Climate change in the critical decade

A summary of the IPCC Sixth Assessment Report and its implications for the UK

THE ROYAL SOCIETY

The information in this report is supported by supplementary evidence available on the Royal Society website (royalsociety.org/climatechange) that describes the evidence base and literature sources used.

List of abbreviations used throughout report:

AR6 Sixth Assessment Report of the Intergovernmental Panel on Climate Change

CH_4 Methane

CO_2 Carbon dioxide

COP26 26th United Nations Climate Change Conference of the Parties

GDP Gross Domestic Product

$GtCO_2$ Gigatonnes of carbon dioxide. 1 Gigatonne is equal to 1 billion tonnes of carbon dioxide

IPCC Intergovernmental Panel on Climate Change

RFC Reasons for concern

SDGs United Nations Sustainable Development Goals

SSPs Shared socioeconomic pathways

UK United Kingdom of Great Britain and Northern Ireland

UN United Nations

UNFCCC United Nations Framework Convention on Climate Change

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Cover image
Hurricane Brian, Porthcawl Wales.
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Contents

Policy highlights

This report provides a summary of the findings of the Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report (AR6) and an assessment of the implications for the UK.

The following points are key messages for policymakers:

- The planet has warmed by more than 1°C in the last 150 years because of greenhouse gas emissions from human activities. The extent of further global warming will be determined by future greenhouse gas emissions. To stabilise temperature requires that global emissions of carbon dioxide (CO_2) and other greenhouse gases are cut back to net zero.

- Current policies and commitments by countries are not in line with the Paris agreement goal of limiting warming to well below 2°C. Stabilisation of the climate below 2°C can only be achieved with immediate actions that lead to deep cuts in global emissions.

- The UK, as an important contributor to historical cumulative emissions, has set a target of net zero greenhouse gas emissions by 2050. Such a target would meet the UK's commitment to the Paris Agreement. Helping other nations to reduce emissions and adapt to climate change impacts would also reduce the risks to the UK and globally.

- The UK needs to adapt now to warmer summers, changes in flood and drought occurrence, and rising sea level, allowing for uncertainties in how these will change in the future. The UK is also vulnerable to the impacts of climate change overseas, such as displacements of people and interruption of food and other supplies.

- Strategies to achieve net zero greenhouse gases in the UK include a shift to low-carbon energy, structural demand reduction, support for more efficient use of energy and land, and removal of CO_2 from the atmosphere. It will be very hard to achieve net zero greenhouse gases without all of these. This in turn requires consistent policy, infrastructure planning, and research and development in areas including energy storage, renewable energy, agricultural emissions reductions and carbon capture and storage.

Image: Offshore windfarm in the UK. © iStock / Ian Dyball .

Introduction

It is now widely recognised that climate change is a major global challenge of our times, and rapid action is required to limit its further impacts.

Climate change harms many aspects of our lives, the economy and the built and natural world, and this harm will greatly increase as warming increases. As so much of our economy and lifestyle is currently enabled by actions that emit greenhouse gases, tackling climate change requires transformative change across all sectors of the economy. The current decade is widely seen as critical to implement actions that will limit global warming to targets set out in the 2015 United Nations Framework Convention on Climate Change (UNFCCC) Paris Climate Agreement.

Every few years, the Intergovernmental Panel on Climate Change produces a series of reports that synthesise our knowledge of the causes of observed climate change, its impacts, what is expected in the future, and the ways to both adapt to and mitigate the impacts. The reports are authored by hundreds of scientists and reviewed by thousands of scientists and other stakeholders. The latest (sixth) Assessment Report, issued by the three working groups of the IPCC during 2021 and 2022, provides the scientific basis for decisions that will be taken by governments, organisations and citizens.

The Royal Society sets out here a brief and accessible summary of the IPCC Sixth Assessment Report, supplemented by an assessment of the implications for the UK. This briefing was informed by a meeting of scientists, policy professionals and influencers held at the Royal Society in April 2022.

Image: People with relief supplies during flooding in Sylhet, Bangladesh, June 2022. © HM Shahidul Islam.

The scientific basis

This section provides a summary of the findings of Working Group I of the IPCC, which examines the latest climate science and current understanding of the climate system and climate change[1].

The effects of warming are already clear

It is unequivocal that human activities have warmed the climate. The rate of warming is unprecedented in at least the last 2000 years. This warming is mainly caused by greenhouse gas emissions from human activities, in particular CO_2 emissions from burning of fossil fuels and land use change. The levels of greenhouse gases in the atmosphere today are higher than seen for at least 800,000 years.

In the decade ending 2020, the average annual global surface temperature on Earth was approximately 1.1°C higher than in the period 1850 – 1900, with larger warming observed over many land areas. Figure 1 shows how the increase in global temperature is most pronounced in recent decades.

Human-induced climate change is already affecting weather and climate extremes across the globe, with human influences identified as the main driver of the increasing frequency of heatwaves and heavy rainfall events over many land regions. Human influence is contributing to observed changes in precipitation patterns and drought. Human influence is also clear in the retreat of glaciers and reduction in Arctic sea ice, warming and acidification of the ocean and rising sea levels.

Impacts of future warming

Further emissions of greenhouse gases will cause further warming. All the changes that have been observed will become progressively larger for every additional increment of global warming, and some of the impacts are irreversible on timescales comparable to multiple human generations or longer. This includes deep ocean warming, acidification of the ocean, melting of ice sheets and sea level rise.

Under all conceivable future emissions scenarios, global temperature will continue to rise until at least mid-century. For warming to be limited to below 2°C above preindustrial global average temperature[2] during this century, actions planned now must lead to deep reductions in emissions of CO_2 and other greenhouse gases in the next decades, well before 2050.

Many types of extreme weather event will intensify and become more frequent in many regions of the globe as warming approaches 1.5°C and even more so with 2°C and beyond. At 2°C warming and above, there is a higher likelihood of many regions experiencing compound extreme events with high societal risks. These are high impact events where multiple climate hazards occur at the same time, for example heatwaves combined with droughts, or storm surges combined with extreme rainfall. It is likely that the chance of such compound events has already increased under current climate change.

