foreign saving, and better protection from global shocks, among other benefits. More broadly, giving up the credibility and transparency benefits of inflation-targeting frameworks will reverse a range of important gains achieved by a large number of emerging economies.

Technical clarity has also been an important benefit of inflation targeting frameworks, in particular in estimating potential growth rates. This has benefits for how central banks will need to assess the economic effects of climate change and measure relative price movements. Relatively low and stable inflation and overall macroeconomic stability should support the transition, by reducing social discount rates and supporting green investment in adaptation and mitigation projects, which are turned to below.

4.1.2 Central banks and the social discount rate

Most institutions continue to use measures of the social discount rate that rely on market rates to quantify the marginal rate of time preference or the social cost of capital (Campos, Serebrisky, and Suárez-Alemán 2015; Nordhaus 2007).¹⁵ As such, central banks can do something about social discount rates, which play an important role in determining the viability of climate related investments. Higher social discount rates make climate-related investment

¹³ See, for example, Dikau and Volz (2019b).

¹⁴ See, for example, Frankel (2012), Creamer and Botha (2017), Hassan and Loewald (2013) and Andersson and Claussen (2017).

¹⁵ There is little consensus in the economic literature on how to calculate the social discount rate. In the absence of distortions, the market interest would be the appropriate interest rate. There are always distortions, however, and two alternative and very different approaches have emerged. The descriptive approach is based on exponential discounting. The alternative approach focuses on intergenerational equity. Equity considerations reduce the social discount rate significantly as the wellbeing of future generations is considered more important. This approach, however, generates large discrepancies between the market cost of funding and the social discount rate, making it less useful for many savings constrained emerging and developing economies.

less attractive. This reflects long payback periods as well as smaller returns if environmental benefits are excluded.¹⁶

The structure of interest rates includes inflation expectations and inflation risk premium. In line with their main mandate, central banks in emerging and developing economies can reduce market interest rates by reducing inflation expectations and the inflation risk premium, hence reducing the social discount rate. This supports greener investment, which can have longer payback periods. Reducing volatility, of both GDP and inflation, provides certainty, which also supports a lower social discount rate.

4.1.3 Green QE

Excessive use of balance sheet operations to support green investment has the potential to destabilize economies and generate hyperinflationary episodes, depending on the degree of interventions. At the same time, small scale purchases as part of the ordinary operations of a central bank can support green investment and the development of markets for green assets.¹⁷ These purchases will substitute for other asset classes on the balance sheet of central banks, particularly government bonds. This will test the independence of central banks as governments, facing fiscal pressures, object to these policies.

Large-scale purchases (green QE) are substantially more dangerous if used under the wrong conditions or by countries which have weak institutions, low levels of financial development and limited macroeconomic policy credibility. The experience with unconventional monetary policy after 2008 provides some useful insights when these policies should be used and their likely impacts.

Only seven central banks engaged in large-scale asset purchase programmes after the 2008 financial crisis, with Mexico being the only emerging market economy involved.¹⁸ No developing economies engaged in large-scale asset purchase programs. The conditions confronting these seven countries included policy rates stuck at the effective lower bound (also known as the zero lower bound); deflation and falling inflation expectations, increasing real rates and real value of debt (exacerbating credit constraints for consumers and businesses)¹⁹; recessionary conditions; and financial sectors in distress (banks were unable to intermediate and provide credit) (Borio and Zabai 2018). These seven countries also have strong economic institutions (including independent central banks) and credible macroeconomic policy. In other countries, the use of such policies can easily become a tool to fund large fiscal deficits, generating hyper-inflationary episodes (Sargent 1982). Even appropriate use of these policies can generate uncertain results and deliver some unintended consequences.^{20,21} The best option

¹⁶ See Campos, Serebrisky, and Suárez-Alemán (2015) for a comprehensive review of the literature on social discount rates.

¹⁷ A few central banks, such as the French one, have managed their balance sheets in a way to highlight their high level of climate change responsibility. Recently, Sveriges Riksbank sold bonds issued by the Canadian state of Alberta and the Australian states of Queensland and Western Australia, as they supported high greenhouse gas emissions activities.

¹⁸ The others were the central banks of England, Japan, the United States, Euro Area, Switzerland and Sweden.

¹⁹ Under these circumstances increasing money supply and inflationary pressures in the economy is positive for economic activity.

²⁰ Estimates for the different programmes vary from a very small reduction in yields to a reduction of more than 100 bps. The impact on inflation and output is positive but the range of estimates is very wide. The empirical evidence suggests that in some countries the programmes have reduced bond-trading volumes and caused price dislocation of specific bonds. Other unintended effects include excessive risk-taking, compression of interest rate margins and profitability of banks, excessive reliance on central bank funding, higher levels of moral hazard as investors expect central bank bailouts, and misallocation of capital (CGFS 2019)

²¹ Related proposals include for central banks to use their balance sheets to provide guarantees for large green investment loans or to provide funding lines to commercial banks for funding of low-carbon projects (Aglietta, Espagne, and Perrissin-Fabert

for many emerging economies and all developing countries is to improve institutions and macroeconomic policy credibility before considering green QE.

