Chapter 1: Revisiting the science of climate change

Introduction

In our 2008 report ‘Building a low carbon economy – the UK’s contribution to tackling climate change’ we reviewed the scientific evidence on future climate risks. Based on that evidence we proposed a climate objective: to limit central estimates of global temperature increase by 2100 to as little above 2°C over pre-industrial levels as possible, and limit the likelihood of a 4°C increase to very low levels (e.g. less than 1%). We assessed emissions pathways to meet this objective and concluded that global emissions of Kyoto greenhouse gases must peak by 2020, then decline rapidly so that they are halved by 2050, and continue to decline thereafter.

From these global pathways we assessed an appropriate contribution for the UK, and recommended that the aim should be to reduce emissions by 80% in 2050 relative to 1990 levels. The resulting UK emissions in 2050 of around 2 tCO₂e per person would, if replicated around the world, deliver a 50% cut in global emissions, consistent with our climate objective.

In this chapter we do three things:

• We review the basic science of climate change.
• We consider recent inquiries, notably concerning the Climatic Research Unit (CRU) at the University of East Anglia and the Intergovernmental Panel on Climate Change (IPCC).
• We consider developments in climate research since our 2008 report was published, assessing their implications for our climate objective and the global emissions pathways required to meet it.

Our aim is to set out the science which underpins our advice on carbon budgets. We do not present a comprehensive review; more detailed introductions are available from specialist science groups.

There are five key messages in the chapter:

• There is a robust scientific case for human-induced climate change, supported by a vast body of theory and observation developed over many years. Although gaps and uncertainties in understanding remain, the case for action remains strong:
  – Global climate change is already happening.
  – It is very likely that this is largely a result of human activity.
  – Without action, there is a high risk of global warming well beyond 2°C, with significant consequences for human welfare and ecological systems over the course of this century and beyond.

1 ‘less than 1%’ should be taken as indicative in the context of limiting severe warming. We set 1% as the maximum allowable likelihood of 4°C arising from the modelling methods used in our 2008 report. Alternative modelling methods may give slightly different odds of 4°C for the global emissions paths we use, because of uncertainties in quantifying the upper tail of the distribution of possible outcomes.

Recent public controversies have sparked several independent inquiries into the activities of climate scientists. As a result there have been recommendations for reinforcing the IPCC assessment process and increasing the transparency of research data and methods, which are being addressed. A small number of minor factual errors have been found in the IPCC’s reporting of climate change impacts in its Fourth Assessment Report. However, no new findings have emerged that call into question the robustness of the fundamental science.

We have reviewed developments in research on the impacts of climate change since 2008. We find no major change in the picture of future damage, although some risks may have increased slightly (e.g. the effect of climate change on food production). Based on this review, we judge that the climate objective we set in 2008 remains appropriate (i.e. to limit central estimates of global average temperature change by 2100 to as little above 2°C over pre-industrial levels as possible, and limit the likelihood of a 4°C increase to a level around 1%).

Our review of developments in projecting future climate change for a given global emissions path provides more confidence in the conclusions of our 2008 report: early peaking of global emissions, followed by cuts throughout the century consistent with a halving of emissions by 2050, should meet our climate objective.

The precise consequences of climate change remain uncertain in a number of areas. Periodic review of our climate objective and emissions targets is required to understand any implications as information improves.

Our evidence and analysis underpinning these conclusions is set out in five sections:

1. The basic science of climate change
2. Appropriate climate objectives and global emissions pathways: recap on our 2008 approach
3. Recent inquiries relating to climate science
4. Recent scientific developments
5. Remaining uncertainties and implications for our approach to mitigation

We use this chapter as a benchmark for assessing international progress towards mitigating climate change (Chapter 2), and also to underpin UK emissions trajectories through the 2020s consistent with required global trajectories (Chapter 3).

1. The basic science of climate change

It is important when drawing on the science of climate change to distinguish those things which we know with near certainty from those where our understanding is less certain. Overall however the evidence provides strong reasons for believing that human emissions are producing global warming, and that the resulting climate change is likely to cause adverse consequences for human welfare and ecosystems.

(I) The greenhouse effect

Greenhouse gases (GHGs) warm the Earth’s surface, which is around 33°C warmer than it would otherwise be in the absence of the greenhouse effect:

- The primary source of the Earth’s heat is the Sun, but simple calculations show that solar heating alone (without an atmosphere) cannot explain the temperatures we observe on Earth; average surface temperatures are about 33°C warmer than would be expected for a planet of Earth’s reflectivity and distance from the Sun.
- There is now a large and very well established evidence base showing that atmospheric GHGs create the extra warmth by trapping heat. This natural ‘greenhouse effect’ was first deduced by Joseph Fourier in the 1820s, with significant contributions to understanding during the 19th Century by John Tyndall and Svante Arrhenius.
- Since then, repeated and varied measurements from laboratories, aircraft and satellites have all confirmed that atmospheric GHGs trap heat.

Status: the fact that the Earth’s surface is warmer than it would otherwise be without atmospheric GHGs is as close to certain as any scientific finding, based on fundamental laws of physics.

