BANK OF ENGLAND

Staff Working Paper No. 603

Let's talk about the weather: the impact of climate change on central banks

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May 2016

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Abstract

This paper examines the channels via which climate change and policies to mitigate it could affect a central bank's ability to meet its monetary and financial stability objectives. We argue that two types of risks are particularly relevant for central banks. First, a weather-related natural disaster could trigger financial and macroeconomic instability if it severely damages the balance sheets of households, corporates, banks, and insurers (*physical risks*). Second, a sudden, unexpected tightening of carbon emission policies could lead to a disorderly re-pricing of carbon-intensive assets and a negative supply shock (*transition risks*). Climate-related disclosure could facilitate an orderly transition to a low-carbon economy if it helps a wide range of investors better assess their financial risk exposures.

Key words: Climate change, natural disasters, financial stability, monetary policy.

JEL classification: E58, G21, G22, Q43, Q54.

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The views expressed in this paper are those of the authors, and not necessarily those of the Bank of England, the Monetary Policy Committee, Financial Policy Committee or PRA Board. We are grateful to Alex Bowen, Ben Caldecott, Paul Fisher, Sujit Kapadia, Sarah Kemmitt, Helen Lau, Jason Lowe, Lavan Mahadeva, Richard Millar, Adele Morris, Sinead O'Leary-Barrett, James Orr, Nicolas Pondard, Jake Reynolds, Matthew Scott, Peter Sinclair, Andrew Voysey, Matthew Waldron, Matthew Willison and seminar participants at the Bank of England for useful comments, and Angelina Carvalho, Osvay Csongor and Thomas West for excellent research assistance. We also benefited from helpful discussions with Myles Allen and Cameron Hepburn.

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ISSN 1749-9135 (on-line)

Introduction

In December 2015, 196 Parties (195 states and the European Union) adopted the Paris Agreement to set a goal of limiting global warming to well below 2 degrees Celsius (ºC) above pre-industrial levels and to pursue efforts to limit the temperature increase to 1.5ºC above pre-industrial levels. The Agreement also recognised that climate change represents an urgent and potentially irreversible threat to human societies and the planet, and that deep reductions in global green house gas (GHG) [1] emissions will be required in order to achieve this goal. It also aims to make financial flows consistent with a pathway towards low GHG emissions and climate-resilient development.

The projected increase in global temperatures and associated changes in climate, such as variations in rainfall or storm characteristics, as well as the transition to a low-carbon economy implied by the Paris Agreement, have potentially far reaching consequences for the macroeconomy and the financial system. This paper examines the channels via which climate change and policies to mitigate climate change could affect central banks' ability to meet their monetary and financial stability objectives. Our analysis builds on Bank of England (2015) and Carney (2015) which have examined the impact of climate change on the insurance industry, but broadens the scope of the analysis. Specifically, our paper examines the impact of climate change and the changes in the composition of energy supply associated with the transition to a low-carbon economy on the financial system and the macroeconomy, and thus goes beyond the analysis of the European Systemic Risk Board (2016) that considered the potential impact of the transition to a low-carbon economy on financial stability. While climate change is expected to have more adverse macroeconomic impacts on some developing countries, the focus of this paper is mainly on the impact of climate change from the perspective of central banks in advanced economies.

Section 1 of the paper briefly reviews the causes of climate change and the technological possibilities that affect the extent to which fossil fuels can remain in use while limiting the global warming to below 2ºC. Section 2 considers the implications of climate change for financial stability. This section will also examine whether stress tests can be used to assess the risks to financial stability arising from climate change, and consider how climate-related disclosure could be designed to help inform a wide range of investors. Section 3 reviews the potential impact of climate change on monetary policy, and Section 4 concludes.

1. The causes of climate change and the usability of fossil fuels

i) The causes of climate change

The World Meteorological Organization (2016) estimates that 2015 was the hottest year on record, with the global average temperature reaching approximately 1ºC above the 1850-1900 average. The *Synthesis Report* (2014) published by the Intergovernmental Panel on Climate Change (IPCC) suggests that significant climate impacts are already occurring in certain parts of

[1] Green house gases include water vapour (H_2O), carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), Ozone (O_3), and Chlorofluorocarbons (CFCs).

the world today, and that the risks of climate-related damage – such as extreme weather events and large-scale singular events that cause irreversible change to the ecosystem – increase with global temperature. It also warns that warming above 2ºC relative to the pre-industrial period could lead to potentially catastrophic consequences.

The IPCC have calculated that GHG emissions were the primary cause of the observed warming during the 1951-2010 period (IPCC (2014)). The 2015 Paris Agreement aims to reach a global peak in GHG emissions as soon as possible, but does not set out a global emissions reduction target, or a specific date at which global emissions should reach a particular level. The Paris Agreement also acknowledges that the voluntary Nationally Determined Contributions (NDCs), in which each country sets out its strategy for how it will act on climate change, are insufficient to reach the 2ºC pathway and that much greater emission reduction efforts will be required.[2]

According to IPCC (2014), carbon dioxide (CO_2) emissions from fossil fuel combustion and industrial processes accounted for 78% of the total GHG emission increase between 1970 and 2010, with a contribution of similar percentage over the 2000-2010 period. Whereas some GHGs, such as methane, are short-lived, some fraction of CO_2 emissions remains in the atmosphere for centuries and hence will have irreversible effects on climate, unless measures are taken to remove CO_2 from the atmosphere (Fuss *et al.* 2009). Consequently, peak global temperature changes depend primarily on the *cumulative emissions* of CO_2 into the atmosphere over all time periods, and hence the *net flow* of CO_2 released into the atmosphere will ultimately need to reach zero to stop the rise in global temperatures (Allen *et al*, 2009, Menshausen *et al.* 2009).[3]

The physical importance of cumulative CO_2 emissions gives rise to the concept of a 'carbon budget', which captures the cumulative CO_2 emissions that are consistent with a given rise in global temperatures relative to the pre-industrial period. According to IPCC (2014), limiting the total human-induced warming (accounting for both CO_2 and other human influences on climate) to less than 2ºC relative to the period 1861-1880 with a probability greater than 66% would require cumulative CO_2 emissions from all anthropogenic sources since 1870 to be limited to about 2900 $GtCO_2$. About 1900 $GtCO_2$ were emitted by 2011, implying that no more than 1000 $GtCO_2$ can be further emitted in order to contain human-induced warming to less than 2 ºC relative to the pre-industrial period, although there is considerable uncertainty around this estimate.

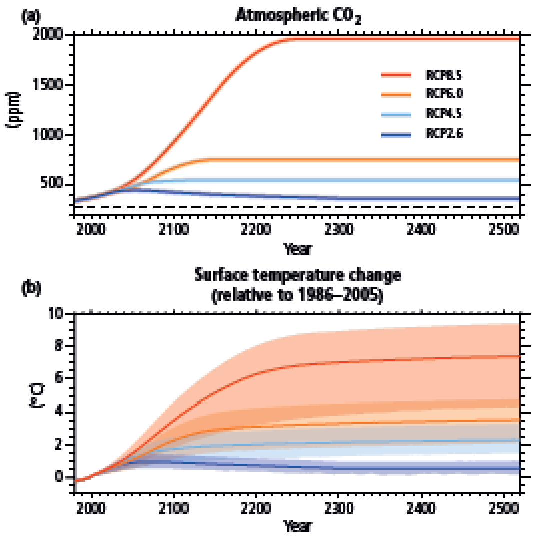
IPCC (2014) also projects the future global mean surface temperature subject to a range of possible future pathways – known as Representative Concentration Pathways (RCPs):[4] RCP2.6 involves very significant global GHG mitigation policy action, RCP8.5 represents a 'business-as-usual' high emission scenario, and RCP4.5 and RCP6.0 represent scenarios in between. The projected global mean surface temperature change for the period of 2016-2035 remains similar

[2] United Nations Framework Convention on Climate Change (UNFCCC) estimates that commitment to follow the INDCs could cap the global temperature increase to around 2.7 ºC above pre-industrial levels, assuming that GHG emissions do not start rising again after 2030. See http://newsroom.unfccc.int/unfccc-newsroom/indc-synthesis-report-press-release/.
[3] The IPCC's (2014) analysis suggests that, in order to keep global warming *likely* below 2 ºC above the levels in the pre-industrial period, emissions of other GHGs (notably methane (CH_4) and nitrous oxide (N_2O)) would also need to be reduced.
[4] See van Vuuren *et al.* (2011) for further details on RCPs.

for all four RCPs, but diverges more sharply after 2035 (Figure 1). Specifically, in high emission scenarios (RCP 6.0 and RCP 8.5), the warming is likely[5] to exceed 2ºC relative to the pre-industrial period by the end of the 21st century. The scenarios that are likely to maintain warming at below 2ºC (RCP 2.6) are characterised by a 40-70% reduction in GHG emissions by 2050 relative to 2010 levels, and emissions levels near or below zero in 2100.

ii) The impact of technology on the amount of 'usable' fossil fuels

Figure 1: IPCC projection of atmospheric carbon dioxide and global mean surface temperature change (relative to 1986-2005*)



Source: IPCC (2014), Fig 2.8.
Note: *IPCC (2014) estimates that the1986-2005 period was approximately 0.61ºC warmer than the 1850-1900 period.

Maintaining warming at below 2ºC (as in RCP 2.6) will require substantial additional efforts to reduce GHG emissions beyond those in place today, including more rapid improvements in energy efficiency, and a shift towards zero- and low-carbon energy supply, for example from renewable energy, nuclear energy, and fossil energy with carbon dioxide capture and storage (CCS) or bioenergy with CCS (BECCS) by the end of 2050.

CCS can capture CO_2 before it is released into the atmosphere and store it underground, thus providing low-carbon electricity generation when applied to power stations using fossil fuels.[6] It is also the only currently available technology which can help reduce carbon emissions from large industrial installations and processes, such as cement manufacture. BECCS, which combines bioenergy production with CCS, can potentially achieve "negative CO_2 emissions" by using biomass that has removed atmospheric carbon while growing, then storing the carbon emissions from combustion underground.[7] Fossil fuel energy production with CCS could also be critical for ensuring that intermittent renewable energy (e.g. solar and wind) is backed by flexible, low-carbon energy sources to allow electricity systems to operate smoothly. The International Energy Agency (IEA (2015)), for example, estimates that CCS could deliver 13% of the cumulative emissions reductions needed by 2050 to limit the global increase in temperature to 2ºC.