4.1.4 Reserve requirements

The last proposal discussed under monetary policy interventions is changes to reserve requirements to support green investment. Reserve requirements play a role in operationalizing monetary policy in a cash reserve system. Reserve requirements are also used as a micro prudential tool and a liquidity management tool. Supporters of using the reserve requirements to encourage green lending argue that banks with greener, less carbon-intensive assets should be required to hold less reserves. Another proposal is to have central banks accept carbon certificates, which are linked to loan concessions for low-carbon projects, as legal reserves (Dikau and Volz 2019b).

Many emerging and developing economies are still operating cash reserve systems, but the number is decreasing. Changes to reserve requirements in support of green investment is a less effective tool for two main reasons. Firstly, in the modern financial system, deposit creation is driven by lending. This process is mainly constrained by profitability and solvency considerations (Kumhof and Jakab 2015). This, along with changes to financial regulation and supervision, has reduced the effectiveness of reserve requirements. Secondly, central banks are also not able to change the reserve requirements and the price of reserves at the same time. Changing the reserve requirement increases the volatility of market rates, increasing uncertainty (Campiglio 2016).

A more effective way for central banks to encourage the use of green assets by the financial sector is to include green assets as a collateral option when commercial banks borrow from the central bank. This again improves relative price signals in the economy and reduces the bias of the financial system towards government bonds.

4.2 Financial regulation

4.2.1 Macroprudential regulations

Macroprudential regulations affect the relative returns of assets and their maturity structure. Changes to certain macroprudential tools can facilitate the greening of the economy by improving relative price signals, without compromising financial stability. Requiring financial institutions to account for climate risk in the calculation and measurement of financial sector risk as part of their Basel III requirements is a positive step, with the potential to both enhance the stability of the financial system and improve relative price signals in the economy.²² The next section discusses disclosure proposals in more detail.

A more controversial proposal is changes to risk weights to reduce the risk profile of green assets relative to other asset classes or penalize ‘brown’ assets in the calculation of macroprudential ratios (Bolton et al. 2020). These changes also have the potential to improve price signals in the economy and financial stability, but only if green assets truly have lower risk profiles (Carney 2015). For some emerging and developing economies, macroprudential regulations are skewed towards government bonds with a low credit rating and liquidity. In this case, green asset classes provide an attractive alternative to foreign investors, which also

2015; Dasgupta, Hourcade, and Nafo 2019). Depending on the scale, these face the same challenges as the green QE programme and are likely to undermine the independence of the central bank as demand for other types of policies increases.

²² The requirements to take into account climate-related risks in financial sector risk assessments and improved disclosure will have to be incorporated into Pillar 1, Pillar 2 and Pillar 3 of the Basel III regulations (NGFS 2019).

enhances the stability of the financial system. Greater roles for green bonds can also address unintentional bias of the macroprudential regulations towards ‘brown’ investments. For example, the Net Stable Funding ratio unintentionally penalizes longer-term investments by making longer term lending more expensive. Many adaptation and mitigation investments have longer payback periods. Central banks need to consider ways to reduce this bias either directly or indirectly by improving market access for green bonds.

4.2.2 Disclosure

Central banks have an important role in reducing market frictions such as asymmetric information and adverse selection. These affect market efficiency, push borrowing costs up and amplify the impacts of financial crises (Mishkin 1990). By participating in efforts to increase disclosure of climate-related risks, central banks in emerging and developing economies can support adaptation and mitigation efforts, while also improving market efficiency and financial stability.

Table 2: TCFD disclosure by region (per cent responses)

Recommendation	Recommended Disclosure	Asia Pacific (484)	Europe (363)	Middle East and Africa (83)	North America (163)	South America (33)
Governance	Board oversight	23	36	26	20	17
	Management's role	27	44	22	21	13
Strategy	Risks and opportunities	29	59	24	51	39
	Impact on organisation	44	61	23	40	41
	Resilience of strategy	5	13	3	7	4
Risk management	Risk ID and assessment processes	23	45	17	26	18
	Risk management processes	22	41	16	33	32
	Integration into overall risk management	10	24	7	8	8
Metrics and targets	Climate-related metrics	39	62	18	38	36
	Scope 1,2,3 GHG emissions	25	48	13	37	33
	Climate-related targets	32	58	17	33	34

Note: The number in parentheses represents the size of the review population

Source: TCFD (2019)

The Network for Greening the Financial System identifies two important steps. In the first, central banks identify climate-related risks to the financial system. This step requires the development of indicators for climate-related risks and stress-testing of the financial system. The second step involves the integration of climate-related risks into financial supervision. Central banks need to set supervisory expectations, regarding how institutions should monitor and manage financial risks associated with climate change events. This process is similar to the current BASEL III process.

