



Climate change: a summary of the science

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Glossary

Wm⁻² (watts per metre squared)

The amount of energy that falls on a square metre in one second. Sometimes known as a flux.

Carbon cycle

The term used to describe the flow of carbon, in its various forms, between the atmosphere, oceans, plants, soils and rocks. In the atmosphere, carbon mostly exists as carbon dioxide, but it exists in different forms in other components, such as organic carbon in the soil.

Climate forcing (also known as radiative forcing)

The imbalance in the Earth's energy budget resulting from, for example, changes in the energy received from the Sun, changes in the amounts or characteristics of greenhouse gases and particles, or changes in the nature of the Earth's surface. Hence climate forcing can result from both human activity and natural causes. It is given in units of Wm⁻².

Climate sensitivity

This is the amount of climate change (as measured by the change in globally-averaged surface temperature) for a given amount of climate forcing. It is often quoted (as will be the case here) as the temperature change that eventually results from a doubling in CO₂ concentrations, which is calculated to cause a climate forcing of about 3.6 Wm⁻².

Internal climate variability:

Climate change that occurs in the absence of natural or human-induced climate forcing as a result of interactions within and between the various components of the climate system (such as the atmosphere, the oceans and the frozen world).

Introduction

- 1 Changes in climate have significant implications for present lives, for future generations and for ecosystems on which humanity depends. Consequently, climate change has been and continues to be the subject of intensive scientific research and public debate.
- 2 There is strong evidence that the warming of the Earth over the last half-century has been caused largely by human activity, such as the burning of fossil fuels and changes in land use, including agriculture and deforestation. The size of future temperature increases and other aspects of climate change, especially at the regional scale, are still subject to uncertainty. Nevertheless, the risks associated with some of these changes are substantial. It is important that decision makers have access to climate science of the highest quality, and can take account of its findings in formulating appropriate responses.
- 3 In view of the ongoing public and political debates about climate change, the aim of this document is to summarise the current scientific evidence on climate change and its drivers. It lays out clearly where the science is well established, where there is wide consensus but continuing debate, and where there remains substantial uncertainty. The impacts of climate change, as distinct from the causes, are not considered here. This document draws upon recent evidence and builds on the Fourth Assessment Report of Working Group I of the Intergovernmental Panel on Climate Change (IPCC), published in 2007, which is the most comprehensive source of climate science and its uncertainties.

Climate and climate change: some background science

The greenhouse effect

- 4 The Sun is the primary source of energy for the Earth's climate. Satellite observations show that about 30% of the Sun's energy that reaches the Earth is reflected back to space by clouds, gases and small particles in the atmosphere, and by the Earth's surface. The remainder, about 240 Watts per square metre (Wm^{-2}) when averaged over the planet, is absorbed by the atmosphere and the surface.
- 5 To balance the absorption of 240 Wm^{-2} from the Sun, the Earth's surface and atmosphere must emit the same amount of energy into space; they do so as infrared radiation. On average the surface emits significantly more than 240 Wm^{-2} , but the net effect of absorption and emission of infrared radiation by atmospheric gases and clouds is to reduce the amount reaching space until it approximately balances the incoming energy from the Sun. The surface is thus kept warmer than it otherwise would be because, in addition to the energy it receives from the Sun, it also receives infrared energy emitted by the atmosphere. The warming that results from this infrared energy is known as the greenhouse effect.
- 6 Measurements from the surface, research aircraft and satellites, together with laboratory observations and calculations, show that, in addition to clouds, the two gases making the largest contribution to the greenhouse effect are water vapour followed by carbon dioxide (CO_2). There are smaller contributions from many other gases including ozone, methane, nitrous oxide and human-made gases such as CFCs (chlorofluorocarbons).

