BANK OF ENGLAND

Staff Working Paper No. 706

Climate change and the macro-economy: a critical review

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January 2018

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Abstract

Climatic factors can directly affect economic outcomes such as output, investment and productivity, and understanding the economic consequences of climate change is becoming a necessity not just for climate economists but also for a wider range of economic professionals involved in modelling and forecasting macroeconomic variables. The focus of this review is on the key theoretical and empirical modelling issues in the analysis of the macroeconomic risks deriving from climate change. The paper develops the taxonomy introduced by a number of previous Bank of England studies, which distinguish between *physical* and *transition* risks of climate change. The paper then identifies the different channels through which these risks are transmitted to the macro-economy, either through (unpredictable) economic shocks or through predictable, longer-term impacts. The different approaches to modelling these macroeconomic effects are then discussed and assessed in light of the increasing need to routinely monitor and quantify the impact of emerging climate change risks on the economy.

Key words: Climate change, global warming, natural disasters, macroeconomic models.

JEL classification: E10, H23, Q51, Q54, Q56.

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I am grateful to Parisa Bastani, Stuart Berry, Ben Caldecott, Alan Castle, Paul Fisher, Bill Francis, Sujit Kapadia, Stephen Millard, Sinead O'Leary-Barrett, Nicolas Pondard, Matthew Scott, Peter Sinclair, Rhiannon Sowerbutt, Nicholas Stern, Misa Tanaka, Andrew Voysey, Tomasz Wieladek, participants to seminars at the Bank of England, the 4th Stranded Assets Forum, the 2016 IMAEF Conference, the 2017 FSR Climate Annual Conference and Alex Bowen, the external referee, for useful comments and discussions. All remaining errors are solely the author's.

The Bank's working paper series can be found at www.bankofengland.co.uk/working-paper/Working-papers

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ISSN 1749-9135 (on-line)

1 Introduction

Climatic factors directly affect economic outcomes, such as agricultural output, and critical economic resources, such as water and human health. Climate shifts can also impact indirectly on a wider range of economic activities, such as manufacturing, energy production, transport and other services (Arent et al., 2014).

Economists have been drawing attention to the macro-economic impacts of climate change for some time. Recently, William Nordhaus, among the first to examine the economic aspects of reducing carbon emissions, warned that our current response to global warming is probably inadequate (Nordhaus, 2016); Kenneth Arrow joined a group of economists in warning that the cost of carbon emissions is being underestimated by current models (Revesz et al., 2014); Joseph Stiglitz, lead author of the 1995 Report of the Intergovernmental Panel on Climate Change (IPCC), comments regularly and incisively on climate issues[1] and both Kenneth Rogoff and Paul Krugman also recently opined on the subject.[2]

Understanding the economic consequences of climate change is becoming a necessity for a wider range of economic professionals: not just those directly involved in the design of optimal climate policy but also, and especially, those involved in modelling and forecasting macro-economic variables, whether in a national government, central bank, international organization, or private institution.

Policy-makers in central governments need to be aware of the risks to economic growth deriving from climate change and need to ensure that their policy framework is robust to such risks. They also need to consider possible implications of climate-related large scale extreme weather events on public budgets and fiscal policy. The economic impacts of climate policies directed at implementing global commitments to reducing carbon emissions also need to be considered. [3] Climate policy should not be seen in isolation, but should rather be considered an integral part of the broader policy agenda to promote economic growth.[4]

It has also become clear recently that central banks should pay attention to climate change and climate policies, as these could affect their ability to meet their monetary and financial stability objectives. Inflationary pressures might arise from a decline in the supply of goods or from productivity shocks caused by weather-related events such as droughts, floods, storms and sea level rises. These events can potentially result in large financial losses: if these are insured they can negatively affect insurance companies, while if they are uninsured they can affect the value of physical assets. The transition to a low-carbon economy could also pose financial risks if investors do not adapt their investment strategies in line with climate policies. A number of recent Bank of England publications addresses these issues: Carney (2015) discusses a number of climate-related issues, including the risks for the insurance industry and for financial stability;

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[1] See e.g. ‘After the Hurricanes’ Project Syndicate, 8 September 2017.

[2] Ken Rogoff ‘Extreme Weather and Global Growth’ Project Syndicate, 11 January 2016 and Paul Krugman ‘Wind, sun and fire’ New York Times, 1 February 2016.

[3] For example, the 2008 Climate Change Act requires the UK government to carry out a UK-wide detailed analysis of potential effects of climate change through a Climate Change Risk Assessment (CCRA) every five years. The first was completed in 2012 and the second in 2017. More details can be found at: https://www.theccc.org.uk/uk-climate-change-risk-assessment-2017/

[4] See e.g. the UK government approach outlined in ‘The Clean Growth Strategy’.

Bank of England (2015) focuses on the impact of climate change on the insurance industry; Batten et al. (2016) examine the impact of climate change and the transition to a low-carbon economy on monetary policy and financial stability and Scott et al. (2017) discuss the Bank of England's response to climate change.

Several studies, most notably the IPCC Assessment Reports (see e.g. IPCC, 2007, 2014),[5] have identified a number of channels through which climate change can affect economic outcomes: these are discussed in detail in the next section.

If climate factors are significant enough to have an impact on the economy, macroeconomic analysts and forecasters need to be able to *model* the risks arising from climate change and *quantitatively* assess their impact on economic outcomes such as GDP, inflation, consumption, investment and technological progress. A meaningful quantification of the macro-economic impacts of climate change, however, faces a number of severe challenges, some of which have been extensively addressed by the economic literature, while others are only just emerging. These challenges are directly related to the features that distinguish the climate change externality from other externalities:[6] (1) it is *global* in its causes and consequences; (2) the impacts of climate change are *long-term* and ***persistent***; (3) the *uncertainties* about the economic impacts are pervasive and (4) there is a serious risk of major, *irreversible change* (Stern, 2007).

Most of the economic literature on climate change has adopted a cost-benefit approach, which compares the current costs of reducing future climate change risks with the benefits in terms of avoided future damage. These studies face the formidable task of capturing the feedback loop between climate and the economy: greenhouse gases (GHGs) generated from fossil fuel combustion are a by-product of economic activity, and the amount of GHG emissions per capita depend on a country's level of economic development, as well as government policies to reduce emissions.[7] When GHGs accumulate in the atmosphere, they tend to cause increases in temperatures and other climatic shifts. These in turn can have profound economic impacts.[8]

Modelling this feedback loop is a necessary step in computing the optimal climate policy response. If, however, the main interest of the macroeconomist is to model the economic impacts of climate change without attempting to design the optimal climate policy, the policy variable can be treated as exogenous and the analysis is considerably simplified, because the feedback loop is eliminated. While few economists are directly concerned with the design of optimal climate policies, most economists in other policy areas such as growth policy, industrial strategy, energy policy, and also fiscal and monetary policy, need to be able to understand the impact of climate change on the economy in the short and medium term.

The focus of this review is on the key theoretical and empirical issues in the analysis of the macroeconomic risks deriving from climate change, with the aim to provide a broad introduction

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[5] Many studies also have a specific country focus: some examples that analyse the UK impacts are: Foresight (2011), Defra et al. (2012), PWC (2013) and CCC (2017).

[6] Greenhouse gas emissions entail costs that are not paid for by those who create the emissions, and therefore represent a negative *externality*.

[7] GHGs also arise from certain industrial processes and land-use changes.

[8] Damages from GHGs extend beyond climatic ones: ocean acidification is an important example.

for macroeconomists who are new to the subject.[9] The paper gives an overview of modelling issues, with particular attention to the current treatment of economic damage from climate change. Because the literature on climate change economics is large and rapidly growing, this review does not examine any specific model in detail, and concentrates instead on some specific issues. Inevitably, the narrow focus of this paper means that some important areas of the literature are omitted: where this is the case, a reference is made to the relevant studies.[10]

Climate policy is discussed only in relation to its effects on macroeconomic outcomes, while a discussion of the design and implementation of optimal climate policy is outside the scope of this review.

The review focuses predominantly on the risks and impacts of climate change in advanced economies: it is important to recognize, however, that the macroeconomic implications of climate change will differ across countries at different levels of economic development, with less developed countries likely to suffer more from climate-related risks.[11]

This paper focuses on economic issues and references to climate science were kept to a minimum: a detailed discussion of climate science is outside the scope of this review.

The rest of this paper is organised as follows: section 2 describes the concept of macroeconomic risks from climate change, section 3 discusses the economic impact of gradual global warming while section 4 discusses the economic impact of extreme climate events; section 5 discusses the risks from the transition to a low-carbon economy, while section 6 concludes and suggests areas of future research.

2 Climate change risks and the macro economy

Global warming is happening: according to data produced by the Met Office and the Climatic Research Unit at the University of East Anglia, global annual average surface temperatures reached 1°C above the pre-industrial average (i.e. the average computed over the 1850-1900 reference period) for the first time in 2015 (Blunden and Arndt, 2016). This section gives an overview of the different risks from climate change, and how they can affect economic outcomes.

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[9] The material in this review should be considered as theoretical background for the companion paper on the impact of climate change risks on central banks (Batten et al., 2016) and therefore complementary reading.

[10] Two important areas which are outside the scope of this review are the choice of discount rate and the role of uncertainty. These are briefly discussed in Section 3.

[11] for a discussion see e.g. Bowen et al. (2012).

2.1 *Climate risks*

Defining a ‘risk’ involves defining its different components: Jones and Boer (2005) describe the major elements of risk as: hazard, probability and vulnerability (or exposure). A hazard is an event with the potential to cause harm: climate hazards are related to climate or weather systems and have the potential to affect natural or human systems adversely. Probabilities can be assigned to the frequency of a given hazard or a given socio-economic consequence. Climate vulnerability can be defined as the outcomes of climate hazards in terms of their cost. This paper focuses on those climate hazards that have the potential to cause harm to the economic system, and discusses climate vulnerability in terms of economic outcomes. Previous Bank of England work (Carney, 2015, Bank of England, 2015) introduced a framework for understanding the risks posed by climate change which distinguishes between ***physical*** and ***transition risks:*** this paper employs the same taxonomy.[12] ***Physical risks*** can be defined as “those risks that arise from the interaction of climate-related hazards (including hazardous events and trends) with the vulnerability of exposure of human and natural systems, including their ability to adapt” (Batten et al., 2016). Two main sources of physical risks can be identified: ***gradual global warming*** and increase in ***extreme weather events***. ***Transition risks***, on the other hand, are defined as those risks that might arise from the transition to a low-carbon economy.

2.2 *Economic outcomes from climate risks*

Climate change risks could manifest themselves as economic ***shocks*** – defined as unpredictable events that produce a significant change within an economy – and could affect either the demand or the supply side of the economy. ***Demand-side shocks*** are those that affect the components of the aggregate demand, such as private (household) or public (government) consumption and investment, business investment and international trade. ***Supply-side shocks*** affect the productive capacity of the economy, acting through the components of potential supply: labour, physical capital and technology.

The occurrence of *extreme weather events* is very close to the definition of economic shock: these are mostly unpredictable events that can have significant economic consequences. Not all climate risks classify as economic shocks: some of these risks, such as those deriving from *gradual global warming*, can have predictable outcomes. There is reasonable scientific consensus around some of the consequences of global warming on the natural environment, and the channels of transmission to the socio-economic systems have also been identified. Nevertheless, significant uncertainty remains in the quantification of these impacts. To the extent that climate change risks can be predicted, climate change adaptation is possible. The degree to which countries are able to adapt to climatic changes is another source of uncertainty for climate economics. Uncertainty in climate models is discussed below.

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[12] The Bank’s initial work was focused on the insurance sector and included a third category: ‘liability risks.’ These are particularly relevant to the insurance sector and are not discussed in this paper.

In order to understand the economic impacts of climate change it is useful to discuss these impacts in relation to the different types of climate risks, whether physical or transition risks, as well as distinguishing between physical risks that derive from extreme weather events from those deriving from gradual global warming.