The Task Force on Climate-Related Disclosure (TCFD) has developed one of the larger voluntary disclosure systems.²³ Companies need to describe the impact of climate-related events on four aspects of their operation: governance, strategy, risk management, and, metrics and targets (TCFD 2017).²⁴ Disclosure requirements are becoming more common across jurisdictions but there are large differences in reporting.²⁵ The 2019 TCFD survey results indicate that firms in emerging and developing economies are far behind firms in advanced economies (see table 2). More disclosure by emerging and developing economies will assist with valuation of companies, inform investment decisions and improve capital allocation and productivity (Carney 2015; Krogstrup and Oman 2019). More importantly, it will help with attracting green funding.

4.2.3 Prescribed assets

Prescribed assets policies can provide a source of funding for green investment by requiring that a certain portion of domestic assets is used for green investment. This proposal can improve the allocation of capital, but it depends on how the proposal is designed and implemented. These schemes can easily become a funding tool for badly-designed industrial policy, lead to large transfers to politically connected people, and cause loss of central bank independence and financial repression of savers (Dikau and Volz 2019a). Asset substitution effects in prescribed asset portfolios can reduce the demand for government bonds, causing governments to oppose the scheme.

4.3 Developing classifications of green assets and activities

Many of the proposal discussed above require the presence of green assets. Internationally accepted norms for green assets, however, are still missing despite some progress (Breedon 2018). The only green assets that we can measure accurately are green bonds. Their issuance cost is similar to that of conventional bonds at the moment, but their liquidity is still low (IMF 2019b).²⁶ The OECD estimates that green bond annual issuance has the potential to reach between USD 620–720 billion and USD 4.7–5.6 trillion in outstanding securities by 2035 (OECD 2017).

Central banks in emerging and developing economies should support efforts to develop classifications of green assets and activities. Classifications should be customized to local conditions but they should also be based on international norms to assess risks across jurisdiction and ensure a level playing-field (NGFS 2019). More universal classifications are more likely to attract foreign buyers of domestic assets.²⁷

²³ As of 2019, the organization has the support of 785 companies and other organizations, of which 374 are financial companies. These are based in advanced and emerging markets. The reporting is supported by 36 central banks and supervisors (TCFD 2019).

²⁴ There are various other disclosure schemes, including the Carbon Standards Disclosure Board, Integrated Reporting, the Carbon Disclosure Project, and the UN Principles for Responsible Investment. A critical challenge is that various schemes have different legal status, cover different environmental issues, and have different requirements in terms of level of disclosure. The absence of universal disclosure rules hinders the proper assessment of climate-related risks and it also create arbitrage opportunities for greater risk-taking in jurisdictions with lower disclosure requirements (TCFD 2019).

²⁵ In some countries there are non-binding disclosure requirements, while others are opting for compulsory disclosure of a specific set of quantitative and qualitative data (NGFS 2019).

²⁶ The Climate Bonds Initiative is involved in the certification of green bonds and the development of green markets. They provide several examples of green bonds. See <https://www.climatebonds.net/>. China has progressed significantly in developing green assets. The Chinese central bank issued Guidelines for Greening the Financial System in 2016 and has recently established a group to standardize green finance definitions.

²⁷ For more information on measures to facilitate the development of green markets see Carney (2016).

4.4 Policy overreach and policy coordination

Central banks do not have the tools to address directly climate change-related market failures (Dikau and Volz 2019a; Volz 2017). Their interventions can only be effective as part of a well-coordinated national and international strategy. On a national level, coordination with fiscal policy is critical to implement measures in support of green investment, provide funding space for green assets, and maintain macro stability. In the absence of this coordination, central banks risk taking over the policy space of government departments and agencies (“mission creep”). Additionally, expanding the central bank mandate can reduce central bank accountability, reduce policy independence, and overburden central banks’ existing mandates (Bolton et al. 2020).

International policy coordination is important to agree on common definitions and standards and share knowledge. For central banks in emerging and developing economies, this coordination can also assist with capacity-building. As stated above, developing more universal classifications and disclosure rules can attract higher levels of green funding. Participating in international debates is equally important to develop policy recommendations, which reflect the realities in emerging and developing economies.

5 Central Banks, Economic Modelling, and Climate Change

A key contribution of central banks in confronting climate change is likely to be through analytical efforts to understand the implications of climate change. Efforts by central banks to better comprehend the economic implications of climate change should inform the conduct of monetary policy, general policy formulation in government, and the decisions of market participants, notably investors and financial institutions. A major component of central banks’ efforts to develop and disseminate information on the implications of climate change will be via modelling efforts. Rather than enter into details of and debates over specific models, it may be more valuable to identify basic properties of models that will help central banks come to grips with climate change. Here, three properties are focused on.