Thus, the amount of fossil fuels – such as oil, gas and coal – that could be used while maintaining the warming at below 2ºC will depend on the availability of cost-effective CCS and BECCS, and potentially also on the future development of other carbon dioxide removal (CDR)

[5] IPCC (2014) uses 'likely' to refer to an event which is expected to occur with a probability of 66-100%.
[6] According to IEA (2015), the existing and planned applications of CCS include industrial sectors (steel, cement, chemicals, fertiliser, hydrogen and refining), natural gas processing, gas-fired power, coal-fired power, CCS with bioenergy (BECCS) and enhanced oil recovering using CO_2.
[7] A key challenge facing the BECCS technology is that the production of bioenergy could encounter competition with other uses of land (e.g. food production) under large-scale deployment scenarios (Fuss *et al*, 2014).

technologies that allow the removal of CO_2 from the atmosphere.[8] In the absence of such technologies, maintaining the warming to 2ºC would imply that some of the existing fossil fuel reserves would become 'stranded', i.e. unusable. For example, McGlade and Etkins (2015) estimate that, without CCS, 35% of known global oil, 52% of gas and 88% of coal reserves will be 'unburnable' before 2050 in order to achieve the 2ºC target.[9]

The deployment of CCS has been slow, however: as of October 2014, only 17 projects were operational across the world, and no commercial scale CCS installation is currently in place in the European Union (Bassi *et al.*, 2015). This in part reflects cost considerations, both in terms of R&D expenditure, fixed cost of investment, and the marginal cost of capturing and storing carbon dioxide, plus the long time lag in ascertaining the presence of sufficient storage capacity that can be accessed at reasonable cost (IEA, 2015). Bassi *et al.* (2015), for example, estimate that the carbon price (which could take a form of a carbon tax or determined via a carbon emission trading scheme) would need to be about €35-60/tCO_2 for CCS coal-fired power plants to compete against coal-fired plants with unabated emissions, and €90-105/tCO_2 for CCS-gas fired plants to compete against gas-fired plants with unabated emissions.

2 Impact of climate change on financial stability

Bank of England (2015) and Carney (2015) set out three types of risk factors created by climate change and climate change policies that could affect the insurance industry in particular: physical risks, transition risks, and liability risks. This section examines the channels via which these give rise to financial risks that could affect the stability of the financial system more generally.

2.1 Physical risks

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. According to IPCC (2014), climate change related risks from extreme events, such as heat waves, heavy precipitation, and coastal flooding, are already "moderate".[10] These risks will be higher with 1ºC of additional warming relative to the 1986-2005 period, and risks associated with some types of extreme events (e.g. extreme heat) increase progressively with further warming.[11] The strength of scientific evidence linking climate change to the likelihood of specific types of hazards is variable. For example, IPCC (2014) suggests that there is reasonably strong evidence linking climate change to a decrease in cold temperature extremes, an increase in warm temperature extremes (e.g. heat waves), an

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[8] CDR technologies other than BECCS, such as direct air capture, are still at an early stage of development and not yet viable for large-scale deployment. But large scale deployment of BECCS and other CDR technologies which can achieve negative carbon emission creates the possibility of some unabated fossil fuels remaining in use while staying within the 2ºC 'carbon budget'. Future development of solar radiation management (SRM) technologies that offset the warming effects of GHGs by causing the Earth to absorb less solar radiation, is potentially also relevant, but no outdoor SRM project is currently underway.

[9] They also project that 33% of oil, 49% of gas, and 82% of coal reserves will be need to remain 'unburnable' before 2050 even under the assumption that CCS becomes widely used from 2025 onwards if the cost of CCS remains high.

[10] IPCC (2014) classifies the level of additional risk due to climate change into 'undetectable', 'moderate', 'high' and 'very high'.

[11] Increasing warming also increases the risk of triggering 'tipping points' – such as thawing of permafrost, release of methane and collapse of land-based polar ice sheets – which could have profound, irreversible consequences (Stern, 2013).

increase in extreme high sea levels (e.g. storm surges) and an increase in the number of heavy precipitation events in a number of regions. By contrast, evidence linking climate change to frequency and magnitude of fluvial floods, droughts, and tropical cyclone activity is either more limited or less robust, and varies across regions, although links have been made in specific cases (e.g. Schaller *et al.*, 2016).

2.1.1. The impact of financial sector activities on physical risks

Financial sector activities can influence physical risks through a number of channels. First, the decision of financial institutions to fund activities that are intensive in CO_2 emissions can contribute to increasing the climate-related physical risks, albeit indirectly; and conversely, their financing of technologies that help reduce CO_2 emissions can contribute to a reduction of climate-related physical risks. This is a problem of externalities, as the financial institutions that fund these activities do not necessarily suffer the losses and gains resulting from changes in climate-related physical risks, most of which may occur in the future, and hence may not internalise these losses and gains when making the funding decisions. The standard ways of addressing such externalities include appropriate use of taxes and subsidies, and legislation that directly targets the specific externalities.

By contrast, prudential regulations are fairly blunt instruments for dealing with climate-related externalities. For example, capital requirements for banks and insurers are designed to mitigate prudential risks, and hence adapting these to reflect externalities could undermine their primary purpose, or could give rise to undesirable effects. On the one hand, relaxing regulations just to encourage particular types of lending, for example by reducing risk weights that are used in calculating the regulatory capital ratios below their prudentially sound levels, could jeopardise the safety and soundness of financial institutions.[12] On the other hand, tightening regulations on financial exposures to carbon-intensive firms could also have the unintended effect of increasing the cost of finance for those borrowers, thus reducing their ability to invest in emission-reducing technologies (e.g. CCS and renewables), unless exclusions can be applied to financing specifically earmarked for such investments. Thus, targeted policy measures are more likely to be effective in achieving climate-related objectives than adapting prudential regulations. Such policies might include appropriately priced carbon taxes on firms' activities, which could vary over time.

Second, both the size of the financial losses arising from the occurrence of a given hazard and the allocation of those losses are influenced by the *ex ante* decisions of the financial sector. For example, the amount of insurance and credit available for financing the construction of buildings in flood-prone areas will determine the size of the eventual financial losses arising from the materialisation of such risks, as well as the allocation of these losses. The market outcome can be expected to be efficient as long as all contracting parties are fully aware of the risks and can price them efficiently, but various market imperfections could result in mispricing of risks. For example, the price of insurance could be driven up if asymmetric information leads

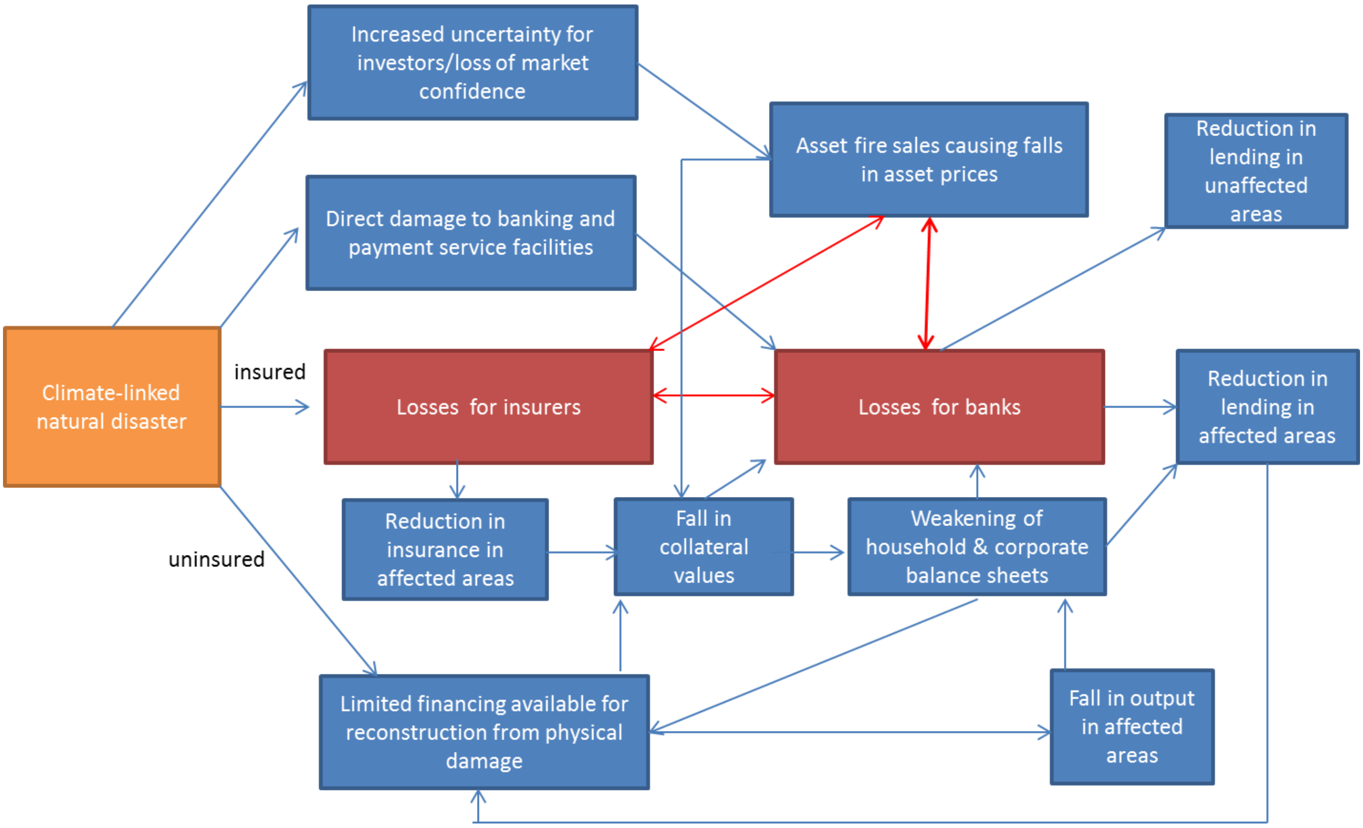
[12] A private sector firm which specialised in such lending, based on reduced capital risk weights – an entirely plausible outcome - would have insufficient capital to be prudentially safe and sound. Such lending could, however, be made by an entity with a state guarantee.

to adverse selection problems, in which only those parties that are inherently higher risk than average choose to buy insurance.[13] Moreover, uncertainty about the wider repercussions of extreme weather events implies that certain risks – such as the likelihood that they trigger riots that could cause further damage – are inherently hard to model.

2.1.2. The impact of climate-related natural disasters on the financial system

The materialisation of climate-related physical risks – e.g. via natural disasters that are influenced by climate change – can potentially result in large financial losses, some of which are borne by insurers while others are uninsured. As illustrated in Figure 2, losses resulting from climate-related natural disasters could affect the soundness of individual financial institutions and the stability of the financial system via a number of possible channels.

