Climate change: Macroeconomic impact and implications for monetary policy

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Abstract

Climate change and policies to mitigate it could affect a central bank's ability to meet its monetary stability objectives. Climate change can affect the macroeconomy both through gradual warming and the associated climate changes (e.g. total seasonal rainfall and sea level increased) and through increased frequency, severity and correlation of extreme weather events (physical risks). Inflationary pressures might arise from a decline in the national and international supply of commodities or from productivity shocks caused by weather-related events such as droughts, floods, storms and sea level rises. These events can potentially result in large financial losses, lower wealth and lower GDP. An abrupt tightening of carbon emission policies could also lead to a negative macroeconomic supply shock (transition risks). This chapter reviews the channels through which climate risks can affect central banks' monetary policy objectives, and possible policy responses. Approaches to incorporate climate change in central bank modelling are also discussed.

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Introduction: Why central banks care about climate change

Central banks across the world have been increasingly paying attention to climate change, having to acknowledge that it could affect their ability to meet their monetary and financial stability objectives. Climate change also poses economy-wide and societal challenges, which inevitably require the financial system to take a central role in managing climate risks and financing the carbon transition.

The Bank of England was the pioneer among central banks in the assessment of the climate risks for central banks: from understanding the impact of climate change on the insurance industry (Bank of England 2015), the banking sector (Bank of England 2018) and the wider central bank objectives (Carney 2015; Batten et al. 2016, 2018) to devising a response to these challenges (Scott et al. 2017).

Many other central banks and financial supervisors are now involved in climate change initiatives. For example, central banks and financial regulators and supervisors have supported the initiatives by the Financial Stability Board to establish the Task Force for Climate-related Financial Disclosures (TCFD), in order to help improve disclosure of climate-related risks by firms (TCFD 2018).

In 2017, central banks and supervisors have also established the Network for Greening the Financial System (NGFS) to "help strengthening the global response required to meet the goals of the Paris Agreement and to enhance the role of the financial system to manage risks and to mobilize capital for green and low-carbon investments" (NGFS 2019). As of March 2019, the Network included 30 members and five observers across five continents.[2]

And in early 2019, a group of US Senators have written to the Chairman of the Federal Reserve Powell urging him to ensure that the US financial system "is prepared for the risks associated with climate change" and requesting information on the steps the Fed has taken to identify and manage climate related risks in the U.S financial system (US Senate 2019). Soon after that, Rudebusch (2019) published an article examining the implications of climate change on the Federal Reserve.

This chapter focuses on the impact of climate change on central banks' monetary policy objective of maintaining low and stable inflation. For most central banks, price stability is usually the primary monetary policy objective, while some have output stability as an additional or a secondary objective. For example, the Bank of England's monetary policy objective is to maintain price stability within the United Kingdom and subject to that, to support the economic policy of Her Majesty's Government, including its objectives for growth and employment. The US Federal Reserve's mandate includes three goals of equal priority: maximum employment, stable prices, and moderate long-term interest rates in the U.S. economy. The single monetary policy objective of the Euro system – i.e. the European Central Bank (ECB) and the national central banks of the euro area countries – is to maintain price stability.

[2] The NFGS's First comprehensive report was published in April 2019 (NFGS 2019).

The chapter is organised as follows. Section 1 introduces the risks arising from climate change. Section 2 discusses the channels of transmission of those risks to the macroeconomy, and section 3 introduces the implications of climate change for monetary policy. Sections 4 and 5 discuss the implications of physical and transition risks in more detail, while section 6 discusses the implications for the modelling framework of central banks and Section 7 describes the interaction between financial and macroeconomic aspects of climate change.

1. *Climate change risks*

This section sets out the risks from climate change that could affect the macroeconomy and price stability, and therefore affect the core objectives of monetary policy, following the established taxonomy that distinguishes physical and transition risks of climate change (Carney 2015; Bank of England 2015).

Physical risks can be defined as "those risks that arise from the interaction of climate-related hazards (including hazardous events and trends) with the vulnerability of exposure of human and natural systems, including their ability to adapt" (Batten et al. 2016, p.5). There are two main sources of physical risks: i) ***gradual global warming*** and the associated physical changes, for instance in total seasonal rainfall and sea level; and ii) increased frequency, severity and correlation of certain types of ***extreme weather events***. The effects of these two types of risks on the macroeconomy are likely to differ in terms of timing and severity, and therefore their implications for monetary policy.

Transition risks, on the other hand, are defined as those risks that might arise from the transition to a low-carbon economy, which will be required to limit the cumulative emission of greenhouse gases, particularly carbon dioxide, to achieve the Paris Agreement of limiting the global warming to well below 2ºC above pre-industrial levels.

While the definition of physical and transition risks is well established, it is important to stress that these risks are dynamic, in the sense that they evolve over time, and are not independent from each other but tend to interact. For example, the physical risks of climate change are likely to intensify in the future, even under the benign scenario of limiting global temperature increase to 1.5ºC (IPCC 2018). Moreover, the increasing frequency and severity of extreme weather events has been linked to global warming (see e.g. Stott 2016; Stott et al. 2016). In particular, evidence shows that climate change has already led to an increase in the frequency and intensity of daily temperature extremes (Bindoff et al. 2013) and contributed to the intensification of daily precipitation extremes (Zhang et al. 2013) in certain countries.