First, climate change highlights the real economy in general and the supply side in particular. Effective climate change mitigation, implying a shift to net zero or net negative emissions over the next three decades, has strong implications for energy, industrial processes, transport, agriculture, and forestry, and, in turn, for prices, output and financial stability. On the impacts and adaptations side, climate change augments the profile of supply-side shocks (such as the Australian fires of 2020).

Second, treatment of risk and uncertainty should play a prominent role in modelling efforts by central banks. The fundamental distributions of events are shifting. Globally, the world is becoming warmer and with more precipitation in aggregate. Alongside changes in expected or average outcomes, these changes shift distributions of events of strong interest to central banks, such as the frequency and intensity of cyclones, locust storms, wildfires, flooding, high heat, and drought. The likely existence of tipping points, increasing the probability of catastrophic events, further complicates matters (Krogstrup and Oman 2019). Low-probability events with high impact (catastrophic outcomes or green swans as labelled by Bolton et al. (2020)) are difficult to model precisely because they are rarely observed. Tipping-point thresholds that have never been crossed are even more challenging to model appropriately. Nevertheless, trends towards more frequent and/or more intense extreme events are highly relevant to current decision-making. Effectively grappling with these and other uncertainties is a key role for central banks starting today (Bolton et al. 2020). Simply pointing them out is a start.

Finally, the nature of climate change demands greater accent on structural models that build from first principles as opposed to statistically estimated reduced form models that rely on historical patterns/experience. The nonergodic nature of economic time series has long had fundamental implications, which central banks had to confront (see, for example, Weitzman, (2007)). Climate change puts even greater accent on fundamental changes in structure driven by climate change itself and the policies to limit it.

Alternatively put, climate change pushes central banks to adopt modelling frameworks that emerge or are adapted from integrated assessment model (IAM)²⁸ traditions, especially those with the properties listed above. In some ways, these approaches are very different from current tools typically applied by central banks. Specifically, IAMs are longer-term, supply side-oriented and structural. Other key aspects are closely related to issues that central banks treat on a daily basis, at least conceptually. These aspects include appropriate treatment and communication of risk and uncertainty and tracing the implications and adjustment paths of economic shocks. From the perspectives of central banks, IAMs are not suited for monetary policy and financial stability analysis as they have no balance sheet information or short-term cyclical dynamics. At the same time, central banks' models, such as dynamic stochastic general equilibrium (DSGE) models, have no climate change dynamics.²⁹ Figuring out how to get these two modelling universes to communicate to one another in ways that illuminate decisions relevant to the policy levers is a priority task.

5.1 Options

All models are subject to criticism, but they can be useful in managing information and understanding the impact of multiple mechanisms operating simultaneously. So, what models should central banks in emerging and developing economies use, given their capacity constraints? Some options are outlined below.

5.1.1 Modifying computable general equilibrium models within IAM frameworks.

The most advanced IAM frameworks deploy computable general equilibrium (CGE) models for the analysis of economic implications. These CGE models in IAM frameworks can be judiciously modified to include cyclical and financial sector dynamics where appropriate. For example, Makrelov et al. (2020) show how CGE models can be changed to incorporate balance sheets and financial sector dynamics based on the theoretical mechanisms developed by Woodford (2010) and Borio and Zhu (2012). Elements of these models can be incorporated into the CGE models deployed in IAM frameworks. A major drawback is that this type of models requires detailed balance sheet information, which is often not available in emerging and developing economies. Some progress has been made through the IMF's Data GAP Initiative³⁰, but the focus has been mainly on the G20 countries. Incorporating financial markets dynamics will require some simplifications³¹ in the real side of the current CGE models to

²⁸ Integrated assessment models have been the main tool used in the analysis of climate change impacts on the economy. IAMs represent a broad tent describing an array of approaches. For more information on IAMs and their structure see Weyant (2017) and Pindyck (2013).

²⁹ Central banks also use various smaller than DSGE models and macro-econometric models, which are based on co-integrating relationships. More recently, central banks in advanced economies have started to use 'hybrid' models, which incorporate elements of large macro-econometric models and DSGE models (see, for example, Gervais and Gosselin (2014)). These also have no climate change dynamics.

³⁰ For more information on the G20 Data Gap Initiative see <https://www.fsb.org/2019/10/g20-data-gaps-initiative-dgi-2-the-fourth-progress-report-countdown-to-2021/>.

³¹ For example, this can include reduction in the number of sectors and goods and services.

reduce complexity and increase tractability. The models share some of the characteristics of DSGE models and can incorporate some of the dynamics important to central banks.

5.1.2 Link models

Rather than merging models together, an attractive option is to use current climate models, plus associated economic models, and feed their outputs into the standard central bank macroeconomic and financial stability models. In effect, this essentially lengthens the IAM modelling chain by appending analytics relevant to central banks. This is the approach in many advanced economies. The approach is simpler and less resource-intensive. And, in most emerging and developing economies, models are available to assess impact in important domains such as agriculture, infrastructure, and water resources.

