The Science of Climate Change

An Introduction by Sir David King

RSA

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This booklet on the science of climate change is based on a lecture I gave at the launch of the RSA's Arts and Ecology programme. I have updated and expanded it to bring the science up-to-date and to cover a wider range of topics. It aims to explain how we know we are changing our climate, the predictions of future climate change and the impacts that this will have.

Even a year ago, climate change was still reported by some as a controversial issue; however new scientific findings have continued to fill in the gaps in our understanding and have countered the last of the sceptics' arguments. The causal link between global warming and increased greenhouse gas emissions from human activities is now established beyond all reasonable doubt and, while there is still some uncertainty in the details, it is clear that the potential impacts are so severe that urgent action is needed.

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CLIMATE CHANGE SCIENCE

The Greenhouse Effect

Our understanding of our climate system was greatly enhanced in 1827 with the recognition, by the French mathematician Joseph Fourier, of what has become known as the greenhouse effect. Fourier realized that the Earth's temperature is determined not only by the radiation absorbed by, and emitted from, the Earth, but also by the existence of the atmosphere. The atmosphere absorbs some of the radiated heat and acts as a blanket over the Earth that maintains the temperature higher than it would otherwise be, and keeps night-time and day-time temperatures more similar. You can see a diagram of this concept in figure 1. While it's got a bad name recently, we wouldn't have our benign climate if it wasn't for this greenhouse effect, as the global average temperature would be a very chilly minus 18 degrees Celsius (°C).

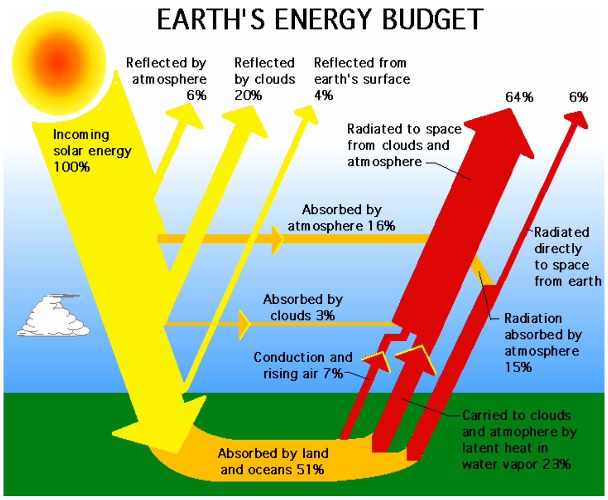


FIGURE 1: The Earth's Energy Budget (Source: Atmospheric Science Data Center – adapted from J. T. Kiehl and Kevin E. Trenberth original version 1997: Earth's annual global mean energy budget. Bull. Amer. Meteor. Soc., 78, 197–208): When the Sun's energy reaches the Earth some of it is reflected back into space by the atmosphere, clouds and the Earth's surface but most is absorbed by the land and oceans, the atmosphere and clouds. This warms the Earth causing it to in turn radiate energy, predominately as infrared radiation. Unlike the radiation from the Sun much of the outgoing infrared radiation is absorbed by the gases in the atmosphere. This effectively traps some of the energy so raising the Earth's temperature.

The next big step was made in 1860 by the British scientist John Tyndall who, by measuring the absorption of radiation by different gases, made the then remarkable discovery that the most prevalent gases in the atmosphere, oxygen and nitrogen, weren't absorbing any of the energy at all. Only the minority gases in the atmosphere, such as water vapour, carbon dioxide, methane and nitrous oxide were doing so. These gases are called greenhouse gases.

The Swedish scientist Svante Arrhenius, one of the early Nobel Prize winners, was the first person to try to calculate what would happen to our global temperature if we burnt enough fossil fuels to double the amount of carbon dioxide in the atmosphere. In 1896 he published the first crude estimate of global warming; he said that on average the global temperature would rise by 5°C.