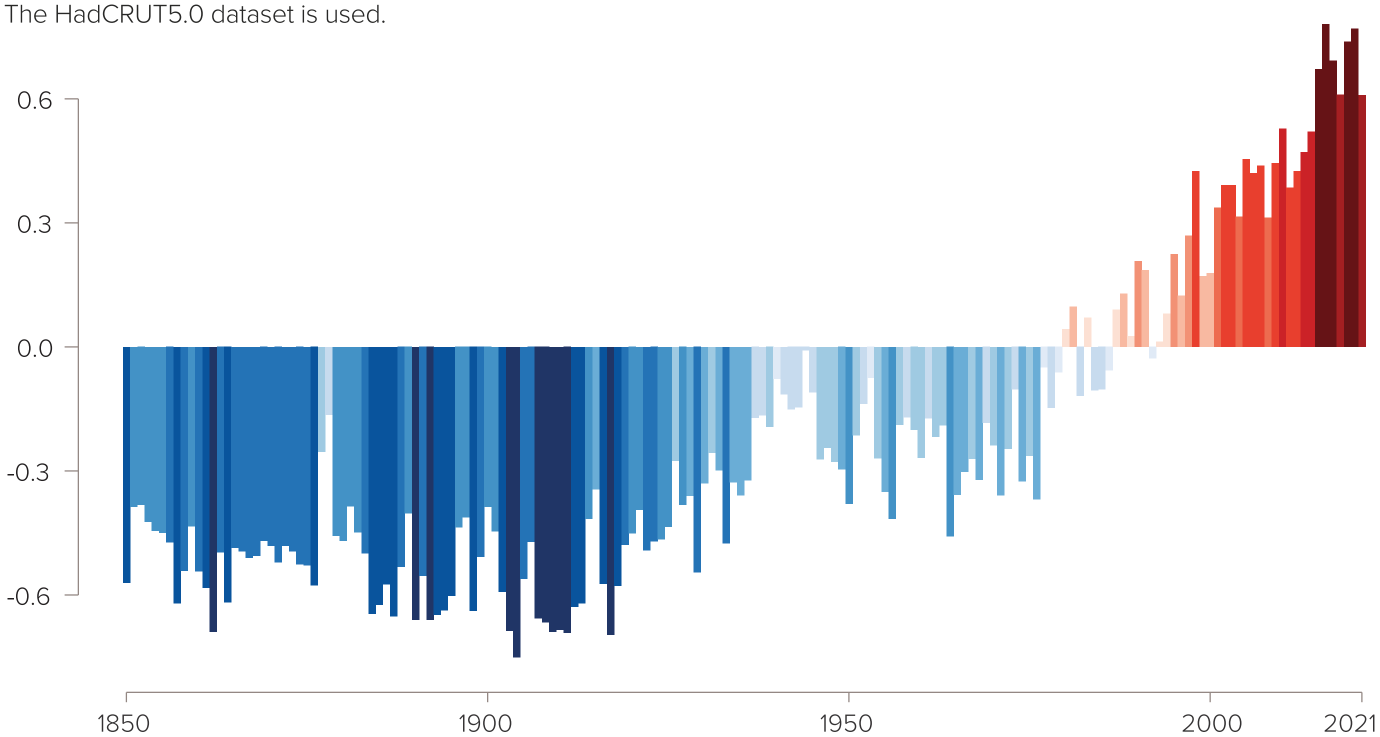
Global mean sea level will continue to rise over the 21st century. If warming is limited to 1.5°C, then sea level rise of a few tens of centimetres is expected by 2100. Under a pessimistic high warming scenario, sea level rise is expected to reach up to 1 metre by 2100. Even if global warming is limited to 1.5°C, continued ocean warming and melting of ice sheets commit sea level to rise for centuries to millennia, leading to 2 – 3 metres of additional sea level rise in the next 2000 years. Higher levels of warming will lead to further metres of sea level rise over the long term. Many densely inhabited areas of land lie close to sea level. An example is the Nile delta in Egypt, where large areas are only 1.5 metres above sea level, and where 41 percent of Egypt's population live.

Future climatic changes that are currently assessed as low likelihood, but would have very high consequences, cannot be ruled out. These include rapid ice sheet collapse, abrupt ocean circulation changes, substantially higher levels of warming and higher than anticipated sea-level rise.

FIGURE 1

Global temperature change 1850 to 2021, relative to average of 1971 – 2000 (°C).

Both the colour and length of the bars indicate the departure from the 1971 to 2000 average with pale colours being the closest to the average (white) and the darker red indicating the warmest and the darker blue the coolest temperatures. The HadCRUT5.0 dataset is used.



Source: Professor Ed Hawkins, (University of Reading), www.showyourstripes.info

Stopping warming requires net zero emissions
The IPCC has confirmed that the amount of global warming is proportional to the cumulative sum of CO_2 emissions. Therefore, to stabilise the planet's temperature and limit the impacts of additional global warming, emissions of CO_2 must drop to 'net zero'. Net zero means that the amount of CO_2 released into the atmosphere is no more than the amount being removed through deliberate actions to increase the carbon sinks, thereby allowing CO_2 concentrations to stabilise. Reaching net zero implies 'strong, rapid and sustained' cuts in CO_2 emissions.

As the concentration of CO_2 in the atmosphere rises, natural carbon sinks such as forests and the ocean are likely to absorb a smaller proportion of emissions, exacerbating the need for rapid emissions cuts. Negative emissions, where CO_2 is removed from the atmosphere, are also required in the lowest emissions scenarios that have a chance of limiting warming to below 2°C.

CO_2 emissions are the dominant contributor to human induced warming and rapid reductions are essential. However, other greenhouse gases, notably methane and nitrous oxide, have increased compared to pre-industrial levels. Although methane (CH_4) lingers in the atmosphere for a shorter duration than CO_2, CH_4 molecules have a much higher warming effect than CO_2 molecules. A rapid implementation of strong and sustained cuts in methane emissions and a reduction in nitrous oxide emissions will be important for limiting warming, particularly in the near term.