Figure 2: A transmission map from a natural disaster to financial sector losses and the macroeconomy



i) <u>Insured vs uninsured losses</u>

As illustrated in Figure 2 above, the transmission mechanism of a climate-linked natural disaster may depend on the extent to which losses are covered by insurance. Data from Munich RE

[13] Some existing research suggests that market-based catastrophe risk price is significantly higher than implied by the expected loss, although this by itself does not necessarily point to a market failure. For example, Lane and Mahul (2008) estimate that the market-based catastrophe risk price was around 2.7 times expected loss over the long-term, based on data from about 250 catastrophe bonds issued during 1997-2008Q1.

suggest that, on average, only about 26% of the losses from the world's largest natural catastrophes (in terms of total losses, including those unrelated to climate change) occurring during 1980-2015 had been insured, while only 50% of the largest storm events had been insured (see Annex 1, Tables A1-A2). Their data also show that, of those natural disasters that were related to weather, hurricanes in North America led to largest losses, while losses from floods and winter storms in Europe were considerably lower (see Annex 1, Tables A2-4). In the United Kingdom, PwC (2016) has recently estimated that only about half (£1-1.4 billion) of the total UK economic loss (of £2-2.8 billion) from the 2015 December – January 2016 storm events (Storms Desmond, Eva and Frank) was insured, and noted that many small businesses had not covered for flood damage.[14]

ii) Impact of insured losses on the balance sheets of insurers

If insured losses resulting from an event or a series of events are sufficiently large and concentrated, they could lead to distress or failure of insurance companies. For example, Hurricane Andrew in 1992 resulted in the insolvency of several insurance companies. The failure and distress of insurance companies in turn could affect financial stability if they were to lead to disruptions to critical insurance services and systemically important financial markets, such as securities lending and funding transactions (French and Vital, 2015). Large-scale fire sales of assets by distressed insurers could reduce asset prices which could adversely affect the balance sheets of other financial institutions, such as banks.

Natural disasters are more likely to lead to distress or failures of insurance companies if they underestimate the risks *ex ante* and hold insufficient capital as a result. The existing analyses suggest that the insurance industry may indeed be underestimating the impact of climate change on catastrophe risks. Standard and Poor's (2014a) argues that reinsurers might be underestimating their exposure to one-in-10 year and one-in-250 year catastrophe losses by an average of about 50%, using an illustrative scenario analysis to test the potential impact of climate change. Lloyd's (2014) suggests that, despite improvements since Hurricane Andrew, most catastrophe models – which are now used extensively by insurers and reinsurers, as well as governments, capital markets and other financial entities – still tend to rely heavily on historical data and do not necessarily incorporate climate change trends explicitly. More recently, however, some institutions have started to develop catastrophe models that incorporate the impact of climate change.[15] But the issue is not just about the possible underestimation of the likelihood of particular types of events. Climate change may also change the correlation between individual risks – for example the extent to which European wind storms happen in clusters – and the assumptions made about these correlations affect the setting of insurance firms' capital requirements. Larger catastrophes could also affect multiple sectors and thus can result in correlated losses across business lines. The impact of climate change on these correlations is highly uncertain but may imply that benefits from diversification are reduced.

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[14] See http://pwc.blogs.com/scotland/2016/01/scotland-storm-flood-damage-pwc-update-on-business-and-insurance-loss-impact.html for PwC estimate as of 7 January 2016.
[15] See, for example, RMS: http://www.rms.com/blog/2014/06/24/rms-and-risky-business-modeling-climate-change-risk/

To date, weather-related catastrophes have not led to large-scale failures of insurance firms or system-wide financial instability in advanced economies.[16] What has been more common, however, is collective withdrawal of insurers from covering risks that they consider to have become uninsurable (Chartered Insurance Institute (2009)). Less severely, insurers may simply respond by raising premiums for covering similar risks. The reduced insurance coverage could in turn reduce the collateral values in affected areas (and potentially, also unaffected areas that face similar risks), which could tighten the borrowing constraints of households and corporates. Thus, even if losses are largely insured and financing for reconstruction is immediately available, a severe weather-related catastrophe could affect the banking sector and the real economy in the medium-term (Figure 2).

In advanced economies, the public sector has often stepped in to avoid this impact, either to assume these risks directly or to support the creation of privately-funded entities to assume them. For example, the 1992 Hurricane Andrew led to the creation of the state-run Citizens Property Insurance Corp which provides "the insurance of last resort" for home and business owners in Florida. In the United Kingdom, Flood Re was established by the insurance industry in agreement with the government in April 2016 to offer a reinsurance mechanism for flood risk, and thus enable household insurers to offer affordable flood insurance to UK households with domestic properties facing higher levels of flood risk. Its operations are funded through a levy collected from UK household insurers.[17] Flood Re, however, does not cover flood risks to business premises, second homes, buy-to-let properties, and any property built after 1 January 2009.

iii) Impact of uninsured losses on the balance sheets of banks

Insurance is a key mechanism via which losses arising from natural disasters are spread across time and people. Thus, while withdrawal of insurers from covering weather-related risks would help protect the insurance industry from losses, this does not necessarily represent an efficient outcome for the financial system or the economy as a whole. *Ex ante*, an excessively high price for catastrophe insurance could lead to underinsurance, which in turn could reduce collateral values. The reduction in collateral values could in turn reduce lending to inefficiently low levels in the presence of borrowing constraints. For example, Garmaise and Moskowitz (2009) show that a poorly functioning catastrophe market leads to about 20% less bank-financing of catastrophe-susceptible commercial real estate *ex ante*.

Ex post, underinsurance could magnify the economic impact of a natural disaster by constraining the financing of the post-disaster reconstruction that contributes positively to GDP (a 'flow' measure). The resulting delay in reconstruction could also reduce the collateral values securing the loans – such as the properties securing mortgage or small business loans – thus further tightening the financing constraints of affected households and corporates. Indeed, von

[16] Bank of England (2015) noted that the use of catastrophe risk modelling, portfolio diversification, alternative risk transfer and short-term contracts would suggest general insurers are reasonably well equipped to manage the current level of direct physical risks.
[17] In agreeing to set up Flood Re, the insurance industry obtained a commitment from the government that it will continue minimum levels of investment in flood defence and maintenance over the 25-year period. See Bank of England (2015) and http://www.floodre.co.uk/ for further details on Flood Re.

Peter, van Dahlen and Saxena (2012) find that it is the uninsured losses that drive the negative impact on GDP after a natural disaster, while insured losses have insignificant impact both in the short- and long-run.

In the United Kingdom, over 85% of loans to individuals and 75% of loans to small- and medium-sized enterprises (SMEs) are secured on property. The UK's Environmental Agency (2009) also suggested that around 5.2 million of properties in England, or one in six properties, are already at risk of flooding, while the Met Office (2011) highlighted that climate change is likely to increase the risk of both fluvial and coastal flooding in the United Kingdom. Thus, floods and other natural disasters could potentially have a negative impact on the value of the collateral securing these loans, especially if the collateralised properties are uninsured.[18]

The post-disaster reduction in collateral values is likely to be larger, the less the risk of such disasters was reflected in property prices *ex ante,* and the more insurers pull out from covering properties in the affected regions *ex post*. In the United Kingdom, there is some evidence that flood risks are generally not r in property prices until floods actually occur. For example, Lamond's (2009) study of the flood event in 2000 find that being designated as a high flood risk area has no effect on property prices. An actual flooding, however, has a temporary (3 year) effect on property values. Lamond (2009) reports that less than half of the respondents reported that they were fully aware of the flood risk to their property at purchase, and for transacted property about one third were alerted to the risk status of their potential purchase by insurance premiums.

Households' and corporates' balance sheets could be further weakened if output and employment fall in affected areas due to a slow reconstruction, which is more likely when the affected parties suffer large uninsured losses and fiscally-funded aid is limited. For example, a survey of firms conducted by the Federal Reserve Bank of New York (2014) after Superstorm Sandy (2012) found that almost a third of the affected firms had no insurance, and only a few had business disruption or flood insurance. Losses also came from sources which are harder to insure: 59% of firms reported losses from decreased customer demand, in contrast to 29% reporting damage to or loss of assets, which is easier to insure. The impact on firm balance sheets was considerable: half of the firms covered storm-related financing needs with personal resources while others increased debt levels. One year after the disaster, 9 out of 10 of the affected firms reported persistent financing needs to cover operating expenses or to reposition their business.

A reduction in collateral values and a weakening of household and corporate balance sheets in turn could increase the loss-given-default (LGD) and the probability of default (PD) of loans, thus could adversely affect the banking system (Figure 2). There is some empirical evidence that supports the hypothesis that natural disasters affect the soundness of banks, and that the structure of the financial system influences the losses borne by banks. For example, Klomp (2014) finds evidence that, for a sample of 160 countries in the period 1997-2010, meterological

[18] Although most mortgage providers generally require buildings insurance as a condition for granting a mortgage, they do not necessarily require cover for specific hazards, such as floods, to be in place.

and geophysical disasters (hydrological disasters including floods; meteorological disasters concerning storms and hurricanes; geophysical disasters including earthquakes, tsunamis and volcanic eruptions; and climatic disasters including extreme temperatures, droughts and wildfires) increase the likelihood of bank default. This effect, however, is mitigated in countries with rigorous financial regulation and supervision, and highly developed economies where banks tend to have well-diversified asset portfolios and borrowers are typically better insured. In a separate study using US data on property damages from hurricanes, earthquakes and other natural disasters during 1976-2010, Lambert, Noth and Schuwer (2014) also find that disaster damages in banks' business regions significantly increase the probability of their failure in the medium-term, i.e. about five to nine years after the disaster damage. The authors conjecture that public financial aid and insurance payouts, as well as borrower savings could cushion the impact of a disaster on banks in the short term, but not in the medium term when support from these sources are depleted. Landon-Lane, Rockoff and Steckel (2009) find evidence that, for some regions and periods in the United States, droughts were associated with farm mortgage foreclosures and bank stress, but climate-related bank stress has become less important after 1940 due to adaptation of both farmers and banks.

Finally, major natural disasters abroad could also affect domestic banks, particularly if the resulting economic disruptions, fall in tax revenues and rise in fiscal expenditures lead to a sharp increase in sovereign default risk. A recent analysis by Standard and Poor's (2014b) suggests that the countries that are most vulnerable to climate change are emerging market countries, mostly in Africa and Asia, and that sovereigns with low credit ratings tend to be more vulnerable compared to those with high ratings.

iv) <u>Impact on the credit flow to the real economy and financial markets</u>

If banks suffer losses on their capital as a result of a natural disaster, and cannot raise new capital immediately, then they could reduce lending to both affected and unaffected areas in order to improve their regulatory capital ratios. The resulting reduction in credit supply could in turn exacerbate the fall in the collateral values and further damage the balance sheets of households and corporates, potentially deepening the post-disaster downturn (Figure 2).

A natural disaster could potentially also 'crowd out' bank lending in unaffected areas, as credit demand increases in affected areas when households and corporates seek to fund the reconstruction of damaged homes and buildings by supplementing insurance payments through bank credit; and banks operating in these areas could be constrained in increasing credit supply, especially if they have suffered losses on their capital due to the disaster. Cortes and Strahan (2015) examine how banks in the US reallocate capital when credit demand increases in areas affected by a natural disaster, and show that bank lending in other markets declines by about 50 cents per dollar of additional lending in the area which experienced the disaster. Banks were also found to increase sales of more liquid loans and increase deposit rates to attract funds.