Climate Change

Basic, well-understood science, as introduced above, suggests that we can change our planet's climate by increasing the greenhouse gas levels in the atmosphere. The ideal proof would require a controlled experiment on the planet as a whole. With two identical planets we could increase the level of greenhouse gases in the atmosphere of one planet while leaving the other unchanged, and by then comparing the temperatures of the two planets we could see the effect of the increase. However, as in other areas of science such as cosmology, this is obviously not possible and other ways to test the theory have to be found instead. Recent advanced computer models of the planet are as close as we can come to conducting experiments with our climate system.

Such models have demonstrated that the observed warming we are now experiencing is consistent with the theory that human emissions of greenhouse gases are the main driver of this warming, while other theories that could feasibly have provided an alternative explanation have at the same time been ruled out.

A comprehensive discussion is outside the scope of this booklet, however in the next few pages I have pulled out some of the key pieces of research that have helped us to address some of the key questions: How do we know that levels of carbon dioxide and other greenhouse gases are increasing? How do we know that the climate is changing? Is climate change theory consistent with the temperature increase and other available data? Can we reject alternative reasonable explanations of the temperature rise?

Atmospheric levels of carbon dioxide and other greenhouse gases

An archive of the past state of the atmosphere and climate has been preserved in the ice sheets of Antarctica and Greenland. The ice sheets are made up of layers of ice formed from the annual cycle of snowfall in winter and partial melting in summer. By drilling out ice cores, scientists can analyse air bubbles in the ice going back in time; these contain the atmosphere captured when the ice formed. The latest ice core, from the Antarctic, is three kilometres long and records at least 740 thousand years.

From this core, measurements of carbon dioxide levels for the last 650,000 years have now been published. Nowhere in this record have the levels come close to their present level [1]. Figure 2 shows just the last sixty thousand years of these ice core records. You can see that in the last ice-age, the period up to about 15,000 years ago, the carbon dioxide level was around 200-220 parts per million (ppm). Then, up to about 12,000 years ago, when we entered into our current warm period, the carbon dioxide level increased. During this warm period, the period in which civilization has flourished, carbon dioxide levels have been fairly constant at around 260-270 ppm. That is until you get to the green data points, which are from the industrial period; here you see the carbon dioxide levels rising again sharply.

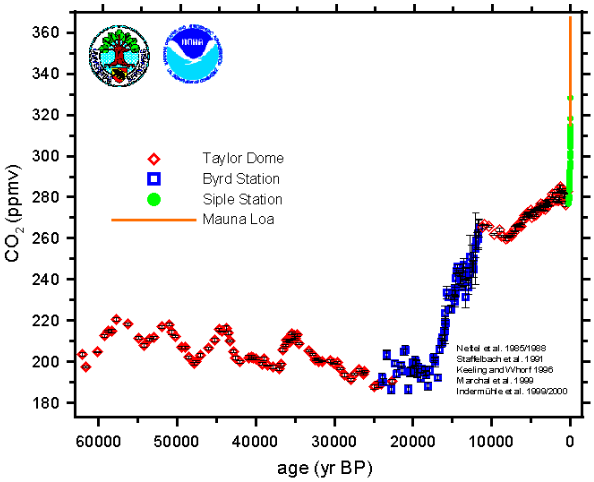
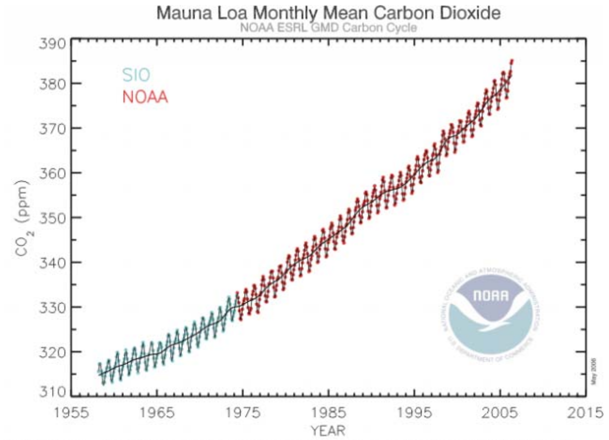