(II) Non-GHG drivers of climate change

Several factors other than changes in atmospheric concentrations of GHGs can lead to global climate change:

- Changes in incoming solar radiation.
  - Solar output. The Sun undergoes a characteristic cycle in output every 11 years or so, but has also shown some variability over longer timescales which may be linked to historic variations in Earth’s temperature (e.g. there was an extended period of low solar activity which could have caused some cooling particularly in the European region during the 17th Century).
  - Earth’s orbit. Gradual cycles in Earth’s orbit cause regular, alternating patterns in the distribution of solar radiation over the Earth, occurring over timescales of many thousands of years.
• Changes in the atmosphere
  – Clouds. These exert large and complex effects on Earth’s energy balance. Cloud patterns can be influenced either directly (e.g. by contrail formation from aircraft) or indirectly (e.g. in response to warming or cooling).
  – Aerosols. In addition to GHGs, other particles or droplets suspended in air cause complex climate effects, some cooling and some warming. They are emitted by human activity but also by natural volcanic explosions. For instance, in 1991 Mt Pinatubo ejected enough sulphate aerosol to cause measurable global cooling over the following year or so.

• Changes in the reflectivity of Earth’s surface. Surface change (e.g. clearing of forest, development of urban areas and melting of ice & snow) can alter the amount of sunlight absorbed by the Earth, causing potentially strong, local effects on climate.

• Natural variability. Even in the absence of the above drivers, Earth’s average temperature shows some natural variability. Complex interactions between the atmosphere, land surface and oceans cause the daily fluctuations we know as weather, but also give rise to variability over years or decades. For instance, the El Niño phenomenon occurs every three to seven years, whereby a warm pool of water is formed for a season or more in the Tropical Pacific, altering weather patterns around the Pacific and beyond.

Status: the fact that there are other potential drivers of global climate change is well understood. A key challenge in climate science is to identify the extent to which these different GHG and non-GHG drivers are responsible for observed changes, recognising that initial changes produced by one factor can be enhanced or reduced by feedback responses from other factors.

(III) Long-term climate history before human effects

The climate of the Earth has varied greatly over very long timescales. Past changes have been caused by various drivers, but it is clear throughout that CO₂ and other GHGs have played an important role either as an initial trigger of change or as an amplifying feedback.

• The last 50 million years. Geological records suggest that the Earth was around 6-7°C warmer 50 million years ago. CO₂ concentrations were also high, and there were no major ice sheets (such as those currently over Greenland and Antarctica). Since then there has been a slow, long-term decline in both CO₂ concentration and global temperature.

• The last million years. Earth’s climate over the last million years or so has been cooler than today on average, characterised by a natural cycle between ice ages and warmer interglacial periods:
  – Records from ice cores spanning the last 800,000 years show a series of ice ages and interglacials (Figure 1.1). Transitions between the two have taken around 5,000 years and are estimated to have led to an eventual 4-7°C of global temperature change.\(^{3}\)

Atmospheric CO₂ is directly measurable over this time from air bubbles trapped in the ice cores.
  – There is strong evidence that these climate shifts were triggered by regular cycles in Earth’s orbit which altered the distribution of sunlight over the Earth.
  – But while orbital cycles acted as the initial driver, other factors then amplified the change. For example, cooling causes snow and ice to advance, reflecting more sunlight away from the Earth’s surface, and CO₂ concentrations also decrease, amplifying the cooling effect further.
  – This record provides direct evidence that altered CO₂ concentrations exert a significant influence on global temperature, whether acting in response to an initial change or as an initial driver. It also shows that additional feedback processes are an important consideration when understanding past and future climate change.

\(^{3}\) See for example Schneider von Deimling et al. (2006) How cold was the Last Glacial Maximum? Geophysical Research Letters.
• The last 10,000 years. Since the end of the last ice age we have lived in a relatively warm period with stable CO₂ concentrations and global temperatures. Some regional changes have occurred in this time, affecting local societies and ecosystems. For instance, persistent droughts have occurred in Africa and North America, and both El Niño and the Asian monsoon have undergone changes in frequency and intensity. These have not however been part of a coherent global change.

Status: there is a high degree of confidence that temperature changes over the last one million years have been amplified by closely-linked changes in atmospheric CO₂ concentration.

(IV) Human emissions as an additional factor

Human-caused emissions of GHGs have now driven atmospheric concentrations well outside the natural cycle of the last million years:

• Data from the Global Carbon Project suggest that total global CO₂ emissions rose six-fold over the 20th Century (Figure 1.2); this is largely a result of fossil fuel burning, with additional contributions from deforestation and cement production.

• The concentration of CO₂ in the atmosphere is now nearly 390 parts per million by volume (ppm) and rising, compared to around 280ppm in pre-industrial times (Figure 1.2). This increase is clearly due to CO₂ emissions from human activity, as underlined by several sources of evidence (e.g. the balance of different carbon atom isotopes in the atmosphere).

• The magnitude and rate of CO₂ increase in recent decades are far greater than anything seen in the ice core record (Figure 1.3).