Climate change

- 7 Climate change on a global scale, whether natural or due to human activity, can be initiated by processes that modify either the amount of energy absorbed from the Sun, or the amount of infrared energy emitted to space.
- 8 Climate change can therefore be initiated by changes in the energy received from the Sun, changes in the amounts or characteristics of greenhouse gases, particles and clouds, or changes in the reflectivity of the Earth's surface. The imbalance between the absorbed and emitted radiation that results from these changes will be referred to here as "climate forcing" (sometimes known as "radiative forcing") and given in units of Wm^{-2} . A positive climate forcing will tend to cause a warming, and a negative forcing a cooling. Climate changes act to restore the balance between the energy absorbed from the Sun and the infrared energy emitted into space.
- 9 In principle, changes in climate on a wide range of timescales can also arise from variations within the climate system due to, for example, interactions between the oceans and the atmosphere; in this document, this is referred to as "internal climate

variability". Such internal variability can occur because the climate is an example of a chaotic system: one that can exhibit complex unpredictable internal variations even in the absence of the climate forcings discussed in the previous paragraph.

- 10 There is very strong evidence to indicate that climate change has occurred on a wide range of different timescales from decades to many millions of years; human activity is a relatively recent addition to the list of potential causes of climate change.
- 11 The shifts between glacial and interglacial periods over the past few million years are thought to have been a response to changes in the characteristics of the Earth's orbit around the Sun. While these led to only small changes in the total energy received from the Sun, they led to significant changes in its geographical and seasonal distribution. The large changes in climate, in moving in and out of glacial periods, provide evidence of the sensitivity of climate to changes in the Earth's energy balance, whether attributable to natural causes or to human activity.

Mechanisms of global climate change

- 12 Once a climate forcing mechanism has initiated a climate response, this climate change can lead to further changes; for example, in response to a warming, the amount of water vapour is expected to increase, the extent of snow and ice is expected to decrease, and the amount and properties of clouds could also change. Such changes can further modify the amount of energy absorbed from the Sun, or the amount of energy emitted by the Earth and its atmosphere, and lead to either a reduction or amplification of climate change.
- 13 The overall effect of the changes resulting from climate forcing determine a key characteristic of the climate system, known as the "climate sensitivity" – this is the amount of climate change (as measured by the equilibrium change in globally-averaged surface temperature) caused by a given amount of climate forcing. It is often quoted (as will be the case here) as the temperature change that eventually results from a doubling in CO₂ concentrations since pre-industrial times, and is calculated to cause a climate forcing of about 3.6 Wm⁻².
- 14 The nature of the climate system is determined by interactions between the moving atmosphere and oceans, the land surface, the living world and the frozen world. The rate at which heat is moved from the surface to the ocean depths is an important factor in determining the speed at which climate can change in response to climate forcing.
- 15 Since variations in climate can result from both climate forcing and internal climate variability, the detection of forced climate change in observations is not always straightforward. Furthermore, the detection of climate change in observations, beyond the expected internal climate variability, is not the same as the attribution of that change

to a particular cause or causes. Attribution requires additional evidence to provide a quantitative link between the proposed cause and the observed climate change.

Modelling the climate system

- 16 Current understanding of the physics (and increasingly the chemistry and biology) of the climate system is represented in a mathematical form in climate models, which are used to simulate past climate and provide projections of possible future climate change. Climate models are also used to provide quantitative estimates to assist the attribution of observed climate change to a particular cause or causes.
- 17 Climate models vary considerably in complexity. The simplest can be described by a few equations, and may represent the climate by global-average surface temperature alone. The most complicated and computer-intensive models represent many details of the interactions between components of the climate system. These more complex models represent variations in parameters such as temperature, wind and humidity with latitude, longitude and altitude in the atmosphere, and also represent similar variations in the ocean. In complex climate models climate sensitivity emerges as an output; in the simpler calculations it is specified either as an input or it emerges as a consequence of simplified (but plausible) assumptions.
- 18 By applying established laws of fluid dynamics and thermodynamics, the more complex climate models simulate many important weather phenomena that determine the climate. However, limitations of computer power mean that these models cannot directly represent phenomena occurring at small scales. For example, individual clouds are represented by more approximate methods. Since there are various ways to make these approximations, the representation can vary in climate models developed at different climate institutes. The use of these different approximations leads to a range of estimates of climate sensitivity, especially because of differences between models in the response of clouds to climate change. There are intensive efforts to compare the models with observations and with each other. The spread of results from these models gives useful information on the degree of confidence in the reliability of projections of climate change.
- 19 Unlike weather-forecast models, climate models do not seek to predict the actual weather on a particular day at a particular location. The more complex models do however simulate individual weather phenomena, such as mid-latitude depressions and anticyclones, and aim to give simulations of possible weather sequences much farther into the future than weather forecast models. From such simulations, one can derive the characteristics of climate likely to occur in future decades, including mean temperature and temperature extremes.