FIGURE 2: (Source: Departure of Climate an Environmental Physics, University of Bern, NOAA-CMDL): Reconstruction of the atmospheric carbon dioxide concentration over the past 62,000 years

The most recent data, the orange line, are not from an ice core but are direct measurements of the carbon dioxide level in the atmosphere. These measurements are the result of the work of the scientist Charles Keeling who, in 1957, started atmospheric measurements at the Mauna Loa Observatory in Hawaii, an ideal location due to its remoteness from the direct influences of the industrialized world. His data, shown in figure 3, clearly show a long-term rise in the carbon dioxide level since the measurements began. Today many measurements are made at remote locations around the world, all showing the same picture. The latest data point is about 380 ppm, and levels are now rising by about two ppm each year [2].



Atmospheric carbon dioxide monthly mean mixing ratios. Data prior to May 1974 are from the Scripps Institution of Oceanography (SIO, blue), data since May 1974 are from the National Oceanic and Atmospheric Administration (NOAA, red). A long-term trend curve is fitted to the monthly mean values. Contact: Dr. Pieter Tans, NOAA ESRL GMD Carbon Cycle, Boulder, Colorado, (303) 497-6678, pieter.tans@noaa.gov, and Dr. Ralph Keeling, SIO GRD, La Jolla, California, (858) 534-7582, rkeeling@ucsd.edu.

FIGURE 3: (Source: NOAA, Earth System Research Laboratory, Boulder, Colorado): Measurements at Mauna Loa of the monthly mean atmospheric carbon dioxide concentration. The zigzag effect results from the annual cycle in natural carbon uptake in the Northern Hemisphere. In spring, leaves grow and take carbon dioxide out of the atmosphere, and then when the autumn comes, leaves fall and the carbon dioxide is released again. This Northern Hemisphere cycle shows more clearly than the Southern Hemisphere cycle because there are more continental land mass and deciduous trees in the Northern Hemisphere than in the Southern Hemisphere.

Carbon dioxide levels have risen in the past without human intervention. However, we can tell that the recent increase has primarily arisen from the burning of fossil fuels because carbon comes in different types, called isotopes. The ratio of the isotopes is different in carbon dioxide that comes from burning fossil fuels to that in the atmosphere, and its large-scale release since the Industrial Revolution has changed the ratio of carbon isotopes observed in the atmosphere [3]. In addition, we can see that the concentration of carbon dioxide is slightly greater in the Northern Hemisphere where fossil fuel use is greatest, and the overall rise in levels is consistent with the amount of carbon dioxide we have been emitting. Unfortunately, any one molecule of carbon dioxide can remain in the atmosphere for around one to two hundred years on average, so even if we stop emissions today, it will take a long time for levels to fall.

Carbon dioxide is not the only greenhouse gas whose concentration is increasing due to our activities. Levels of methane, nitrous oxide and other greenhouse gases are also rising. Methane, for example, is released in natural gas extraction and from agriculture. If we take these other greenhouse gases into account then the increase in the level of greenhouse gases since the pre-industrial period is equivalent to about 430 ppm of carbon dioxide [4].

Increases in Temperature

We can learn about changes in past temperature by looking at the concentration of an isotope of hydrogen called deuterium in the air bubbles of ice cores. Over the last 740,000 years the Earth has seen eight cycles of ice ages and warmer periods [5], with temperature differences between the ice ages and warm periods of around 5 to 8°C. It seems likely that these changes were started off by changes in the Earth's orbit or tilt. We can also see that there is a correlation between temperature and carbon dioxide, with carbon dioxide levels around 200 ppm during ice ages and 260 to 270 ppm in warm periods.