• Similar trends in other long-lived GHGs are taking place:
  – Methane (CH₄) concentrations have increased to nearly 1,800 parts per billion (ppb) from pre-industrial levels of around 700ppb, as a result of emissions from agriculture, waste and fossil fuel use.
  – Emissions of nitrous oxide (N₂O), primarily from intensive agriculture, have led to concentrations exceeding 320ppb, up from a pre-industrial level of around 270ppb.
  – A range of halocarbons (artificial compounds such as CFCs and HFCs which did not exist in pre-industrial times) are now present in the atmosphere.

• The influence of different climate change drivers is measured by their radiative forcing. There is high confidence that current overall forcing from human activity is strongly positive (leading to warming), and it is most likely about an order of magnitude larger than the forcing from changes in the Sun (Figure 1.4).
In fact, we do already see unequivocal evidence that warming is occurring:

- Near-surface air temperatures over land are increasing.
- Near-surface air temperatures over the oceans are increasing.
- Sea surface temperatures are increasing.
- Ocean heat content is increasing.
- Sea level is rising (water expands as it warms, and there are additional contributions to sea level through melting of ice and snow on land).
- Atmospheric humidity is increasing (warmer air is able to hold more moisture).
- The temperature of the lower atmosphere (troposphere) is increasing.
- Northern hemisphere snow cover during March-April is decreasing.
- Total glacier mass is decreasing.
- Arctic sea ice extent in September is decreasing (Arctic sea ice changes cyclically over the year, usually reaching a minimum in September).

The last decade showed the warmest global average surface temperatures since records began, about 0.8°C above pre-industrial levels. Although there is variability between years and regions, the long-term trend still shows warming:

- Data from three separate research groups, all based on direct thermometer measurements from land and sea around the world, agree that 2000-2010 was the warmest decade on record (Figure 1.6).

- This is true even though 1998 was the hottest year so far, according to one record (HadCRUT, produced by the Met Office and the Climatic Research Unit). 1998 temperatures were exacerbated by a particularly strong El Niño event, however the NOAA GISS and NASA NCDC records calculate that 2005 was hotter than 1998, and 2010 is on course to be hotter still.

- And while the 2009-2010 winter in the UK was around 2°C colder than average, with the cold snap extending into Europe and parts of the US, many other regions experienced unusual warmth (Figure 1.7). Global temperature during this period was well above the recent average.

- It is known that natural variability can offset (or enhance) the surface warming trend from GHG emissions for periods of up to a decade or so. Scientists therefore tend to use 20-30 year periods in order to identify climate trends over the noise of short-term variability. From this perspective it is clear that temperatures are on a long-term rising trend.

**Status: it is close to certain that the planet has warmed since the late 19th Century.**
Figure 1.5: Time series of ten climate parameters which would be expected to correlate strongly with global surface temperature change. All show changes over the last decades consistent with a warming world.

Figure 1.6: Global average surface temperatures since 1880 as calculated by three different research centres.

Figure 1.7: Map of surface temperatures for the period December 2009 to February 2010, relative to the 1968-1996 average.
While natural variability and other factors continue to play a role in climate, the pattern of warming also suggests they are not the primary drivers of change in the last few decades:

- **Natural variability** within the climate system is unlikely to explain such a large worldwide increase, sustained for so long. Although we cannot rule out some form of large internal variation, as yet poorly understood, studies of climate in earlier centuries suggest that the current trend is unusual in the context of natural variation. Those long-term modes of variability that we do know about (such as El Niño) cause distinct regional patterns of warming, partially offset by cooling in some regions. Furthermore, surface warming caused by heat transfer from another part of the climate system, such as the oceans or the cryosphere, would leave a cooling signal in those parts. In fact, however, warming is seen in both the oceans and in the melting of global snow and ice (Figure 1.5), consistent with the influence of an external source such as the Sun or GHGs.

- **Satellite measurements of solar output** since the late 1970s show changes of about ±0.08% over the Sun’s regular 11-year cycle10, and there is still more to learn about the influence of solar variability on climate. However, there is no clear increasing trend in solar output over recent decades. Furthermore, surface warming caused by heat transfer from another part of the climate system, such as the oceans or the cryosphere, would leave a cooling signal in those parts. In fact, however, warming is seen in both the oceans and in the melting of global snow and ice (Figure 1.5), consistent with the influence of an external source such as the Sun or GHGs.

Status: there is a high degree of confidence that human emissions have caused most of the observed warming since the mid-20th century.

---

10 NOAA NGDC: http://www.ngdc.noaa.gov/stp/solar/solarirrad.html

(VII) Projections for the future

Despite this high level of certainty that warming is occurring due to human activity, projections about the exact future level of warming and its consequences are inherently uncertain. This uncertainty derives from the complexities involved in modelling the whole Earth system (including the strength of feedbacks from clouds, etc.) and also from predicting the future path of human activities. Scientists have developed models as best possible to capture these effects and produce projections. These are continually improving and provide us with the best path of human activities. Scientists have developed models as best possible to capture these (including the strength of feedbacks from clouds, etc.) and also from predicting the future uncertainty derives from the complexities involved in modelling the whole Earth system (e.g. the strength of possible feedbacks from clouds and the natural carbon cycle).