Aspects of climate change on which there is wide agreement

Changes in global-average surface temperature

- 20 Measurements suitable for showing how surface temperature has changed with time across the world became available around 1850. Analyses of these data, in a number of institutes, try to take into account changing distributions of measurements, changing observation techniques, and changing surroundings of observing stations (e.g. some stations become more urban with time, which can make measurements from them less representative of wider areas).
- 21 Measurements show that averaged over the globe, the surface has warmed by about 0.8°C (with an uncertainty of about $\pm 0.2^\circ\text{C}$) since 1850. This warming has not been gradual, but has been largely concentrated in two periods, from around 1910 to around 1940 and from around 1975 to around 2000. The warming periods are found in three independent temperature records over land, over sea and in ocean surface water. Even within these warming periods there has been considerable year-to-year variability. The warming has also not been geographically uniform – some regions, most markedly the high-latitude northern continents, have experienced greater warming; a few regions have experienced little warming, or even a slight cooling.
- 22 When these surface temperatures are averaged over periods of a decade, to remove some of the year-to-year variability, each decade since the 1970s has been clearly warmer (given known uncertainties) than the one immediately preceding it. The decade 2000-2009 was, globally, around 0.15°C warmer than the decade 1990-1999.
- 23 Local temperatures are generally a poor guide to global conditions. For example, a colder-than-average winter in the UK does not mean that colder-than-average conditions are experienced globally. Similarly, observed variations in global temperature over a period of just a few years could be a misleading guide to underlying longer-term trends in global temperature.

Other changes in climate

- 24 Not all aspects of the climate system have been observed over as long a period as surface temperatures – for example, those based on satellite observations date back, at best, to the 1970s. Nor are the measurements of other aspects of the climate system always of the same quality. Collectively, however, they provide much evidence of climate change consistent with the surface temperature changes. This includes increases in the average temperature of both the upper 700m of the ocean and the troposphere (the atmosphere up to 10-18km), widespread (though not universal) decreases in the length of mountain glaciers and increases in average sea level. There has been an overall decline in the area covered by sea-ice floating on the Arctic Ocean over the past 30 years (although there has been a small increase in the area covered by sea-ice around Antarctica).

Changes in atmospheric composition

- 25 Global-average CO₂ concentrations have been observed to increase from levels of around 280 parts per million (ppm) in the mid-19th century to around 388 ppm by the end of 2009. CO₂ concentrations can be measured in “ancient air” trapped in bubbles in ice, deep below the surface in Antarctica and Greenland; these show that present-day concentrations are higher than any that have been observed in the past 800,000 years, when CO₂ varied between about 180 and 300 ppm. Various lines of evidence point strongly to human activity being the main reason for the recent increase, mainly due to the burning of fossil fuels (coal, oil, gas) with smaller contributions from land-use changes and cement manufacture. The evidence includes the consistency between calculations of the emitted CO₂ and that expected to have accumulated in the atmosphere, the analysis of the proportions of different CO₂ isotopes, and the amount of oxygen in the air.
- 26 These observations show that about half of the CO₂ emitted by human activity since the industrial revolution has remained in the atmosphere. The remainder has been taken up by the oceans, soils and plants although the exact amount going to each of these individually is less well known.
- 27 Concentrations of many other greenhouse gases have increased. The concentration of methane has more than doubled in the past 150 years; this recent and rapid increase is unprecedented in the 800,000 year record and evidence strongly suggests that it arises mainly as a result of human activity.