BOX 1

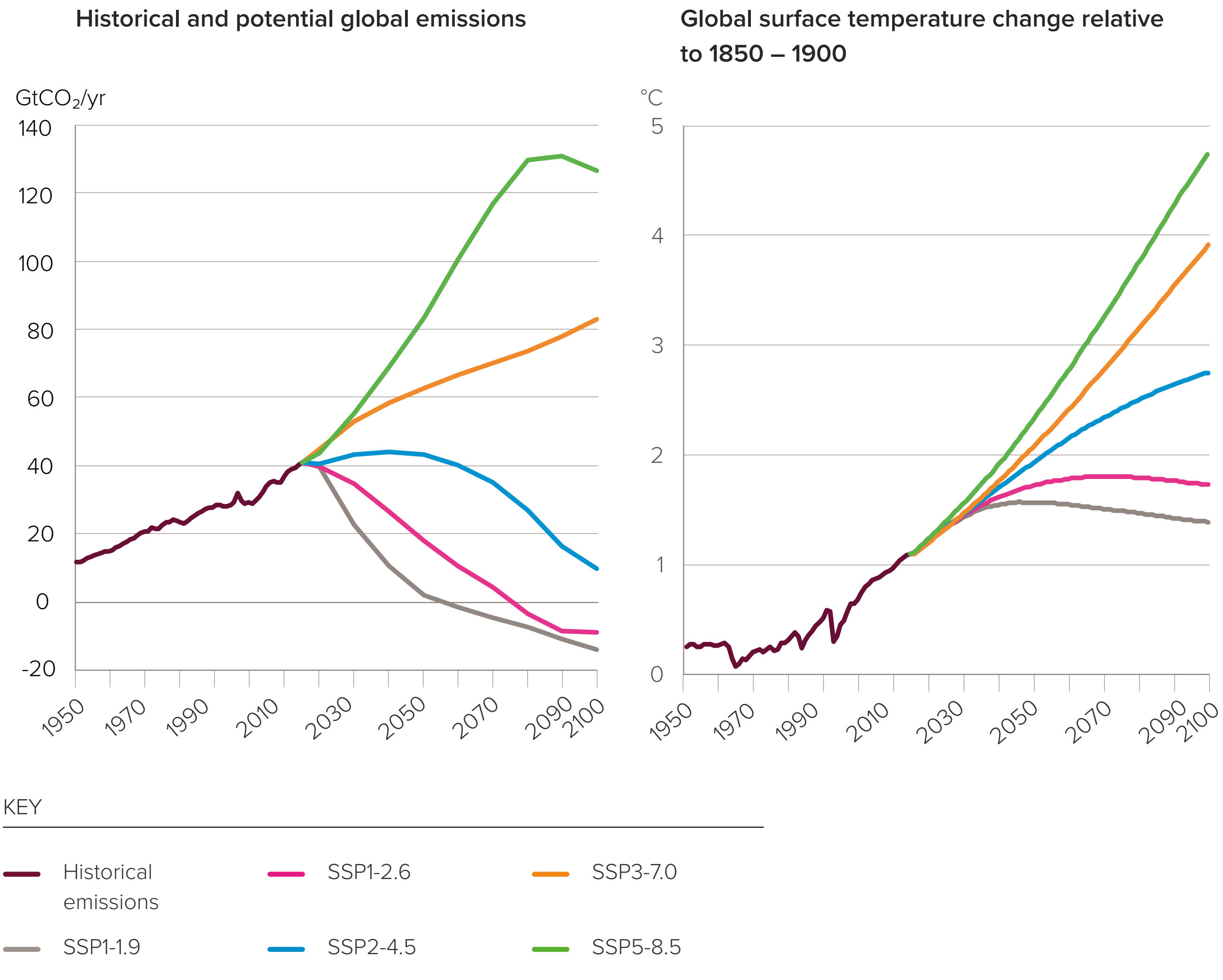
Emissions scenarios

The IPCC uses five storylines that explore a range of possible futures for our climate. They provide a set of greenhouse gas emissions scenarios, known as shared socio-economic pathways[3] (SSPs) from 2015 – 2100. These are based on a range of possible socioeconomic development pathways, mitigation achievements and other factors. They are then used in climate models to assess the resulting concentrations of greenhouse gases, temperature increases, and changes to the climate over the 21st century (Figure 2).

Broadly speaking, the most ambitious scenario, called SSP1-1.9, would give a good chance of keeping global warming below 1.5°C by 2100. This scenario requires CO_2 emissions to drop to net zero by 2050 with strong reductions in other greenhouse gases, followed by negative emissions from CO_2 removal. The two scenarios with highest emissions (SSP3-7.0 and SSP5-8.5) would lead to global warming of around 3.5 and 4.5°C by 2100, respectively.

FIGURE 2

Historical and projected CO_2 emissions and global temperature from 1950 to 2100 under five emissions scenarios[4].



Impacts, adaptation, and vulnerability

This section provides a summary of the findings of Working Group II of the IPCC, which examines the impacts of climate change, vulnerability of human and natural systems to those impacts and adaptation options[5].

Human-induced climate impacts are evident now

Human-induced climate change is already causing adverse observed impacts on nature and people across the globe. These impacts are greater and more widespread than those assessed in earlier IPCC reports[6]. Changes to temperature and precipitation patterns and weather extremes have reduced food and water security; affected physical and mental health; had a negative impact on economies, livelihoods, infrastructure and services; and hindered progress on the UN Sustainable Development Goals (SDGs). Wildfires are affecting larger areas in some regions of the world, and pests and diseases are appearing in new areas, harming human and environmental health.

Accelerating and complex risks

The IPCC report analysed 127 key risks across different sectors. In Figure 3 these are grouped into five 'reasons for concern' (RFC). Figure 3 illustrates how the severity of impacts will increase as the climate continues to warm. Climate impacts will be considerably less damaging if global efforts to limit warming are successful. Nevertheless, many impacts will not be avoided, and impacts to unique and threatened ecosystems and from extreme weather events are already judged to be high with current levels of warming or will become high as warming approaches 1.5°C. Many impacts may become irreversible, as natural, built, and human systems are pushed beyond their ability to adapt.

Climate hazards and impacts are increasingly interacting with each other and non-climatic factors, creating complex risks. These are more difficult to adapt to, as they cascade across sectors and localities and can have severe impacts on nature and people.

An example might be where a flood causes a direct impact by damaging an electricity sub-station, which then causes interruption to electricity supply with associated cascading impacts on traffic management, transport of goods, IT services and communications, leading to compound impacts on social infrastructure and services.

Recognising vulnerability

People are not equally vulnerable or exposed to climate change, both within and between countries. Location greatly influences exposure, whilst poverty, inequities in access to resources and decision making, and unsustainable development increase vulnerability. The most vulnerable people and systems are disproportionately affected by climate impacts, often resulting in them becoming more vulnerable to future climate impacts, for example by exacerbating poverty or ill health.