The extent to which climate change influenced the likelihood and severity of specific weather-related events is the focus of a relatively new but active area of scientific research called 'event attribution.' One of the vehicles for the *dissemination* of the results of such attribution studies is the annual reports in the Bulletin of the American Meteorological Society, which seek to explain extreme events of the previous year. For example, the 2018 report (AMS 2018) showed that, in 2017, the droughts in the U.S. Northern Plains and East Africa, the floods in South America, China and Bangladesh, and the heatwaves in China and the Mediterranean were made more likely by human-induced climate change.

To deliver on the international commitment to limit temperature increases to less than 2ºC, carbon emission will have to be reduced significantly relative to the 'business as usual' scenario. Climate policies to achieve a reduction in carbon emissions need to be implemented swiftly and extensively to limit the physical risks from climate change. The longer the implementation of these policies and the transition to a low-carbon economy are delayed, the sharper the future reduction in carbon emission to meet the climate goal will need to be, and the higher the transition risks (Carney 2018). A late and sudden transition ("hard landing") will also exacerbate the physical risks of climate change (ESRB 2016).

2. *Climate change and the macroeconomy: the transmission channels*

Climate change risks manifest themselves as economic shocks – defined as unpredictable events that produce a significant change within an economy. ***Supply-side*** shocks affect the productive capacity of the economy: examples that can arise from physical climate risks are the price volatility caused by shortages of commodities such as food and energy, or the damage to the capital stock and infrastructure due to the extreme weather events. The supply-side risk from the transition to a low-carbon economy is represented by the *trade-off* between the need to limit the future damage from global temperature increases and the present cost of reducing emissions, which reduces the resources available for economic growth in the near term.

Representing the physical and transition risk from climate change as purely supply-side type shocks (McKibbin et al. 2017; Cœuré 2018) however, is too simplistic. Losses deriving from extreme climate events such as floods and storms also lead to ***demand-side*** shocks, for example by reducing household wealth and thus private consumption. While reconstruction activities could lead to an increase in investment, business investment could also be affected negatively by uncertainty and financial losses following climate disasters. Batten et al. (2016) noted that weather-related natural disasters are more likely to lead to a negative demand shock if losses are largely uninsured. Moreover, the impact of natural disasters on bilateral trade is well established (Gassebner et al. 2010; Oh and Reuveny 2010; Felbermayr and Gröschl 2013; El Hadri et al. 2017). Finally, demand-side shocks can also be caused by transition to a low carbon economy. Tighter climate policy could cause dislocations in high carbon sectors, including a large and sudden reduction in investment. Moreover, like all forms of public investment, government investment in low-carbon technologies could result in 'crowding-out' of private investment in those technologies. Some examples of the macroeconomic risks deriving from climate change are presented in Table 1.

Table 1: Macroeconomic risks from climate change

Type of shock/impact		Physical risks: From extreme weather events	Physical risks: From gradual global warming	Transition risks
Demand	Investment	Uncertainty about climate events		'Crowding out' from climate policies
	Consumption	Increased risk of flooding to residential property		'Crowding out' from climate policies
	Trade	Disruption to import/export flows due to natural disasters		Distortions from asymmetric climate policies
Supply	Labour supply	Loss of hours worked due to natural disasters	Loss of hours worked due to extreme heat	
	Energy, food and other inputs	Food and other input shortages		Risks to energy supply
	Capital stock	Damage due to extreme weather	Diversion of resources from productive investment to adaptation capital	Diversion of resources from productive investment to mitigation activities
	Technology	Diversion of resources from innovation to reconstruction and replacement	Diversion of resources from innovation to adaptation capital	Uncertainty about the rate of innovation and adoption of clean energy technologies

Source: Batten (2018)

3. *Implications of climate change for monetary policy – a summary*

Climate change can affect monetary policy in different ways. First, the physical and transition risks from climate change can affect the macroeconomy and the prospects for inflation. Second, climate change can also affect monetary policy indirectly, through its impact on households and firms' expectations about future economic outcomes (Lane 2019).

The impact of climate change on the economy is subject to profound uncertainty, in particular over the magnitude of the effects and on the horizon over which they will play out. While central bankers might believe the horizon of climate change impacts might be beyond the horizon relevant for monetary policy, climate change is likely to affect monetary policy whether it is addressed in the present – through the economic cost of reducing carbon emissions (transition risk) – or whether it is left unchecked, through the impact of increased extreme climate events (physical risk) (Cœuré 2018). Indeed, these two scenarios are likely to coexist for the foreseeable future. A summary of the economic impacts of climate change and their timing is presented in Table 2.

Table 2: Economic impacts relevant for monetary policy and time horizon for the materialization of climate risks

Type of risk		**Economic outcome**	**Timing of effects**
Physical risks from:	Extreme climate events	Unanticipated shocks to components of demand and supply	Short to medium run
	Global warming	Impact on potential productive capacity and economic growth	Medium to long run
Transition risks		Demand/supply shocks or economic growth effects	Short to medium run

The next two sections examine the implications of physical and transition risks for monetary policy in more detail.