While temperatures have changed dramatically in the past, the temperature has been fairly constant during this current warm period. From 1850 we have enough measurements to estimate global temperature directly; you can see this data in figure 4. Since 1900, the global climate has warmed by an average of 0.7°C, with much of this seen over the past 30 years. In fact, the ten warmest years on record have all occurred since 1990 [6].

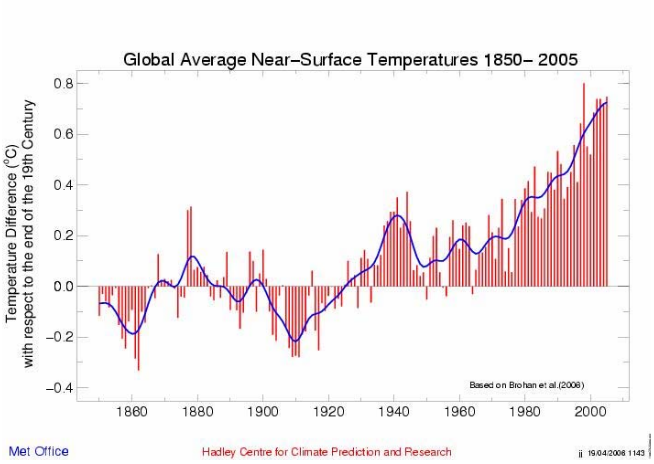


FIGURE 4: (Crown Copyright 2006, data supplied by the Met Office and CRU, University of East Anglia): Global average near-surface temperatures from 1850 to 2005. The red bars show each year's average temperature; from year to year there is a significant amount of variability. The blue line shows the trend; there is a warming period from 1920-1940 followed by a period of little change, the last three decades show a further warming period. Measurements of air temperature over land, over sea at night and of sea-surface temperature are consistent, giving confidence in the data. [Based on 7]

Further evidence of this global warming has been observed in numerous physical and biological systems: ice sheets are melting, sea levels are rising, glaciers across the world are in retreat, and the behaviour of plants and animals is changing.

We are losing ice around the world at a tremendous rate. In Glacier National Park, Montana, USA, there are now only 26 named glaciers out of the 150 counted in 1850, and those that remain are remnants of their previous size [8].

Attribution and the use of climate models

The global system is so complex that only with advanced computing can we begin to get credible predictions of how and where climate will vary. Computer models help us to understand the observed climatic changes and project future changes. These models are based on the equations of the basic physical laws that govern our climate. Underlying them are the results of thousands of supporting observations and experiments.

The models include many important `feedback’ mechanisms. One of the most important is the effect of water vapour. Models show that this causes a positive feedback; i.e. any initial warming is significantly increased due to the fact that a warmer atmosphere is able to hold more water vapour, itself a powerful greenhouse gas, so causing further warming. Recent observations of changes in atmospheric water vapour by satellite have confirmed this effect [9] and so provided an important validation of climate change theory and the validity of climate models.

Other important feedbacks include changes in cloud formation and ocean-circulation. Different types of clouds can either warm or cool the atmosphere. Ocean currents are important in the transport of heat around the Earth, e.g. the thermohaline circulation in the Atlantic, which helps to keep Europe balmier in winter than comparable Northern climes.

Figure 5 shows a comparison between a climate model produced by the UK’s Hadley Centre for Climate Research and measurements of actual global temperature over the last 135 years [10]. The model is able to represent what actually happened fairly well. Hadley scientists have included in the model both anthropgenic (man-made) effects, such as the burning of fossil fuels, and also natural factors such as volcanic effects and changes in solar intensity. This agreement between real data and the model predictions gives us considerable confidence in our theories of climate change.