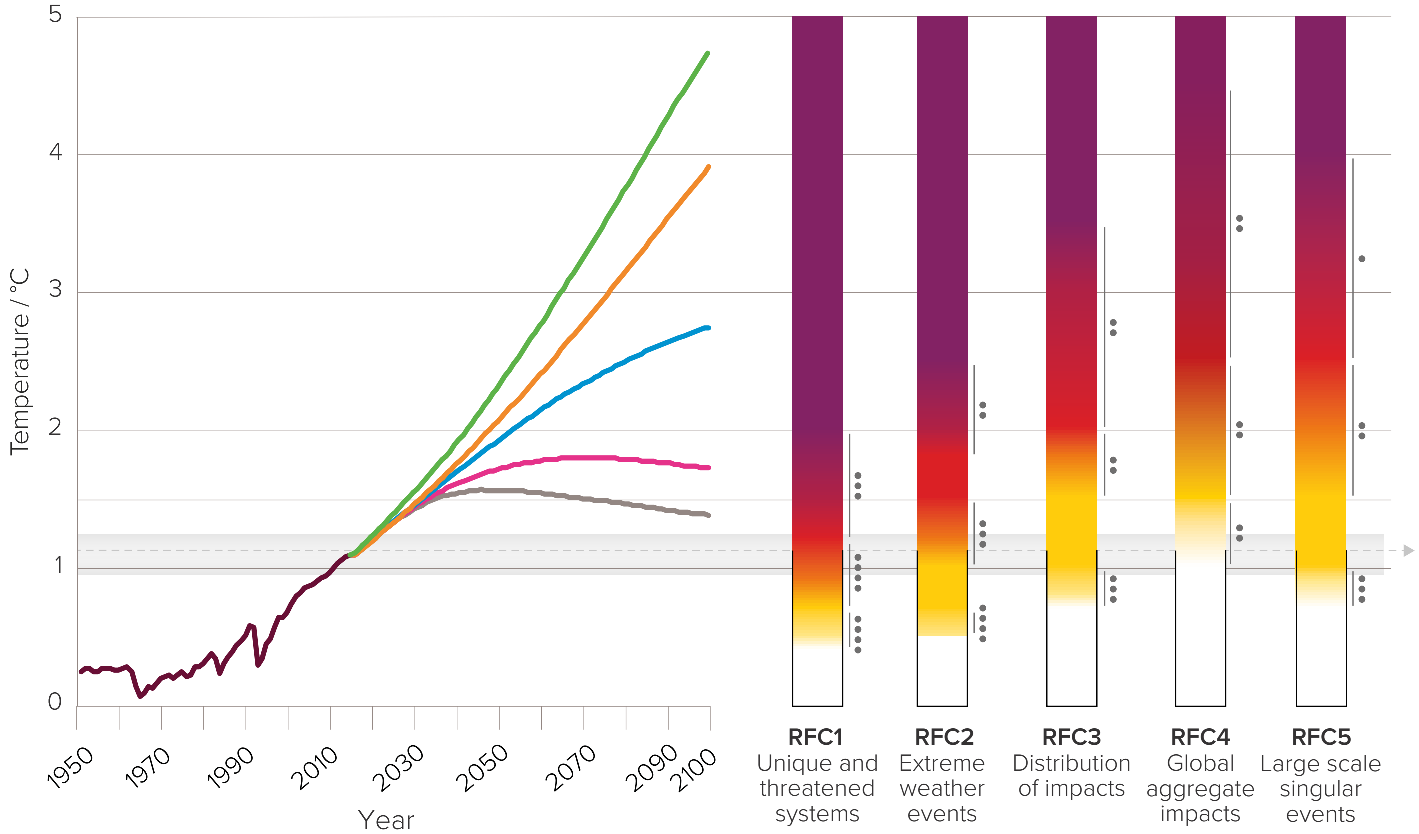
Adaptation and its benefits

Adaptation refers to a 'process of adjustment to actual or expected climate and its effects'[5]. Adaptation planning and implementation can reduce vulnerability and exposure to climate risks and provide benefits for tackling other priority challenges, for instance by reducing poverty and inequality and avoiding biodiversity loss. All sectors and regions have adaptation options. Adaptations include structural measures such as levees to reduce exposure to flooding, non-structural measures such as improved early warning systems and emergency preparedness planning, and economic measures such as insurance or social safety nets.

The IPCC emphasises the need to act now on adaptation, since delayed action will limit adaptation options for the future. However, there is a gap between the level of action underway and the level of adaptation required, for all sectors. The focus for adaptation has remained on addressing current and near-term risks to individual sectors. There is a danger that this approach could reduce the opportunity for the transformations required to adapt to risks associated with higher levels of warming in the mid to longer term. Transformational adaptation involves deep-rooted changes in society, energy systems, industry, infrastructure and how we produce and consume food, that address how societies interact with ecosystems. It also tackles underlying causes of vulnerability, often involving changes to social goals and values.

FIGURE 3

Increase in global impacts and risks for the five IPCC 'reasons for concern' (RFC) with increasing levels of warming[7, 8].



Global surface temperature change increase relative to the period 1850 – 1900[7].

Reasons for concern (RFC). Impact and risk assessments assuming low to no adaptation[8].

KEY

Historical emissions

SSP1-1.9

SSP1-2.6

SSP2-4.5

SSP3-7.0

SSP5-8.5

Risk/impact

Very high

High

Moderate

Undetectable

Transition range

Confidence level assigned to transition range

Low ⟶ Very high

Historical average temperature increase in 2011 – 2020 was **1.09°C** (dashed line) range 0.95 – 1.20°C

As urban areas continue to grow throughout the world, investments in urban infrastructure and land use planning that incorporate social and ecological approaches can provide resilience to climate impacts. For example, the use of vegetation, sustainable urban drainage systems and restoration of water courses can help to manage extreme rainfall events and reduce heat island effects and extreme temperatures in urban areas. Infrastructure improvements to tackle adaptation must be considered alongside measures to meet net zero goals.

Conditions for enabling adaptation

Some adaptation actions have been observed to have unintended consequences, for example causing increases in greenhouse gas emissions, or reducing risk for some but increasing it for others. Adaptation that reduces climate risk, has fair outcomes and is inclusive in approach, is more likely to be considered successful.

Many adaptation options take significant time to plan and implement. Providing the right enabling conditions is crucial for implementing, accelerating and sustaining adaptation. These include adequate funding, political commitment, clear vision, policies with clear goals and priorities and inclusive planning that incorporates flexibility. An improved knowledge of climate impacts and solutions is key to this, as is adequate monitoring of adaptation measures to ensure they are achieving their aims.

Insufficient funding for adaptation is a key constraint, notably for developing countries. Globally, the public and private funds allocated for meeting climate goals have been increasing in recent years, but the focus has been on mitigation rather than adaptation. Global finance systems and capital flows do not adequately account for climate risks.

Limits to adaptation

It will not be possible to adapt to all climate risks, even at lower levels of warming. Critically, some ecosystems are approaching limits where the natural adaptive capacity is overwhelmed by the magnitude and pace of climate change. Examples include some warm water coral reefs, rainforests, and polar and mountain ecosystems. This underlines the urgency of actions to reduce greenhouse gas emissions.