4. *Physical risks, macroeconomic impacts and implications for monetary policy*

The existing climate-economy literature points to a number of channels via which ***gradual global warming*** could reduce the potential growth rate of the economy: first, global warming could lead to a reduction in the effective labour supply in the economy, due to the reduction in labour productivity caused by diminished physical and cognitive performance of human capital.[3] Extreme heat could also reduce effective labour supply by increasing the mortality and morbidity of the population, for example due to the increased incidence of diseases such as malaria (Fankhauser and Tol 2005). Deryugina and Hsiang (2014), for example, found that productivity declines roughly by 1.7% for each 1°C increase in daily average temperature above 15°C, using variations across counties within the United States over a 40-year period, while Acevedo et al. (2018) found that higher temperatures also have a negative effect on a broader measure of human well-being as measured by the Human Development Index, a weighted average of per capita income, educational achievement, and life expectancy.

A second effect of global warming could be a reduction in the rate of productive capital accumulation, through permanent or long-term damage to capital and land (Stern 2013) or increase in the rate of capital depreciation (Fankhauser and Tol 2005).

Finally, global warming could lead to a reduction in the growth rate of total factor productivity (TFP), because adaptation to rising temperatures will divert the resources available from research and development (R&D). Moreover, if adaptation requires more investment to be directed to repair and replacement, there may be less productivity gains through 'learning by doing' than if more investment is directed towards innovation (Pindyck 2013; Stern 2013).

While economists are still debating whether global warming affects the level or the growth rate of the economy, ignoring these effects could potentially lead central banks to misjudge the evolution of the output gap and inflationary pressure. The impact of climate change on productivity in the first half of the 21st century could be modest in most advanced economies if the increase in local temperatures itself is limited during this period. Monetary policy authorities may still need to take these effects into account in the coming decades if global temperature increases lead to international inflationary pressures on food and other commodities.[4]

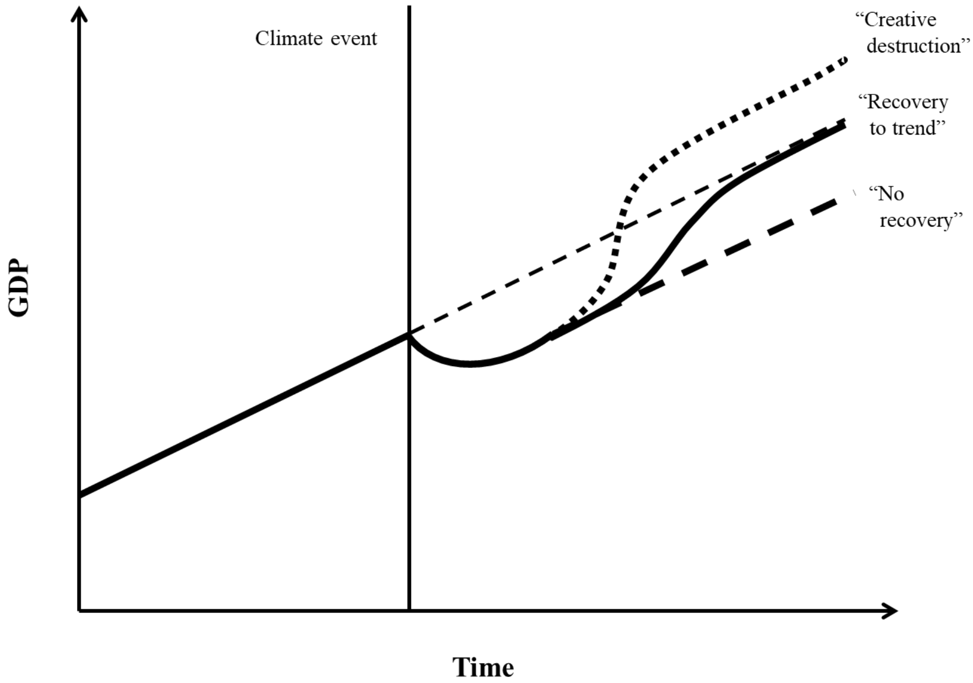
Over a shorter time horizon, on the other hand, some ***extreme weather-related events*** could have a significant impact on the aggregate economy and inflation, requiring the monetary policy authorities to react appropriately, depending on the response of output and inflation to these events. Three competing hypotheses that describe the impact of environmental catastrophes on output in the short and long-run are illustrated in Figure 1. In the aftermath of a natural disaster, a loss of GDP is very likely. In the medium and long run, however, different scenarios might occur (see e.g. Hsiang and Jina 2014):

1. The 'creative destruction' hypothesis argues that, following a natural disaster, there might be a period of faster growth that puts the economy on a higher GDP path than before the event, due, for example, to an increase in demand for goods and services as lost capital is replaced, growth-promoting international aid following the disaster or innovation stimulated by the environmental disruption.

[3] A survey of experimental studies reported in Dell et al. (2014) concluded that there is a productivity loss in various cognitive tasks of about 2 percent per 1ºC for temperatures over 25ºC.
[4] Batten (2018) provides a more detailed discussion of the literature.