Extreme weather events are defined – in a meteorological sense – as events at the "edges of the complete range of weather experienced in the past."[13] They include extreme values of certain meteorological variables, such as large amounts of precipitation (e.g., floods), high wind speeds (e.g., cyclones), high temperatures (e.g., heat waves). The frequency and severity of extreme weather events has been linked to global warming (see e.g. Stott, 2016) and will be discussed in more detail in section 4. The impact of extreme weather events is most apparent in the agricultural sector, but they can also cause damage to buildings and infrastructure, thereby affecting production in other sectors such as construction, energy and manufacturing, and also service sector activities such as telecommunications, transport, financial services and tourism (Defra et al., 2012, Arent et al., 2014).

On the *demand* side, losses deriving from climate events such as floods and storms could reduce household wealth and therefore private consumption. Business investment could also be reduced by damage to physical and financial assets. The impact of extreme climate events on trade has been highlighted by two studies which find significant effects of natural disasters on bilateral trade (Gassebner et al., 2010, Oh and Reuveny, 2010). Economies which are less exposed to extreme weather can nevertheless have extensive interactions with global markets and could be adversely affected by climate change shocks in their trading partners, in particular via reduced exports as a result of failure in transportation and distribution network.[14]

The main *supply*-side shocks caused by the extreme weather aspects of climate change are represented by a shortage of imported inputs, in particular commodities such as food and energy, and by the volatility in import prices as result of these shortages. Supply shocks also arise from damage to the capital stock and infrastructure.

Broadly speaking, ***gradual global warming*** can cause economic losses because higher temperatures tend to reduce the productivity of workers and agricultural crops (Dell et al., 2014).

On the *demand* side, expectation of future losses could change current preferences, for example towards greener consumption. Business investment could also be reduced by uncertainty about future demand and growth prospects. On the supply side, global warming could have large impact in terms of reducing the potential of the economy to grow in the future, by reducing labour productivity and diverting resources from investment in productive capital and innovation to climate change adaptation. These channels are discussed in more detail in Section 3.

The *supply*-side risk from the ***transition*** to a low-carbon economy is represented by the *trade-off* between reduction of current emissions, which comes at a direct mitigation cost, and therefore is likely to reduce near term growth, and the need to preserve the planet's environmental

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[13] UK Met Office: http://ukclimateprojections.metoffice.gov.uk/23146

[14] Evidence presented in PWC (2013), for example, suggests that the international threats of climate change for the UK could be an "order of magnitude larger than domestic threats," in particular for trade and investment and food supply.

conditions. Climate policies to promote investment in low-carbon technologies can also cause demand-side shocks if they result in ‘crowding-out’ of private investment and consumption.

Table 1 presents some examples of the macroeconomic risks deriving from climate change.

Table 1: Examples of macroeconomic risks from climate change

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

A large part of the existing literature analyses the impact of climate change on aggregate GDP, rather than its components, and this paper will reflect this focus. The impact of climate of inflation was discussed in the companion paper (Batten et al., 2016).[15]

2.3 Timing and persistence of climate impacts

The timing and persistence of the economic consequences of climate change are likely to differ depending on the type of risk. Extreme weather events tend to cause immediate economic damage, which may last in the medium term (see Section 4). Damage from gradual global warming, on the other hand, will manifest over the longer run, and could potentially be more permanent.

Depending on the timing of the transition to a low-carbon economy, the reduction in economic growth due to the costs of transition may be spread out over time or be more concentrated in the initial period of the transition. There is also a risk that the transition to a low carbon economy could be "too late and too sudden," with severe consequences for the economy caused by sharp reductions in energy supply and shocks to energy prices (ESRB, 2016). A summary of the type of economic impacts from climate change and their timing is presented in Table 2.

Table 2: Summary of the economic impacts from climate change risks

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

2.4 Uncertainty and discounting

Climate economics is beset with uncertainty: Heal and Millner (2014) distinguish between scientific uncertainty – the uncertainty around climate science – and socioeconomic uncertainty, which can be further divided into *positive* and *normative* uncertainty. *Positive* uncertainty refers

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[15] According to PWC (2013), increased volatility in food prices is one of the top five climate threats for the UK by magnitude and urgency.

to our inability to model the impact of climate change on society and the economy with any degree of accuracy: two large sources of uncertainty are, for example, the future ability of societies to adapt to climate change and the effect of technological change on future GHG emissions – through changes in the production and use of different energy sources – and on their concentration in the atmosphere – by providing solutions for their removal. *Normative* uncertainty derives from disagreement about key parameters in the model.

The choice of *discount rate* is an important source of uncertainty in climate modelling. Because GHGs persist in the atmosphere for a century or more, the costs of climate change and the benefits of mitigation must be measured on longer timescales than most other socio-economic policy issues, and climate models are therefore extremely sensitive to the choice of the discount rates used to aggregate costs and benefits occurring at different points in time. The Ramsey formula (see e.g. Heal, 2017) decomposes the discount rate r into two components:

$$r = \delta + \eta g$$

The first component, δ, is the pure rate of time preference; the second component represents aversion to inequality in consumption between generations: it determines how much weight is given to the welfare of future generations, and is expressed as the product of the elasticity of marginal utility η and the rate of economic growth g. Estimating the discount rate therefore involves both positive uncertainty in the forecasts of the future economic growth rate g, and normative uncertainty of the subjective welfare parameters δ and η. In practice, most of the debate around the choice of discount rate in climate models has been focused on the choice of δ, considered by most authors an ethical parameter.

3 The macroeconomics of gradual global warming

3.1 Climate and economic performance

The fact that hot countries tend to have lower incomes per capita was observed as early as the 18th century by Montesquieu (1750). This correlation tends to be a robust feature of the data: Chart 1, for example, shows the existence of a negative correlation between a country's average temperature over the period 1961-1999 and its GDP per head in 2014. The regression line implies a (statistically significant) decline of 7% in GDP per capita for a 1°C increase in average temperature across countries. In this dataset, temperature alone can account for 25 percent of the variation in cross-country per capita income.[16] This correlation does not necessarily imply a causality link, and it might well be that other variables which are correlated with climate, such as a country's institutions and policies, are the more *fundamental* determinants of economic performance (Acemoglu, 2009).

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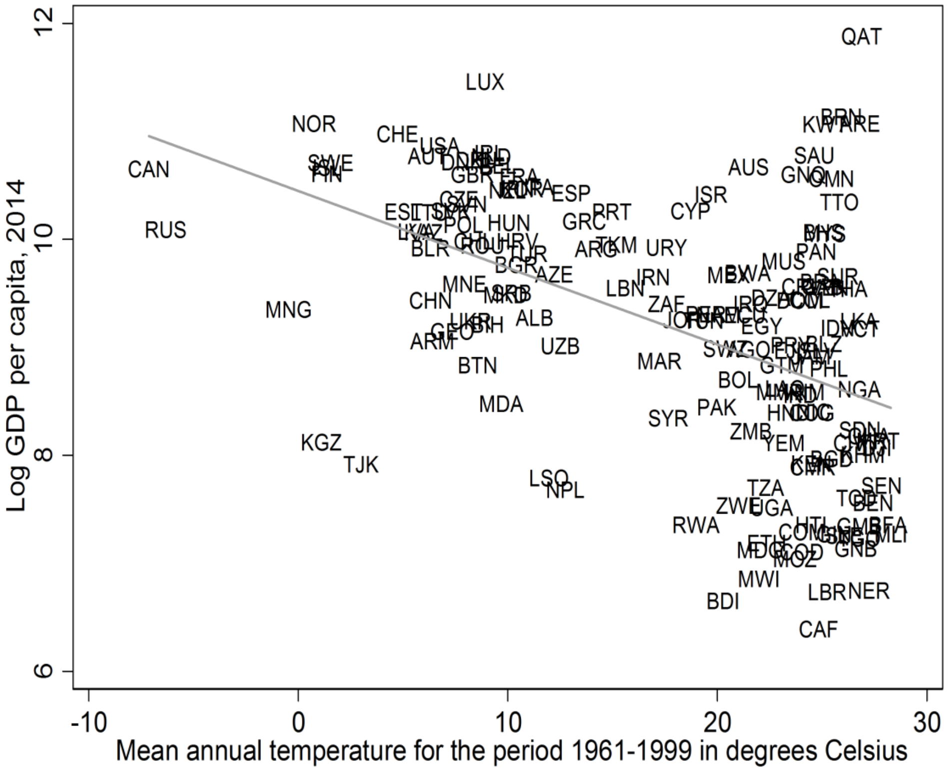
[16] When oil producing countries are dropped from the sample, the correlation rises to 8% and the R-squared to 0.33. Dell et al., (2009) find similar results using within-country data, controlling for other climatic variables such as precipitations.

Chart 1: Relationship between mean annual temperature and GDP per capita.



Source: Penn World Tables 9 and World Development Indicators; p-value=0.00

In any case, climate change adds a new dimension to this debate: temperatures might become a more direct and important influence on economic performance as they increasingly move away from their historical averages. There is little doubt that temperatures are reaching historical highs: a recent study, for example, estimates that without greenhouse gas emissions, the odds that 13 out of the 15 warmest years ever measured would all have happened in the current century are extremely small (Mann et al., 2016).[17] The observed runs of record-setting temperatures were, by contrast, quite likely to have occurred in the presence of anthropogenic climate change.

With global temperatures expected to rise substantially over the next century, it has become crucial to understand the relationships between temperature and economic performance in order to assess the potential economic implications of future climate change. The rest of this section discusses the possible channels through which increasing average temperatures could affect the macro-economy and then presents the existing empirical evidence.[18]

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[17] The likelihood is between 1 in 5,000 and 1 in 170,000 chances.

[18] The focus of this review is on the impact of climate change on developed economies; however the macroeconomic effects will be different for different economies depending of their level of development: for a discussion see e.g. Bowen et al., (2012).

3.2 The transmission channels: a theoretical framework

Extremely hot temperatures are likely to affect the productive capacity of the economy through a number of channels. The starting point for modelling these channels is usually a production function, which describes the relationship between aggregate output and the stocks of productive factors and technical efficiency in production. This relationship is typically assumed to be of the Cobb-Douglas form:

$$Y_t = A_t \prod_{j=1}^{J} K_{jt}^{\alpha_j}$$

where Y_t is output at time t, A_t is technical efficiency and K_{jt} represents different inputs, which can be interpreted as different types of capital, such as natural capital, physical capital, human capital, infrastructure capital and so on (see e.g. Haldane, 2015). The α_j are parameters that measure the responsiveness of output to a change in the level of the different types of capital used in production, everything else equal: that is, they measure the output elasticity of the different types of capital. As will be discussed below, global warming can affect each of the different inputs of this production function.

Natural capital

The concept of natural capital relates to the *stock* of natural resources (e.g., freshwater) together with the *flow* of environmental *services* they provide and the ecosystems that support them. It includes four categories: *water* (fresh and marine), *air*, *land* (including minerals and landscape) as well as *habitats*, i.e. the summation of water, land and air, including the ecosystems and the plants and species the habitats support (Knight et al., 2013). In a realistic production function, natural capital would be included alongside manufactured and human capital as an input to production. In practice, natural capital is often omitted, because assessing its contribution to production is difficult due to the complexity of natural processes.[19]

Physical capital

Physical capital consists of buildings, plant and machinery and other equipment e.g. transport equipment. To counter the impact of warming, a degree of adaptation investment will be required, for example in more air conditioning equipment and insulation. This *adaptation* capital is not productive *per se*, and is only needed to protect the current factors of production from losses deriving from higher temperatures. As temperatures rise, a larger part of capital

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[19] For example, the contribution of the inputs such as machinery, fertiliser and labour to food production is relatively easy to identify because they are mostly purchased inputs and their costs is known. However, the separation of the contribution of soil to food production from that of water (especially rain) is effectively impossible. Either too much or too little water can damage agricultural productivity, but by how much will also depend on the type of soil and crop and on the timing of the water deficit or surplus (Knight et al., 2013).

investment will need to be devoted to adaptation capital, and fewer resources will be available for productive capital investment, leading to lower output growth (Pindyck, 2013). Some adaptation studies (e.g., Fankhauser et al., 1999) have also pointed out that a continuously changing climate will require more frequent adjustments to the capital stock, leading to a lower efficiency in its use in production.