Major natural disasters could potentially also trigger a sharp increase in precautionary demand for liquidity by financial institutions, households and corporates, for example due to disruptions in banking services directly caused by disasters (e.g. due to closures of bank branches and

ATMs in areas affected by the disaster) and the increased uncertainty facing households and financial market participants in the immediate aftermath of a disaster. A surge in liquidity hoarding could potentially destabilise the financial system and the economy in the absence of central bank intervention to supply liquidity.[19] The existing literature also points to the possibility that major natural disasters could lead to long-term changes in risk preferences of affected people, which could have longer term impact on financial market dynamics.[20]

2.2 Transition risks

Transition risks can be defined as the risks of economic dislocation and financial losses associated with the transition to a lower-carbon economy. As we discuss below, a smooth transition to a low-carbon economy is possible if the expectation of a future policy tightening on carbon emission induces an early and orderly shift of private investment towards low-carbon technologies. Moreover, not making a transition implies that the physical risks from climate change are likely to increase over time. Nevertheless, it is possible that a late and abrupt policy tightening on carbon emission could lead to a loss in value – or 'stranding' – of carbon-intensive investment. Although any economic transition induced by a tightening of regulation could potentially create winners and losers, the aggregate impact is likely to depend on the size of the sectors affected: for example, oil and gas sectors alone account for 12.5% of FTSE 100 index (as at 31 March 2016).

A substantial reduction in CO_2 emission can be achieved without a large sacrifice in GDP growth if it is possible to increase energy efficiency (i.e. reduce energy intensity of GDP)[21] and reduce carbon intensity of energy, as summarised by the Kaya identity below:

$$\text{Carbon emissions} = \text{Population} \times \frac{\text{GDP}}{\text{Population}} \times \frac{\text{Energy used}}{\text{GDP}} \times \frac{\text{Carbon}}{\text{Energy used}}$$

Transition to a low-carbon economy would therefore require investments to shift from high-carbon energy production technologies towards low- and ultimately zero-carbon energy production. If investments in low-carbon energy production do not take place in sufficiently large scale, and the policy on carbon emission is abruptly tightened, then the transition to a 'low carbon' economy could be associated with sharp falls in asset prices, such as those of fossil fuels and firms that depend heavily on their use (Carney, 2015).[22]

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[19] For example, after the Great East Japan Earthquake in March 2011 – which remains the largest natural disaster since 1980 based on total losses – the Bank of Japan had to offer record amounts of liquidity (BoJ (2011)).

[20] Evidence on the impact of natural disasters on risk preference is mixed. Some studies suggest that exposure to natural disasters leads to an increase in observed risk aversion (see Cassar, Healy and von Kessler (2011); Cameron and Shah (2013)). Other studies, however, find a decrease in risk aversion and an increase in risky behaviours such as gambling and drinking (see Ingwersen (2014); Eckel, El-Gamal, and Wilson (2009); and Hanaoka, Shigeoka and Watanabe (2015)). Bernille, Bhagwat and Rau (2015) find that CEOs who experience natural disasters without suffering extremely negative consequences lead firms to behave more aggressively, whereas CEOs who witness the extreme downside of natural disasters behave more conservatively.

[21] The reduction in energy intensity of GDP can be achieved in a number of ways, including via i) changes in energy consumption behaviour and life styles, ii) changes in economic incentives to consume energy, and iii) the low cost availability of energy-efficient technology.

[22] Policies aimed at reducing carbon emissions can either target a given quantity of emissions (through a cap-and-trade system such as the EU Emission Trading Scheme – ETS) or their price (through carbon taxes).

Below, we set out a simple framework to conceptualise the transition to a low-carbon economy as a multiple equilibrium problem, and examine empirical evidence on the pricing of the transition risk in financial markets.

2.2.2 Transition risk as a multiple equilibrium problem

Consider a very simple stylised 'game' between the government and the electricity companies in determining investment in low-carbon electricity generation, for example investment in CCS. At time T, private electricity companies decide whether to invest in CCS, which costs i_T for each company. At time T+1, the government chooses to 'shut down' unabated fossil-fuel fired power plants if the benefit B_{T+1} of doing so, in terms of preventing the adverse impact on climate, exceeds the costs C_{T+1}, in terms of the increased cost of electricity for the population. The cost to the government of shutting down unabated electricity production at T+1, however, depends on the amount of electricity that can be generated by low-carbon alternatives, e.g. renewables and coal and gas-fired power plants with CCS. Thus, we assume that the more investment takes place in low-carbon electricity production at time T, the lower will be the cost of shutting down high-carbon electricity production at T+1: so $C_{T+1}(I_T)$ is decreasing in I_T, where I_T is the *aggregate* investment in low-carbon electricity production at time T.

The private return from investing in low-carbon electricity production at time T depends on whether private electricity companies (and their investors) expect the government to shut down unabated electricity production at time T+1. The private investors know that the government will shut down unabated electricity production at T+1, if $C_{T+1}(I_T) < B_{T+1}$, which occurs if I_T rises above a critical threshold I^*_T, which is defined by the condition $C_{T+1}(I^*_T) = B_{T+1}$. Thus, if a sufficiently large number of companies invest in low-carbon electricity production, then they will expect the government to shut down the unabated electricity production facilities in the future.

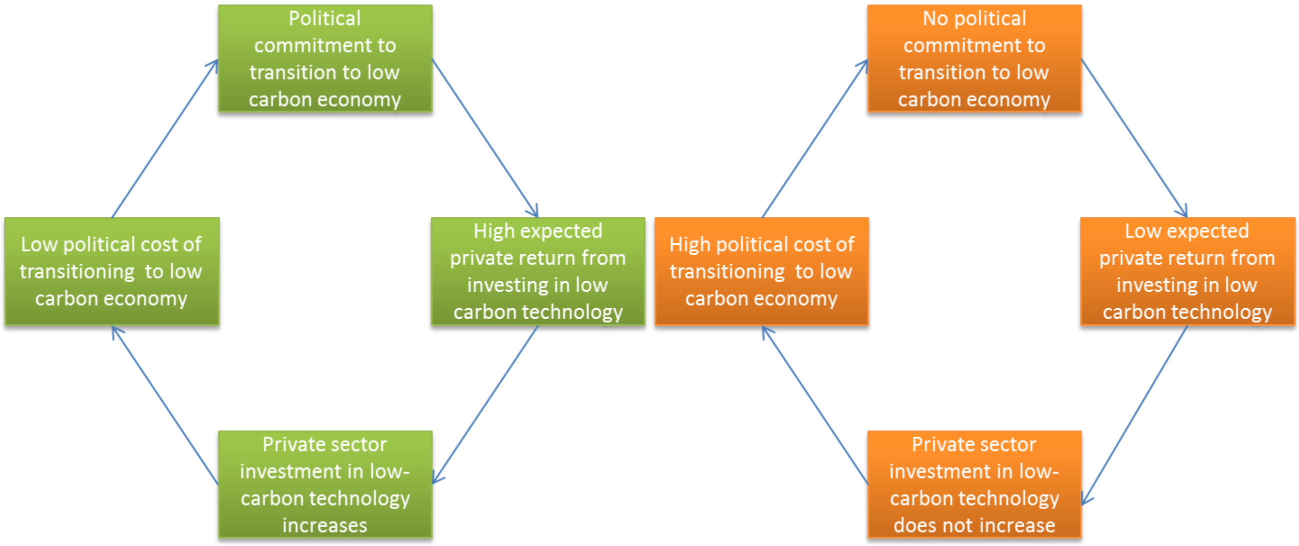
Table 1: Stylised payoffs of electricity companies under different scenarios about climate change policy

	Government shuts down unabated electricity production at T+1 (low emission)	**Government continues to allow unabated electricity production at T+1 (high emission)**
Invest in CCS at T	$(P_H-A)R-i_T>0$ 'low-carbon equilibrium'	$(P_L-A)R-i_T<0$ 'low-carbon investment becomes loss making'
Don't invest in CCS at T	0 'some fossil fuels and unabated power plants become stranded'	$P_LR>0$ 'high-carbon equilibrium'

Suppose that the government decides to shut down the unabated electricity production facilities at T+1 (Table 1, column 2). We assume that those electricity companies that had invested in CCS at time T can obtain a 'high' price, P_H, per unit of fossil fuel R converted into electricity, minus the abatement cost A: thus, their net profit will be $(P_H\text{-}A)R\text{-}i_T$, which we assume to be positive. By contrast, those companies that had not invested in CCS at time T will be shut down, and hence obtain zero profits: in this case, capital in unabated fossil-fuel power plants and fossil fuel reserves, R, that would have been used for power generation, will become 'stranded'.

Suppose now that the government decides to keep unabated power plants open at T+1 (Table 1, column 3). In this case, those companies that had invested in CCS at time T can only obtain a 'low' price, P_L, due to the availability of abundant electricity supply from unabated power plants. We assume that, in this case, those companies that had invested in CCS at time T will earn negative profits: $(P_L\text{-}A)R\text{-}i_T<0$. By contrast, those companies that had not invested in CCS will obtain a profit of P_LR by selling unabated electricity.