2. The ‘recovery to trend’ hypothesis argues that, after growth slows following the natural disaster, income levels should eventually return to their pre-disaster trend through a catch-up period of faster than average growth. This rebound should occur because the marginal product of capital will rise when capital is destroyed by a natural disaster and becomes relatively scarce, causing resource reallocation into devastated locations.
3. The ‘no recovery’ hypothesis argues that disasters slow down growth by either destroying productive capital directly or by destroying durable consumption goods (e.g. homes) that are replaced using funds that would otherwise be allocated to productive investments. In this case, no rebound occurs because the reallocation of resources fails to compensate for the negative effect of a natural disaster on productivity. While post-disaster output may continue to grow in the long-run, it remains permanently lower than its pre-disaster trajectory.

Figure 1: Possible effects of natural disasters on GDP



Source: This figure is taken from Batten (2018) and is a modified version of Figure 1 in Hsiang and Jina (2014).

The literature surveyed in Cavallo and Noy (2010) concluded that, on average, natural disasters had a negative impact on short-term economic growth. The literature on the long-run effects of natural disasters is relatively scarce and the results are mixed, in part reflecting the difficulty associated with constructing the appropriate counterfactual research. Some studies found that natural disasters tend to have contractionary effects on growth due to the cumulative output losses associated with indirect damages, while others found expansionary effects due to ‘creative destruction’ processes, especially in developed countries. In a recent cross-country study of the economic impact of tropical cyclones during 1950-2008, Hsiang and Jina (2014) found a small but persistent suppression of annual growth rates over the 15-year period following the disaster.

Because any tightening monetary policy reaction might worsen the impact of the weather disaster on economic activity, flexible inflation targeting would allow a central bank to use discretion to avoid exacerbating any real effects of weather shocks. Central banks would need to assess the size and persistence of the impact on supply relative to demand, and hence the output gap: unpredictable shocks such as climate-related events would, however, increase the difficulty of forecasting potential output.

The destruction of capital stocks due to natural disasters tends to reduce aggregate supply, while reconstruction efforts could increase aggregate demand. If a natural disaster generates a positive output gap and an upward pressure on inflation, then a central bank might consider tightening monetary policy (Keen and Pakko 2010). But a natural disaster could also have a large and persistent negative effect on demand – and thus generate a negative output gap – if it severely damages household and corporate balance sheets in affected areas and reduces their consumption and investment. A natural disaster could also undermine business confidence and trigger a sharp sell-off in financial markets, which in turn could increase the cost of funding new investments and thus reduce investment demand.

In practice, central banks have responded differently to natural disasters depending on their magnitude and their estimated impact on the output gap. For example, the Federal Reserve had increased the interest rate in its first meeting after Hurricane Katrina in August 2005 – which caused a total loss of US$125 billion (1.0% of US GDP in 2005) – as had been expected before the disaster, characterising the macroeconomic effects of the hurricane as significant but "essentially temporary".[5] By contrast, the Bank of Japan (BoJ) eased monetary policy following the Great East Japan Earthquake in March 2011 – which caused a total loss of US$210 billion (3.6% of Japan's GDP in 2011) – by expanding its asset purchase programme "with a view to pre-empting a deterioration in business sentiment and an increase in risk aversion in financial markets from adversely affecting economic activity".[6] The G7 also issued a statement to express their 'readiness to provide any needed cooperation', while the Federal Reserve, Bank of England, Bank of Canada and the European Central Bank joined the BoJ in intervening in the foreign exchange market to stabilise the yen exchange rates.[7] The Bank of Thailand also cut policy rates after the 2011 flood, which generated total losses of US$43 billion, or 11.6% of Thai GDP in 2011.

Extreme weather events are likely to have the most significant impact on the agricultural sector. Dell et al. (2012) report that, for developing countries at least, panel models typically found consistently negative impacts of bad weather shocks on agricultural output. A more recent cross-country panel study covering the 1964–2007 period by Lesk et al. (2016) also found that droughts and extreme heat significantly reduced national cereal production by 9–10%.

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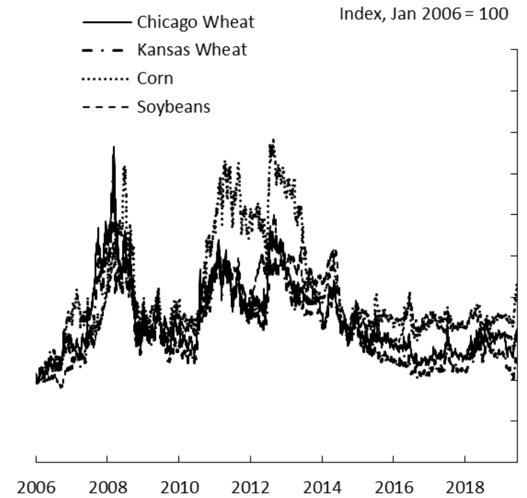
[5] See the minutes of the FOMC Meeting on 20 September, 2005.
[6] See the minutes of the BoJ Monetary Policy Meeting on 14 March, 2011.
[7] See the statement of G7 Finance Ministers and Central Bank Governors released on 18 March 2011; and Bank of Japan (2011).