Human capital

The climate literature suggests that gradual global warming is likely to reduce the physical and cognitive performance of workers, causing a decrease in the *effective labour supply*. Modern experiments investigating the impact of temperature on labour productivity in laboratory settings have shown that some tasks respond adversely to hot temperatures: these include estimation of time, vigilance, and higher cognitive functions such as mental arithmetics and simulated flight. A survey of experimental studies by Dell et al. (2014) concluded that each degree over 25ºC is associated to a productivity loss in various cognitive tasks of about 2 percent.[20]

Extreme temperatures could also lead to negative health effects, and lead to an increase in the mortality and morbidity of the population, for example due to the increased incidence of diseases such as malaria (Fankhauser and Tol, 2005, Watts et al., 2015).[21] In the longer term, global warming could also impact human capital through other phenomena such as mass migration, and increases in poverty, inequality, crime and social unrest.[22]

Other forms of capital

Social and organizational capital could suffer long-term or permanent damage due to a hostile climate and to migration, disruption and conflict resulting from climate change (Stern, 2013). Finally, *public infrastructure* networks, such as transport, energy and water supply networks, provide productive services to the private sector of the economy as well as direct consumption benefits: these networks are inherently vulnerable to environmental disruption.

Efficiency, technology and learning

Even if relevant capital stocks might survive, the ability to use them effectively might be damaged by a hostile environment, thus reducing efficiency in production, or 'total factor productivity' (TFP), captured by the term *A* in the production function above (Stern, 2013). Adaptation to rising temperatures could also divert the resources available from research and development (R&D) activities. And if investment is mostly repair and replacement, it may carry

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[20] Call centre studies also find a link between indoor climate and performance, with high temperatures (e.g., above 24–25ºC) generally associated with worse performance (Dell et al., 2014). This relationship is complex and other aspects (e.g., humidity, amount of outdoor air, carbon dioxide levels) also interact with temperature. These studies show that increasing the temperature from 23 to 30ºC reduces productivity by about 9 percent.

[21] Some of these negative impacts might be offset by a reduction in cold-weather-related morbidity and mortality.

[22] See Dell et al., (2014) for a summary of the most recent literature on these effects.

much less ‘learning by doing’ than investment in new productive capital, which involves innovation and technology transfer. Climate change could therefore undermine the key drivers of economic growth (Pindyck, 2013, Stern, 2013).

Adaptation

Adaptation to climate change will to some extent reduce the negative effects of climate change on economic outcomes. Adaptive capacity – i.e. the ability to deal with climate stress – depends on factors such as institutions, health and sanitation systems, the level of education and the the degree of development of the financial sector. These factors tend to be positively associated with economic growth and therefore policies to improve economic growth will also increase adaptive capacity (see Bowen et al., 2012, for a discussion).

3.3 Modelling the macroeconomic effects of global warming

The main analytical tools used to assess the damage posed by global climate change are the ‘Integrated Assessment Models’ (IAMs). These models are designed to capture complex interactions among the physical, natural and social dimensions of climate change and have been used, among others, in the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC, 2014) and the Stern Report (Stern, 2007). The models bring together a description of GHG emissions and their impact on temperature (a climate science module) with a description of how changes in climate affect output, consumption, and other economic variables (an economic module).[23]

While they differ greatly in the way the complexity of the economic and climate sectors is represented, these models usually include six main elements (see e.g. Pindyck, 2013): the first three elements constitute the climate science module, while the last three are part of the economic module (Figure 1).

Each of these elements can be global in nature or disaggregated on a national or regional basis. The six elements are:

1. **Carbon emissions:** this element includes projections of future GHG emissions under different scenarios, usually a ‘business as usual’ scenario and one or more abatement scenarios.

2. **Carbon concentration:** this element includes projections of future atmospheric GHGs concentrations resulting from past, current, and future emissions.

3. **Climate sensitivity:** this component converts GHG concentrations into average temperature changes and other climatic effects that are likely to result over time from a given level of GHG concentration.

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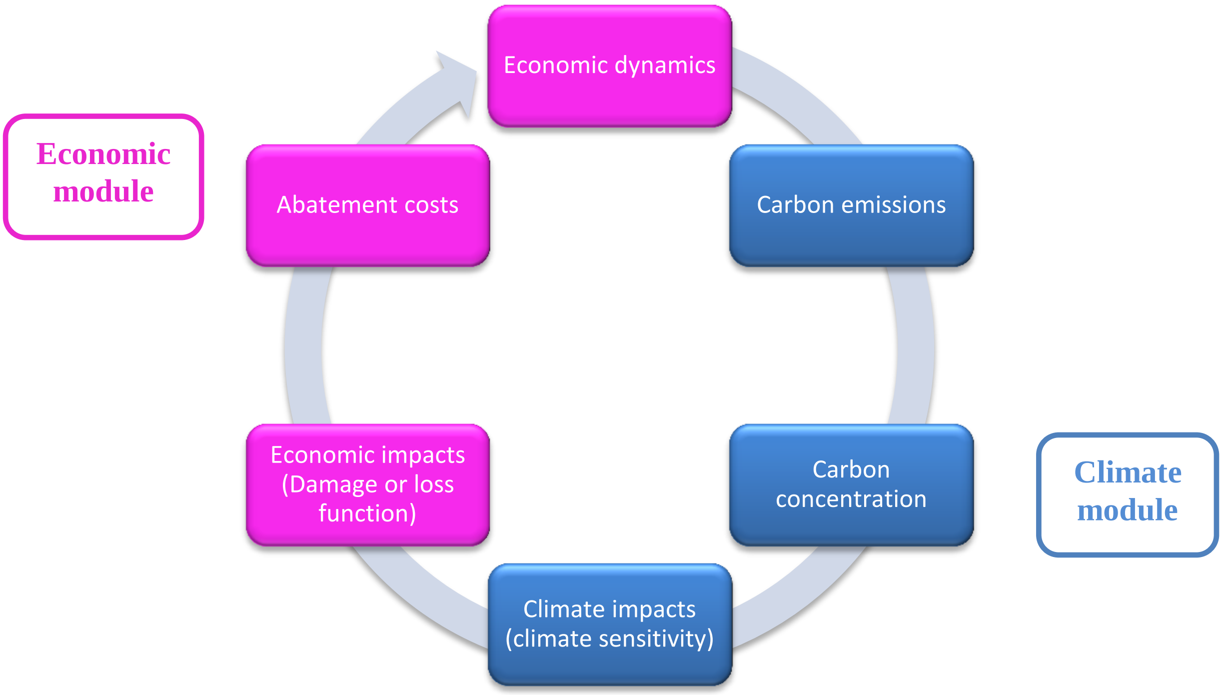
[23] A full review of IAMs is outside the scope of this paper: for a more detailed description see, for example, Ortiz and Markandya (2009).

Figure 1: Integrated Assessment Models of Climate Change



4. **Damage or loss function:** this element includes a set of functional forms that determine the economic impact of rising temperatures, usually expressed in terms of lost GDP and consumption.

5. **Abatement costs:** this section includes estimates of the cost of reducing GHG emissions by various amounts, both now and throughout the future.

6. **Economic dynamics:** this element is usually represented by a Computable General Equilibrium (CGE) model with a detailed characterization of the economy, including the energy sector and, in most cases, the choice of technology. The dynamic element may derive from a dynamic-recursive structure, such as the MIT's 'Emissions Prediction and Policy Analysis' (EPPA) (Chen et al., 2015) or a full forward-looking rational expectations structure, such as the 'Dynamic Integrated Climate and Economy' (DICE) model (Nordhaus, 2008). A third (small) class of models relaxes some of the common assumptions of the CGE approach (such as fully rational behaviour) in favour of an empirical approach in the form of estimated econometric relationships (e.g. Cambridge Econometrics' E3MG model, Barker et al., 2005).[24]

The rest of this section focuses on the representation of the economic damage from climate change in these models.

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[24] See e.g. Döll (2009) for a survey of CGE modelling in IAMs.

Economic damages from global warming: the loss function

Most economic studies of climate change assume that changing temperatures have a direct impact on the *level* of GDP, which is modelled as a 'damage' (or 'loss') function *D(.)*. Consider a simple production function which describes output Y at time t as a function of physical capital K and labour L:

$$Y_t = A_t D(\Delta T_t) F(K_t, L_t) \tag{1}$$

where A is a measure of technical efficiency. In equation (1), $F(K_t, L_t)$ denotes output in period t in the absence of warming. The 'damage function' $D(\Delta T)$ specifies how temperature changes affect the level of economic activity, measured by real GDP. The relevant temperature change ΔT is measured as "the global mean atmospheric temperature relative to the period just before the industrial revolution" (see e.g. Dietz and Stern, 2015). In absence of climate change there is no loss of GDP, i.e. $D(0) = 1$, but as the temperature increases the loss also increases i.e. $D' < 0$. The most common functional form for the loss function is an inverse quadratic function:

$$D(\Delta T) = \frac{1}{1 + \pi_1 \Delta T + \pi_2 (\Delta T)^2}$$

where the π's are parameters to be estimated. This functional form appears for example in Nordhaus' DICE model. The parameters of the damage function are usually calibrated by fitting them to a small set of current temperatures. In the DICE model, the π parameters are calibrated to match cross-sectional estimates of climate damages reviewed in Tol (2009) (see e.g. Nordhaus, 2013).[25]

Because the quadratic functional form results in implausibly low damage at high temperatures (Stern, 2008), Weitzman (2009) suggested using an exponential loss function instead, which allows for greater losses when ΔT is large:

$$D(\Delta T) = e^{\beta (\Delta T)^2}$$

with $\beta < 0$. Other models allow for a more complex damage functions.

Persistence of climate damage: level versus growth effects

In most of the existing climate models, temperatures affect the *level*, not the *growth rate*, of GDP.[26] As discussed in Section 3.2 above, however, climate change can cause lasting damage to

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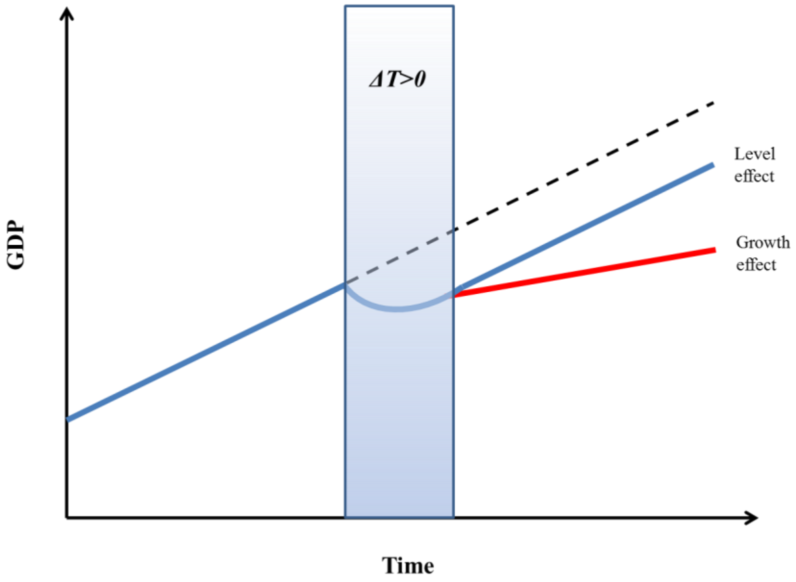
[25] Losses are then adjusted up by 25 percent to incorporate non-monetized damages and to account for potentially catastrophic scenarios. Non-monetised damages include, for example, the impact on biodiversity. Catastrophic scenarios include sea level rises, changes in ocean circulation, and accelerated climate change.