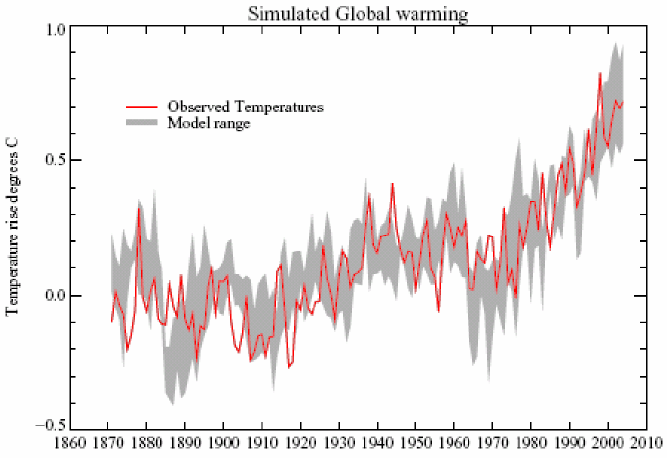


FIGURE 5: (Crown Copyright 2005, data supplied by the Met Office): Comparison of observed changes in global temperature (red line) with climate model simulation (grey band). This figure covers the period in which direct measurements of global temperature are available.

It is important to test whether there are alternative explanations of the warming we are experiencing, for example an increase in radiation from the sun. These natural factors have been the subject of considerable study. For example, measurements of the radiation from the sun show that its output has been relatively stable over the last 50 years and has had little impact on global climate compared to that from increased greenhouse gas emissions [11]. If the Hadley model only included these natural factors, and not the anthropogenic ones, there would not be the agreement between theory and measurement that you see demonstrated in figure 5.

This agreement between theory and measurement exists in other variables beyond global temperature. For example, recent research has shown good agreement in the way ocean temperature is changing with depth [12] and the relative warming or cooling at different levels of the atmosphere [13]. This gives real confidence in our understanding of the climate system. Taken together the evidence is very compelling and I find it difficult to imagine what other explanation would be able to account for all observed effects. Despite how the topic is sometimes presented in the media, the overwhelming majority of credible scientists take a similar view, both here in the UK and globally.

FUTURE CLIMATE CHANGE

Predictions of future temperature

We are already committed to some degree of future warming from previous greenhouse gas emissions due to the time lag in the climate system. However if we continue to emit these gases the warming will be far greater. The models used to explain recent climate change can also be used to predict our future climate, although with some uncertainty. The main sources of uncertainty are twofold: putting a precise value on how much warming will be caused by a given increase in greenhouse gas levels and predicting what amount of greenhouse gases mankind will emit.

While there is uncertainty in predicting how much warming will be caused by a given increase in greenhouse gas levels, recent advances have enabled this uncertainty to be quantified. Figure 6 shows a probability distribution of the temperature rise that might occur for a given level of carbon dioxide, as predicted by the Hadley Centre climate model [14]. If the level of greenhouse gases reaches the equivalent of 450 ppm of carbon dioxide then the probability of temperatures staying at 2°C or below is around 50% (0.5 on the graph's scale); if levels rise to 550 ppm then there is around a 50% chance they could exceed 3°C [15].

Some of the most significant contributions to the uncertainties in the models relate to cloud formation and the effect of small particles and droplets (known as aerosols) in the atmosphere, such as soot and sulphates droplets. The effect of sulphate aerosols may have offset some greenhouse gas warming, which may explain why you see very little warming in the period from 1950 to 1970 in figure 4. This counter-effect has been dubbed by some 'global dimming'.

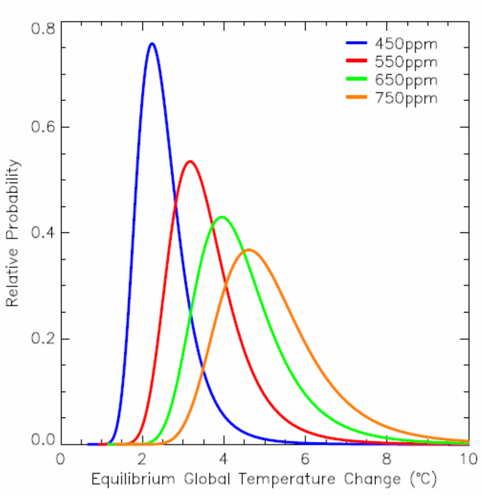


FIGURE 6: (Crown Copyright 2007, data supplied by the Met Office): The relative probability of a global temperature change as predicted by the Hadley Climate Change model for carbon dioxide levels of 550 ppm, which is roughly double pre-industrial levels (red line) and for levels of 450, 650, 750 ppm (see key). Other climate models give roughly similar results.