Figure 3: 'Low carbon emission' and 'high carbon emission' equilibria

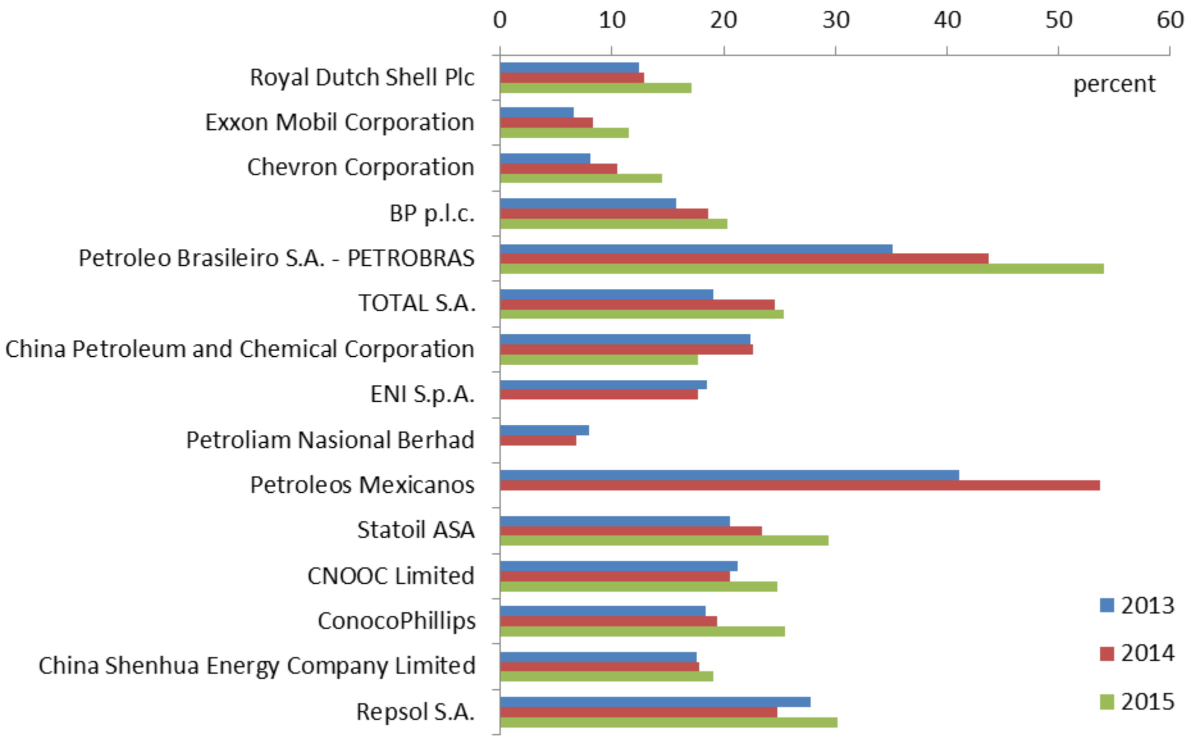


In this set up, the electricity companies' investment choice in CCS is subject to 'strategic complementarity', where the return from investing in the technology depends on whether others also invest. If everyone invests in CCS at T such that the aggregate investment exceeds I^*_T, then the cost of transitioning to a low carbon economy for the government is reduced sufficiently such that it becomes credible for the government to shut down unabated power plants at T+1. This in turn creates incentives for private electricity companies to invest in low-carbon technology: the result is an orderly transition to a 'low-carbon' equilibrium, in which fossil fuels can continue to be used for power generation as a result of CCS being in operation.[23] By contrast, if nobody invests in CCS at T, then the cost of shutting down all the unabated fossil-fuel powered plants at T+1 becomes too high and hence the government's commitment to transition to a low carbon economy becomes 'time inconsistent', or not credible, leaving the economy stuck at a 'high carbon' equilibrium (Figure 3).

[23] Van Vuuren et al. (2011) notes that, by 2100, the total fossil fuel energy use is projected to rise above the levels used in 2000 under all RCPs, including in RCP 2.6 which is likely to keep the warming below 2 ºC, due to the assumed deployment of CCS technologies.

However, a disorderly transition is possible if, for example, the government's policy on carbon emission were to tighten abruptly – for example, due to a sudden change in popular attitude towards climate change, or a technological breakthrough in low-carbon energy generation, which increases the benefits of transition, B_{T+1}. In a disorderly transition scenario, the value of fossil fuels and firms that depend on high-carbon energy production could fall sharply: in the stylised example in Table 1, the value of the electricity company without CCS would fall from $P_L R$ to zero. Such disorderly adjustments in asset prices could lead to corporate defaults and distress, and hence trigger financial instability if the affected companies are highly leveraged. Figure 4 shows that the major oil companies have varying degrees of indebtedness, but are becoming increasingly more levered. As we discuss in Section 3, a disorderly transition could also be associated with a negative supply shock for the aggregate economy.

Figure 4: Debt-to-asset ratios of major oil companies, 2013-2015



Sources: Moody's and authors' calculations.
Note: The ratio is calculated as short-term plus long-term debt as a percentage of total assets. 2015 figures are presented where they were available.

The simple framework above underscores the value of transparent, predictable policy on carbon emission in anchoring private investors' expectations. In particular, a pre-commitment of policy tightening on carbon emission strengthens private investors' incentives to invest in low-carbon technologies, thus making an orderly transition to a low-carbon economy more likely. Such a pre-commitment could, for example, take the form of a pre-announced path for a carbon price which helps to internalise some of the externalities associated with carbon emission. But even a less well-defined commitment, such as the 2015 Paris Agreement, might help coordinate private investments towards low-carbon technologies if investors perceive this to be a credible signal for future tightening of policy on carbon emission.[24]

2.2.3. To what extent is the transition risk reflected in asset prices?

There is evidence that some institutions have already started divesting from high-carbon assets, such as fossil fuel companies, and that this is already having some market impact. A movement to divest from fossil fuels started in US universities and religious institutions. By the end of 2015, more than 500 organizations across the world with US$3.4 trillion in assets have pledged to divest from fossil fuel companies.[25] This movement to reduce investment in high-carbon assets has not been confined to asset managers. In May 2015, Bank of America announced plans to reduce its financial exposure to coal companies. Since then, Crédit Agricole, Citibank and Allianz have all made similar announcements regarding their financial exposures to the coal sector.

By using standard event study methodology it is possible to examine the market reaction to specific events, which could be associated with a change in market expectations about the profitability in investing in carbon-intensive assets. To estimate the impact we look at changes in the market valuation of the firm's equity measured by abnormal returns (returns above and beyond those expected under normal market activity and movement, i.e. residual returns after stripping out market returns) following the event. For this exercise we examine the effect on all energy firms on the spectrum from coal companies to renewable energy firms.[26] To find and date events, we search for news stories in major newspapers or energy specific investment press mentioning the words 'carbon bubble'[27], 'unburnable carbon, and 'fossil fuel divestment', and use data from climate organisations which track divestment announcements. Although we have over 50 different events between January 2008 and January 2016, many of them happened close together, and so we excluded any event which happened within five days of another event from the analysis. We also test major significant events, such as the Paris Agreement, individually. Detailed discussion of the methodology is found in Annex 2.

Figure 5 illustrates the contrasting cumulative abnormal returns experienced by a petroleum refining company (CVR Energy) and a wind turbine manufacturer (Nordex) in the immediate aftermath of the announcement of the Paris Agreement on 12 December 2015. More generally, we find that these events had a negative but statistically insignificant effect on the abnormal returns for oil and gas companies, but a positive and significant effect for renewable energy companies.

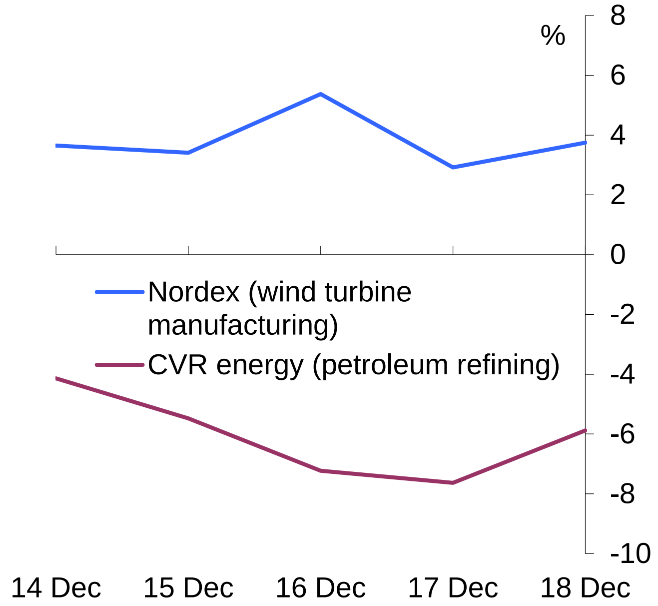
[24] There is a possibility that a pre-commitment of policy tightening on carbon emission (e.g. via a carbon tax that increases over time) could incentivise fossil fuel producers to extract fossil fuels (e.g. oil) at a faster rate before policy is tightened further (e.g. Sinclair 1994). This incentive could be mitigated by the low elasticity of oil demand, which implies that increased oil supply could lead to a collapse of oil and other fossil fuel prices.

[25] https://350.org/in-the-space-of-just-10-weeks/

[26] The sector includes all the firms in the exploration and production, integrated oil and gas, oil equipment and services, pipelines, renewable energy equipment and alternative fuels sectors

[27] Carbon bubble is the notion that the companies that are dependent on fossil-fuel-based energy production could be considered as overvalued when the possibility that some fossil fuel reserves may become unusable, or 'stranded' if the global warming is to be kept within certain limits.

Figure 5: Cumulative abnormal returns after the Paris Agreement, December 2015



Sources: Thomson Reuters Datastream, Bloomberg and authors' calculations.

There are a number of reasons why the events may not have had a significant impact on the market values of fossil fuel companies. First, investors may be uncertain about both the future course of climate-related policies and their impact on the value of fossil fuel companies. Second, investors concerned about the transition risk may choose to divest from fossil fuels over several years rather than liquidating their portfolios immediately based on specific news. Altogether, the results suggest tentatively that, although some investors are beginning to incorporate expected changes in energy policy into their assessment of firms, in general this has not been producing large and sudden movements in equity prices.

2.3 Liability and other legal risks

Parties that have suffered loss and damage arising from physical or transition risk from climate change could seek to recover losses from others who they believe may have been responsible. If such claims are upheld, those parties against whom the successful claims are made will either have to bear the losses themselves, or could seek to pass on some or all of the losses to their liability insurance providers.[28] Conceptually, liability and other legal risks are about the distribution of losses arising from physical and transition risks amongst different parties. Bank of England (2015) noted that there are three primary lines of argument for establishing liability:

1. **Failure to mitigate**: the claimant could allege that the defendant (e.g. an oil company) has altered the climate to the detriment of the claimant by causing the release of GHGs.

2. **Failure to adapt**: the claimant could allege that the defendant, with whom he or she has a contractual or other direct relationship, has exposed the claimant to an increased level of weather-related losses by supplying goods or services that are not of satisfactory quality or fit for purpose; or that the defendant has exposed the claimant to an increased level of financial losses by failing to take into account the possibility of tighter regulation on carbon emissions.

3. **Failure to disclose or comply**: the claimant could allege that the defendant has not sufficiently disclosed information relevant to climate change, has done so in a manner that is

[28] Liability insurance is part of the general insurance system of risk financing to protect the purchaser from the risks of liabilities imposed by lawsuits and similar claims.

misleading, or has otherwise not complied with climate change-related legislation or regulation.

At present, there are several barriers to holding GHG emitters legally liable for causing climate change (point 1 above). First, in most cases, the current scientific knowledge is still insufficiently advanced to discriminate between natural variability and anthropogenic causes of specific extreme events.[29] Second, the GHG emitters are widespread, making it challenging to attribute the cause of losses to specific emitters, or allocate these losses amongst them (Chartered Insurance Institute, 2009).

Claims relating to failure to adapt, disclose or comply could potentially affect various types of liability insurance, including directors' and officers' liability insurance (e.g. if directors of companies are sued for the delay taking action on climate change, or are inadequately); professional indemnity insurance (e.g. due to claims arising from litigations against insured architects and engineers for failures to buildings due to extreme weather conditions); public liability insurance (e.g. public authorities could be sued for damages for providing inadequate infrastructure that can withstand extreme weather); employers' liability insurance (e.g. if employers are held liable for heat-related injury and illnesses); and product liability insurance (e.g. if failure of products because of extreme weather conditions, such as high temperature, could also result in claims over fitness for purpose, compliance with specification and recommended usage).