[26] Some exceptions are Pindyck (2011), Tol (2015) and Krusell and Smith (2012).

capital stocks and productivity, and is therefore likely to impact on GDP growth, as recognized by an increasing number of authors (see e.g. Pindyck, 2013, Stern, 2013, 2015, Moyer et al., 2014, Diaz, 2015). Figure 2 depicts these two types of effects. Consider a period of increasing temperatures compared with historical averages ($\Delta T > 0$), which is eventually stopped but not necessarily reversed. This temperature increase is likely to result in a loss of GDP: once temperatures are stabilised, the economy can then either resume growth at the trend rate (blue line) resulting in a permanently lower GDP *level* compared with the original trajectory (represented by the dotted line), or the loss can be so severe that it reduces the trend *growth rate* of GDP (red line).

If temperature changes affect the *growth rate* of GDP, output and consumption at some future date will depend not simply on the temperature at that date, but instead on the entire path of temperature, output and consumption up to that date (Pindyck, 2013).

Figure 2: Level versus growth effects of temperature on GDP



Dietz and Stern (2015) provide two key examples of how growth effects of climate change can be incorporated in the production function. The first example models climate change impacts on the physical capital stock: in each period, the stock of physical capital in the economy is increased through capital investment I_t and decreased through physical depreciation δ and climate damage D_t^K:[27]

$$K_{t+1} = (1 - D_t^K)(1 - \delta)K_t + I_t$$

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[27] This is a modification of the law of motion of the capital stock in standard growth models:

$$K_{t+1} = (1 - \delta)K_t + I_t$$

The term D_t^K represents direct climate damage to the capital stock, for example through abandonment of capital in coastal areas due to sea-level rise. D_t^K could also include broader impacts of climate change on productivity, specifically in endogenous growth models, in which a firm's investment in physical capital also increases economy-wide productivity via learning-by-doing.

A second way Dietz and Stern (2015) model the growth effects of climate change is through its direct impact on productivity:

$$A_{t+1} = (1 - D_t^A)A_t$$

Because growth effects, even small ones, ultimately dominate even large level effects, the way through which climate impacts are modelled is crucial, and ruling out growth effects from the model substantially limits the possible economic damages from climate change. This in turn can negatively affect the policy conclusions from the models: Moyer et al. (2014), for example, simulate the effects of climate change on productivity growth in an IAM, and find that even a modest growth effects have strong implications for optimal climate policy. Moore and Diaz (2015) calibrate climate damages to the growth rate in a climate model using the empirical results from Dell et al. (2012) and find that allowing climate change to directly affect GDP growth can significantly increase the optimal rate of near-term mitigation.

3.4 Empirical evidence: the 'new weather – economy'

A number of recent empirical studies on the climate-economy relationship were sparked by the desire to inform the analysis of the potential consequences of global warming. Most studies rely on identification from *short-run* weather variations for estimating weather impacts on the economy, with panel data studies that exploit year-to-year and within-country variations in temperature and precipitation showing the most promising results thus far. The empirical framework is based on a version of the production function (1) above, in which potential output Y at time t is a function of labour at time t, L_t, and total factor productivity, A_t (see e.g. Dell et al., 2012):

$$Y_t = e^{\beta T_t} A_t L_t \qquad (2)$$

and where T_t measures the temperature in period t and $D(T) = e^{\beta T}$. Equation (2) captures the *level effect* of temperature variation on production through the parameter β: an example of level effect would be the reduction in crop yields due to exceptionally high temperatures in a specific year. As discussed above, however, there are strong theoretical reasons to believe that climate change can affect the growth rate of GDP, not just its level. The *growth effect* of temperatures can be expressed as:

$$\Delta ln A_t = g_0 + \gamma T_t \qquad (3)$$

where a temperature anomaly in period t affects the future path of A, and the parameter γ captures the strength of this growth effect.

Taking log differences of (2) with respect to time and substituting in equation (3) yields the dynamic growth equation:

$$g_t = g_0 + (\beta + \gamma)T_t - \beta T_{t-1} \tag{4}$$

where g_t is the growth rate of output per unit of labour (Y/L). The *level* effect of weather shocks on output, which comes from equation (2), appears through β. The *growth* effect of weather shocks, which comes from equation (3), appears through γ.

Equation (4) allows empirical identification of the level and growth effects of temperature through the examination of transitory weather shocks. Both effects influence the growth rate in the initial period of the shock: the level effect eventually reverses itself as the weather returns to its prior state, while the growth effect that appears during the weather shock is not reversed. The failure to innovate as a result of adverse weather events in one period, for example, can leave the country permanently behind.

Further lags of temperature T can be included in (4) with the growth effect then given by the sum of the temperature coefficients over time. Dell et al. (2012), for example, run panel regressions of the form:

$$g_{it} = \theta_i + \theta_t + \sum_{j=0}^{J} \rho_j T_{it-j} + \varepsilon_{it} \tag{5}$$

where θ_i are country fixed effects, θ_t are time fixed effects and the ε_{it} is an error term. The summation of the lag coefficients ρ_j corresponds to the parameter γ, the growth effect, in equation (4) above.

Dell et al. (2012) find that higher temperatures reduce not just the level of output but also its growth rate in poor countries: they show that, over the 1950–2003 period, a 1°C rise in temperature in a given year reduced economic growth in that year by 1.1 percentage points. They do not, however, find significant effects of higher temperature in rich countries: this could be due to the lower percentage of GDP accounted for by the agricultural sector, which is particularly vulnerable to weather shocks, or might indicate that populations in these countries are better equipped to adapt to climate change, for example by developing new crop varieties robust to adverse climates. Deryugina and Hsiang (2014) use within-county variation in US counties over a 40-year period, and, even after controlling for many different forms of adaptation, such as factor reallocation and adaptation investments, find that productivity declines by roughly 1.7% for each 1°C increase in daily average temperature above 15°C. This indicates that adapting to all climatic conditions might be too costly.

In a recent article in the journal Nature, Burke et al. (2015) reconcile these apparently contradicting results by modelling the growth rate of GDP per capita as a nonlinear function of temperature, on the basis that both excessive heat and extreme cold are detrimental for growth. The authors find that the growth rate of output per capita peaks at an annual average temperature of 13°Celsius and declines strongly at higher temperatures. They also find that this relationship is globally generalizable, unchanged since 1960, and valid for agricultural and non-agricultural activity in both rich and poor countries.

While most empirical studies focus directly on the relationship between temperatures and output per capita, a small but growing literature started focussing on different economic variables. Climate change is associated with a shift in the distribution of daily temperatures to include not only more hot days, but also more days with temperature exceeding the threshold for heat tolerance in individuals. For this reason, the impact of temperature on workers is particularly important. In the first study of the impacts of daily temperature shocks on labour supply, Graff Zivin and Neidell (2014) observe that weather might play an important role in individuals' time allocation decisions, especially in climate-exposed industries, such as agriculture, construction, and manufacturing. Using individual-level data from the American Time Use Surveys linked to weather data, the authors find evidence that at daily maximum temperatures above 29°C, workers in industries with high exposure to climate reduce daily time allocated to labour by as much as 1 hour, most of which is reallocated to indoor leisure. No labour-market impacts for climate-insulated industries are found, highlighting the importance of climate control technologies.

Graff Zivin et al. (2015) provide the first estimates of the impacts of climate change on human capital accumulation. The authors examine the effects from both short-run weather and long-run climate on the same population to estimate the relationship between weather and cognitive performance. Using assessments of children's cognitive ability merged with meteorological conditions on the day of the assessment, the authors find that performance in math tests declines linearly above 21°C, with the effect statistically significant beyond 26°C.[28] The authors, however, find no evidence that climate is significantly related to human capital accumulation in the long run, highlighting the fact that slow moving changes associated with climate change provide greater opportunities for behavioural adaptation.

3.5 Discussion and conclusions

IAMs suffer from a number of severe limitations: because their scope is broad, they consist of multiple components of both climate and economic systems and necessarily rely on simplified representation of each individual component. While its simplicity makes the damage function approach appealing, it has also attracted strong criticism and it remains the most speculative element of the analysis.

As discussed in the previous sections, a major criticism of the current damage function approach is that it is mostly static and tends to ignore the dynamic effects through which climate change may affect economic growth and hence future welfare. This shortcoming can be addressed by modelling climate damage in a growth, rather than level, framework.

Another important criticism of the damage function approach is the significant degree of subjectivity involved in the choice of its parameters and its functional form. In most cases, the functional form for the damage function is chosen with little or no explanation or justification: it is not based on any economic (or other) theory, nor has any empirical foundation. Damage

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[28] The authors do not find a statistically significant relationship with reading performance.

functions are just arbitrary functions linking a fall in GDP to an increase in temperatures (Stanton et al., 2008, Pindyck, 2013).

Ackerman and Stanton (2012) and Moyer et al. (2014), among others, have observed that current economic modelling of climate damages is not consistent with the recent evidence on impacts and have pointed out that the calibration of the damage function could be significantly improved using the results of the emerging empirical evidence on climate impacts, the 'new weather-economy' literature reviewed in Dell et al. (2014) and discussed above.[29]

The empirical models discussed in this section also present some limitation, in particular, they rely on year-to-year weather variability to estimate the impact of a weather shock on economic outcomes, and it is not clear whether they can be used to infer the impact of gradual global warming over the long-run. Dell et al. (2014) point to a number of additional effects that might occur in the long run: (1) climate change adaptation, which might make long run effects smaller that the estimated short run ones, (2) the possible intensification of climate effects, which would act in the opposite way, (3) resource reallocation: capital and labour are likely to move in response to climate change, thus reducing the long-run impacts. Finally, extrapolating from historical temperature data might not be reasonable if nonlinearities arising in the range of temperature outside the historical experience are different from those within it.[30]

Some of the difficulties with IAMs such as DICE derive from the fact that they are based on a Cost-Benefit approach. They are used to calculate the optimal balance between GHG abatement and economic damages from climate change in order to maximize intertemporal welfare. This approach requires capturing the feedback loop between climate and the economy: in order to estimate the social cost of carbon and compute the optimal policy response to climate change. If the main interest of the macroeconomist is to model the economic impacts of climate change without attempting to design the optimal climate policy, however, policy can be treated as exogenous and the analysis considerably simplified, because the feedback loop is eliminated. A CGE model of the economy could then be used to describe the impacts of climate change in a more detailed way, in specific sectors such as agriculture, energy, coastal properly, health and labour. This is the approach taken for example in OECD (2015) and in the book by Houser et al. (2015), which builds on the best available climate science and econometric evidence to assess the risks that climate change poses to a number of sectors of the US economy. Climate impacts are modelled at a very high level of granularity, in a way that highlights the regional variation of climate impacts.

4 Extreme weather events: the macroeconomics of natural disasters

The previous section focused on modelling the economic implications of future changes in *average* temperatures. This section discusses the issue of climatic variations *around* averages, in

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[29] Other limitations of the damage function approach include for example the treatment of nonlinearities and extreme climate events. Most researchers also agree that at higher temperatures the models go beyond their useful limits and that there is not sufficient evidence to extrapolate reliably beyond 3°C (Stern, 2013).

[30] Crop productivity for example shows non-linear effects with temperature increase.

particular those associated with extreme weather events such as storms, hurricanes, intense precipitations, droughts, heat waves and cold spells (see the Annex for a complete list and description of extreme weather events).

Extreme weather events are events that have extreme values of certain important meteorological variables and are characterised by attributes such as their rate of occurrence (i.e. their probability per unit time), their intensity, their temporal duration and timing and their spatial scale (footprint) (Stephenson, 2008). The temporal duration of extreme events plays an important role in the exposure and hence total losses. For example, Hurricane Katrina in 2005 led to large insurance losses due to business interruption and property damage losses due to the long duration of the flooding in New Orleans.