- For several different scenarios of ‘business as usual’ emissions growth over the next century, IPCC AR4 gave a likely range of 1.8-2.1°C warming above pre-industrial levels by 2100\(^2\) (i.e. two to nine times greater than has been experienced so far). This range comes both from the different possible future paths of global emissions, and from imprecise knowledge of the climate system (e.g. the strength of possible feedbacks from clouds and the natural carbon cycle).

- Projections of trends in surface temperature from the IPCC’s earlier assessments appear to be in broad agreement with observations since 1990, although the noise of year-to-year variability makes this a relatively short time period for comparison (Figure 1.10). This gives us some confidence in the range of global average projections for the 21\(^{st}\) century.

\(^2\) IPCC (2007) WG2-AR4 Summary for Policymakers: Table SPM.3.

---

**Figure 1.10:** Comparison of global average surface temperature trends since 1990 with projections from the IPCC First (FAR), Second (SAR) and Third (TAR) Assessment Reports

**Figure 1.11:** Examples of global impacts projected for climate change associated with global average surface temperature increases in the 21\(^{st}\) Century

- Uncertainty increases when translating these temperature changes into impacts on human welfare and ecological systems. Impacts will depend crucially on climate changes at local scales (including shifts not only in temperature but also precipitation, sea level, extreme weather events, etc) and the level to which human and ecological systems can adapt, which are more difficult to predict than future global average temperature. However, there are likely to be significant consequences for human and ecological systems, as set out in IPCC AR4 (Figure 1.11):

  - **Water.** Climate change is likely to amplify precipitation patterns around the world, so that wet regions will generally get wetter and dry regions drier. Precipitation is also projected to shift towards heavier rainfall events interspersed with longer droughts. Warming will lead to retreating glaciers and reduced snow cover, which are important freshwater resources for over one-sixth of the world’s population.
– Ecosystems. Extinctions of species are of particular concern because they are irreversible. Many ecosystems are in any case facing a range of pressures due to human activity, however, 20-30% of plant and animal species assessed so far would face a commitment to extinction as a direct result of 2-3°C of global warming. Further change could lead to major species loss.

– Food. The impacts of climate change on crop production are projected to differ markedly by region and crop. Positive impacts could be experienced in temperate zones for 1-3°C local warming (which would correspond to a lower increase in global average temperature) and increased CO₂ levels, but in low latitudes, where a high fraction of GDP depends on agriculture, falling productivity is likely even for low levels of warming. World food production is projected to fall beyond a 3°C global increase.

– Coasts. Some of the largest cities are situated on coasts, such as those on the US Eastern seaboard or the mega-deltas of Bangladesh and Eastern China. Many small islands are also very exposed to sea level rise. This would lead to heightened risk of inundation during storms, and freshwater supplies becoming increasingly contaminated with salt.

– Health. Despite some benefits, such as fewer deaths from cold exposure, climate change is likely to have a net negative impact on human health. Increases in deaths, diseases and injuries from heatwaves, floods, fires and droughts are predicted, as well as problems associated with poorer urban air quality. Overall impacts will be critically dependent on socio-economic factors such as education and healthcare.

– Singular events. Strong warming leads to the possibility of large, irreversible shifts in the Earth system. For example, complete melting of the Greenland and West Antarctic Ice Sheets could result in an additional 12m of sea level rise over several centuries. In addition, strong warming could accelerate release of CO₂ and CH₄ from large natural reserves in wetlands, permafrost and oceans, resulting in increased GHG concentrations and therefore further warming.

**Status: precise scientific projections are uncertain, but they are the best evidence on which to base policy. Current evidence points to major potential impacts on human welfare and ecological systems if efforts are not made to curb emissions.**

**Overall conclusion: policy needs to reflect the clear scientific conclusion that warming is occurring and is being induced by human activity, while recognising the inevitably wide range of uncertainty over the precise scale and timing of future impacts. This uncertainty on precise scale should not however be confused with uncertainty on direction, and provides a strong case for action rather than for inaction.**

---

13 ‘Commitment to extinction’ describes the long-term stability of a species to sustain itself, due to changes in its current habitat and a lack of suitable adjoining habitats to which the species can migrate.

14 IPCC (2007) WG2 AR4 Chapter 19, p781. Note: pre-industrial global average temperatures were 0.6°C below 1990-2000 level.

---

**2. Appropriate climate objectives and global emissions pathways: recap on our 2008 approach**

**Global climate objective**

In our 2008 report we set out an approach to assessing what level of future climate change should be seen as dangerous and hence avoided, given the scientific evidence and uncertainties set out above.

- We considered the range of climate impacts in the IPCC AR4, along with some subsequent published research papers, and concluded that there is highly likely to be a range of increasingly harmful effects, unevenly distributed around the world and quickly becoming severe in some regions:

  - Risks from a relatively small temperature increase (e.g. 1°C) are likely to be manageable in many regions with adaptation efforts, and there may be some benefits in temperate areas.
  - Benefits are likely to disappear and scope for adapting likely to decline for more significant increases.
  - The impact of temperature change on human welfare is highly likely to be non-linear (e.g. a 4°C rise is highly likely to be more than twice as harmful as a 2°C rise).
  - Damage would be more pronounced in certain regions (such as polar, mountain, Mediterranean regions and coral reefs), and disproportionately impact the world’s poor.