The liability insurance market, however, is relatively small in size: as of 2013, the liability insurance market was worth US$160 billion, or 10% of global non-life premiums (Swiss Re 2014). Thus, while liability risk matters for individual insurers that are active in this market, the risk it poses to the macroeconomy or financial stability may be limited unless a series of successful climate-related liability insurance claims result in a distress or failure of a major liability insurer which then could affect the financial system as a whole.

To sum up, the transition risk is most likely to affect the financial system as a whole, although effective policies to re-direct private investment towards low-carbon technologies could mitigate this risk. The physical risk is likely to affect the system as a whole only if the magnitude of weather-related disaster is very severe and affects highly populated areas with significant productive capacity. The liability risk is most likely to affect specific institutions within the system active in the liability insurance market.

2.4 Climate-related stress tests and disclosure

This section examines high-level considerations for designing climate-related stress tests and disclosure, both of which are relevant for assessing and mitigating risks to financial stability.

2.4.1 Stress tests

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[29] Further scientific and other analytical developments, however, could change this: for example, Lloyd's (2014) argues that the 20 cm of sea level rise at the Southern tip of Manhattan Island increased Superstorm Sandy (2012)'s surge losses by 30% in New York alone, citing scientific evidence.

It has been suggested that stress tests could be used to examine the extent to which the financial system is exposed to climate-related risks (e.g. Garman and Fox-Carney, 2015; ESRB, 2016; and Farid *et al*., 2016). A stress test examines the potential impact of a hypothetical adverse scenario on the health of the financial system and individual institutions within it. Stress tests allow policymakers to assess the resilience of the financial system and individual institutions to a range of adverse shocks; and, if needed, take measures to ensure that financial institutions are resilient and can continue to supply credit to the real economy even under stress. Conducting a climate-related stress test would require: a) formulating a coherent 'tail risk' stress testing scenario which could have a major impact on the stability of the financial system; b) identifying sectors that are most exposed to financial loss in that scenario; c) identifying available data and additional data that need to be collected; and d) modelling the transmission mechanism of shocks across the financial system.

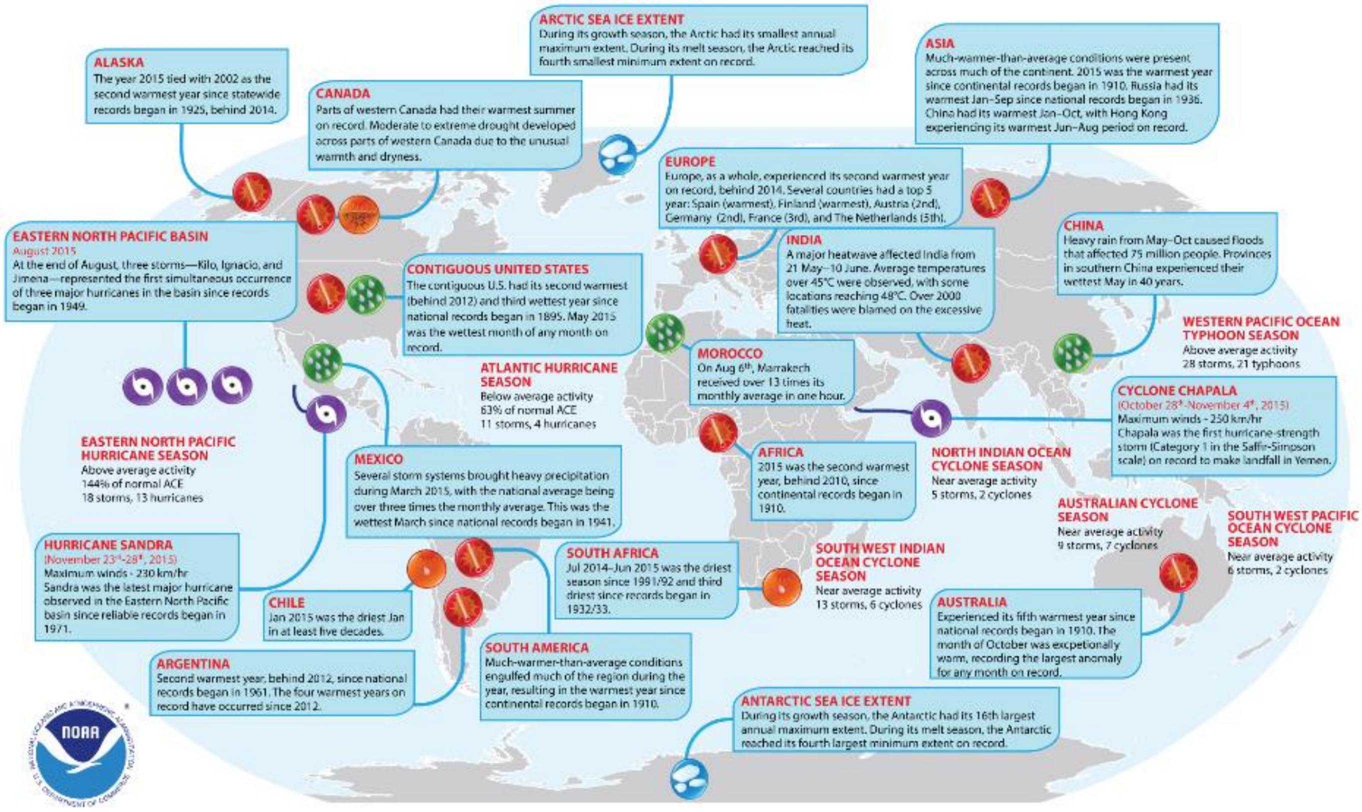
i) <u>Stress testing against physical risks</u>

A key challenge in conducting a climate-related stress test lies in identifying a relevant scenario in which the financial sector is expected to suffer a large financial loss. As stress tests can only examine the resilience of the financial system to particular adverse scenarios, the scenario design will be a key determinant of the informativeness of any climate-related stress tests. Although UK weather-related events have caused losses that are small relative to weather-related events abroad, such as hurricanes (see Annex, Tables A1-A4), it may be reasonable to conduct a stress test if it is possible to identify, based on climate science, a plausible UK scenario which could give rise to large economic losses – for example one that involves substantial and long-lasting physical damages to key infrastructures, production facilities, London's financial centre, and other heavily populated metropolitan areas.[30]

It is also possible that UK banks and insurers are more likely to suffer large losses from extreme weather events abroad. For example, Lloyd's (2015) has recently published a climate-related global stress scenario which involves a sharp reduction in food production across a number of countries. However, there are challenges associated in identifying a global stress scenario which is most relevant for the stability of the UK financial system, as climate change physical risk could manifest itself in a multitude of ways and locations: as Figure 6 shows, there have been significant climate anomalies and weather events in many parts of the world in 2015. Moreover, the behaviour of foreign governments and financial institutions is likely to be a key determinant of the impact of an extreme weather event abroad on the stability of the UK financial system. More generally, designing a credible system-wide stress test for global climate-related physical risks remains a challenge given the uncertainties about the effects of climate change on weather events across the world and the transmission of weather-related disasters through the financial system.

[30] For example, Climate UK (2012) notes that, while London is well protected against tidal flooding through the Thames Barrier, it is vulnerable to surface water flooding which could increase in frequency if climate change leads to heavier rainfalls, which could overcome the drainage system.

Figure 6: Selected significant climate anomalies and weather events in 2015



Source: National Centers for Environmental Information. Available from: https://www.ncdc.noaa.gov/sotc/global/201513.

Nevertheless, the disclosure of new information used in stress tests could help enable financial market participants make their own assessments about climate-related risk exposure of particular institutions. For example, although many authorities have been criticised for conducting stress tests that lacked credibility, some have welcomed them on the ground that they helped to release large volume of information that enabled market participants to make their own assessments (Ahmed et al, 2011; Ong and Pazarbasioglu, 2013; and Candelon and Sy, 2015).

To be informative, climate-related stress tests should aim to identify how the economic losses would be distributed and propagated within the financial system under a given scenario, and not simply on the amount of insured losses that may be generated by a weather-related event. Such a stress test would also need to examine the possibility that the insurance and banking sectors may react to the initial shock in such a way to magnify the impact on the economy, as described in Section 2.1. It is also important to ensure that any policy response to such stress test results does not induce a reduction in the supply of insurance against climate-related physical risks, as this may simply pass on the risks elsewhere in the financial system without necessarily increasing the stability of the financial system as a whole.

ii) <u>Stress testing against transition risks</u>

Stress testing the financial system against transition risks is *conceptually* more straightforward. For example, the financial system could be stress tested against a specific path of carbon price which could affect its exposure to non-financial corporates in several industries. This approach has the advantage of capturing the financial impact of internalising the carbon externalities on firms to which the financial sector is exposed to, without having to specify the policy used to implement it, or prejudging the entities and sectors being affected.

There may be *practical* challenges associated with such a stress test, however. First, there may be significant data gaps, as such a stress test would require each financial institution to evaluate how individual firms in their portfolios are affected by a given increase in carbon price. As noted by Battiston et al (2016), most of the data about exposures through bonds and loans – to do a full stress test of the financial system – are unavailable, even to regulators. Second, leaving significant leeway for individual financial institutions in estimating how a given change in carbon price could affect their financial exposures might be problematic in the absence of reliable information that allows regulators and investors to verify these estimates. Thus, in the absence of such information, using a transition stress scenario that is associated with a specific amount of losses in specific industries might be more informative. These considerations suggest that further progress on climate-related disclosures at company level could help inform such stress tests.

2.4.2 Disclosure

In December 2015, the Financial Stability Board (FSB) set up an industry-led Task Force on Climate-related Financial Disclosures to make recommendations for consistent company disclosures that will help financial market participants understand their climate-related risks.[31] Disclosure is a tool which is mainly aimed at removing asymmetric information between the firm's management and investors. Investors may be interested in different types of climate-related disclosures depending on their objectives and concerns. For example, those investors that only care about the financial risks to which they are exposed may be interested primarily in disclosures about firms' forward looking strategies to increase the robustness of their business models to a tighter policy on carbon emissions, changes in technology and societal attitude on carbon emissions.[32] By contrast, those investors that also care about the externalities caused by carbon emissions generated by firms in their portfolios for ethical reasons might also care about firms' current carbon emissions and their strategies for reducing them in the future.[33]

If asymmetric information is the only friction in the market, then its removal through disclosure should enable market participants to price risks more accurately and to avoid investing in firms that they consider are causing large negative externalities. Well-designed climate-related disclosures should help investors to price risks associated with a tighter policy on carbon emissions. This in turn could encourage firms to adopt strategies that lower their exposures to such risks, e.g. by investing in products that are less carbon-intensive. Thus, effective disclosure could facilitate orderly transition to a low-carbon economy. It could also help inform policy institutions that can either influence or are affected by transition risks, including governments and central banks.

[31] See: http://www.fsb.org/2015/12/fsb-to-establish-task-force-on-climate-related-financial-disclosures/

[32] The first type of investors are likely to care about firms' current and past carbon emissions only if they think the risk of these firms being successfully sued for causing climate change is sufficiently high.