From an economic perspective, a 'natural disaster' can be defined as a "natural event that causes a perturbation to the functioning of the economic system, with a significant negative impact on assets, production factors, output, employment, or consumption" (Hallegatte and Przyluski, 2010). A similar concept is that of 'severe events,' i.e. events that create large losses in measures such as number of lives, financial capital, or environmental quality (Stephenson, 2008). The severity can be measured by the expected long-term loss.

While not all natural disasters or severe events are weather-related (e.g. earthquakes), the emerging economic literature on natural disasters is a useful starting point. Much research in the natural sciences has been devoted to increasing our ability to predict natural disasters and mitigate their costs, but research on the macro-economic impacts of natural disasters is still in its infancy.

Human induced climate change has led to an increase in the frequency and intensity of daily temperature extremes (Bindoff et al., 2013) and has contributed to a widespread intensification of daily precipitation extremes (Zhang et al., 2013). But has it also made specific extreme weather and climate events such as floods, droughts and heat waves more likely? The extent to which climate change influences an individual weather or climate event is more difficult to determine, because it involves consideration of a number of both natural and anthropogenic factors that might combine to produce the specific event. This relatively new area of science – called 'event attribution' — has developed very rapidly over the past decade and is still evolving. The advances have been driven by two main factors: (1) the understanding of the climate and weather mechanisms that produce extreme events is improving and (2) rapid progress is being made in the methods that are used for event attribution.

A recent report by the National Academies of Sciences, Engineering, and Medicine (NASEM, 2016), which examined advances in the science of event attribution, has concluded that, in many cases, it is now possible to make and defend quantitative statements about the extent to which human-induced climate change "has influenced either the magnitude or the probability of occurrence of specific types of events or event classes."

4.1 Theoretical framework: direct and indirect damages from natural disasters

Natural disasters affect the economic system in a number of ways: the initial impact is to cause mortality, morbidity, and damage to fixed assets, inventories, raw materials, extractable natural resources and physical infrastructure (residential housing, roads, telecommunication, electricity networks etc.). These immediate consequences of the physical phenomenon of natural disasters are termed '*direct losses*.'[31]

Direct losses are often further classified into direct *market* losses and direct *non-market* losses. Market losses are losses to goods and services that are traded on markets and for which a price can easily be observed: these losses can be estimated by the repairing or replacement cost of the destroyed or damaged assets. Non-market direct losses include all damage that cannot be repaired or replaced through purchases on a market, and where there is no observed price that can be used to estimate losses. This is the case, for example, of health impacts, loss of lives, damage to natural assets and ecosystems, and damage to historical and cultural assets. A price for non-market impacts is usually estimated using indirect methods (e.g. the statistical value of human life).

These initial impacts are usually followed by *'indirect damage.'* These are losses that are not provoked by the disaster itself, but by its consequent impacts on the economy, including 'output losses,' i.e. the fall in economic production caused by the disaster, such as the cost of business interruption caused by disruptions of water or electricity supplies, and longer term consequences of infrastructure and capital damages. Other impacts can relate to inflation, employment, the sectoral composition of production, etc. These indirect effects are generally divided into *short run* effects (usually occurring up to three years after the event), and *long run* effects.

4.2 Channels of transmission

The emerging consensus in the literature is that natural disasters have, on average, a negative impact on the economy, at least in the short term. It is possible to use the framework of Section 3 to identify the different transmission channels. Extreme climate events such as storms or inundations can cause permanent or long-term damage to physical capital. An increase frequency in extreme weather events could also affect the longevity of physical capital through an increased speed of capital depreciation (Fankhauser and Tol, 2005). Even if the relevant capital stocks might survive, efficiency might be reduced. Replacement investment might displace resources for innovation and growth. If it is necessary to abandon certain areas, for example, land will have zero use value and might be essentially lost. Public infrastructure networks such as transport, energy and water supply are characterised by complex supply chains that rely heavily on international infrastructure, and are therefore inherently vulnerable to disruptions caused by weather events across the globe.

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[31] For a more detailed discussion of these issues see e.g. Hallegatte and Przyluski (2010).

4.3 Modelling the effects of natural disasters

The emerging consensus in the literature is that natural disasters have, on average, a negative, short lived impact on economic growth, as the loss of productive capacity depresses output in the immediate aftermath of a major catastrophe.[32] Over the medium to long run, however, natural disasters may have growth-enhancing effects since investment for reconstruction is part of measured GDP (a flow), whereas the destruction of physical capital stock is not.

Three competing hypotheses that describe the response of output to environmental catastrophes in the short and long-run are illustrated in Figure 3.[33] In the aftermath of a natural disaster a loss of GDP is very likely, a conclusion shared by most the evidence on the short run effects discussed in Section 4.4 below. In the medium and long run, however, different scenarios might occur (see e.g. Hsiang and Jina, 2014):

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

2. The ‘recovery to trend’ hypothesis argues that, after growth slowed following the natural disaster, income levels should eventually return to their pre-disaster trend through a catch-up period of faster than average growth. This rebound should occur because the marginal product of capital will rise when capital and labour become relatively scarce after a disaster (due to destruction and mortality), causing resource reallocation into devastated locations.

3. The ‘no recovery’ hypothesis argues that disasters slow down growth by either destroying productive capital directly or by destroying durable consumption goods (e.g. homes) that are replaced using funds that would otherwise be allocated to productive investments. In this case, no rebound occurs because the reallocation of resources fails to compensate for the negative effect. While post-disaster output may continue to grow in the long-run, it remains permanently lower than its pre-disaster trajectory.

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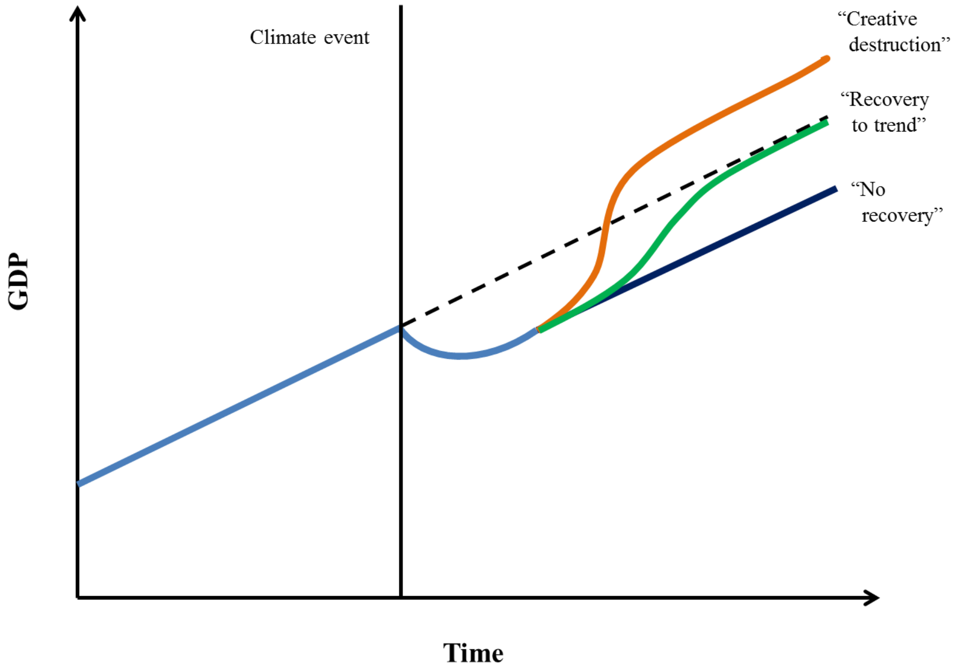
[32] Keen and Pakko (2011), for example, examine the short run effects of catastrophic events in the context of a dynamic stochastic general equilibrium (DSGE) model, in order to investigate how monetary policy should respond to natural disasters. In their model, infrequent catastrophic events cause the destruction of a portion of the capital stock and a temporary negative technology shock that reduces output and are modelled using a two-state Markov switching process.

[33] This is a modified and simplified version of the chart in Hsiang and Jina (2014).

Figure 3: Possible effects of natural disasters on GDP



Let y_{it} denote real GDP *growth* in country *i* in period *t* and x_{it} measure the severity of a natural catastrophe which occurs in country *i* and period *t*, and equals zero otherwise. Growth dynamics can be described by an autoregressive model of the form (see e.g. von Peter et al., 2012):

$$y_{it} = \alpha_i + \sum_{n=1}^{N} \beta_n y_{it-n} + \sum_{n=0}^{M} \lambda_n x_{it-n} + \varepsilon_{it} \tag{6}$$

The coefficients on x_{it} and its lags translate natural catastrophes into growth outcomes. The effect on the growth rate at the time of the disaster is λ_0. Over time, the *cumulative* effect of a disaster on growth converges to:

$$E(y_i) = \frac{\sum \lambda_n}{1 - \sum \beta_n} x_i \tag{7}$$

The ratio in equation (7) is a multiplier that translates a catastrophe of severity x_i into the long-term cumulative effect on growth. The lag structure allows the estimation of a time profile of the growth response to a natural catastrophe, as its impact works its way through the economic system.

4.4 Empirical evidence

This section briefly reviews the results from econometric studies that assess the impact of natural disasters on GDP. Most studies are based on country-level panel datasets, and estimate a version of equation (6) above.

Data on natural disasters

Most of the existing econometric studies are based on data from the Emergency Events Database (EM-DAT), compiled from various sources, including UN agencies, non-governmental organizations and insurance companies.[34] These are self-reported measures that depend on the economic and political characteristics of the country. Because these characteristics also affect economic growth, empirical studies based on these data might suffer from endogeneity issues.

Two studies that depart from the EM-DAT are von Peter et al. (2014) and Hsiang and Jina (2014). The first uses data obtained from the NatCatService of Munich Re, a global insurance and reinsurance group. These statistics specialize in economic losses and draw extensively on industry sources and might be better suited for answering research questions than the EM-DAT.[35] Hsiang and Jina (2014) construct a novel dataset of all tropical cyclones observed on the planet during 1950-2008, using physical parameters and meteorological observations as measure of their intensity.[36] Unlike the self-reported statistics contained in EM-DAT, these measures are unlikely to be influenced by economic or political factors and are therefore fully exogenous. Both these studies are discussed in more detail below.

Short-run Effects

Noy (2009) finds a strong short-term negative impact of natural disasters on GDP growth. This negative impact is only observed in developing countries and not in developed ones, possibly because they are better able to pursue countercyclical fiscal and monetary policy following adverse shocks. Noy (2009) also concludes that countries with better institutions, higher per capita income and a higher degree of openness to trade – among the other things – are better able to withstand the initial disaster shock and prevent further spillovers into the macro-economy. Using a Panel-VAR version of equation (6), Raddatz (2007) analyses the contribution of various exogenous shocks, including natural disasters, in explaining output fluctuations in developing countries. He finds that climatic disasters can only explain 2 percent of the output volatility found in a typical developing country.

Leiter et al. (2009) use firm level data to examine the impact of floods in Europe on firms' capital accumulation, employment growth and productivity. They find evidence of a negative short-run effect on productivity and a higher post-flooding employment growth for companies in

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[34] The dataset is maintained by the Centre for Research on the Epidemiology of Disasters (CRED) at the Catholic University of Louvain, Belgium: see http://www.emdat.be/.

[35] Reinsurance companies not only track their own global insurance liabilities, but also have incentives to collect statistics on the entire universe of natural catastrophes in order to set appropriate terms and premiums on their (re)insurance contracts. As a result, the NatCat statistics provide the most accurate data on insured and total losses. There is however considerable overlap between the two sources and any inconsistencies are eliminated by regular exchange between the two institutions.