Climate forcing by greenhouse gas changes

- 28 Changes in atmospheric composition resulting from human activity have enhanced the natural greenhouse effect, causing a positive climate forcing. Calculations, which are supported by laboratory and atmospheric measurements, indicate that these additional gases have caused a climate forcing during the industrial era of around 2.9 Wm⁻², with an uncertainty of about ±0.2 Wm⁻². Other climate change mechanisms resulting from human activity are more uncertain (see later); calculations that take into account these other positive and negative forcings (including the role of atmospheric particles) indicate that the net effect of all human activity has caused a positive climate forcing of around 1.6 Wm⁻² with an estimated uncertainty of about ±0.8 Wm⁻².
- 29 Application of established physical principles shows that, even in the absence of processes that amplify or reduce climate change (see paragraphs 12 & 13), the climate sensitivity would be around 1°C, for a doubling of CO₂ concentrations. A climate forcing of 1.6 Wm⁻² (see previous paragraph) would, in this hypothetical case, lead to a globally-averaged surface warming of about 0.4°C. However, as will be discussed in paragraph

36, it is expected that the actual change, after accounting for the additional processes, will be greater than this.

Carbon dioxide and climate

30 Evidence from ice cores indicates an active role for CO₂ in the climate system. This is because the amount of carbon held in oceans, soils and plants depends on temperature and other conditions. In other words, changes in CO₂ can lead to climate change and climate change can also alter the concentrations of CO₂.

Aspects of climate change where there is a wide consensus but continuing debate and discussion

The carbon cycle and climate

31 Once atmospheric CO₂ concentrations are increased, carbon cycle models (which simulate the exchange of carbon between the atmosphere, oceans, soils and plants) indicate that it would take a very long time for that increased CO₂ to disappear; this is mainly due to well-known chemical reactions in the ocean. Current understanding indicates that even if there was a complete cessation of emissions of CO₂ today from human activity, it would take several millennia for CO₂ concentrations to return to pre-industrial concentrations.

Other drivers of global climate change

32 In addition to changes in greenhouse gas concentrations, there are a large number of less well characterised contributions to climate forcing, both natural and human-induced.

33 Volcanic eruptions are examples of a natural climate forcing mechanism. An individual volcanic eruption has its largest effects on the climate for only a few years after the eruption; these effects are dependent on the location, size and type of the eruption.

34 Natural forcing due to sustained variations in the energy emitted by the Sun over the past 150 years is estimated to be small (about 0.12 Wm⁻²); however, direct observations of the energy emitted by the Sun only became available in the 1970s and estimates over longer periods rely on observations of changes in other characteristics of the Sun. A number of mechanisms have been proposed that could reduce or amplify the effect of solar variations; these remain areas of active research.

35 Human activity results in emissions of many short-lived gases (such as carbon monoxide and sulphur dioxide) and particles into the atmosphere. These affect the atmospheric concentrations of other climate-important gases such as ozone, and other particles which lead to a climate forcing. Calculations, coupled to a variety of atmospheric observations, indicate that particles have caused a negative climate forcing of around 0.5 Wm⁻² with an uncertainty of ±0.2 Wm⁻². The particles also directly influence cloud properties; this more uncertain effect is discussed in paragraph 47.

Climate sensitivity

36 The more complex climate models, supported by observations, allow climate sensitivity to be calculated in the presence of processes that amplify or reduce the size of the climate response. Increases in water vapour alone, in response to warming, are estimated to approximately double the climate sensitivity from its value in the absence

of amplifying processes. There nevertheless remain uncertainties in how much water vapour amounts will change, and how these changes will be distributed in the atmosphere, in response to a warming. Climate models indicate that the overall climate sensitivity (for a hypothetical doubling of CO₂ in the atmosphere) is likely to lie in the range 2°C to 4.5°C; this range is mainly due to the difficulties in simulating the overall effect of the response of clouds to climate change mentioned earlier.