[33] For disclosure aimed at climate-conscious investors, see, for example, the proposal by Oxford Martin School (2015).

The existing literature points to a number of high-level considerations which need to be taken into account in order to ensure that disclosure produces a more efficient outcome. First, the published information needs to be relevant to the investors' objectives in order for them to pay attention to it (Sowerbutts, Zimmerman and Zer, 2013). For example, if only a subset of investors care about the externalities associated with carbon emissions by firms that they invest in, then the information about firms' carbon emissions might not necessarily influence the investment decisions of those that only care about financial risks.

Second, if multiple frictions are present, then 'the theory of the second best' might apply: in general, if there are several frictions in the market, then removing one friction could lead to worse outcomes.[34] In such a context, disclosure could induce firms to change their strategy to focus on improving the metric which is being disclosed, rather than long-term economic efficiency. This highlights the importance of choosing the right metric: for example, encouraging firms to disclose only their current carbon emissions might incentivise them to invest in technologies that can reduce them in the near term, rather than investing in technologies that could reduce emissions more substantially in the longer term.

Third, if the disclosed information is difficult to interpret and investors face differential costs in understanding it, then disclosure could end up making some investors better informed while leaving others uninformed, thus encouraging uninformed investors to demand a higher premium from investing in firms in order to avoid losing to better informed investors (Easley and O'Hara (2004)).[35] Disclosure of information that is hard to interpret could also encourage uninformed investors to hold less information-sensitive debt, and the resulting fall in the cost of debt relative to equity could encourage firms to take on greater leverage (Dang, Gorton, and Holmstrom (2009)). This strand of literature suggests that climate-related disclosure needs to be designed in such a way to better inform a wide range of investors.

To sum up, the existing literature suggests that climate-related disclosures are more likely to benefit a wider range of investors, and hence be more effective, if they are based on forward-looking information that is simple to interpret, and relevant for assessing financial risks and returns. For example, firms could be encouraged to disclose their own estimates of how their market value would be affected by a given increase in carbon price, which would capture the impact of a tighter policy on carbon emissions. Such disclosure could be accompanied by publication of the assumptions used for estimating the impact of a higher carbon price on demand for their output and input prices, as well as the value of their assets (e.g. the value of oil reserves in the case of an oil company), so as to help enable investors to scrutinise the calculations. Disclosure of such information by non-financial firms could also inform central banks in assessing the impact of transition risks on the financial system, e.g. via a stress test.

[34] Goldstein and Sapra (2014), for example, show that disclosure requirements could encourage the firm management to choose less productive assets which are simpler for market participants to understand.
[35] Thakor (2015) also shows that mandatory disclosure of soft strategic information may make firms more fragile, as it could generate disagreements amongst short-term debt holders and induce them to 'run' or to not finance projects.

3 Impact of climate change on monetary policy

This section examines how physical and transition risks could affect the macroeconomy and price stability, which is the core objective of monetary policy.

3.1 Physical risks

The existing literature suggests that climate change can affect the aggregate economy both through increased incidence and severity of certain types of *extreme weather events* in some parts of the world, and through *gradual warming* and the associated climate changes – for instance in total seasonal rainfall and sea level. The effects of these two types of risks on the macroeconomy are likely to differ in terms of timing and severity, which determine their implications for monetary policy.

3.1.1. The economic impact of global warming

One important debate in climate economics is whether global warming affects the level or the growth rate of the economy. The existing literature points to a number of channels via which climate change could reduce the potential growth rate of the economy:

1) A reduction in effective labour supply growth, due to the reduction in labour productivity caused by diminished physical and cognitive performance of human capital.[36] Extreme heating 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 (Frankhauser 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.

2) 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 (Frankhauser and Tol, 2005).

3) 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).

Ignoring these effects could potentially lead central banks to misjudge the evolution of the output gap and inflationary pressure. However, the impact of these effects in the first half of the 21st century could be modest, as the increase in global temperatures itself is likely to be limited during this period (see Section 1). Although there are uncertainties around the existing

[36] 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.

projections of global temperatures, this could suggest that the monetary policy authorities may not need to take these effects into account for the coming decades.[37]

3.1.1. The impact of extreme weather events on the output gap and inflation

Some extreme weather-related events could have a significant impact on the aggregate economy and inflation, requiring the monetary policy authorities to react appropriately.

i) Impact of natural disasters on supply, demand, and the output gap

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. Some studies found that natural disasters tended 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 (2013) found a small but persistent suppression of annual growth rates over the 15-year period following the disaster.

In choosing the appropriate monetary policy response to a natural disaster, central banks will need to assess the size and persistence of the impact on supply relative to demand, and hence the output gap. 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, 2007). 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 (see Figure 2 in Section 2). 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".[38] 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.[39] The G7 also issued

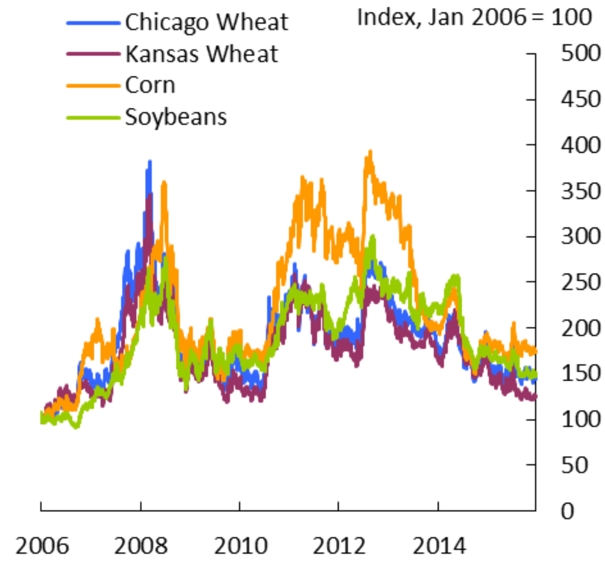
[37] Batten (2016) provides a more detailed discussion of the literature.
[38] See the minutes of the FOMC Meeting on 20 September, 2005.
[39] See the minutes of the BoJ Monetary Policy Meeting on 14 March, 2011.

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.[40] 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.

ii) <u>Impact of extreme weather events on food prices</u>

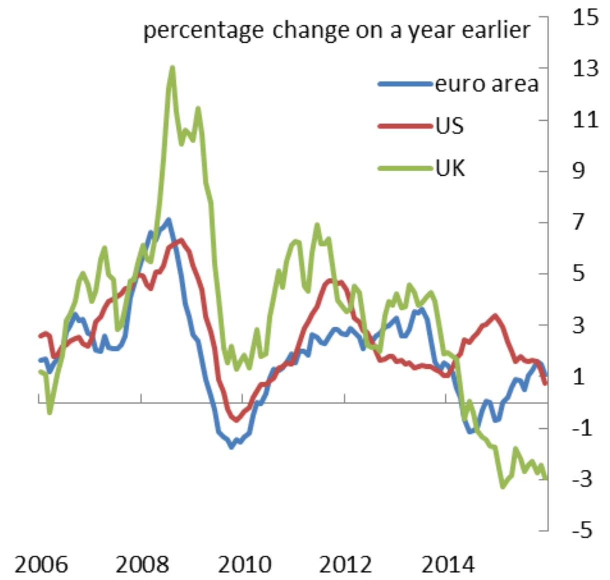
Extreme weather events are likely to have the most significant impact on the agricultural sector. Dell *et al*. (2014) report that, for developing countries at least, panel models typically found consistently negative impacts of bad weather shocks on agricultural output. A more recent cross-country panel 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%. 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 7). This was a factor which contributed positively to food price inflation in other countries (Figures 8).

Figure 7: Selected food commodity prices, 2006-2015



Source: Thomson Reuters Datastream.

Figure 8: Food price inflation in the UK, the US and the Euro Area, 2006-2015



Source: Thomson Reuters Datastream.

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 price moving is a flexible price and hence it does not induce distortions in the allocation of resources and the effects on inflation is short-lived and monetary policy cannot affect

[40] See the statement of G7 Finance Ministers and Central Bank Governors released on 18 March 2011; and Bank of Japan (2011).

inflation over that horizon. Thus, 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 represent 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.

3.2 Transition risks

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 introduced in Section 2. It implies that the reduction in GDP growth needed to achieve a given reduction in carbon emissions will depend on the increase in energy efficiency (a reduction in energy used/GDP) and the reduction in carbon intensity of energy (a reduction in carbon/energy used) that can be achieved. If a reduction in carbon emissions is to be achieved entirely via a reduction in energy use, 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.[41] 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 is accompanied by 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.[42] Although this effect could be mitigated by a gradual reduction in the share of 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 affects weather patterns.

3.3 Implications for the analytical framework of monetary policy authorities

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.[43]

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

[42] The share of bioenergy is assumed to increase in the RCP 2.6 which is likely to keep the warming below 2 ºC (van Vuuren et al. 2011). IEA (2013) also projects that, in order to achieve a 50% reduction in energy-related CO_2 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).

[43] Stockton (2012) suggested "creating a forecast with an extended horizon beyond the current three-year period—a horizon of sufficient length to allow consideration of the development and likely unwinding of major economic and financial imbalances."

Future impacts of climate change on GDP 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 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 makers.

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 the best available climate science and econometric research. The study models climate impacts at a very high level of granularity, close to the level of business decisions and in a way that highlights 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 impact of climate change on the long-run growth in the future, but the literature is not yet sufficiently evolved to enable this with any degree of accuracy at the moment.

Conclusion

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

First, a weather-related natural disaster could trigger financial instability and 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 and financial stability objectives by gauging the impact on the output gap, inflationary pressure and the financial system – for example, by adjusting monetary policy and supplying liquidity to the financial system if needed.

Second, gradual warming could also affect an economy's potential growth rate. However, 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 lead to a disorderly re-pricing of carbon-intensive assets and generate a negative supply shock (*transition risks*). This has a potential for generating significant balance sheet losses and financial instability. An orderly transition to a low-carbon economy is possible, and is likely to be facilitated by transparent and predictable policies on carbon emissions that encourage an early re-direction of private investment towards low-carbon technologies. Climate-related disclosure by industries could encourage this re-direction if it enables a wide range of investors to better assess their financial risk exposures. Such disclosure is likely to be more effective if it is both forward-looking and simple to understand – for example, how a given change in carbon price will affect the value of the firm. Such disclosure could potentially also help inform the central banks' assessment of financial stability risks arising from the transition to a low-carbon economy, for example via a stress test.

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.