5.1.3 Deploy sector-specific models

Many questions related to climate change are best addressed using sector-specific models. For example, in seeking to understand decarbonization pathways and how these choices may impact inflation, output and other indicators, the best choice is to make recourse to energy-planning models. These exist and are widely used globally but are still fairly complex. Some of the energy-planning models have been linked to macroeconomic models (e.g., Arndt et al. (2016)). Similarly, models can be developed to link how these energy choices may impact specific industries and their associated financial assets.

5.1.4 Additional considerations

Technical change has dramatically lowered the standard economic costs associated with mitigation, especially the most logical first steps (e.g., Arndt et al. (2019)). With the costs of inaction rising and the costs of action falling, a consensus has emerged that action on climate change is overdue (e.g. IPCC (2018)). The focus of modelling has thus shifted to answering questions such as how to rapidly decarbonize the electricity generation system? How to electrify transport? What are key adaptation investments to be made in the relatively near term? How to minimize transition costs? What new institutional frameworks are required under emerging new paradigms? What are distributional implications of these transitions? What is the political economy of transition? And so forth. Rigorous assessments of many of these questions must consider risk and apply appropriate discount rates. Nevertheless, the days of weighing large current costs to avoid larger costs 80 years into the future, where discounting very frequently dominates, are largely gone. Instead, central banks confront a current reality of impacts, adaptations, and ongoing structural change associated with mitigation.

5.2 Building capacity to confront climate change

Developing and maintaining the full suite of models necessary to confront climate change will be costly and resource-intensive. Hence, for many emerging and developing economies, there is a compelling logic for developing broad collaborations within the public and private sectors as well as with regional and international institutions. For example, there is no reason for central banks to run their own general circulation model of the earth and atmosphere. However, there is a need for a subset of personnel within central banks to understand the strengths and weaknesses of these models in order to be able to intelligently deploy their outputs.

Economies will differ in relative priorities and hence in the shape of networks that should be in focus. The Vietnamese economy is highly vulnerable to the combination of sea-level rise and cyclone strike. The South African economy is not (though neighbouring Mozambique is exposed). The Vietnamese central bank should be especially attuned to this vulnerability. In South Africa, the incremental pressures that the combination of rapid technical advance in renewable energy generation with excellent renewable energy endowments (sun and wind) are

adding to the financial position of the state electricity utility are currently high priority. These divergent needs demand different forms of collaboration.

Nevertheless, the general guidance to develop appropriate modelling networks is clear. Central banks should include universities and research centres, while at the same time developing bridges for themselves and their collaborators into international networks. International model and research networks such as the Central Bank Research Association and the Euro Area Business Cycle Network provide examples of international networks. A different model is to anchor a regional or a domestic network around an institution, which has significant experience in modelling the economics of climate change in developing countries such as the International Food Policy Research Institute.

5.3 Data

Building new frameworks requires data. Current data gaps are large in advanced economies and even larger in emerging and developing markets. Central banks have significant statistical wings and ability to collect data. Advances in technology allow for easier collection of administrative data and its management. Central banks should develop their data capabilities to collect financial data, which can support mitigation and adaptation. Currently, The Network for Greening the Financial System has an initiative to identify the major data gaps. Central banks should also incorporate climate change factors in the compilation of official statistics, which will increase awareness of climate risks.³²

6 Conclusions

Emerging and developing economies are likely to be affected by climate change more than advanced economies. This reflects their location and climate dependence as well as their institutional and structural characteristics. These factors also limit the ability of central banks to respond to climate change, rendering the tools that are available more important.

Many emerging and developing economies are savings-constrained; as a result, much adaptation and mitigation funding will come from outside. For many of these countries, the best and only available macro policy option to attract funding is maintaining macroeconomic stability, using fiscal space well, and enabling clear pricing of positive and negative climate change externalities by maintaining low and stable inflation.

An important part of a central bank's role in dealing with adaptation and mitigation is improving information flows. This includes not only developing disclosure rules but also generating analytical work to inform policy and market decisions. This will require the development of new models by central banks. These models (or set of models) need to improve on the specification of risk, climate change supply-side shocks, and financial sector dynamics. It will also require new research agendas, building on the ideas discussed in this paper and focusing on specific emerging and developing regions.