[36] They study the class of natural disaster that includes hurricanes, typhoons, cyclones and tropical storms.

flooding regions. In the first study to examine the impact of extreme weather on UK businesses, Martin et al. (2011) differentiate among three channels through which weather can affect a UK company: losses due to weather shock that affect (1) the company's own production location (production channels), (2) its suppliers (upstream channels) or (3) its customers (downstream channels). The authors find that summer heat waves in the UK negatively affect labour productivity. Moreover, importing from countries that have experienced exceptional heat reduces productivity, while exporting to 'hot' countries increases productivity, i.e. upstream disruptions have a negative impact, whereas downstream disruptions have a positive impact. This could be due for example to consumers abroad shifting to UK suppliers in response to shocks to their domestic producers.

Long-run Effects

The literature on the long-run effects of natural disasters is scarcer and its results less clear-cut than for short-run effects, partly due to the difficulty of constructing the appropriate counterfactual. This section summarises the existing evidence in light of the four different hypotheses presented in Figure 3.

Skidmore and Toya (2002) investigate the correlation between the frequency of natural disasters over the period 1960–1990 and average measures of economic growth, physical and human capital accumulation and productivity. They find a long-run expansionary impact of natural disasters on growth, thus supporting the hypothesis of creative destruction (hypothesis 1). Cuaresma et al. (2008) investigate the creative destruction hypothesis by examining how R&D from foreign origin is affected by catastrophic risk. They conclude that the creative destruction dynamic most likely only occurs in countries with high per capita income. For developing countries, disaster occurrence is associated with less knowledge spillovers and a reduction in the amount of new technology being introduced.

Cavallo et al. (2010) construct a counterfactual by building a synthetic control group of a weighted set of untreated countries. They do not find any significant long-run effect of disasters, even very large ones, on economic growth, thus supporting the 'recovery to trend' hypothesis (hypothesis 2).[37]

The 'no recovery' hypothesis seems to be supported by the largest number of empirical studies. Using a similar approach to Skidmore and Toya (2002), Noy and Nualsri (2007) reach the opposite conclusion to theirs, that natural disasters have contractionary effects on GDP. Raddatz (2009) examines the response of real per capital GDP to different types of natural disasters using cumulative impulse response functions and finds that, in the long run, per capita GDP is 0.6 percent lower as a result of a single climatic event.

In a recent study, Hsiang and Jina (2014) analyse the economic impact of tropical cyclones across different countries during the period 1950-2008. They reject the hypothesis that disasters stimulate growth, and find instead that disasters cause a small but persistent suppression of

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[37] Only when very large events that were also followed by radical political revolution (e.g. the Islamic Iranian Revolution and the Sandinista Nicaraguan Revolution of 1979) are included in the sample, they find economically meaningful and statistically significant negative long-run effects on GDP.

annual growth rates over the fifteen years following the disaster: a one standard deviation in a year's cyclone exposure lowers GDP by 3.6 percentage points twenty years later.[38]

Finally, Von Peter et al. (2012) estimate a dynamic stochastic growth model such as the one in equation (6) to simulate the impact of natural catastrophes on a country's growth path. The generated impulse response functions indicate that, following a natural catastrophe, real growth declines by 0.64% on impact and countries generally do not recover their previous GDP trajectory. Instead, the years of sluggish growth in the aftermath of a natural catastrophe cause a cumulative output loss of 1.7%. They conclude that major natural catastrophes have large and significant negative effects on economic activity, both on impact and over the longer run.[39]

4.5 Discussion and conclusions

The literature discussed in this section seems to agree that there are short term negative effects of natural disasters on GDP. The long term evidence is more mixed, with some studies supporting a 'creative effect' of disasters, while a large number finds the opposite results of a permanent (level) GDP loss.

Two observations can be drawn from the literature examined so far. First, it appears that the channels through which natural disasters affect GDP have not been fully examined. Few studies look at the different components of GDP, such as consumption, investment and trade, and there also appear to be few studies that look at the impact on different sectors of the economy, such as agriculture, manufacturing and services.

The second observation relates to the absence in these models of any forward looking features, indirect contrast with the IA models discussed in the previous section. With advances in the science of event attribution, there is scope for incorporating the evidence and predictions from climate science into economic models, in order to simulate the possible future economic consequences of natural disasters across different regions and in time.

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[38] These results are valid around the world, appearing in each region independently and for countries with different income and geographic size.

[39] In their study, however, they conclude that it is mainly the uninsured losses that drive the subsequent macroeconomic cost, while insurance should facilitate the financing of the reconstruction effort.

5 Transition risks from climate change

On 12 December 2015 the 196 participants to the 21st UN Conference of the Parties (COP21) in Paris set a goal of limiting global warming to well below 2ºC above pre-industrial levels and to pursue efforts to limit the temperature increase to 1.5ºC above preindustrial levels.[40]

Since it is the concentration of GHGs in the atmosphere that is responsible for climate change, to limit future temperature increases will require the stabilisation of GHG concentration, and, in the absence of significant improvements in current technologies for extracting GHGs from the atmosphere, this can only be achieved through zero net emissions. In Paris, countries have agreed to undertake rapid reductions of greenhouse gas emissions in order to achieve "a balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases in the second half of this century,"[41] a goal widely interpreted as being roughly equivalent to achieving zero net-emissions (CCC, 2016).

5.1 Transition risks and transmission channels

Due to the lack of private incentives for curbing GHG emissions, achieving reductions on the scale agreed in Paris will require widespread and decisive climate policy actions, especially in those countries with significant levels of emissions.

The trade-off between represent a major source of transition risks. This section discusses the different types of climate policies, as well as their macroeconomic transmission channels.

In principle, there are three ways to reduce carbon emissions:

(1) Reduce the *production and consumption* of high carbon products, especially energy produced using fossil fuels.

(2) Improve the energy efficiency of existing products and processes, that is, reduce the ratio of energy used per unit of output (*energy intensity*).

(3) Move to low-carbon energy production, that is, reduce the amount of carbon emissions per unit of energy produced (*carbon intensity*) by switching to low-carbon energy sources.

The first option would require a series of behavioural (demand-side) adjustments, while (2) and (3) can be achieved through technological (supply-side) innovation. While options (1) and (2) will help initially, the ultimate goal should be to de-carbonise the economy through (3), with technology most likely to become the dominant factor (Fankhauser, 2013).

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[40] The United States subsequently withdrew from the Paris Agreement in 2017.

[41] Article 4.1 of the Paris agreement. The full text of the agreement can be found here: http://unfccc.int/files/meetings/paris_nov_2015/application/pdf/paris_agreement_english_.pdf

A number of different policies can be used to address climate change: price based instruments, subsidies, R&D policies, regulations and standards. In practice, a mix of policy instruments will be required to reduce emissions at minimum costs and the effectiveness of climate policy will depend on policy characteristics as well as their mix (see e.g. Stern, 2007, Burniaux et al., 2008).

Carbon price

The accumulated stock of GHGs in the atmosphere poses a negative value or a 'negative externality.' Government policy intervention is thus needed to internalise the climate change externality. This can be achieved by putting a price on carbon, with the aim of discouraging the production and consumption of high GHG emission goods.

A carbon price can affect both production and consumption of high GHG emission goods and services. First, it encourages firms to alter their production processes so as to reduce emissions per unit of output. Second, it affects consumers' decisions by increasing the prices of carbon-intensive goods relative to other goods, which encourages shifts in consumption toward less carbon-intensive goods. A reduction in energy use will – everything else constant – lower GDP growth, at least until a clean energy technology becomes available.[42]

Different instruments can be used to establish a price for carbon: a carbon tax or a cap-and-trade system (such as the EU Emission Trading Scheme, ETS). Under a carbon tax, the price of carbon is set directly by the regulatory authority. Under a cap-and-trade system, the price of carbon or CO2 emissions is established indirectly: the regulatory authority stipulates the allowable overall quantity of emissions and the price of carbon is then established through the market for allowances.

In a market economy with perfect competition, setting a carbon tax which reflects the expected marginal damage of emission or 'social cost of carbon,' represents the first-best outcome. In practice, estimating the expected social cost of carbon is complex, leading to difficulties in choosing the appropriate level and trajectory for carbon prices.

Difficulties in estimating carbon prices also arise because of departures from the model of a perfectly competitive economy with complete markets, as for example in the presence of monopoly rents on fossil-fuel reserves. Owners of fossil fuel reserves will experience the carbon price as a kind of expropriation, and will have the incentive to extract more fossil fuel initially. This phenomenon, which arises because of a failure to account for supply-side effects of fossil fuel, has been named the 'green paradox' (see e.g. Sinclair, 1994, Sinn, 2008).[43]

Other climate change policies

Many other types of policies can be used to tackle GHGs emissions, including energy efficiency, subsidies for clean energy production, incentives for low carbon R&D and innovation, as well as

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[42] Given the share of energy in GDP is small, a simple growth accounting exercise suggests that a 10% reduction in energy use reduces output at most by 1%.

[43] Hoel (2013) studies the existence of the 'green paradox' in the case of supply-side policies, i.e. policies aimed at reducing the supply of fossil fuels instead of the use of fossil fuels.

policies that promote sustainable infrastructure, land use and cities. These are briefly discussed below.

Energy efficiency is often the cheapest and fastest way of mitigating climate change in the short term, and can be achieved through technological change (e.g. with more efficient coal fired power plants or cars) or socio-behavioural change (e.g. car sharing). Energy efficiency opportunities, however, are not always taken up by firms and households, and a gap exists between actual and theoretical levels of energy efficiency. The reason for this gap is usually a market failure, for example asymmetric information (e.g. between landlords and tenants) or hidden transaction costs. Thus, despite its attractiveness, energy efficiency is unlikely be implemented without government policy intervention (see e.g. Fankhauser, 2013, Mazzucato et al., 2015). Policy measures to close the energy efficiency gap include price incentives, regulation (e.g. efficiency standards for buildings and appliances), access to information (e.g. energy performance certificates for buildings), access to services and know-how (e.g. subsidised energy audits) and supplier obligations on energy companies.

Another type of policy aims to promote low-carbon technology, either through direct subsidies to low-carbon energy production or consumption or by incentivising low-carbon innovation, i.e. by addressing the market failures related to research and innovation. Knowledge produced through the research process is only partially excludible, and companies performing the R&D cannot fully appropriate its benefits: knowledge spillovers mean that other companies can make use of the same knowledge without incurring the costs of producing it. To correct this externality, governments put in place innovation policies such as R&D grants, R&D tax credits, and the patent system.[44]

Additional relevant market failures related to climate change, for example in the provision of networks and public goods, motivate other types of aggressive climate policy. Three areas in particular appear important (see, e.g., Global Commission on the Economy and Climate, 2016):

- Infrastructure: human-built structures such as energy systems, transport systems, buildings and industrial operations underpin all the major sources of greenhouse gas emissions. Many infrastructure projects have a public-goods component and therefore tend to be under-supplied by the market. Investing in sustainable infrastructure is critical to combating climate change and building resilience to its impacts.
- Land use: the way the ‘natural infrastructure’ is used can affect climate goals. Land use has strong emission reduction potential, and the natural environment is the only sector that can currently remove carbon from the atmosphere on a large scale. The conservation and restoration of forests and the rehabilitation of degraded lands are examples of such policies.
- Cities: the expected rapid growth in urban population will create significant demand for additional infrastructure. Cities are highly vulnerable to climate change and extreme

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[44] Decarbonisation of the electricity sector is at the core of the low-carbon transition, and a number of low-carbon technologies are available, including renewable (wind, solar, biomass, hydro) and nuclear energy. Decarbonised electricity has also an important role to play in reducing emissions in other sectors, in particular transport, through technologies such as battery operated electric cars, plug in electric vehicles and fuel-cell based vehicles.

weather events and the rapidity of urbanisation requires extensive planning of ‘low carbon’ cities.