In addition, future temperature rise will depend on the amount of greenhouse gases mankind will emit. So, scientists use a number of different projections of future emissions to give a range of possible outcomes. These include variations in a range of factors, such as the rate of population growth. Based on such projections, and using a range of climate models, the Intergovernmental Panel on Climate Change in 2007 projected temperature increases in the range of 1.1 to 6.4°C above 1990 levels by 2100 [16]. Some recent findings suggest an even higher figure may be possible [17].

There are a number of effects that still have to be properly factored into the calculations that have the potential to be positive feedback mechanisms. For example, while currently stable, a large enough warming could release methane currently trapped within ocean sediments, permafrost and wetlands. This would be problematic because methane is a greenhouse gas twenty times more powerful than carbon dioxide and so such releases could lead to significant warming. There are uncertainties over whether this could happen, at what temperature such releases might be triggered and how large the effects might be.

Another potential positive feedback effect relates to the way carbon dioxide is absorbed by the land and oceans. Initially, higher carbon dioxide levels may cause more vegetation growth in some areas, so absorbing more carbon dioxide. However, as temperatures increase the amount of carbon dioxide that can be absorbed may start to reduce as, for example, plant matter decays faster and if large areas of forest begin to dry out and disappear.

Physical Impacts of Climate Change

Having described the impacts of climate change in terms of the global temperature rise, I now want to discuss the physical impacts of this. Firstly, and purely to provide perspective, I would point out that 5°C, while it may not seem a lot in relation to our day to day weather, is the difference in global average temperature between an ice age and our current climate.

A change in global temperature will not be uniformly distributed and some areas will see much more warming than the average. For example, land warms up more quickly than the oceans leading to greater warming over large continental areas such as Africa. A 2°C average global temperature rise could mean as much as a 4°C rise in the middle of the continent. The Arctic, where the disappearance of sea ice produces a positive feedback effect, is also predicted to warm more significantly. The predictions of the Hadley Centre model for one emissions scenario are shown in figure 7 [18]. A higher average temperature will also shift upwards the baseline for the day-to-day temperatures that we all experience, leading to more heat waves and fewer very cold days.

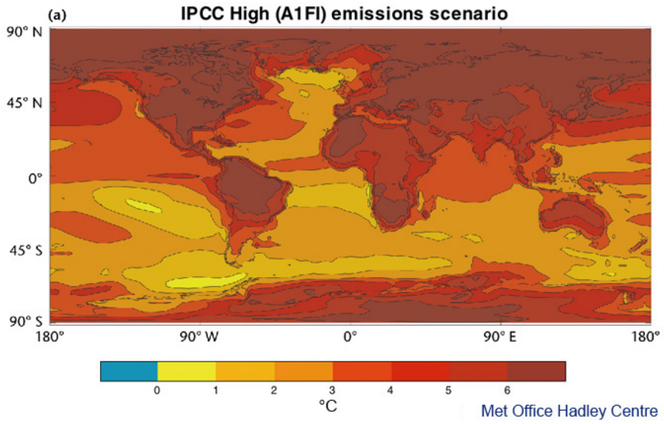


FIGURE 7: (Crown Copyright 2005, data supplied by the Met Office): Pattern of annual temperature changes in the 2080s relative to the present day. The change in surface temperature in the northern winter (December to February) averaged over that last 30 years of the century (centred on the 2080s) compared to a recent reference period (1961-1990) if emissions follow a high emissions scenario.