³²See for example UN's *Climate Change Statistics at the global level* presentation available here <https://unstats.un.org/unsd/statcom/49th-session/side-events/documents/20180307-1M-UNSD-Global-work-on-climate-change-indicators-13Feb2018.pdf>

References

- Aglietta, M., Espagne, E. and Perrissin-Fabert, B. 2015. A proposal to finance low carbon investment in Europe. France Stratégie: Paris.
- Alton, T., Arndt, C., Davies, R., Hartley, F., Makrelov, K., Thurlow, J. and Ubogu, D. 2014. Introducing carbon taxes in South Africa. *Applied Energy* 116: 344-54.
- Andersson, B., and Claussen, C.A. 2017. Alternatives to inflation targeting. *Sveriges Riksbank Economic Review* 1: 51-82.
- Arndt, C., Arent, D., Hartley, F., Merven, B. and Mondal, A.H. 2019. Faster than you think: Renewable energy and developing countries. *Annual Review of Resource Economics* 11: 149-68.
- Arndt, C., Chinowsky, P., Fant, C., Paltsev, S., Schlosser, C.A., Strzepek, K., Tarp, F. and Thurlow, J. 2019. Climate change and developing country growth: The cases of Malawi, Mozambique, and Zambia. *Climatic Change* 154(3-4): 335-349.
- Arndt, C., Davies, R., Gabriel, S., Makrelov, K., Merven, B., Hartley, F. and Thurlow, J. 2016. A sequential approach to integrated energy modeling in South Africa. *Applied Energy* 161: 591-99.
- Arndt, C., McKay, A. and Tarp, F. 2016. Growth and poverty in Sub-Saharan Africa. Oxford University Press. Available at: <http://fdslive.oup.com/www.oup.com/academic/pdf/openaccess/9780198744795.pdf>.
- Batten, S. 2018. Climate change and the macro-economy: A critical review. DOI: 10.2139/ssrn.3104554
- Batten, S., Sowerbutts, R. and Tanaka, M. 2016. Let's talk about the weather: The impact of climate change on central banks. DOI: 10.2139/ssrn.2783753.
- Bolton, P., Desprez, M., Pereira da Silva, L.A., Samama, F. and Svartzman, R. 2020. The green swan: Central banking and financial stability in the age of climate change. Bank for International Settlements. Available online at <https://www.imperial.ac.uk/business-school/faculty-research/research-centres/centre-climate-finance-investment/research/green-swan-climate/>.
- Borio, C. and Zabai, A. 2018. Unconventional monetary policies: A re-appraisal. BIS Working Papers 570, Bank for International Settlements.
- Borio, C., and Zhu, H. 2012. Capital regulation, risk-taking and monetary policy: A missing link in the transmission mechanism? *Journal of Financial Stability* 8: 236-51.
- Breeden, S. 2018. The shared response to climate change: Turning momentum into action. Speech, available online at <https://www.bankofengland.co.uk/speech/2018/sarah-breeden-remarks-to-the-green-finance-initiative-and-green-finance-committee>. Bank of England.
- Campiglio, E. 2016. Beyond carbon pricing: The role of banking and monetary policy in financing the transition to a low-carbon economy. *Ecological Economics* 121: 220-30.
- Campos, J., Serebrisky, T. and Suárez-Alemán, A. 2015. Time goes by: Recent developments on the theory and practice of the discount rate. Inter-American Development Bank. Available

online at <https://publications.iadb.org/en/publication/17020/time-goes-recent-developments-theory-and-practice-discount-rate>.

Carney, M. 2015. Breaking the tragedy of the horizon – climate change and financial stability. Speech, available online at <https://www.bankofengland.co.uk/speech/2015/breaking-the-tragedy-of-the-horizon-climate-change-and-financial-stability>. Bank of England.

Carney, M. 2016. Resolving the climate paradox. Speech, available at <https://www.businessgreen.com/opinion/2471831/mark-carney-speech-in-full-resolving-the-climate-paradox>. Bank of England.

CGFS [Committee on the Global Financial System]. 2019. Unconventional monetary policy tools: A cross-country analysis. Report prepared by a Working Group chaired by Simon M. Potter (Federal Reserve Bank of New York) and Frank Smets (European Central Bank). Available at <https://www.bis.org/publ/cgfs63.htm>.

Creamer, K., and Botha, R.T. 2017. Assessing nominal GDP targeting in the South African context. *Central Bank Review* 17: 1-10.

Crespo Cuaresma, J., Hlouskova, J. and Obersteiner, M. 2008. Natural disasters as creative destruction? Evidence from developing countries. *Economic Inquiry* 46: 214-26.

Dasgupta, D., Hourcade, J.-C. and Nafo, S. 2019. A climate finance initiative to achieve the Paris agreement and strengthen sustainable development. Centre International de Recherche sur l'Environnement et le Développement. Available online at <https://hal.archives-ouvertes.fr/hal-02121231>.

Dell, M., Jones, B.F. and Olken, B.A. 2014. What do we learn from the weather? The new climate-economy literature. *Journal of Economic Literature* 52: 740-98.

Deryugina, T. and Hsiang, S.M. 2014. Does the environment still matter? Daily temperature and income in the United States. National Bureau of Economic Research Working Paper No. 20750. Online at https://www.nber.org/papers/w20750?utm_campaign=ntw&utm_medium=email&utm_source=ntw.