- Despite this complex picture, the IPCC drew some general conclusions which we cited in 2008 as relevant in setting our objectives:

  - ‘Global mean temperature changes of up to 2°C above 1990-2000 levels would exacerbate current key impacts, and trigger others such as reduced food security in many low-latitude nations. At the same time, some systems such as global agricultural productivity could benefit.

  - Global mean temperature changes of 2°C to 4°C above 1990-2000 levels would result in an increasing number of key impacts at all scales, such as widespread losses of biodiversity, decreasing global agricultural productivity and commitment to widespread deglaciation of Greenland and West Antarctic ice sheets.

  - Global mean temperature changes greater than 4°C above 1990-2000 levels would lead to major increases in vulnerability, exceeding the adaptive capacity of many systems.’
• Ideally the world should therefore aim to limit temperature increase to very low levels. In practice, high current concentrations of GHGs that will remain in the atmosphere for many years commit the world to further warming, and continued emissions make it impossible to be certain that warming less than 2°C can be avoided.

Our climate objective reflected both the potential damage from further climate change and the difficulty in aiming for a very low temperature target, given current GHG concentrations and emissions. We recommended that the aim should be to keep central estimates of global mean temperature change by 2100 to as little above 2°C over pre-industrial levels as possible, and limit the likelihood of extremely dangerous climate change above 4°C to very low levels (e.g. less than 1%).

**Global emissions pathways**

We developed a set of global emissions pathways and tested them against our climate objective in collaboration with the Met Office Hadley Centre (Box 1.1). We concluded that credible pathways to deliver our climate objective broadly require early peaking of global emissions, and deep cuts beyond this peak, consistent with halving or more by 2050:

- We constructed global pathways out to the year 2200, covering all Kyoto GHGs (plus many other relevant emissions such as sulphate aerosols and oxides of nitrogen) from all major sources (including CO₂ emissions from land-use and international aviation & shipping), and with two sets of peaking years (2016 and around 2030).
- In each case CO₂ emissions were reduced after peaking at 1.5%, 2%, 3% or per year until they reached a minimum ‘floor’ beyond which they could not be reduced further, with non-CO₂ emissions reduced at consistent rates.
- The pathways delivering the climate objective were characterised by early peaking with subsequent annual emissions reduction of 3% or more; no late peaking pathways delivered the objective (i.e. peaking after about 2025) irrespective of the rate of cuts after the peak.
- Early peaking followed by annual cuts of 3% or more would result in at least a halving of global emissions by 2050.
- In order for the UK to have emissions per person equal to the global average in 2050, a global halving of emissions requires an 80% UK reduction on 1990 levels.

**Box 1.1: Modelling climate change arising from future global emissions pathways**

Researchers use a range of climate models to understand and predict climate change, from relatively simple to highly complex. The most complex models split the atmosphere and ocean into a three-dimensional grid and solve the equations of fluid motion, thermodynamics and various other processes at each point on the grid. They typically have more than 100 parameters and take weeks on a supercomputer to produce a single 200-year simulation. Several such models have been built by research groups around the world. Each produces a slightly different outcome for a given future scenario because of differences in their construction and uncertainties in some of the parameter values used.

Simpler climate models are able to emulate the large-scale features of the more complex models, such as global average temperature. A key benefit of these simpler models is that they are faster to run, and by varying a small number of parameters they can explore the full range of uncertainty across the more complex models.

With the Met Office Hadley Centre, we used a modified version of a simple model known as MAGICC 4.116, which has been used extensively in IPCC assessments. For each emissions pathway the model was run several hundred times, each with a different combination of values for key climate parameters (Figure B1.1). In this way we accounted for a broad range of climate system uncertainties. By weighting these runs according to the likelihood of each parameter combination, an overall likelihood distribution of global temperature increase was built for each pathway.

These results comprehensively cover the range of possible global temperature outcomes from the leading complex models covered in IPCC AR4. They do not, however, account for other possible processes which may affect global temperature but are not included in those complex models, such as additional release of carbon from large natural reserves in wetlands, permafrost and oceans.

---

15 For further details on this section, see Chapter 1 of the 2008 report and accompanying technical appendix (Projecting global emissions, concentrations and temperatures).

16 http://www.cgd.ucar.edu/cas/wigley/magicc/index.html
3. Recent inquiries relating to climate science

Climatic Research Unit (CRU), University of East Anglia

CRU is known primarily for its work in reconstructing past surface temperatures, extensively cited by the IPCC. These reconstructions fall into two types:

- A dataset of land surface temperature based on direct thermometer measurements going back to 1850, which is in close agreement with at least three other records (Figure 1.5, top left panel).