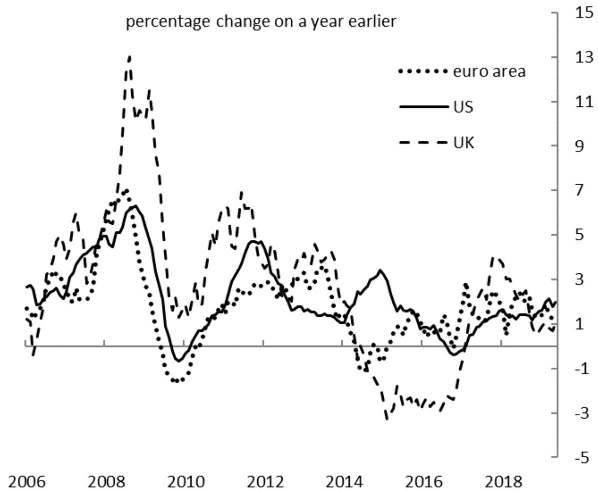
Extreme weather events affecting the global food production could temporarily increase food price inflation in countries that rely on imported food, and this impact could be exacerbated if the exporting countries resort to protectionist measures to keep domestic food prices down. For example, Russia banned grain exports following the 2010 drought and heatwave, thereby pushing up international prices for grains (Figure 2). This was a factor that contributed positively to food price inflation in other countries (Figure 3).

Figure 2: Selected food commodity prices, 2006-2019



Source: Thomson Reuters Datastream

Figure 3: Food price inflation, 2006-2019



Source: Thomson Reuters Datastream

Heinen et al. (2016) find a large inflationary impact of extreme weather events in developing countries: a result confirmed by Parker (2018), who also find effects are heterogeneous across disaster types. These inflationary effects in developing countries could also spread through international commodity trade: Peersman (2018) finds that exogenous international food commodity price shocks have a strong impact on consumer prices in the euro area, and these shocks can explain on average 25%-30% of inflation volatility.

Thus, climate change could lead to greater volatility of headline inflation rates via increased volatility of food price inflation rates. While sectoral price shocks could have a temporary effect on the headline inflation in the short-run, central banks do not necessarily need to react to it if the sectoral price shocks do not affect inflation expectations and thus the effects on inflation are short-lived. As a result, central banks in those countries with a credible monetary policy framework and well-anchored inflation expectations are less likely to face the need to react to sectoral price shocks, although such volatility could complicate the communication of the monetary policy strategy at times. But the increased volatility of inflation rates represents a bigger challenge for those central banks with less well-established credibility, where sectoral price shocks risk de-anchoring inflation expectations and triggering a second round effect that increases inflationary pressure in the medium-term.

If, as discussed in section 1, climate change leads to more severe or frequent extreme weather events in the future, monetary policy makers will be faced with larger and more frequent negative supply shocks. It will also become more important for central banks to be able to disentangle the impact of climate-related weather events from other inflation drivers, and to be able to model the impact of these events on macroeconomic variables (modelling issues are discussed in more detail in section 6).

5. *Transition risks, macroeconomic impacts and monetary policy*

The risks to the macroeconomy from the transition to a low (and ultimately zero) carbon economy can be understood in terms of the Kaya identity (Kaya 1990), which provides a framework for analysing emission drivers by decomposing overall changes in GHG emissions into underlying factors:

$$CO_2\ emissions = population \times \frac{GDP}{population} \times \frac{Energy}{GDP} \times \frac{CO_2\ emissions}{Energy}$$

In the Kaya identity, CO_2 emissions are expressed as a product of four underlying factors: (1) population, (2) per capita *GDP* (*GDP / population*), (3) energy intensity of *GDP* (*Energy / GDP*), and (4) CO_2 intensity of energy (CO_2 *emissions / energy*).

This formulation implies that the reduction in GDP growth needed to achieve a given reduction in carbon emissions will rely on the decrease in energy intensity (a reduction in energy used/GDP), which can be achieved through lower or more efficient energy consumption, and the reduction in carbon intensity of energy (a reduction in carbon/energy used), through the adoption of cleaner sources of energy. If a reduction in carbon emissions is to be achieved entirely via a reduction in energy intensity, then the resulting reduction in output could be substantial: for example, using a simple growth accounting framework, Smulders et al. (2014) report that a 10 per cent reduction in energy use reduces output by around 1 per cent.[8]

By contrast, if the reduction in carbon emissions can be achieved through shifts to cost-effective low- and zero-carbon energy supply, and greater energy efficiency, then the growth impact of a tightening of policy on carbon emissions can be expected to be smaller. This implies that the transition to a low-carbon economy could be achieved without causing a large negative supply shock if sufficient investment takes place in low-carbon energy sources at an early stage.

If the transition leads to an increasing share of bioenergy, the volatility of inflation rates could also increase as both energy and food prices could be affected by the same weather-related shocks.[9] Although this effect could be mitigated by a gradual reduction in the share of

[8] Growth accounting assumes that the output elasticity of energy equals the cost share of energy in production in a competitive economy.