The impacts are not restricted to temperature. A warmer world will mean more evaporation and so more water held in the atmosphere leading to more rain on average. Importantly, this also means that there is more energy available in the water cycle. The net result of these factors is that the water cycle becomes more intense leading to more storms and flash floods and also more droughts. The influence of climate change on patterns of natural climate variability such as the El Nino or the Asian monsoon are still not well understood, but could have significant impacts on global rainfall patterns; this is an important area of research.

A further impact is that the warming of the oceans leads to sea level rise, which I discuss in more detail below. Finally, carbon dioxide can dissolve in the oceans and make them more acidic, impacting on the ability of the oceans to further absorb carbon dioxide and on marine ecosystems and the resources they provide worldwide.

Sea Level Rise

As the oceans warm they expand, causing the sea level to rise. The transfer of heat to the oceans takes place very slowly and so, just from the global warming that has already occurred, sea level will continue to rise for many centuries to come. Further contributions to sea level rise come from the water from the melting of glaciers and ice sheets. Climate models predict that sea level will rise somewhere between 18 and 59 cm by 2100 [16]. Measurements show a higher rate of sea level rise of around three millimetres per year since 1993 [19], but this could be due either to natural climate variability or to anthropogenic climate change, or a combination of both. The figures quoted relate to the global average sea level rise, but there is a large amount of regional variation, dependant on factors such as local sea temperature.

Scientists estimate that if Greenland's climate undergoes a sustained warming equivalent to a global average of around 3°C, the Greenland Ice Sheet will eventually disappear, leading to a rise in sea levels of around seven metres. The melting process would take thousands of years, contributing maybe one to three millimetres per year to sea level rise; but may be impossible to stop once the threshold temperature has been exceeded. Figure 8 shows a prediction of the extent of the melting [20].

On the other hand, Antarctica is expected to increase in mass due to extra snowfall, although there is still the possibility of collapse of the Western Antarctic Ice Sheet, leading to several metres sea level rise on the time scale of thousands of years.

To put this in context, eleven of the world's fifteen largest cities lie along the coast or on estuaries [21]. For Bangladesh, a one-metre rise in sea level would mean a loss of one-fifth of the viable land area, affecting 15 million people [22]. For India, a similar rise could mean around 7 million people displaced [22]. Those people living in low lying, smaller island states may be forced to abandon their land altogether.

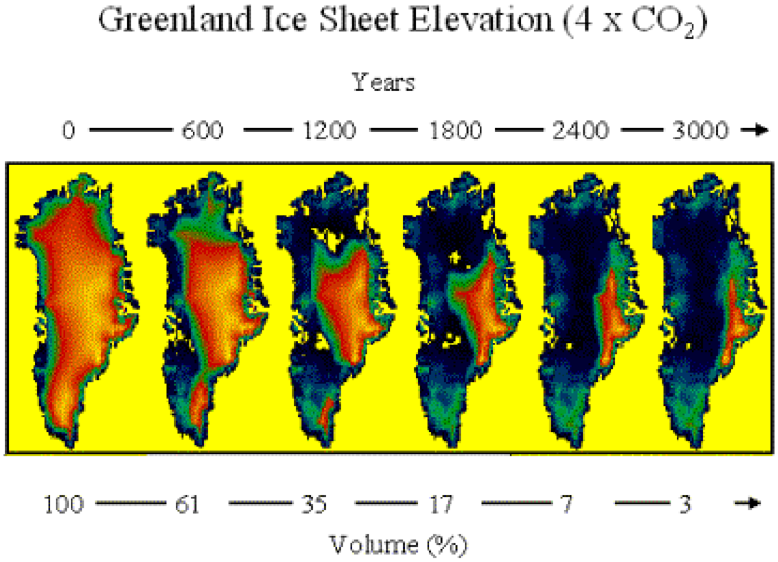


FIGURE 8: (Crown Copyright 2005, data supplied by the Met Office): Change in the ice sheet volume predicted by the Hadley Centre climate model coupled to the Alfred-Wegener Institute ice-sheet model, following a quadrupling of atmospheric carbon dioxide. Yellow indicates thick ice while blue indicates thin (or no) ice. This shows that about half the ice would melt in the first 1,000 years, with almost all melting after 3,000 years. The melt water contribution to sea level rise would peak at about 5 mm/year.