Attribution of climate change

- 37 The size and sustained nature of the observed global-average surface warming on decadal and longer timescales greatly exceeds the internal climate variability simulated by the complex climate models. Unless this variability has been grossly underestimated, the observed climate change must result from natural and/or human-induced climate forcing.
- 38 When only natural climate forcings are put into climate models, the models are incapable of reproducing the size of the observed increase in global-average surface temperatures over the past 50 years. However, when the models include estimates of forcings resulting from human activity, they can reproduce the increase. The same result is found, albeit with a greater spread between different models, for the simulation of observed surface temperature changes for each of the habitable continents separately.
- 39 When known uncertainties in both observed trends and climate models are taken into account, the observed vertical and latitudinal variations of temperature change are also broadly consistent with those expected from a dominant role for human activity. There is an ongoing controversy concerning whether or not the increased warming with height in the tropical regions given by climate models is supported by satellite measurements.

Future climate change

- 40 As with almost any attempts to forecast future conditions, projections of future climate change depend on a number of factors. Future emissions due to human activity will depend on social, technological and population changes which cannot be known with confidence. The underlying uncertainties in climate science and the inability to predict precisely the size of future natural climate forcing mechanisms mean that projections must be made which take into account the range of uncertainties across these different areas.
- 41 The 2007 assessment by the Intergovernmental Panel on Climate Change (IPCC) made projections of future changes using a number of possible scenarios of future emissions,

based on a diverse range of assumptions. The IPCC's best estimate was that globally-averaged surface temperatures would be between 2.5 - 4.7°C higher by 2100 compared to pre-industrial levels. The full range of projected temperature increases by 2100 was found to be 1.8 - 7.1°C based on the various scenarios and uncertainties in climate sensitivity.

- 42 Even in the extremely unlikely event that there is no further increase in climate forcing, a further warming would be expected to occur as the oceans slowly respond to the existing climate forcing, amounting to a further few tenths of a degree centigrade by the year 2100.
- 43 The uncertainty in the predicted warming as a result of human activity over the next two decades is smaller, the range being 0.2 to 0.4°C per decade. On these shorter time-scales, the actual change could however be reduced or enlarged significantly by internal climate variability and natural climate forcings.
- 44 Increases in temperature are predicted to be larger on land, particularly on the northern continents in winter. Less warming is predicted, for example, over the North Atlantic Ocean. Climate models tend to predict that precipitation will generally increase in areas with already high amounts of precipitation and generally decrease in areas with low amounts of precipitation.
- 45 Because of the thermal expansion of the ocean, it is very likely that for many centuries the rate of global sea-level rise will be at least as large as the rate of 20 cm per century that has been observed over the past century. Paragraph 49 discusses the additional, but more uncertain, contribution to sea-level rise from the melting of land ice.

Aspects that are not well understood

- 46 Observations are not yet good enough to quantify, with confidence, some aspects of the evolution of either climate forcing or climate change, or for helping to place tight bounds on the climate sensitivity. Observations of surface temperature change before 1850 are also scarce.
- 47 As noted above, projections of climate change are sensitive to the details of the representation of clouds in models. Particles originating from both human activities and natural sources have the potential to strongly influence the properties of clouds, with consequences for estimates of climate forcing. Current scientific understanding of this effect is poor.
- 48 Additional mechanisms that influence climate sensitivity have been identified, including the response of the carbon cycle to climate change, for example the loss of organic carbon currently stored in soils. The net effect of changes in the carbon cycle in all current models is to increase warming, by an amount that varies considerably from model to model because of uncertainties in how to represent the relevant processes. The future strength of the uptake of CO₂ by the land and oceans (which together are currently responsible for taking up about half of the emissions from human activity – see paragraph 26) is very poorly understood, particularly because of gaps in our understanding of the response of biological processes to changes in both CO₂ concentrations and climate.
- 49 There is currently insufficient understanding of the enhanced melting and retreat of the ice sheets on Greenland and West Antarctica to predict exactly how much the rate of sea level rise will increase above that observed in the past century (see paragraph 45) for a given temperature increase. Similarly, the possibility of large changes in the circulation of the North Atlantic Ocean cannot be assessed with confidence. The latter limits the ability to predict with confidence what changes in climate will occur in Western Europe.
- 50 The ability of the current generation of models to simulate some aspects of regional climate change is limited, judging from the spread of results from different models; there is little confidence in specific projections of future regional climate change, except at continental scales.