- Estimates going further back (up to around 1,000 years) based on tree rings as a ‘proxy’ measure of temperature. Proxy measures are much more uncertain, but several records using different methods (boreholes, glacier lengths, corals, sediments and other tree ring analyses) all suggest that the rate of warming over recent decades has been unusual in the context of the last few centuries. It should be noted however that the scientific argument presented in the first part of this chapter does not rest on evidence from these proxy measures.

Three separate inquiries were launched following the email controversy:

- Over 1,000 selected CRU emails were leaked, drawn from the period 1996-2009, containing conversations between climate scientists at CRU and other institutions around the world.

- The emails were used to accuse scientists of using inadequate data analysis methods, deliberately withholding or deleting data that should have been made available and conspiring to block competing conclusions being published in journals and IPCC assessments, all with the intention of overstating recent warming.

- A group chaired by Sir Muir Russell was convened by the University of East Anglia to review the emails and assess whether or not CRU scientists had acted with due honesty, rigour and openness. It did not specifically address the validity of their published scientific work.

- The University of East Anglia also convened a Science Assessment Panel chaired by Lord Oxburgh to look at 11 pre-selected research papers written by CRU scientists.

- The aim of the panel was to establish whether the conclusions reached in these papers were ‘honest and scientifically justified’ rather than correct or incorrect.

Based on a set of CRU emails leaked in 2009, scientists were accused of malpractice:

- The Muir Russell review found no evidence that might undermine the conclusions of IPCC assessments, and no evidence that scientists subverted the peer review processes in order to suppress other studies.

- The Science Assessment Panel found that CRU work included suitable discussion of uncertainties and showed no hint of tailoring results to a particular agenda.

- The Science and Technology Committee stated that researchers should be more transparent by publishing raw data and methodologies given the importance of decisions being made in light of the scientific evidence.

There has been some controversy about the inquiries themselves, with allegations that critical views were not listened to and the veracity of the science was not directly addressed. The new Science and Technology Committee, appointed after the General Election, followed up on the earlier reviews in subsequent evidence sessions involving the University of East Anglia, Sir Muir Russell and Lord Oxburgh.

Intergovernmental Panel on Climate Change (IPCC)

The IPCC was established to help inform climate change decision makers by producing comprehensive assessments that are accurate, balanced and impartial with respect to policy; its most recent assessment (AR4) was published in 2007.

The assessment process involves three working groups, covering the physical science basis (Working Group 1), impacts, adaptation and vulnerability (Working Group 2) and mitigation (Working Group 3). In addition to providing in-depth reports in each area, all three groups contribute to a single synthesis report.

- The House of Commons Science and Technology Committee carried out an inquiry into the accuracy and availability of CRU’s data and methods, the issue of withholding these data in light of the Freedom of Information Act, and the suitability of the reviews set up by the University of East Anglia. Its conclusions were published in advance of the other reviews and before the recent General Election.

All three inquiries concluded that there was no evidence of scientific malpractice and none found anything to question the fundamental science, but they did make suggestions to support increased transparency of the data and methods used by the researchers:

- The Muir Russell review found no evidence that might undermine the conclusions of IPCC assessments, and no evidence that scientists subverted the peer review processes in order to suppress other studies.

- The Science Assessment Panel found that CRU work included suitable discussion of uncertainties and showed no hint of tailoring results to a particular agenda.

- The Science and Technology Committee stated that researchers should be more transparent by publishing raw data and methodologies given the importance of decisions being made in light of the scientific evidence.

19 Oxburgh (2010) Report of the International Panel set up by the University of East Anglia to examine the research of the Climatic Research Unit http://www.uea.ac.uk/mac/comm/media/press/CRUstatements/SAP
20 House of Commons Science and Technology Committee (2010) The disclosure of climate data from the Climatic Research Unit at the University of East Anglia http://www.publications.parliament.uk/pa/cm200910/cmselect/cmsctech/387/387i.pdf
In early 2010 a number of claimed errors in the IPCC AR4 were widely reported, and IPCC responses criticised:

- Two specific errors in the most recent Working Group 2 assessment were highlighted by experts:
  - Overstatement of the likely future rate of retreat for Himalayan glaciers\(^22\).
  - Overstatement of the area of Dutch land lying below sea level\(^21\).
- While the IPCC has published official corrections to both these errors, it has been criticised for responding slowly and handling the issue badly.
- Furthermore, some critics have voiced concerns over aspects of the IPCC assessment process, such as the use of ‘grey’ literature\(^24\) and the handling of dissenting views.

Three independent inquiries were launched in 2010:

- Responding to the claimed errors, the Netherlands Environmental Assessment Agency (PBL) carried out a detailed review of the extent to which the IPCC impact summaries accurately presented the state of scientific knowledge\(^25\).
- The US Environmental Protection Agency (EPA) reviewed its use of IPCC evidence after petitions were raised by various energy companies and sceptical groups\(^26\). These petitions cited the inaccuracy of the Himalayan glacier statement and improper review of IPCC chapters as reasons for the EPA to reconsider its finding that GHG emissions are a danger to health.
- The IPCC itself, along with the UN Secretary General, invited the InterAcademy Council (an umbrella body of science academies, including the UK’s Royal Society) to review its structure and processes\(^27\).