[9] The share of bioenergy is assumed to increase in the RCP 2.6 which is likely to keep the warming below 2ºC (van Vuuren et al. 2011). IEA (2013) also projects that, in order to achieve a 50% reduction in energy-related CO2 emissions by 2050 (from 2005 levels), biofuels would need to provide 27% of the total global transport fuel, up from 3% currently. But there is question over the sustainability of large scale bioenergy production given the competition with other land and biomass needs, such as food security and biodiversity conservation (Fuss et al. 2014).

food and energy in the consumption basket (and hence the consumer price index) as countries become richer, it could be exacerbated by climate change which can make weather patterns more volatile.

The major source of transition risk from climate change to the macroeconomy is represented by climate policy: some of these policies – in particular price based interventions (e.g. carbon pricing) or regulations – impose a burden to economic activity, at least in the short to medium-term, as compliance with environmental regulation forces companies to curb production or to devote some of their resources to emission abatement, and thus are expected to negatively affect firms' profitability, productivity, employment and ultimately GDP.[10]

From a monetary policy perspective, price-based climate policy can be considered a negative supply-side shock.[11] By putting a price on carbon, regulatory authorities aim to discourage the production and consumption of high emission goods. A price for carbon can be established through a carbon tax or through a cap-and-trade system such as the EU Emission Trading Scheme (ETS). Under a carbon tax, the price of carbon is set directly by the regulatory authority. Under a cap-and-trade system, the price of carbon or CO_2 emissions is established indirectly: the regulatory authority stipulates the allowable overall quantity of emissions and the price of carbon is then established through the market for allowances.

A one-off increase in carbon price would normally only have a temporary effect on the inflation rate, provided agents recognise it is a one-off change. The policy would result in higher price level, while the inflation rate would quickly return to its original level. The relative price of carbon-intensive goods would be permanently higher.

The price level effect would generally depend on the carbon pass-through, defined as the incidence of a fixed carbon price or tradable carbon permit, i.e. the proportion of carbon price that is passed into wholesale electricity spot prices.

Recent studies find evidence of a high degree of pass-through. Fabra and Reguant (2014) measure the pass-through of emissions costs to electricity prices using data from the Spanish wholesale electricity market covering the period in which the ETS was introduced and find that emissions costs are almost fully passed through to wholesale electricity prices. Hintermann (2016) finds similar results in a study of cost pass-through to hourly wholesale electricity prices in Germany. Lise et al. (2010) analyse the impact of the ETS on wholesale electricity prices in 20 European countries and find that a significant part of the costs of

[10] Climate policy can also have a range of benefits in addition to the gains from reducing future climate change damage: these are often referred to as *co-benefits*. For example, policies that encourage innovation in low-carbon technologies can *spill over* to other industries and stimulate economic growth. Moreover, climate policy might results in productivity growth if they improve the allocation of resources or increase their degree of utilisation. Mitigation actions targeting clean energy technologies or energy efficiency are found to induce improvements in air quality by reducing local air pollution (LAP) such as particulate matter, sulphur dioxide and nitrogen oxides, which are damaging for human health. Co-benefits can be expected to cover a significant part of climate change mitigation costs (see e.g. Bollen et al. 2009; Groosman et al. 2011). An attractive feature of co-benefits is that they occur in the medium run, while the direct benefits of GHG mitigation policies in terms of reduction of the impact of climate change are likely to occur only in the longer run.
[11] Other types of climate policies, such as incentives to innovation and investment in low carbon technologies, can instead lead to an increase in potential supply.

(freely allocated) CO_2 emission allowances is passed through to power prices, resulting in higher electricity prices for consumers. De Bruyn et al. (2015) find that the pass-through rates of the ETS were was particularly high in carbon-intensive industries such as the utilities and metals industries, which are characterized by relatively large actors and limited competition.

Since the introduction of carbon pricing has a one-off, transitory effect on inflation, the monetary policy authorities will generally ‘look through’ this effect to avoid rising interest rates and depressing the economy. This was the case, for example, of the Bank of Canada’s reaction following the introduction of a carbon price in some of Canada’s provinces (Lane 2017).

6. Implications for the analytical framework of monetary policy authorities

Both the physical aspects of climate change and the transition to a low carbon economy represent major structural changes: they will require system transition and innovation in many sectors of the economy. Many of these changes would be difficult to incorporate directly into existing economic models used by central banks, and the degree of precision around them might be limited: these might nonetheless be helpful ‘for characterizing the forces at work and capturing their interactions’ (Lane 2017).

As discussed above, both the physical risks and transition risks arising from climate change could potentially affect long-run growth. The calibration of the long-run growth rate in forecasting models used by major central banks could have an important impact on short-term forecasts of inflation and output. Thus, if climate change can have permanent effects on the trend growth rate, it is potentially important to consider this in the forecasting process.