Developments in climate science

- 51 Climate change science has advanced markedly over the past 20 years, as a result of many factors. These include improved methods for handling long-term climate data sets, the ever-lengthening record of climate observations, improved measurement techniques, including those from satellites, better understanding of the climate system, improved methods for simulating the climate system, and increased computer power.
- 52 One indication of these advances is the increasing degree of confidence in the attribution of climate change to human activity, as expressed in the key conclusions of IPCC Working Group 1 (WG1) in its assessments.
- 53 In its first assessment published in 1990, IPCC WG1 concluded that the “size of [the observed surface] warming is broadly consistent with predictions of climate models [which simulate the impact of human activity], but it is also of the same magnitude as natural climate variability”. Its second assessment, published in 1995, concluded that “the balance of evidence suggests that there is a discernible human influence on climate change”. Its fourth, and most recent, assessment, published in 2007, concluded that “most of the observed increase in globally average [surface] temperatures since the mid-20th century is very likely due to the observed increase in anthropogenic greenhouse gas concentrations”.
- 54 Remaining uncertainties are the subject of ongoing research worldwide. Some uncertainties are unlikely ever to be significantly reduced, because of, for example, the lack of observations of past changes relevant to some aspects of both climate forcing and climate change.
- 55 Other uncertainties may start to be resolved. For example, satellites now incorporate improved techniques to measure cloud characteristics across the globe. Using climate models for day-to-day weather prediction will enable, for example, identification of errors in the representation of clouds in models; any such errors will lead to errors in forecasts of maximum and minimum temperatures (which are easily observed). New high-performance computers will allow climate models to represent some smaller-scale phenomena (including cloud systems and details of tropical storms) directly, and are expected to improve confidence in regional predictions.
- 56 There remains the possibility that hitherto unknown aspects of the climate and climate change could emerge and lead to significant modifications in our understanding.

Concluding remarks

- 57 There is strong evidence that changes in greenhouse gas concentrations due to human activity are the dominant cause of the global warming that has taken place over the last half century. This warming trend is expected to continue as are changes in precipitation over the long term in many regions. Further and more rapid increases in sea level are likely which will have profound implications for coastal communities and ecosystems.
- 58 It is not possible to determine exactly how much the Earth will warm or exactly how the climate will change in the future, but careful estimates of potential changes and associated uncertainties have been made. Scientists continue to work to narrow these areas of uncertainty. Uncertainty can work both ways, since the changes and their impacts may be either smaller or larger than those projected.
- 59 Like many important decisions, policy choices about climate change have to be made in the absence of perfect knowledge. Even if the remaining uncertainties were substantially resolved, the wide variety of interests, cultures and beliefs in society would make consensus about such choices difficult to achieve. However, the potential impacts of climate change are sufficiently serious that important decisions will need to be made. Climate science – including the substantial body of knowledge that is already well established, and the results of future research – is the essential basis for future climate projections and planning, and must be a vital component of public reasoning in this complex and challenging area.

Background reading

Extensive background references to the scientific literature, and summaries thereof, can be found in the following two documents.

Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, 2007, Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.), Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

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Cover: Artists image of CryoSat-2, ESA, C. Vieux.
The aim of the CryoSat mission is to determine variations in the thickness of the Earth's marine ice cover and understand the extent to which the Antarctic and Greenland ice sheets are contributing to global sea level rise. The CryoSat-2 satellite was launched on 8 April 2010 and will contribute to improved understanding of how the climate is changing. © ESA - C. Vieux.