Transmission channels of the climate transition risks

Like for other environmental policies, the traditional views is that climate policies are a burden to economic activity, at least in the short to medium term, as compliance with environmental regulation forces companies to curb production or to devote some of their resources to emission abatement. These effects can be both direct and indirect, deriving from increases in the price of a firm’s inputs, and tend to result in higher costs which can in turn affect firms’ profitability and productivity.

An important area of concern is related to the employment consequences of introducing climate policies, as these can directly or indirectly cause the creation or destruction of jobs. In this context, ‘direct’ employment effects refer to jobs directly affected by these policies, while ‘indirect’ employment effects refer to jobs created or destroyed in the supply chain for the products and services affected by ‘green’ policies (Bowen, 2012).

A full account of the economy-wide labour market effects of climate policies require the use of some form of general equilibrium modelling, either in the in the neoclassical tradition with complete markets and instantaneous price adjustment or in a neo-Keynesian framework with some form of market friction. Babiker and Eckhaus (2007), for example, use a CGE model which includes sectoral rigidities in labour mobility and in wage adjustments to evaluate the impact of climate policy measures and find that policies to limit greenhouse gas emissions could lead to an increase in unemployment in sectors affected by the policy. Goettle and Fawcett (2009) examine the potential implications of a climate policy for the US using an intertemporal general equilibrium model and find significant reductions in labour input many industries. Château et al. (2011) analyse the direct economic effects of an illustrative greenhouse gas emissions reduction policy on GDP and labour markets using two versions of a computable general equilibrium (CGE) model: in the first version of the model labour markets are perfectly flexible while the second incorporates short-run rigidities in real wage adjustment. The results show that imperfect wage adjustment increases the cost of mitigation policy since unemployment increases in the short-run, but the carbon tax revenue generated can be recycled to offset some or all of this effect.

Any detrimental effects of climate policy on firms’ profitability, productivity, employment and ultimately GDP represent the major source of transition risk from climate change to the macro-economy. Transition risks can be represented as a trade-off between the need to preserve the environment for future generations and the cost of reducing current emissions today, which is likely to reduce economic growth in the near term (‘growth drag’). This trade-off is the focus of the ‘green growth’ literature.

Co-benefits of climate policies

Climate policy can have a range of benefits in addition to the gains from reducing future climate change damages: these are often referred to as *co-benefits*.

Policies that encourage innovation in low-carbon technologies can *spill over* to other industries and stimulate economic growth. Moreover, climate policy might results in productivity growth if they improve the allocation of resources or increase their degree of utilisation.

Mitigation actions targeting clean energy technologies or energy efficiency are found to induce improvements in air quality by reducing local air pollution (LAP) such as particulate matter, sulphur dioxide and nitrogen oxides, since these pollutants are also produced when fossil fuels are burned. Research in this area has shown that the vast majority of damages from such air pollutants occur to human health, and this is the focus of most of the empirical estimates, but there is also a small but emerging literature on crop impacts.[45] This literature tends to conclude that co-benefits can be expected to cover a significant part of climate change mitigation costs (see e.g. Bollen et al., 2009, Groosman et al., 2011).

Other potential co-benefits of GHG mitigation policy include for instance improvements to the sustainability of ecosystems, improvements in biodiversity and increased energy security.

An attractive feature of co-benefits is that they occur in the medium run, while the direct benefits of GHG mitigation policies in terms of reduction of the impact of climate change are likely to occur only in the longer run.

Timing of the effects

The macroeconomic impacts of climate policy, in particular the short term reduction in economic growth caused by the transition costs, will depend on the timing of the transition. A gradual transition would allow enough time to replace the physical capital stock while technological progress would reduce energy costs. The ‘growth-drag’ might also be softened by innovation, investment in green infrastructure and the existence of co-benefits of climate policies.

A more aggressive climate policy might result in inefficient mitigation and a bigger drag on growth in the near term. Indeed, some economists (e.g. Mendelsohn, 2009) argue that an “immediate, aggressive, and inefficient mitigation policy” is the greatest threat posed to economic growth by climate. On the other hand, there is the risk that the transition to a low carbon economy could be “too late and too sudden,” with severe consequences for the economy (ESRB, 2016). A rapid transition away from fossil-fuel-based energy production could lead to a reduction in the supply of energy and an upward shock to energy prices with adverse macroeconomic consequences. Moreover, financial assets whose value depend on the extraction of fossil fuels and other carbon-intensive assets would become unusable or ‘stranded,’ requiring sudden and significant price adjustments. These could in turn lead to corporate defaults and financial instability, which could lead to negative macroeconomic outcomes (for a discussion see Batten et al., 2016).

The employment effects of climate change policies will also be different at different points in time (Fankhauser et al., 2008). In the short term, jobs will be lost in sectors directly affected by new climate change policies and will be gained in replacement industries. Because low-carbon

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[45] As well as adverse effects on human health, reduced yields of agricultural crops and timber, damages from air pollution emissions include: reductions in visibility, enhanced depreciation of man-made materials, and damages due to lost recreation services.

technologies are more labour-intensive than other energy technologies, the short-term employment effect of climate policy should be positive, while labour productivity is likely to decrease. In the medium term, climate change policies will create or destroy jobs along the value chains of the industries that are affected by those policies. In the long run, innovation and the development of new technologies could create opportunities for investment and net job creation, and improve labour productivity and economic growth (dynamic effect).

5.2 Modelling the transition risks

Modelling the economic impacts of climate policies

The most common approach used in modelling the economic cost of reducing GHG emissions it the ‘top-down’ approach typical of the IAMs.[46] Abatement costs are modelled at the aggregate level, as a function of the target carbon emission reduction. The simplest form is to assume that emissions abatement costs reduce GDP (see e.g. Dietz and Stern, 2015):

$$Y_t = A_t D(\Delta T_t)(1 - \Lambda_t)F(K_t, L_t)$$

where Λ_t represents emissions abatement costs. These costs will depend on the fraction of emission abated:

$$\Lambda_t = \theta_{1t}\, \mu_t^{\theta_2}$$

where $\mu_t \in [0, 1]$ is the desired proportional reduction in emissions relative to some baseline. The parameter θ_{1t} reflects the variability of abatement costs across time, as the menu of technological alternatives widens. The parameter θ_2 indicates the degree of non-linearity in abatement costs.

In practice, a number of factors are likely to affect the costs of climate policy: as well as the policy design and policy mix, costs will depend on specific country characteristics, such as the ambition of their mitigation objectives, their rate of growth of GDP and therefore of GHG emissions, the rate of technological innovation and the degree of protection of intellectual property rights, the degree of labour and product market competition and rigidities. Differences in countries’ industrial structure will also be important, as well as their relative endowment of fossil fuel resources and their clean-energy potential.[47] Macroeconomic modelling of climate change abatement policies is unlikely to reflect fully this country heterogeneity.

The ‘green growth’ models

‘Green growth’ can be broadly defined as the need to balance longer term investment in environmental sustainability and near term growth. The ‘weak’ or standard green growth view holds that there are trade-offs between income growth and the environment, but that appropriate

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[46] An alternative, ‘bottom-up’ approach analyses the costs of specific mitigation measures for different economic sectors, such as agriculture, energy etc.

[47] Bowen and Albertin (2011) discuss these issues with reference to the EBRD countries.

policies can soften this trade-off. This is the standard view in climate change economics, with optimal climate change policies prescribing a slightly lower rate of growth of consumption and GDP over the next 50 years to deliver higher expected growth over the longer term (Bowen and Hepburn, 2014). The 'strong' green growth version claims that maintaining natural capital and increasing income growth are complementary rather than alternatives, and environmental policies could improve economic outcomes even in the short term (Jacobs, 2013).

Growth theory is a useful framework to model the trade-offs in the transition to a low carbon economy, for a number of reasons: it can account for the inherently dynamic characteristics of the transition process, such as its timing, speed, and nature; it also allows for general equilibrium effects, which arise in this context because fossil energy is an important input in most sectors of the economy (Smulders et al., 2014). Growth theory can also model the various externalities arising from climate change. Finally, growth theory can highlight how environmental policies affect the sources of economic growth: investment in physical capital and innovation. In general, environmental policy can be expected to slow down capital accumulation and growth, but if it stimulates innovation the trade-off would be improved.

To analyse the implications of the green growth trade-off, one needs to study the interaction between two types of energy: fossil versus clean. Smulders et al. (2014) adapt a version of Heal's (1976) model[48] in which a large non-renewable resource stock is available at extraction costs that increase with depletion and become larger than the cost of substitute energy sources before the full stock is exhausted.

Let N measure the stock of capacity that 'nature' possesses for providing various kinds of goods and services that benefit consumers: this concept can be summarized by the utility function $U(C, N)$ in which nature N is included besides conventional consumption (C). Since households care about present and future consumption as well as nature, social choice should be based on the inter-temporal problem:

$$Max\ W_u = \int_0^\infty e^{-\rho t}\, U(C,N)\, dt \tag{8}$$

where ρ is the constant utility discount rate.

To model the production side, let K denote the stock of man-made capital, and assume that the labour force is constant and thus can be omitted. Energy can be provided either by a 'dirty' resource R extracted from the natural environment (e.g. oil) or by an alternative 'clean' energy B in unlimited supply. The unit extraction cost for fossil fuel is a decreasing function $M(S)$ of the remaining fossil stock S. The unit cost of renewables β exceeds the initial fossil extraction cost but is below the extraction cost of the last fossil reserves. Alternative energy is thus defined as a 'backstop' technology: once alternative energy becomes cheaper than fossil energy, it replaces

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[48] This models is part of the 1970s macroeconomic literature on non-renewable resources, developed from the four original contributions by Dasgupta and Heal (1974), Solow (1974), and Stiglitz (1974a, 1974b) published in a symposium issue of Review of Economic Studies. See Groth (2007) for a discussion.

fossil energy completely.[49] The production function includes natural capital and energy resources as well as physical capital and can be written as:

$$Y = F(K, R + B, N)$$

The part of production that is not consumed is invested in the physical capital stock (which depreciates at rate δ):

$$\dot{K} = F(K, R + B, N) - C - [M(S)R + \beta B] - \delta K \qquad (9)$$

where the term in square brackets indicates the cost of producing energy.
The more fuel is extracted and burned, the more carbon particles cumulate in the atmosphere: because the absorption of GHGs from the atmosphere is negligible, environmental quality – and therefore nature's capacity to provide beneficial goods and services – decreases at the rate of fossil fuel extraction:

$$\dot{N} = -R \qquad (10)$$

The socially optimal policy solves the maximization problem (8) subject to the constraints in (9) and (10). Any green growth policy would always require cuts in fossil energy use, so that less carbon emissions accumulate. This causes a drag on growth since the return to capital falls. However, with less-intensive fossil energy use, extraction costs rise less quickly over time. Depending on how the policy affects the timing of transition to the backstop technology, the growth dip can be concentrated in initial periods and resume quickly, or may be more spread out over time.

Innovation

In the model introduced above, economic growth is mainly the result of the accumulation of man-made capital and takes place while the returns to capital are large enough to generate net investment. If the capital stock expands faster than output, the model runs into 'diminishing returns' – the returns to capital fall – and growth slows down. In the long run, growth can only be sustained if the diminishing returns from capital are offset by technical change.

In green growth models, which include natural as well as man-made capital, growth is also constrained by declining resource availability. Fossil fuel reserves are finite and become costlier to extract as they are depleted, while the flow of renewable resources is constrained by the growth rate of the resource stock. To reconcile growing output with non-increasing resource use, the *resource intensity* of the economy has to fall over time. This requires some combination of resource substitution towards cleaner technologies and input-augmenting technical change.

Because changes in the relative price of energy inputs will affect the types of technologies that are developed and adopted, any climate policy that affects relative prices will also affect technological progress. Acemoglu et al. (2012), for example, introduce a framework that allows

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[49] In this formulation, fossil fuel and the alternative energy are perfect substitutes and only one type of energy is used unless the cost is exactly the same.

different types of technologies to respond endogenously to proposed climate policies. Because of the environmental externality, the decentralized equilibrium is not optimal and policies are needed to both control emission and stimulate innovation in the clean energy. These policies only need to be in place temporarily, however, because once clean technologies are sufficiently advanced, research would be directed towards these technologies without further government intervention. Consequently, in this model, environmental goals can be achieved without permanent intervention and without sacrificing long-run growth.