Future impacts of climate change on GDP – more specifically, the effects of gradual global warming – are often modelled using ‘Integrated Assessment Models (IAMs),’ which seek to capture the complex interactions between the physical and economic dimensions of climate change. Such models are, for example, used to estimate the ‘social cost of carbon’ in order to derive the optimal dynamic path of carbon price. The IAMs typically model the economic impact of global warming using a ‘damage function’, which links the increase in average global temperature from its pre-industrial average to a reduction in GDP in a given year. But as these damage functions are often arbitrary, these models are unlikely to provide reliable quantitative information needed for monetary policy.

By contrast, disaggregated quantitative analysis could potentially be more informative for monetary policy makers. For example, Houser et al. (2015) assess how climate change will affect five key sectors (agriculture, energy, coastal property, health and labour) in the US economy by building on both climate science and econometric research. The study models climate impacts at a very high level of granularity, highlighting the regional variation of climate impacts. Further quantitative studies based on such granular data and climate science could potentially enable monetary policy makers to better estimate the long-term physical impacts of climate change.[12]

[12] Another example is OECD (2015).

While it is important to understand the impact of global warming on trend GDP growth, the medium-term impact of climate change – namely the effects of extreme weather events and the transition risks – are likely to be more important for the conduit of monetary policy.

Central banks are – to some extent – already accustomed to assessing the short run impact of unusual weather conditions on economic activities. Examples include the Bank of England's assessment of unusual snow conditions on the retail, construction and hospitality sectors (BoE 2018), and the Fed's quarterly assessment of winter weather economic impacts (Gourio 2015; Bloesch and Gourio 2015). As a striking example of the kind of economic impact extreme weather can have on economic variables, JP Morgan estimated that the low level of the Rhine and other important German rivers caused by extreme heat in 2018 reduced economic growth by 0.7 percentage points (Bloomberg 2019). And the deviation of weather from the seasonal norms has been shown to significantly affect macroeconomic series such as monthly payrolls in the US (Boldin and Wright 2015). As extreme weather becomes more severe and frequent in the future, it might become necessary to routinely incorporate these effects in standard macroeconomic now-casting or forecasting models in central banks.

Short-term, dynamic stochastic general equilibrium (DSGE) models, of the type used for forecasting output and inflation within the time horizon of monetary policy (2-3 year) can be augmented with climate-related natural disasters. For example, in Keen and Pakko (2011), a natural disaster destroys a significant share of the economy's productive capital stock, as well as temporarily disrupting production, which is modelled as a transitory negative technology shock. There are, however, only a few examples of these types of models, and there is scope for improving the modelling channels to include, for example, the impact of domestic natural disasters on labour supply or the impact of natural disasters in partner countries on international trade and the exchange rate.

Transition risks associated with announced climate policies can be incorporated in macroeconomic forecasting models, while those associated with unannounced future policies and future technical changes are much harder to incorporate. The main transition risks are changes in climate policy, which are included in the broader fiscal policy variables, and energy supply risks, which can be modelled as technology shocks in a DSGE-type model.

There could also be macroeconomic risks from the materialization of transition risks into large and permanent financial losses in asset values. The resulting loss of wealth and collateral might reduce household consumption and firms' business investment plans. These interactions between macroeconomic and financial impact of climate change are discussed in section 7 below.

It is possible that conventional DSGE models are not suited to analysing the complex system-wide transition to a low carbon economy. Such models typically include a 'representative' consumer or firm, and are built on the assumption that individual decisions by these agents can be scaled up to the aggregate economy level.

An example of an alternative modelling approach is agent-based modelling (ABM), which is more suitable for studying the emergent properties of complex systems, because it allows for interactions amongst heterogeneous agents, and the global system properties that result from these interactions (Patt and Siebenhüner 2005).

ABMs are commonly applied in climate change modelling, for example to analyze climate change adaptation (Patt and Siebenhüner 2005), consumer energy choices (Rai and Henry 2016), climate-related migration (Thober et al. 2018). ABMs have also found use in macroeconomics, including the analysis of business cycles (Gualdi et al. 2015) and monetary policy (Gatti and Desiderio 2015) that are of particular interest for central bank policy makers.[13] That said, ABMs often incorporate behavioural rules that are arbitrary and the transmission mechanisms in such models are difficult to identify, such that caution is needed in drawing policy conclusions based on results emerging from these models.