Safeguarding biodiversity and ecosystems is fundamental to maintaining human well-being and ecosystems services that are critical to our health and livelihoods. Analysis suggests that this also depends on effective and equitable conservation or restoration of 30 to 50% of Earth's land, freshwater and ocean areas.

Human systems that are reaching limits to adaptation include, for example, low lying coastal settlements or areas farmed by small holder farmers in many regions of the world with diminishing fresh water supplies.

Image: Pre-fabricated metal flood defences in Bewdley, Worcestershire, UK, February 2022. © iStock / Neil Bussey.

Mitigation of climate change

This section provides a summary of the findings of Working Group III of the IPCC, which examines methods for reducing greenhouse gas emissions and removing greenhouse gases from the atmosphere[9].

Mitigation refers to actions taken to reduce, slow or stop further climate change, such as reducing and preventing greenhouse gas emissions and removing greenhouse gases from the atmosphere. Climate change will continue to worsen without robust and substantial mitigation action to reduce CO_2 emissions to net zero, with strong reductions in other greenhouse gases[10].

Current trends

Global greenhouse gas emissions in the decade 2010 – 2019 were the highest ever recorded. An increase in net greenhouse gas emissions from human activity was seen across all major sectors, including energy, industry, transport, buildings and agriculture, forestry and other land use. Of all human CO_2 emissions since 1850, almost half (42%) have occurred since 1990. While the rate of increase in emissions has slowed in the last decade, emissions are still increasing. This contrasts with the target of limiting warming by reducing CO_2 emissions to net zero.

Meeting the goal of limiting warming to well below 2°C is becoming increasingly challenging. The concept of the remaining carbon budget can help communicate the scale of the challenge (see Box 2).

Transitions

Emissions reductions require rapid and substantial transitions in all sectors. The IPCC outlines potential solutions in each sector to deliver the rapid reductions needed. In many cases, there are mitigation options which are feasible to deploy in the near term.

In energy systems, emissions reductions will require switching from fossil fuels to low and zero-carbon energy sources and use of alternatives such as green hydrogen, alongside reducing the demand for energy, and improving energy efficiency. These shifts can contribute to energy security and equity. Electrification, combined with decarbonisation of electricity production and enabled by better use of data, can make a substantial contribution to reducing emissions.

Reducing greenhouse gas emissions from the energy sector involves transitions in how energy is provided and used across all sectors such as transport, manufacturing, food, and buildings.

Industrial emissions reductions will require action across the supply chain and at all stages of design, manufacture and delivery. Low and zero-carbon energy sources, material and production efficiency, innovative production processes, and circular economy principles can contribute to reduced emissions.

In transport there is most potential for emissions reductions through low carbon technologies such as electric vehicles, enabled by rapid improvements in battery technology, alongside measures to reduce demand. Active travel (cycling and walking) and mass transit are more energy efficient forms of transportation and can be expanded in many places. For harder-to-abate sectors, such as aviation and shipping, alternative fuels, such as sustainable biofuels, green hydrogen, and synthetic aviation fuels may help to reduce emissions. This will require improvements in production processes, as well as cost reductions and measures such as improved standards to promote efficiency gains. Demand management will remain important.

In the building sector, it could be possible to reach net zero greenhouse gas emissions by 2050 using a combination of ambitious policies for new builds and retrofitting. In 2019, global direct and indirect greenhouse gas emissions from buildings, and from cement and steel production for buildings, were equivalent to $12GtCO_2$, equal to approximately one fifth of annual global greenhouse gas emissions. Emissions over the lifetime of a building can be reduced, for instance through innovative sustainable design, use of low-carbon materials, low-emission heating and cooling, use of efficient appliances, and recycling or re-using materials when the building is dismantled. In developed countries, retrofitting of existing buildings will lead to the greatest emissions reduction.

There are opportunities in the agriculture, forestry and land-use sectors both to reduce emissions and to remove CO_2 from the atmosphere, often in a cost-effective way at less than $100 per tonne[11] of CO_2. The most significant contribution to cost effective mitigation comes from protection, restoration and improved management of natural ecosystems, including forests, coastal systems, wetlands, peatlands, and grasslands.

Sustainable crop and livestock management can also contribute to mitigation, as can demand-side measures including reducing food waste and shifts towards sustainable healthy diets, such as those high in plant protein and low in meat and dairy. Such actions are likely to be more effective if they are locally specific and take into account any co-benefits and trade-offs that might arise, such as reduced land under food production, and nutritional needs of the population.

Use of CO_2 removal strategies is essential if net zero CO_2 emissions is to be achieved. The extent to which they are needed will depend on the success of efforts to reduce emissions to actual zero in most sectors and the need to offset residual emissions in difficult-to-decarbonise sectors, such as agriculture and aviation. Research and strong governance can ensure that biological methods such as reforestation and soil carbon sequestration are sustainable in the long term, avoid competition with food production and enhance biodiversity. New technologies that can form a part of carbon removal strategies, like carbon capture and storage, require development and deployment at large scales once feasibility and sustainability constraints are addressed. CO_2 removal will only help to tackle climate change when accompanied by rapid and deep greenhouse gas emissions reduction across all sectors of the economy.

BOX 2

What is the remaining carbon budget?

The remaining carbon budget quantifies the maximum amount of carbon that can be emitted into the atmosphere without causing the planet's temperature to exceed a specified target. For instance, if the remaining carbon budget for a 1.5°C future is exceeded, it becomes very likely that the global temperature will exceed 1.5°C above preindustrial levels and continue to increase until greenhouse gas emissions reach net zero. Because of remaining uncertainties in the underlying science, it is not possible to state with confidence what the remaining carbon budget is to meet a particular temperature target. Instead, budgets are often presented as those with a 50/50 chance of meeting a given target.

It was estimated that from 2020 only 500 $GtCO_2$ (billion tonnes of CO_2) remained in the carbon budget for 1.5°C. This means that in total only 500 $GtCO_2$ could be emitted to the atmosphere in order to have just a 50/50 chance of limiting global warming to 1.5°C. To put the scale of this challenge in perspective, about 410±30 $GtCO_2$ were emitted between 2010 – 2019 alone. At this rate a 500Gt carbon budget would be used up in 2032. By way of comparison, emissions from existing and planned fossil fuel infrastructure are projected to amount to 850 $GtCO_2$, exceeding the carbon budget needed for a 1.5°C future.

CO_2 concentrations in the atmosphere will remain perturbed for centuries to millennia, so it is very hard to turn back when a carbon budget is exceeded, and therefore severe environmental change becomes 'locked-in'. Rapid, substantial and immediate emissions reductions that cut across all sectors are therefore critical if the goal of limiting warming is to be achieved.