Annex 1: Losses from past natural disasters, 1980-2015

Table A1: Costliest natural disasters, ordered by total losses in original values, 1980-2015

Date	Event	Affected area	Overall losses in US$ m original values	Insured losses in US$ m original values	Overall losses in US$ m (real values)	Insured losses in US$ m (real values)	Insured losses to overall losses (%)	Fatalities
11.3.2011	Earthquake, tsunami	Japan: Aomori, Chiba, Fukushima, Ibaraki, Iwate, Miyagi, Tochigi, Tokyo, Yamagata	210,000	40,000	203,270	38,718	19.0	15,880
25-30.8.2005	Hurricane Katrina, storm surge	USA: LA, MS, AL, FL	125,000	60,500	135,889	65,770	48.4	1,720
17.1.1995	Earthquake	Japan: Hyogo, Kobe, Osaka, Kyoto	100,000	3,000	132,760	3,983	3.0	6,430
12.5.2008	Earthquake	China: Sichuan, Mianyang, Beichuan, Wenchuan, Shifang, Chengdu, Guangyuan, Ngawa, Ya'an	85,000	300	85,646	302	0.4	84,000
23-31.10.2012	Hurricane Sandy, storm surge	Bahamas, Cuba, Dominican Republic, Haiti, Jamaica, Puerto Rico, USA, Canada	68,500	29,500	65,105	28,038	43.1	210
17.1.1994	Earthquake	USA: CA, Northridge, Los Angeles, San Fernando Valley, Ventura, Orange	44,000	15,300	59,633	20,736	34.8	61
1.8-15.11.2011	Floods, landslides	Thailand: Phichit, Nakhon Sawan, Phra Nakhon Si Ayuttaya, Pathumthani, Nonthaburi, Bangkok	43,000	16,000	41,622	15,487	37.2	813
6-14.9.2008	Hurricane Ike	USA, Cuba, Haiti, Dominican Republic, Turks and Caicos Islands, Bahamas	38,000	18,500	38,289	18,641	48.7	170
27.2.2010	Earthquake, tsunami	Chile: Concepción, Metropolitana, Rancagua, Talca, Temuco, Valparaiso	30,000	8,000	29,638	7,903	26.7	520
23.10.2004	Earthquake	Japan: Honshu, Niigata, Ojiya, Tokyo, Nagaoka, Yamakoshi	28,000	760	31,418	853	2.7	46

Sources: Munich Re, NatCatSERVICE, (as at March 2016), IMF World Economic Outlook (October 2015), and authors' calculations.
Note: The losses in real values were calculated by deflating the losses in original values by US GDP deflator.

Table A2: Costliest storm events, ordered by total losses in original values, 1980-2015

Date	Event	Affected area	Overall losses in US$ m original values	Insured losses in US$ m original values	Overall losses in US$ m (real values)	Insured losses in US$ m (real values)	Insured losses to overall losses (%)	Fatalities
25-30.8.2005	Hurricane Katrina, storm surge	USA: LA, MS, AL, FL	125,000	60,500	135,889	65,770	48.4	1,720
23-31.10.2012	Hurricane Sandy,storm surge	Bahamas, Cuba, Dominican Republic, Haiti, Jamaica, Puerto Rico, USA, Canada	68,500	29,500	65,105	28,038	43.1	210
6-14.9.2008	Hurricane Ike	USA, Cuba, Haiti, Dominican Republic, Turks and Caicos Islands, Bahamas	38,000	18,500	38,289	18,641	48.7	170
23-27.8.1992	Hurricane Andrew	USA: FL, LA, Bahamas	26,500	17,000	37,552	24,090	64.2	62
7-21.9.2004	Hurricane Ivan, storm surge	USA, Caribbean, Venezuela, Colombia, Mexico	23,000	11,800	25,808	13,241	51.3	120
19-24.10.2005	Hurricane Wilma	Bahamas, Cuba, Haiti, Jamaica, Mexico, USA	22,000	12,500	23,916	13,589	56.8	44
11-14.8.2004	Hurricane Charley	USA, Cuba, Jamaica, Cayman Islands	18,000	8,000	20,197	8,977	44.4	36
20-24.9.2005	Hurricane Rita, storm surge	USA: FL, LA, MS, TX	16,000	9,600	17,394	10,436	60.0	10
20-30.9.1998	Hurricane Georges	Caribbean; United States: LA, M AL, FL	13,300	4,300	16,866	5,453	32.3	4000
3-9.9.2004	Hurricane Frances	United States, Bahamas, Canada, Turks and Caicos, Cayman Islands	12,000	5,500	13,465	6,171	45.8	50

Sources: Munich Re, NatCatSERVICE, (as at March 2016), IMF World Economic Outlook (October 2015), and authors' calculations.
Note: The losses in real values were calculated by deflating the losses in original values by US GDP deflator.

Table A3: Costliest European winter storms, ordered by total losses in original values, 1980-2015

Date	Event	Affected area	Overall losses in US$ m original values	Insured losses in US$ m original values	Overall losses in US$ m (real values)	Insured losses in US$ m (real values)	Insured losses to overall losses (%)	Fatalities
26.12.1999	Winter Storm Lothar	Austria, Belgium, France, Germany, Switzerland	11,500	6,200	14,363	7,744	53.91	110
18-20.1.2007	Winter Storm Kyrill	United Kingdom, Germany, France, Netherlands, Belgium, Denmark, Austria	10,000	5,800	10,274	5,959	58.00	49
25-26.1.1990	Winter Storm Daria	Belgium, Denmark, France, Germany, Ireland, Luxembourg, Netherlands, Poland, United Kingdom	7,000	5,400	10,483	8,087	77.14	94
26-28.2.2010	Winter Storm Xynthia, storm surge	Belgium, France, Germany, Luxembourg, Netherlands, Spain, Portugal, Switzerland	6,100	3,100	6,026	3,063	50.82	65
7-9.1.2005	Winter Storm Erwin (Gudrun)	Denmark, Estonia, Finland, Germany, Latvia, Lithuania, Norway, Sweden, United Kingdom	6,000	2,600	6,523	2,826	43.33	18
15-16.10.1987	Winter Storm 87J	France, Norway, Spain, United Kingdom	5,300	3,100	8,850	5,177	58.49	18
24-27.1.2009	Winter Storm Klaus	France, Spain, Italy	5,100	3,000	5,100	3,000	58.82	26
27.12.1999	Winter Storm Martin	France, Spain, Switzerland	4,100	2,500	5,121	3,122	60.98	30
25-27.2.1990	Winter Storm Vivian	United Kingdom, Germany, France, Netherlands, Belgium, Austria, Switzerland, Italy	3,400	2,000	5,092	2,995	58.82	52
3-4.12.1999	Winter Storm Anatol	United Kingdom, Denmark, Sweden, Germany, Latvia, Lithuania, Russia, Poland	3,100	2,400	3,872	2,998	77.42	20

Sources: Munich Re, NatCatSERVICE, (as at March 2016), IMF World Economic Outlook (October 2015), and authors' calculations.
Note: The losses in real values were calculated by deflating the losses in original values by US GDP deflator.

Table A4: Costliest floods, ordered by total losses in original values, 1980-2015

Date	Event	Affected area	Overall losses in US$ m original values	Insured losses in US$ m original values	Overall losses in US$ m (real values)	Insured losses in US$ m (real values)	Insured losses to overall losses (%)	Fatalities
1.8-15.11.2011	Floods, landslides	Thailand: Phichit, Nakhon Sawan, Phra Nakhon Si Ayuttaya, Pathumthani, Nonthaburi, Bangkok	43,000	16,000	41,622	15,487	37.2	813
27.6-15.8.1993	Floods	USA: MS, MO, IA, IL, ND, IN, MN, WI, KS, NE, SD	21,000	1,300	29,067	1,799	6.2	48
June - September 1998	Floods	China: Hubei, Hunan, Chongqing, Jiangxi, Anhui, Sichuan, Yunnan, Jiangsu, Zheijiang, Guangdong	16,000	300	20,289	380	1.9	3,600
12-22.8.2002	Floods	Germany, Austria, Czech Republic, Hungary, Moldova, Switzerland, Slovakia	16,500	3,400	19,403	3,998	20.6	39
24.7-18.8.1995	Floods	North Korea	15,000	n/a	19,914	n/a	n/a	68
May - September 1991	Floods	China: Anhui, Jiangsu, Hubei	13,600	410	19,711	594	3.0	2,630
30.5-19.6.2013	Floods	Austria, Czech Republic, Germany, Hungary, Poland, Switzerland	12,500	3,000	11,690	2,806	24.0	25
June 2008	Floods	USA: IA, IL, IN, KS, MI, MN, MO, WI	10,000	500	10,076	504	5.0	24
4-6.11.1994	Floods	Italy: Piedmont, Lombardy, Liguria, Aosta valley, Emilia-Romagna	9,300	65	12,604	88	0.7	68
July - August 1993	Floods	Bangladesh, India, Nepal	8,500	n/a	11,765	n/a	n/a	2953

Sources: Munich Re, NatCatSERVICE, (as at March 2016), IMF World Economic Outlook (October 2015), and authors' calculations.
Note: The losses in real values were calculated by deflating the losses in original values by US GDP deflator.

Annex 2: Event study methodology

We apply a standard event study to examine the market reaction to a number of climate/ “carbon bubble” related events. An event study aims to examine behaviour for a sample of firms experiencing a common event – in this case a ‘climate’ related news event that may affect the valuation of firms where a large part of their business is to produce energy.

To determine whether a date is an ‘event’ we search Lexis Nexis for “carbon bubble”, “burnable carbon”, and “fossil fuels divestment”. We restrict our search to news stories appearing in major newspapers such as the New York Times, Wall Street Journal, The Times, the Financial Times, Guardian, and The Telegraph and also to specialist energy periodicals. Where two stories have a high degree of similarity we take the first appearance of that story as a date. When news events appear within five days of each other it is difficult to disentangle the events and the later event is not examined nor is it to calculate normal returns. Although we have over 50 different events during January 2011 – January 2016, this exclusion means we end up with 34 events in total. We also do a separate test for the single event of the COP21 agreement.

We examine energy firms in France, Germany, UK and USA, and the relevant benchmark indexes for each country from 4th January 2011-15th January 2016. This covers all firms on the energy sector from coal firms to renewable energy firms. Equity price data was obtained from Datastream and benchmark data from Bloomberg.

To estimate normal returns we use a very simple market model for our baseline specification, where:

$$return_{it} = \alpha + \beta return_{mkt,t} + \epsilon_t$$

Due to the large number of clustered events it is difficult to find a long period of time without an event and so we use all days which are not within five days of an event for our estimation window.

In our baseline specification we use an event window of 0 to +5 days to estimate cumulative abnormal returns, although we also check that our results are robust to using other estimation windows.

Our null hypothesis is that cumulative abnormal returns (CAR) over the event window are zero and our test statistic is CAR divided by an estimate of its standard deviation. As all the events are clustered in time this renders the independence assumption for the abnormal returns in the cross-section incorrect, biasing the estimated standard deviation downwards and biasing any test statistic upwards. As a result, we use the standard deviation of the equity’s returns in non-event periods to calculate the benchmark test statistic. However, because the climate change events should – in theory – be associated with increased uncertainty for the firms affected, using non-event period variance may understate the true variance of returns during the period. As a result we compute an alternative test statistic using the variance of returns in the estimation window.

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