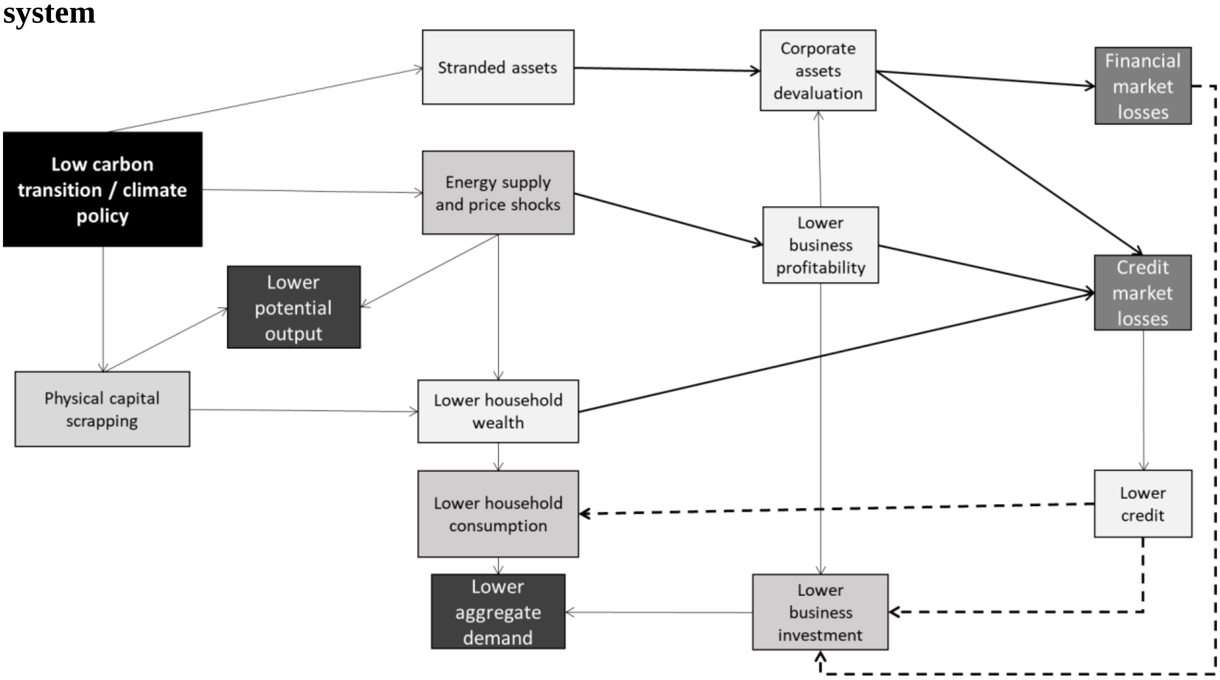
7. Interactions between macroeconomic and financial climate shocks

It is widely recognized that macroeconomic and financial shocks can interact and amplify: in the past, price instability has been shown to contribute to financial crises.[14] Conversely, financial crises can generate large falls in output.

The interaction between macroeconomic shocks from climate change and financial stability shocks – and vice-versa – has not, however, been explored in any detail, and this is a particularly important gap in the current literature. One example is the potential realisation of transition risks as 'stranded assets' and their impact on the real economy. Another example is the possibility of natural disasters reducing collateral values of the housing stock and weakening households' balance sheets, in turn reducing household consumption. Insured losses from natural disasters can lead to financial losses for both insurers and banks, reducing the latter's ability to lend to households and corporates, and thus reducing the financing available for reconstruction of physical capital in affected areas. Increased uncertainty from more frequent climate-related weather events could also increase uncertainty for investors, causing falls asset prices, losses for banks and reduced availability of lending for productive investment to corporates (Batten et al. 2018). Some of the linkages between macro and financial aspects of transition risks are depicted in Figure 4.[15]

[13] See Turrell (2016) for a further discussion of ABMs application to macroeconomics.
[14] See e.g. Bordo et al. (2001).
[15] For a similar diagram for extreme climate events see Figure 10.1 in Batten et al. (2018).

Figure 4: Transition risks, macroeconomic impacts and transmission to the financial system



Conclusion

This paper examined the impact of climate change on the monetary policy objectives of central banks. We have identified four main ways in which climate change and policies on carbon emissions could affect central banks' monetary policy objectives.

First, a weather-related natural disaster could trigger a macroeconomic downturn if it causes severe damage to the balance sheets of households, corporates, banks and insurers (*physical risks*). The economic impact of a given natural disaster is likely to be less severe if the relevant risks are priced in financial contracts *ex ante*, and the financial system has distributed them efficiently, e.g. via insurance and reinsurance. *Ex post*, a central bank will need to react appropriately to a disaster to meet its monetary stability objectives. This requires assessing the impact of the disaster on the output gap and inflationary pressure, and adjusting monetary policy if needed.

Second, gradual warming could also affect an economy's potential growth rate. More reliable quantitative estimates based on detailed sector-level impact analysis would be needed before central banks can incorporate this effect in their monetary policy analysis.

Third, a sudden, unexpected tightening of carbon emission policies could generate a negative supply shock (*transition risks*). While the introduction or an increase of a carbon price would have only a temporary effect on inflation, the short- and medium-term macroeconomic consequences could be severe if the increase is both sharp and sudden. Achieving an orderly transition requires governments to pre-announce a clear and predictable path for future tightening of carbon emission policies.

Finally, both the changes in weather patterns and the increased reliance on bioenergy could increase the volatility of food and energy prices, and hence the volatility of headline inflation rates. This could make it more challenging for central banks to gauge underlying inflationary pressures and maintain inflation close to the target.

Central banks will increasingly need to incorporate climate variables in their macroeconomic models (Campiglio et al. 2018; Mersch 2018; Debelle 2019). Specifically, to assess the impact of short-term extreme weather on economic variables such as GDP and inflation, now-casting and forecasting models could be expanded to include weather effects. Longer term effects of gradual global warming on the growth rate of potential output might also need to be included in the monetary policy modelling toolkit. Finally, the interactions between financial and macroeconomic climate shocks could become an important source of risk for the future conduct of monetary policy.

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