Limitations of green growth models

Climate change raises the question of the long-run sustainability of economic growth, but it is not the only environmental consequence of economic activity: loss of biodiversity, water scarcity and pollution, in particular from air-borne particulates and hazardous chemicals, are other important examples of environmental threats deriving from economic activity (Bowen and Hepburn, 2014). The early debate – in the 1990s and 2000s – on how to reconcile socio-economic development with the scarcity of natural resources developed around the concept of 'sustainable development.'

In economic terms, sustainable economic development is characterised by a time path along which per capita welfare remains non-decreasing across generations.[50] An aspect of this is that current economic activities should not impose significant economic risks on future generations. Modern 'green growth' definitions are somewhat related to the concept of sustainable development but are more narrowly focused on promoting economic growth and pose less emphasis on the social dimension (Bowen and Hepburn, 2014). The macroeconomics of climate change can therefore be viewed as a subset of the broader literature on sustainable development, and might benefit from adopting some of the concepts from the latter.

One area of improvement is around the desirability of economic growth *per se*. Jakob and Edenhofer (2014) claim that the popular concepts of 'green growth' fails to make explicit the objectives that are ultimately to be achieved by promoting economic growth and whether growth is a way to achieve some unspecified objective or is an objective in itself. The authors propose instead to base the debate on economic growth and the environment on the concept of 'social welfare': economic growth then becomes desirable only to the extent that it increases welfare, defined as 'the things that a given society values'. They argue that GDP does not constitute a good measure of social welfare, and propose instead the use of 'net national product', a measure that adjusts GDP to account for the accumulation or depletion of assets relevant for future consumption, and hence welfare.

5.3 Empirical evidence on the impact of climate policy

Climate policies belong to the broader class of environmental policies: the literature on the economic impacts of environmental policies is vast and a number of comprehensive surveys exist (see e.g. Jaffe et al., 1995, Koźluk and Zipperer, 2015 and Dechezleprêtre and Sato, 2017).

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[50] The Brundtland Report defined sustainable development as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (World Commission on Environment and Development, 1987).

While traditionally stringent environmental policies are believed to be a burden to economic activity, at least in the short and medium term, there is no clear a priori direction of the effects of these policies on macroeconomic variables such as productivity, employment, trade and GDP. Indeed, the famous ‘Porter hypothesis’ (Porter, 1991) suggests that well-designed environmental policies might enhance productivity and increase innovation, and therefore deliver direct economic benefits as well as the environmental ones. In a comprehensive survey of the empirical research on the effects of environmental policy on firms’ *productivity*, Koźluk and Zipperer (2015) conclude that existing studies are largely inconclusive, their results are context-specific and therefore difficult to generalize.

Other studies address the potential impact of environmental policy on *competiveness*, defined as the ability of a firm or sector to survive competition in the marketplace, be profitable and grow. In the context of environmental policies, competitiveness effects arise from *asymmetries* in policies across firms or sectors that are competing in the same market.[51] The ‘pollution haven’ hypothesis, which is based on trade theory, predicts that more stringent environmental policies will increase compliance costs and, over time, shift pollution-intensive production toward low abatement cost regions, creating pollution havens and causing policy-induced pollution ‘leakage’ or ‘carbon leakage’ for GHG emissions (see, e.g., Levinson and Taylor, 2008). The first major review on the impacts of environmental regulations (Jaffe et al., 1995) concluded that there is relatively little evidence that environmental policies lead to large losses in competitiveness. A more recent review of this literature concludes that the evidence appears to offer broad support for the existence of a pollution haven effect, with tighter regulation being associated with increased imports of pollution- or energy-intensive goods (Dechezleprêtre and Sato, 2017). However, these effects tend to be small and concentrated in a few sectors, and the effect is dominated by other determinants of trade.

The evidence on specific *climate policy* initiatives is smaller and the literature is still in its infancy: a rigorous evaluation of climate policy initiatives is often difficult, because of the lack of a robust identification strategy or suitable data. Martin et al. (2012), for example, review the existing studies that evaluate the EU Emission Trading System (ETS) and highlight the gaps in the evidence, such as (1) the interaction of the scheme with national policies and (2) the mechanisms that drive the observed impacts.

Martin et al. (2014) use firm level data to evaluate the impact of the UK Climate Change Levy (CCL). The CCL ‘package’ consists of a carbon tax – the CCL – and a scheme of voluntary agreements available to plants in selected energy intensive industries. Upon joining a Climate Change Agreement (CCA), a plant adopts a specific target for energy consumption or carbon emissions in exchange for a highly discounted tax liability under the CCL. The authors use longitudinal data on UK manufacturing plants to estimate the impact of the CCL on energy use, emissions and economic performance.[52] They find robust evidence that the CCL had a strong negative impact on energy intensity, particularly at larger and more energy intensive plants and mainly driven by a reduction in electricity use, which translates into a reduction of CO2

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[51] Competitiveness effects need to be distinguished from the general effects of regulations on polluting firms’ economic outcomes, which are caused by the policy itself rather than by differences in environmental policy faced by competing polluting firms.

[52] The analysis focuses on the first three years following the introduction of the CCL in 2001, thereby avoiding overlap with the EU ETS. Their identification strategy is to compare changes in outcomes between fully-taxed CCL plants and CCA plants, using a difference-in-differences estimator.

emissions. In contrast, they find no statistically significant impacts of the tax on employment, output or productivity, nor any evidence that the introduction of the CCL accelerated plant exit.

Evidence also shows that climate change policies induce innovation in low-carbon technologies: the EU ETS, for example, has been shown to have increased innovation activity in low-carbon technologies among regulated firms (Calel and Dechezlepretre, 2016).

Dechezleprêtre et al. (2014), moreover, find that knowledge spillovers – measured by patent citations – are significantly greater for ‘clean’ technologies than for ‘dirty’ technologies in four technological areas. In particular, the knowledge spillover effect of low-carbon innovations is comparable to the knowledge spillover effect of information and communication technologies (ICT). The authors also find that ‘clean’ patents tend to be cited by more prominent patents. They attribute the superiority of ‘clean’ technologies to the fact that they have more general applications and also represent more radical forms of innovation compared to ‘dirty’ innovations, which are generally incremental.

In terms of the effects of climate policies on jobs and the labour market specifically, the few existing empirical studies tend to focus on the direct impact of the climate policies, ignoring the potential for job destruction in non-green industries and the possibility of crowding out of jobs via general equilibrium effects (see Bowen, 2012, for a discussion).

6 Concluding remarks and directions of future research

Climate effects that impact on aggregate macroeconomic outcomes are difficult to measure, and capturing the gradual changes in climate that might cause economic harm is likely to be particularly difficult. This review has presented a framework to understand the different transmission channels from the climate to economic variables. While these theoretical channels are well understood, it is possible that the economic impacts of climate will be increasingly felt through many local, specific incidents, such as poor agricultural crops in some areas or planes being grounded at some airports due to extreme summer heat. It is unlikely that the productivity losses from any of these specific incidents would be accurately reflected in economic models. However, these incidents might, in aggregate, become a meaningful drag on productivity and growth – perhaps many times more so than single catastrophic events. As the economic modelling of climate impacts evolves, it will be important to understand how to capture and measure these cumulative effects.

There are many ways in which existing economic modelling of climate change could be improved: the following three suggestions focus the role of models as tools for monitoring the gradual changes in the earth’s climate that can cause economic harm, rather than tools for designing or assessing climate policy. First, as suggested by others, the emerging empirical results from the new economic-weather literature could be better used to inform modelling choices for the climate damage function, which is currently unsatisfactory due to the lack of theoretical and empirical foundations. Second, as climate science progresses in its understanding of extreme climate events and becomes better at predicting their occurrence, economists could similarly include the impact of these events in macroeconomic models, both in the short and the long-run. Third, the two areas of gradual global warming (discussed in Section 3) and extreme weather events (Section 4) appear remarkably distinct from each other, and would all benefit from mutual learning. In particular, the macroeconomic impacts of extreme weather events in a warming climate have not been researched, partly due to the formidable challenges in this area, while this appears to be one of the most pressing issues facing the global economy in the current century.

For the future research agenda, there is great scope for the design of a modelling framework to project near future climate damage to the macro-economy, taking into account complex global linkages. For the UK, for example, modelling the macroeconomic impact of climate change on the UK is still at the early stages. The UK Climate Change Risk Assessment (Defra et al., 2012, CCC, 2017) is the main detailed assessment of the risks to the UK deriving from climate change. It gives a thorough insight into the various channels by which climate change could affect different sectors of the UK economy, which could become significant for aggregate economic performance. The assessment, however, does not appear to be immediately applicable to a quantitative economic model of the UK economy, partly due to the extremely high granularity of the analysis, as well as the limited quantification of the effects.

There is scope to construct and calibrate multi-sector models of the economy which include a more detailed description of climate damages than that provided by an aggregate damage function, along the lines of Houser et al. (2015). A similar study for a country such as the UK would present further challenges compared with the US study: the UK has a smaller agricultural sector than the US, and relies more on external imports of food and other commodities, which are affected by complex global interactions. More generally, the UK's position as a small open economy makes it more vulnerable to climate shocks in its trading partners across the globe, which complicates the analysis substantially.

Any economic model of climate risks needs to take into account climate policy, although the specific design of such policy could be treated as exogenous to the model. Evidence on the impact of climate policy on economic activity could then be used to calibrate the aggregate model. For the UK specifically, the evidence in Martin et al. (2014) on the impact of the CCL on productivity and employment is a useful first step in this direction, and more evidence is crucial for future model calibration.

Finally, one important area of empirical research not addressed by Houser et al. (2015) is long-run 'green' growth. According to Jacobs (2013), there is a strong version of green growth by which greater environmental protection generates new industries and drives the next industrial revolution. Empirical validation of this hypothesis would be interesting, and could involve, for example, the analysis of the evolving industrial composition, the estimation of the elasticity of substitution between 'dirty' and 'clean' technologies within firms or across sectors (Acemoglu et al., 2012), and the analysis of the speed of technical progress in the renewable energy sector (Farmer and Lafond, 2016).

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Annex: Examples of extreme climate events

Stephenson (2008) lists a number of examples of extreme climate events:

1. **Tropical cyclones and hurricanes,** the major source of global insured catastrophe loss after earthquakes.
2. **Extra tropical cyclones**, generally referred to as “windstorms”.
3. **Convective phenomena** such as tornadoes, waterspouts, and severe thunderstorms. These phenomena can lead to extreme local wind speeds and precipitation. Deep convection often leads to precipitation in the form of hail, which can be very damaging to crops, cars, and property.
4. **Mesoscale phenomena** such as polar lows, mesoscale convective systems, and sting jets which can lead to extreme wind speeds and precipitation amounts.
5. **Floods** of rivers, lakes, coasts, etc., due to severe weather conditions. Examples are (1)‘flash floods’ i.e. river floods caused by intense precipitation over a short period; (2) wintertime river floods, caused by persistent or recurrent precipitation over many days, (3) river floods caused by rapid snowmelt due to a sudden warm spell, and (4) coastal floods caused by high sea levels due to wind-related storm surges.
6. **Drought**. Meteorological drought is defined usually on the basis of the degree of dryness in comparison to some normal or average amount (monthly, seasonal or annual) and the duration of the dry period.
7. **Heat waves**. Periods of exceptionally warm temperatures that can have profound impacts on human health and agriculture.
8. **Cold waves/spells**, i.e. extremely cold days or a succession of frost days.
9. **Fog**. Extremely low visibility that can have major impact on various sectors such as aviation and road transport.