Dikau, S. and Volz, U. 2019a. Central bank mandates, sustainability objectives and the promotion of green finance. Online at <https://ideas.repec.org/p/soa/wpaper/222.html>.

Dikau, S. and Volz, U. 2019b. Central banking, climate change, and green finance. In Sachs, J.D. et al. (eds), *Handbook of Green Finance: Energy Security and Sustainable Development*. Asian Development Bank.

Fankhauser, S. and Tol, R. 2005. On climate change and economic growth. *Resource Energy Economics* 27: 1-17.

Farid, M., Keen, M., Papaioannou, M., Parry, I., Pattillo, C. and Ter-Martirosyan, A.. 2016. After Paris: Fiscal, macroeconomic, and financial implications of climate change. International Monetary Fund Staff Discussion Note.

Fischer, C., Morgenstern, R. and Richardson, N.. 2015. Carbon taxes and energy-intensive trade-exposed industries: impacts and options. In Parry, I., Morris, A. and Williams, R.C. (eds), *Implementing a US carbon tax*. Online at

<https://www.taylorfrancis.com/books/e/9781315747682/chapters/10.4324/9781315747682-18>.

Frankel, J. 2012. Inflation targeting is dead. long live nominal GDP targeting. Vox. Online at <https://voxeu.org/article/inflation-targeting-dead-long-live-nominal-gdp-targeting>.

Gervais, O. and Gosselin, M-A. 2014. Analyzing and forecasting the Canadian economy through the LENS model. Bank of Canada. Online at <https://www.bankofcanada.ca/2014/07/technical-report-102/>.

Groosman, B., Muller, N.Z. and O'Neill-Toy, E. 2011. The ancillary benefits from climate policy in the United States, *Environmental Resource Economics* 50: 585-603.

Hassan, S., and Loewald, C. 2013. Nominal GDP targeting and the monetary policy framework. South African Reserve Bank Working Papers 5965.

Headey, D.D. 2014. Food prices and poverty reduction in the long run. International Food Policy Research Institute Discussion Paper No 1331.

Headey, D.D. and Martin, W.J. 2016. The impact of food prices on poverty and food security, *Annual Review of Resource Economics*, 8: 329-51.

Hsiang, Solomon M, and Amir S Jina. 2014. The causal effect of environmental catastrophe on long-run economic growth: Evidence from 6,700 cyclones. National Bureau of Economic Research, USA. Working Paper No. 20352. Online at <https://www.nber.org/papers/w20352>.

IEA [International Energy Agency]. 2014. *World Energy Outlook*. International Energy Agency, Paris.

IFS. 2018. *Protecting growing prosperity: Agricultural insurance in the developing world*. Online at <https://www.rafllearning.org/post/protecting-growing-prosperity-agricultural-insurance-the-developing-world>.

IMF [International Monetary Fund]. 2019a. *Fiscal monitor: How to mitigate climate change*. International Monetary Fund: Washington DC, USA. Online at <https://www.imf.org/en/Publications/FM/Issues/2019/10/16/Fiscal-Monitor-October-2019-How-to-Mitigate-Climate-Change-47027>.

IMF [International Monetary Fund]. 2019b. Global financial stability report. International Monetary Fund, Washington DC, USA.

IPCC [Intergovernmental Panel on Climate Change]. 2014. Climate Change 2014: Synthesis Report Summary for Policymakers. Intergovernmental Panel on Climate Change, Geneva. Online at http://pure.iiasa.ac.at/id/eprint/11055/1/ipcc_wg3_ar5_summary-for-policymakers-1.pdf.

IPCC [Intergovernmental Panel on Climate Change]. 2018. Summary for Policymakers. In: Global warming of 1.5°C. An IPCC special report on the impacts of global warming of 1.5°C above Pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change. Intergovernmental Panel on Climate Change, Geneva.

Kahn, M.E., Mohaddes, K., Ng, R.N.C., Hashem Pesaran, M., Raissi, M, and Yang, J-C. 2019. Long-term macroeconomic effects of climate change: A cross-country analysis.