The notion of a carbon budget can also be used to explore the amount of carbon dioxide that can be emitted by a country or organization to meet an emissions reduction goal. In 2020, the UK Climate Change Committee presented its Sixth Carbon Budget[12] to the UK government, outlining target emissions reductions to 2037 to be on track to reach a net zero greenhouse gas target by 2050.

Strengthening mitigation action

The economic benefits associated with mitigation to limit warming to less than 2°C are estimated to be greater than the costs. To realise these benefits, investment in research, development, and deployment of mitigation solutions is crucial. However, investment in mitigation solutions is not yet sufficient, by a factor of three to six, to achieve carbon reduction goals. This insufficiency is present across all sectors and regions. While there is enough money for investing in climate action in terms of global capital and liquidity, there are barriers that are preventing capital from being directed towards climate action.

Climate resilient development

The evidence for the increase in climate risks and limits to adaptation discussed earlier draw attention to the urgent need to act now. Both Working Group II and III of the IPCC draw out critical links between mitigation, adaptation and achieving sustainable development. The concept of climate resilient development calls for comprehensive and effective responses that harness synergies and reduce trade-offs between adaptation and mitigation and deliver the UN Sustainable Development Goals. Emissions reduction efforts such as improved energy efficiency and renewable energy can promote progress on the SDGs through reduced air pollution and improvements to health, for example.

Choices being made now will be key to avoiding lock-in to unsustainable development pathways that lead to higher levels of warming that prevent countries achieving the SDGs and a healthy, fair and resilient future. Such choices include decisions on infrastructure for generating electricity, heating and cooling and transport. Unless greenhouse gas emissions are rapidly brought down, achieving climate resilient development will become ever more out of reach, particularly if global warming exceeds 1.5°C.

Image: Electric vehicle charging points in Paris, 2019. © iStock / Tramino.

Towards a resilient, net zero UK

The IPCC recognises that national policies are critical to progress on climate action. This section interprets the IPCC findings to examine the implications for the UK.

How is climate change impacting the UK and how might this change in the future?

This briefing examines the situation for the UK by combining the IPCC assessment for the Northern Europe region with data provided in the UK Met Office's State of the Climate report, published in 2022[13].

Annual average UK temperature in the last decade (2012 – 2021) is already 1°C warmer than the average for 1960 – 1990. Changes to average temperatures will be experienced most noticeably through changes to extreme temperatures and the UK can expect more frequent and intense warm periods and heatwaves, with associated risks of droughts, wildfires and impacts on human and ecosystem health.

Temperatures in several locations in central and southern England reached more than 40°C for the first time since records began in the summer of 2022 and wildfires caused extensive damage to farmlands, woodlands and property. The probability of such events is expected to increase as global temperatures increase. The UK can also be expected to experience warmer winters, with a reduction in the number of days with air and ground frosts.

The most recent decade has been 10% wetter than for the period 1960 – 1990 across the UK, with particular increases in winter rainfall in parts of Scotland and northern England. With higher levels of warming, winter rainfall is expected to increase further. Increases in extremes of rainfall and the risk of flooding can also be expected, although there are uncertainties in current model predictions. Extreme dry conditions, such as the extended dry periods and drought conditions experienced in Europe and southern and eastern England during the spring and summer of 2022, are also consistent with expected impacts of climate change. Warmer temperatures will exacerbate the impact of dry periods on ecosystems and agriculture, as evaporation and plant transpiration will increase and moisture in soils will decline.

An important question for water resources management is whether warmer, wetter winters will compensate in volume of rainfall for hotter drier summers. Current climate models are not able to provide a clear answer to this question.

Climate risks facing the UK in the longer term, beyond 2050, differ from those experienced now and depend to a great extent on global greenhouse gas emissions over the next 20 years. Sea level has been rising by 3 – 5 mm per year over the last 30 years, after correcting for land uplift in places. The rate of sea level rise is expected to increase. Sea level rise will be a significant factor requiring long term planning for adaptation. Higher sea level combined with storm surges will exacerbate risks to land and infrastructure from coastal erosion and flooding of low-lying coastal areas and tidal floodplains.

Compound and cascading risks will become increasingly important to address. Cascading impacts can occur when extreme weather events affect critical infrastructure. For example, winter storms in early 2022 in the UK caused large numbers of fallen trees, disruption to power supplies and transport services, which combined with heavy snowfall in parts of northern England and Scotland to delay repairs to power networks and create extremely challenging conditions for communities and emergency responders.

As warming continues, the UK will experience increasing exposure to disruptive climate conditions and will also be exposed to the remote impacts of economic and human disruption as a consequence of climate change elsewhere. These include displacements of people as areas of the world become uninhabitable, and disruptions to food supply and other supply chains.

UK progress on tackling climate change

In 2019, the UK government adopted a Net Zero agenda that committed the UK to reducing greenhouse gas emissions to net zero by 2050, with an interim target of 78% reduction from 1990 levels by 2035 (or 63% reduction from 2019 levels).

UK greenhouse gas emissions have fallen by approximately 50% since the peak in the 1970s and by nearly 30% in the last decade. The decoupling of emissions from GDP (shown in Figure 4) and the reduction in UK greenhouse gas emissions, are due to a number of factors, most importantly improvements in energy efficiency and the displacement of coal for electricity generation by gas, and more recently due to an increase in renewable energy sources. There have also been significant emissions reductions in the industrial sector as energy use has become less carbon intensive and more efficient due to improvements in products and manufacturing processes. This has resulted in a UK economy that is becoming less reliant on carbon emitting activities, although it is important to acknowledge that the UK imports products that are associated with emissions of greenhouse gases in other countries. These are known as 'consumption emissions', which for the UK have fallen less than 'territorial emissions', those produced within the boundaries of the UK.

Despite progress, the UK is not on track to achieve its interim target of a 78% reduction in greenhouse gases by 2035, according to the Climate Change Committee, the independent advisory body to the UK government set up under the Climate Change Act 2008. This leaves a large amount to be achieved in the next few years for the net zero goal to remain attainable and consistent with the UNFCCC target of keeping warming to no more than 1.5 or even 2°C.

Even with planned actions by the UK and other countries to reduce greenhouse gas emissions, the UK will experience significant intensification of climate change impacts. Progress on adapting to the impacts of climate change remains slow and the UK is experiencing increasing adverse effects from climate impacts including flooding, storm damage and warm and dry periods.

The third UK climate risk assessment, published in 2022[14], recognised 61 climate risks and eight priority risks for immediate action that include risks to freshwater habitats, soil health, natural carbon stores, crops, supply chains for food and goods, power system resilience, human health, and risks to the UK from climate impacts outside the UK.