These reviews confirmed a small number of minor errors in the Working Group 2 report:

- The PBL review confirmed the two errors already found, and identified an additional error (regarding impacts on African anchovy fisheries\(^23\)). It also made minor comments on several other details and references. However, these errors were small in number relative to the evidence base in the 1,000 page Working Group 2 report, and no significant errors were found in the summary conclusions.

- A greater emphasis on climate change damages rather than benefits was found by PBL in the Working Group 2 summary. This was a deliberate, ‘risk-oriented’ approach taken by the IPCC authors, and was implicitly endorsed by governments involved in drafting the document, but it means that the summary document may present a different balance of evidence to that in the full Working Group 2 report.

The various reviews made recommendations to improve the process of assessing the range of literature and views:

- The InterAcademy Council made a number of recommendations, including review editors fully exercising their authority to ensure genuine controversies are reflected, and the three Working Groups being more consistent and rigorous in communicating levels of understanding and uncertainty.
- Similarly, the PBL review stated that the provenance of summary statements needed to become more transparent.

The IPCC has agreed to implement the InterAcademy Council’s recommendations on procedures, communications policy and conflicts of interest. It will review further the recommendations on governance\(^29\).

More generally, no new evidence has emerged to question the overall conclusions of IPCC AR4:

- The InterAcademy Council found that the IPCC has been successful in following its remit of accuracy, balance and impartiality.
- The EPA found that most, if not all, of the petitions it received about the IPCC were unsupported, not relevant or inconsequential to the EPA’s policymaking on GHG emissions.

In summary, these inquiries have identified important issues of process in climate research and assessment, and have made recommendations for improvement. However, the findings of the CRU researchers have been found honest and balanced, supported by evidence from other lines of research, and the conclusions of IPCC AR4 have been upheld. Therefore the fundamental climate science reviewed in this chapter remains robust.

\(^{22}\) IPCC (2007) WG2-AR4 Chapter 10, p493.
\(^{23}\) IPCC (2007) WG2-AR4 Chapter 12, p410.
\(^{24}\) ‘Grey literature’ often refers to studies which contain original results but have not been published in research journals. Examples include technical reports by government agencies and research institutes.
\(^{27}\) InterAcademy Council (2010) Climate Change Assessments: review of the processes and procedures of the IPCC http://www.epa.gov/climatechange/endangerment/petitions/volume2.html
\(^{29}\) http://www.ipcc.ch/meetings/22/npcc_14review_decisions.pdf
4. Recent scientific developments

Given the rapidly growing research base, we highlighted in our 2008 report a need to monitor developments in climate science, understanding any implications for our recommended emissions pathways.

We have followed this up by commissioning the AVOID consortium30 to review recent publications in relevant fields. This review31 suggests no major changes in the overall picture of future damage (although some risks may have worsened since our 2008 report) and provides more confidence in our approach to modelling the range of possible temperature increases from future global emissions pathways.

New evidence on climate impacts

The AVOID review classifies impacts following broadly similar conventions to the IPCC AR4 and the Committee’s 2008 report: coastal systems, ocean acidification, ecosystems & biodiversity, water resources & desertification, agriculture & food security and human health.

Key conclusions are that many sectors show little new evidence for a change in risk, while some developments have occurred in projections for Arctic sea ice, ecosystems & biodiversity, agriculture & food security and human health (Figure 1.12):

- In ecosystems & biodiversity, tropical ecosystems have now been added to the list of those most vulnerable alongside polar, mountain, Mediterranean and coral reef systems. There is also increasing evidence to support the IPCC AR4 conclusion that 20-30% of plant and animal species are at increasingly high risk of extinction as global warming exceeds 2-3°C.

- In agriculture & food security, assessments which better capture the uncertainties in model projections of future climate are yielding less optimistic results than those presented by IPCC AR4. New research since IPCC AR4 also suggests a smaller fertilisation effect from raised CO2 concentrations on crop productivity.

- In human health, there is evidence that previous projections of heat-related deaths are underestimates because they do not consider the role of temperature variability as well as average temperature. The role of recent climate change in incidences of malaria may also be greater than previously expected. This has implications for future malaria exposure. However, it should be noted that malaria incidence (as with many other vector-borne diseases) is affected by numerous factors other than climate.

Figure 1.12: Post-IPCC AR4 changes in severity, understanding and confidence for projections of impacts across five major sectors


Note(s): This figure is subjective and represents the views of the AVOID authors. It compares pre- and post-AR4 estimates for similar degrees of global warming (top), evaluates what new research has added to current knowledge (middle), and considers the degree of consensus across current studies (bottom). Positions on the chart represent changes relative to AR4, rather than an absolute positive/negative state.
Furthermore, impacts could be affected significantly by some processes that we highlighted in our 2008 report, but are still not captured well by climate models:

- Some large-scale elements of the climate system continue to show potential for nonlinear and irreversible change that is not well captured in current impact assessments. We cited in 2008 the possible dieback of tropical forests, and the likely deglaciation of Greenland and West Antarctica beyond some level of warming, leading to further sea level rise. These continue to be the subject of research, but the last two years have seen few advances in narrowing the uncertainties involved.