- International Monetary Fund Working Paper. Online at <https://www.imf.org/en/Publications/WP/Issues/2019/10/11/Long-Term-Macroeconomic-Effects-of-Climate-Change-A-Cross-Country-Analysis-48691>.
- Kelly, P., Ruch, W., Ruch, F. and Matlhatsi, R. 2018. Inflation in a time of inequality: Assessing the relevance of cost of living measures for the poor. Paper prepared for the Meeting of the Group of Experts on Consumer Price Indices 7-9 May 2018, Geneva.
- Klomp, J. 2014. Financial fragility and natural disasters: An empirical analysis. *Journal of Financial Stability* 13: 180-92.
- Krogstrup, S. and Oman, W. 2019. Macroeconomic and financial policies for climate change mitigation: A review of the literature. International Monetary Fund. Online at <https://www.imf.org/en/Publications/WP/Issues/2019/09/04/Macroeconomic-and-Financial-Policies-for-Climate-Change-Mitigation-A-Review-of-the-Literature-48612>.
- Kumhof, M. and Jakab, Z. 2015. Banks are not intermediaries of loanable funds – and why this matters. Bank of England Working Paper No. 529.
- Lesk, C., Rowhani, P. and Ramankutty, N. 2016. Influence of extreme weather disasters on global crop production. *Nature* 529: 84.
- Liu, Y. and Lu, Y. 2015. The economic impact of different carbon tax revenue recycling schemes in China: A model-based scenario analysis. *Applied Energy* 141: 96-105.
- Makrelov, K., Arndt, C., Davies, R. and Harris, L. 2020. Balance sheet changes and the impact of financial sector risk-taking on fiscal multipliers. *Economic Modelling* 87: 322-43.
- McCall, B., Burton, J., Marquard, A., Hartley, F., Ahjum, F., Ireland, G. and Merven, B. 2019. Least-cost integrated resource planning and cost-optimal climate change mitigation policy: Alternatives for the South African electricity system. Energy Research Centre, University of Cape Town, Cape Town, South Africa.
- McKibbin, W.J., Morris, A.C., Panton, A. and Wilcoxon, P. 2017. Climate change and monetary policy: Dealing with disruption. Brookings Institution, Washington D.C., USA. Online at <https://www.brookings.edu/research/climate-change-and-monetary-policy-dealing-with-disruption/>.
- Mekonnen, A. 2014. Economic costs of climate change and climate finance with a focus on Africa, *Journal of African Economies* 23: ii50-ii82.
- Mishkin, F.S. 1990. Asymmetric information and financial crises: A historical perspective. National Bureau of Economic Research, Cambridge, MA, USA. Working Paper No. 3400. Online at <https://www.nber.org/papers/w3400>.
- NGFS [Network for Greening the Financial System]. 2019. A call for action: Climate change as a source of financial risk. Network for Greening the Financial System, Paris, France.
- Nordhaus, W.D. 2007. A review of the Stern review on the economics of climate change. *Journal of Economic Literature* 45: 686-702.
- Organization for Economic Cooperation and Development (OECD). 2017. *Mobilising Bond Markets for a Low-Carbon Transition*, Paris.

- Parry, I.W.H., Veung, C. and Heine, D. 2014. How much carbon pricing is in countries own interests? The critical role of co-benefits. International Monetary Fund.
- Pindyck, R.S. 2013. Climate change policy: What do the models tell us? *Journal of Economic Literature* 51: 860-72.
- Raddatz, C. 2009. The wrath of God: Macroeconomic costs of natural disasters. Policy Research Working Paper Series, Working Paper no 5039. World bank, Washington, D.C., USA. Online at <http://documents.worldbank.org/curated/en/955981468150888752/The-wrath-of-God-macroeconomic-costs-of-natural-disasters>.
- Sargent, T.J. 1982. The ends of four big inflations. In Hall, R.E. (ed), *Inflation: Causes and effects* University of Chicago Press: 40-109.
- Schlosser, C.A. and Strzepek, K., 2015. Regional climate change of the greater Zambezi River Basin: A hybrid assessment. *Climatic change* 130(1): 9-19.
- Simbanegavi, W., and Arndt, C. 2014. Climate change and economic development in Africa: An overview. *Journal of African Economies* 23: ii4-ii16.
- Smal, D., Pretorius, C. and Ehlers, N. 2007. The core forecasting model of the South African Reserve Bank. South African Reserve Bank Working Paper 3195.
- Stern, N. 2013. The structure of economic modeling of the potential impacts of climate change: Grafting gross underestimation of risk onto already narrow science models. *Journal of Economic Literature* 51: 838-59.
- TCFD [Task Force on Climate-related Financial Disclosures]. 2017. Recommendations of the Task Force on Climate-related Financial Disclosures. Online <https://www.fsb-tcfd.org/publications/final-recommendations-report/>.
- TCFD [Task Force on Climate-related Financial Disclosures]. 2019. Task Force on Climate-related Financial Disclosures: 2019 Status Report. Online at <https://www.fsb.org/2019/06/task-force-on-climate-related-financial-disclosures-2019-status-report/>.
- Volz, U. 2017. On the role of central banks in enhancing green finance. United Nations Environment Programme. Online at <https://unepinquiry.org/publication/on-the-role-of-central-banks-in-enhancing-green-finance/>.
- Weitzman, M. 2007. Subjective expectations and asset return puzzles. *American Economic Review* 97(4): 1102–1130.
- Weyant, J. 2017. Some contributions of integrated assessment models of global climate change. *Review of Environmental Economics and Policy* 11: 115-37.
- Woodford, M. 2010. Financial intermediation and macroeconomic analysis. *Journal of Economic Perspectives* 24: 21-44.