The UK Climate Change Committee reported in 2021 that there has been some progress on preparing for certain climate risks such as flooding and water scarcity, but many gaps remain, and climate risk is increasing at a greater rate than we are adapting.

How can the UK accelerate the response to climate change?

The need for urgent action brings to the fore challenges in the governance, financing, public engagement and delivery of the UK climate response. Addressing these will be key to the well-integrated adaptation and mitigation policies and actions required for a climate resilient, net zero UK.

The UK has a strong legal framework for action on climate change, established under the Climate Change Act of 2008 and the subsequent 2019 amendment that commits the UK to a net zero greenhouse gas target by 2050. The UK Net Zero Strategy published in 2021[15] sets out ways in which emissions reductions can be achieved in each sector of the economy. The Climate Change Committee judges that the ambition in the document matches the desired targets but that adequate policies are not yet in place and there are risks of targets not being met. The remaining task therefore is delivery.

The Royal Society suggests that the UK Net Zero Strategy be accompanied by an evidence-based road map to decarbonisation supported by an advisory group of experts. A net zero advisory group would complement the work of the Climate Change Committee by providing independent expert advice to drive the research and innovation needed for the development and implementation of key technologies.

International cooperation on the common challenges identified would speed up the development and implementation of suitable solutions. It is beyond the scope of this report to make specific recommendations in individual sectors; rather some general principles that should inform decisions and planning are set out here.

Integration of adaptation and mitigation across all sectors

There are opportunities for adaptation and mitigation to be better integrated across all areas of policy and all sectors, so that, for example, all planning decisions are compatible with net zero targets and also consider adaptation. Key sectors to address include energy and transport, urban areas, infrastructure, industry and supply chains, land and ecosystems, and communities and society. The Royal Society emphasises the need to look at all ways of reducing emissions. This includes finding ways to reduce demand for energy intensive activities in parallel with providing ways of supplying that demand with zero carbon technology.

Many of the changes proposed in the government's Net Zero Strategy require changes in infrastructure (e.g. for electricity supply). Ensuring that new infrastructure meets the demands of a net zero UK and is at the same time resilient to current and future climate hazards is an essential part of a successful strategy.

Enabling adequate finance and investment

Adequate financing is critical for meeting net zero commitments and developing adaptation solutions. There is a growing recognition that diverse funding sources will play a role. Addressing barriers to investment and ensuring that investment and finance mechanisms are aligned to climate goals will be important. The impact of net zero measures on GDP is assessed, at worst, to be relatively small, and some studies suggest that they will drive an increase in GDP, even without counting the benefits of avoided costs[16]. Adaptation measures typically deliver high benefit to cost ratios, with some, such as water efficiency measures offering as high as a 10:1 ratio[17].

Planning and monitoring to avoid lock-in to unsustainable pathways and take advantage of co-benefits and no-regrets measures

Delivery of progress on net zero and adaptation requires planning that is supported by evidence from ongoing monitoring and evaluation of the outcomes of policy and actions.

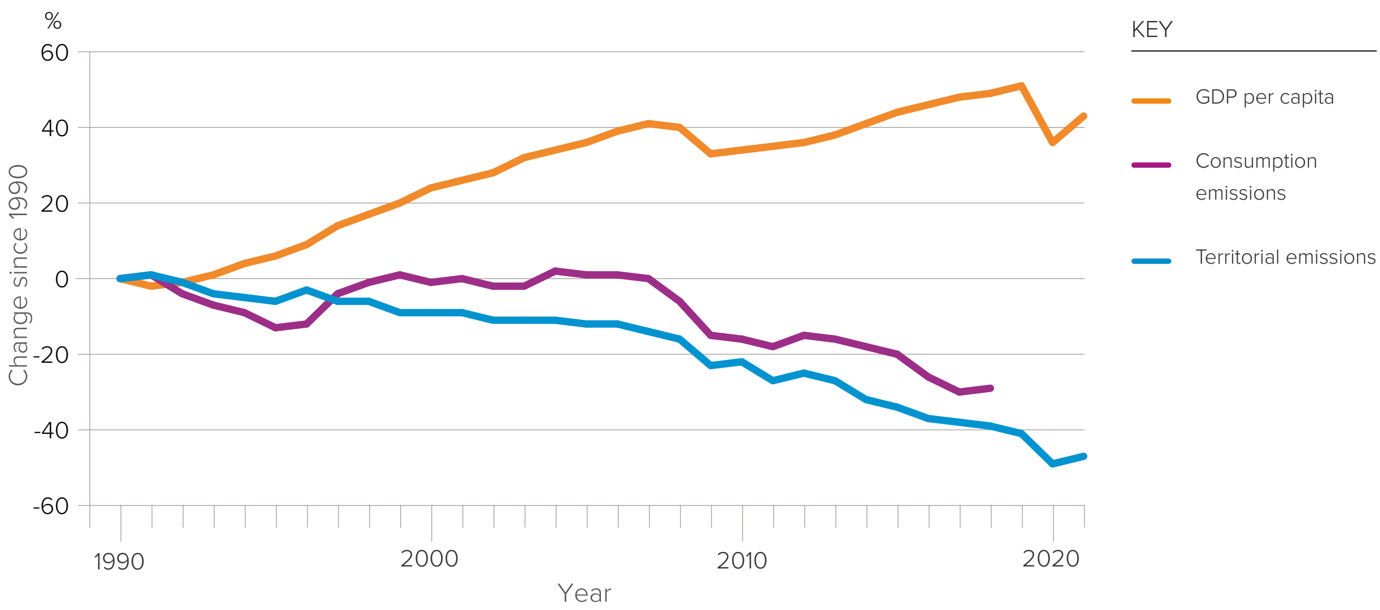
Many sectors can benefit from an adaptive planning approach, where no regrets options are pursued that respond to current climate impacts but avoid lock-in to unsustainable measures and enable adaptation to future climate extremes. Similarly, the concept of adaptation pathways can be helpful, as illustrated by the Thames Estuary 2100 project that addresses adaptation to rising sea levels and increased flood risk in the tidal Thames floodplain. Adaptation pathways are used to identify timely actions that keep options open to allow decisions on further actions as uncertainties reduce.

Well-designed adaptation and carbon reduction measures can deliver significant co-benefits and take advantage of opportunities, for example improvements to air quality resulting in a reduced burden on health services. The area of food and agriculture is another one where encouraging changes in consumer behaviour can lead to diets that are less carbon intensive, whilst having the co-benefit of being healthier.