- In our 2008 report we highlighted loss of Arctic sea ice occurring more rapidly than model projections. Although partial recovery since then has reduced concerns about imminent collapse, it is still likely that the Arctic will be routinely ice-free in summer before the end of the century.

In summary, the scientific evidence now provides at least as strong a case for action as it did in 2008. Some projections indicate greater reason for concern than they did in 2008 (e.g. agriculture & food security) whereas a few others may show a slight reduction (e.g. Arctic summer sea ice).

**New evidence on global pathways to deliver climate objectives**

The AVOID review highlights the consistency of the Committee’s modelling approach and pathways with other, more recent studies:

- Recent independent studies add confidence to our results in 2008, emphasising the role of cumulative emissions and reaching similar conclusions on the emissions limits required to keep central temperature estimates close to 2°C.

- A review of the latest evidence regarding climate sensitivity (a key uncertain parameter in climate projections) concluded that estimates are still consistent with the likely range given in IPCC AR4. Hence the distribution of climate sensitivity values we used in our climate modelling work remains appropriate.

- There is increasing evidence that even if CO₂ emissions are eventually reduced to zero, atmospheric concentrations will fall only very slowly indeed. Temperatures will remain high for even longer, as the oceans continue to absorb heat. Therefore, without significant negative emissions, temperature targets are likely to be very difficult to return to once they are exceeded.

- Some potentially important processes which we cited in 2008 are known still to be missing from leading model projections. In particular, there is greater confidence that there is a risk of additional CO₂ and CH₄ release from large natural reserves in wetlands, permafrost and oceans. Early results suggest these sources may add additional warming of the order of several percent, but large uncertainties remain.

**5. Remaining uncertainties and implications for our approach to mitigation**

The overall case for human induced climate change is underpinned by a vast body of theory and observation which forms a coherent picture, and where we can be confident about several basic tenets:

- Climate has varied regionally and globally throughout Earth’s history, in response to a variety of factors.

- Among these, CO₂ and other gases in the atmosphere give rise to natural warming. Increasing the concentrations of these gases enhances the warming effect.

- Atmospheric concentrations of GHGs have increased during the 20th Century and are still rising as a direct result of emissions from human activity.

- Over the last decades the climate system has warmed, with rising temperatures, ocean heat content and sea levels, and melting glaciers, snow and ice.

- A continued rise in emissions is likely to cause sustained global heating of a magnitude and rate unprecedented in the course of human civilisation.

There are also still some areas where large uncertainties remain:

- Some key processes affecting climate are not yet understood well enough to have complete confidence in their characterisation, but new measurements and theories may improve our understanding. Hence, over time, we could well have better information on the strength of effects from short-lived gases and particles, the size and types of natural climate variability in earlier centuries, the future role of clouds (and other potential feedbacks) and the likely nature and consequences of climate change at a local scale.

- In other areas the limits to our knowledge are more fundamental, meaning uncertainties are unlikely to ever be completely resolved:
  - The exact forecasting of individual weather events is limited by the chaotic nature of the climate system.
  - Furthermore, the exact impacts of future climate on people will depend on social factors: where they are living, what they are doing, and the resources they have to cope and adapt. Scenarios can be used to explore these factors, but forecasts of socio-economic impacts are even more uncertain than forecasts of weather.
Given both our confidence in the fundamental science and current uncertainties, we continue to recommend a two step approach:

- Carbon budgets and targets should be based on the climate objective and pathways in our 2008 report:
  - Central estimates of global temperature increase by 2100 should be limited to as little above 2°C over pre-industrial levels as possible, and the likelihood of a 4°C increase should be kept to very low levels (e.g. less than 1%).
  - To meet this objective, global emissions should peak by 2020 and be halved or more by 2050; the UK should therefore aim to achieve at least an 80% emissions reduction in 2050 relative to 1990 levels.

- Significant research effort is aimed at resolving current uncertainties; we will continue to monitor scientific developments and periodically review implications for carbon targets and budgets.

We therefore use the pathways from the 2008 report as a benchmark for understanding progress and challenges in moving to a new global deal in Chapter 2, and the targets for the UK implied by these pathways in recommending the fourth carbon budget in Chapter 3. Our advice on the fifth carbon budget (scheduled for 2015) will provide an opportunity to revisit these pathways following the publication of the IPCC’s Fifth Assessment Report.

6. Key findings

Global average temperatures from 2000-2009 were around 0.75°C above pre-industrial levels.

Limiting central estimates of global warming by 2100 close to 2°C will reduce (but not avoid) the risks from climate change.

Many societies and ecosystems will not be able to adapt to 4°C of warming. The risk of reaching this should be kept to very low levels.

The number of climate research papers reviewed by the Committee this year, providing us with the latest understanding of climate science.

Global CO₂ emissions increased 6-fold over the 20th Century.

CO₂ concentration has not been as high as today for at least the last million years, possibly much longer.

The last decade has been the hottest since records began.