It is also important to highlight the importance of safeguarding biodiversity and protecting and restoring ecosystems, both for the intrinsic value of ecosystems and the many services, such as climate regulation, that healthy ecosystems provide. Biodiversity has already declined considerably in the UK, largely due to intensive use of land.

FIGURE 4

The UK's historical emissions and GDP[18].



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Action on climate change requires efforts by all

A critical point raised by the IPCC is that responding to climate change requires efforts by all: national and devolved governments; the private sector; local government; civil society; and communities and households. This includes ensuring public engagement so that people understand and support those adaptation and carbon reduction measures that will involve significant change. This can be supported by ensuring that funding and local delivery is fair and inclusive.

Investment in research, development and deployment

In relation to net zero measures, there are some that are ready for implementation and will provide immediate benefits when fully rolled out, such as infrastructure for charging electric vehicles or home renovation measures. Others are not yet ready or are subject to trade-offs and uncertainties and require further research, development and deployment, such as energy storage. Investments in development and deployment are important for reducing technology costs. In a series of documents entitled 'Climate Change: science and solutions'[19], the Royal Society has summarised the current state of research and development in many of the key areas.

It is important that net zero measures retain an emphasis on emissions reductions, but for hard-to-mitigate sectors, CO_2 removal will be needed to meet net zero greenhouse gas targets. It is therefore important to establish which CO_2 removal techniques are feasible for the UK.

Consistent policy for net zero

A final issue is that the measures needed to reach net zero greenhouse gases require decades of consistent policy. In many sectors, reaching net zero by 2050 requires changes in infrastructure or market incentives almost immediately. In relation to the 2022 energy crisis caused by the Russian invasion of Ukraine, policymakers are seeking solutions to short-term supply and rising energy costs. Some of the solutions proposed, such as expanding UK fossil fuel extraction, will undermine net zero policies. Such a strategy fails to recognise that energy security, affordability, and the net zero target all benefit from energy efficiency measures and from the uptake of UK-produced zero-carbon energy sources.

In any case, if net zero is to be attained, such discussions need to be set in a climate and net zero policy framework: if a new (short-term) policy will delay or reduce emission reductions, what compensating policies will be put in place to meet the net zero goal and avoid the most severe negative impacts of climate change?

The UK in a global context

Current global pledges for emissions reductions under the Paris Agreement leave a large gap between the 1.5°C target and current projections of global warming of well above 2°C[20]. The UK can play an important role in encouraging every nation and sector to reach net zero greenhouse gases as soon as possible, and to continue efforts initiated during the UK Presidency of COP26 in Glasgow in 2021. The UK, whilst currently directly responsible for 1% of current global emissions, has emitted 4.6% of cumulative emissions since 1750[21, 22]. The IPCC reaffirms that the amount of warming is proportional to the cumulative sum of CO_2 emissions.

Support for financial flows to countries with less capacity to invest in mitigation and adaptation strategies will be key to accelerating global responses as well as reducing the UK's exposure to the impacts of climate change overseas. There are opportunities for the UK to show leadership in supporting a global finance package for adaptation and mitigation and to support the developing world with access to green energy and technologies. Uptake of new technology by the UK and other countries can also drive cost reductions to make them affordable elsewhere by creating the early markets.

The UK signed up to the global methane pledge that was brokered at COP26. The UK could consider taking a lead by moving beyond leaks from oil and gas to look at methane emissions from agriculture. This would help slow warming in the short term but does not avoid the need for urgent action on CO_2 emissions reductions. In 2020, methane accounted for about 13% of UK (CO_2 equivalent) emissions.

Research needs

Notwithstanding the great advances in knowledge as assessed by the IPCC in its sixth assessment report, further research is essential to improve understanding of climate impacts, assess adaptation strategies and enable effective net zero solutions.

Understanding the climate response to warming

Estimates of warming under different scenarios can be improved by advances in the understanding and modelling of important climate mechanisms, such as how clouds respond to climate change, the response of the carbon cycle to warming, and the behaviour of large ice sheets under high levels of warming. Advances are essential if uncertainties in the remaining carbon budget are to be reduced and all require a mix of improved observations, process-level understanding and modelling.

Research is needed to improve prediction of changes to circulation in the ocean and atmosphere and how this will impact on regional climates and large-scale extreme events. In addition, there is a need for research to understand the risks of low probability but high impact changes in climate. An important emerging topic is that of compound extremes and their interaction with the carbon cycle, ecosystems and food production.

Understanding impacts and knowledge for adaptation

A significant investment in climate models and modelling infrastructure would allow models to represent climate processes at the much more detailed scale necessary for understanding changes in rainfall, soil moisture and impacts of climate change on agriculture, for example[23]. Improvements in resolution must go hand in hand with improvements in observations and understanding of climate feedbacks and processes, as discussed above.

There is a significant gap in the research and literature on climate adaptation to impacts at levels of warming beyond 1.5°C. In addition, there is a need for a better understanding of limits to adaptation including when thresholds are passed, for example those at which the human body can no longer undertake physical activity and survive in extreme climates.

Further work is required on how best to communicate potential climate change impacts to planners and infrastructure providers, to aid adaptation planning at localised scales. Improved methods to account for uncertainty might include the design of adaptation pathways. Research on more inclusive approaches to adaptation planning will also be important. Better metrics are needed to enable improved monitoring and evaluation of which adaptations work.

There is also considerable work to be done to quantify the economic costs of climate impacts and the costs of climate action and inaction. This requires addressing discounting in assessments of costs and benefits of investments, as well as needing more reliable assessments and modelling of future climate impacts.

Technology development

There is much scope for expansion of research in improved technologies for energy, transport, buildings, decarbonising industry, demand management and energy efficiency that are both low carbon and resilient. This includes technologies for CO_2 removal and carbon capture and storage. Several of the Royal Society's Science and Solutions briefings[19] provide details on the areas where research can offer cost-effective pathways towards net zero. Critical evaluation of different mitigation options will be important for ensuring the right choices are made as early as possible that avoid lock-in to greenhouse gas intensive infrastructure. More system-level modelling and modelling that captures the effects of technology change and interactions between systems will facilitate integration of new technologies.

Understanding impacts of policy and behaviour

Integrated assessment models can be improved to better represent social, behavioural and policy variables. In addition, research into the economic, social and political implications of changing the way that energy is used will be important. This includes, for example, an improved understanding of how to incentivise behaviour change that supports the adoption of organisational, household and individual level choices that can provide resilience and reduce demand for high emissions activities, goods and services.

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The contributors to this report are listed below. The Working Group and Review Panel members acted in an individual and not a representative capacity and contributed to the project on the basis of their own expertise and good judgement. The Royal Society gratefully acknowledges the contribution of Working Group and Review Panel members.

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