Agriculture

In temperate regions there may be initial benefits for agriculture from a small global temperature rise, due to the longer growing season and the possible fertilisation effect from increased levels of carbon dioxide. But for temperature rises above 2°C agricultural yields are predicted to fall in many regions. In tropical regions, where much farming is already marginal, even small temperature rises are likely to cause falling yields.

The fall in global cereal production resulting from a 2°C global temperature rise could expose up to 220 million more people to the risk of hunger, and a 3°C rise could expose up to 440 million more people, depending on the social and economic factors and the fertilisation effect of carbon dioxide. Even if there were a significant fertilisation effect from higher carbon dioxide levels, and the predictions on this remain uncertain, a 3°C rise could result in 65 countries losing 16% of their agricultural GDP [23].

Water availability

Around one-sixth of the world's population, mainly in the Indian sub-continent, parts of China and the Andes, rely on glaciers for dry-season water supply and will be at risk if these glaciers melt and disappear [24]. Water availability is likely to also be affected by changes to precipitation, although exact patterns are still uncertain. The impacts of changing water availability will depend on a number of factors, including the pattern and rate of climate change. By the 2050s, between 1.1 and 2.8 billion water-stressed people could see a reduction in water availability due to climate change under the most populous future world [25].

Health

Both warming and extreme weather events can contribute to increased levels of disease. The World Health Organisation has estimated that climate change is already responsible for an extra 150,000 deaths each year and that the climate change induced excess risk of the various health outcomes will more than double by the year 2030 [26]. For the higher temperatures, expected later this century, those impacts will be even more severe. A 3°C temperature rise could expose 50-60% of the world's population to dengue fever (currently 30%) and result in an increase of around 18% in potential malaria transmission zones [23].

Ecosystems

The current levels of human impact on biodiversity are unprecedented, driven by a combination of changes in habitat, overexploitation, invasive alien species, pollution and climate change. By the end of the century, climate change and its impacts may be the dominant direct driver of the loss of biodiversity [27]. Many species are unlikely to cope with rapid changes in temperature, precipitation, sea level rise or ocean acidification. One recent study estimates that around 15 – 40% of land species could face extinction with only a 2°C of warming [28].

The loss in biodiversity is a threat to the ecosystem services on which we all depend. For example, 25% of global fish stocks are over-harvested and yet hundreds of millions of people rely on the ocean, lakes and rivers for their food and income. Changes in land cover, such as tropical deforestation, can reduce rainfall and contribute to water shortages. While ecosystems, such as mangroves, play a key role in mitigating the effects of extreme weather events, are in decline. Biodiversity is also important in the capture of carbon dioxide by habitats such as oceans, forests and peat lands, so reducing the atmospheric concentrations.

Extreme Weather Events

As global temperatures rise we can expect increasing extremes in our weather. We have always experienced extreme events and one of the traps in talking about climate change is to attribute a given extreme event as part of a global trend. But certainly we've seen changes in the frequency of extreme events. Previous experience shows that extreme weather related events have significant human and economic costs, for example Hurricane Katrina caused 1300 deaths and €200 billion of direct costs [29] while the
European floods in 2002 caused 37 deaths and €16 billion of direct costs [30].

The European heat wave of 2003 was the biggest natural disaster in Central Europe for at least 200 years, and has been attributed with more than 30,000 deaths and an estimated direct economic cost of $13.5 billion [30]. It has been subjected to a very detailed statistical analysis and as a result, with 90% certainty, we can say that half the severity of that heat wave can be attributed to global warming. Models predict that in about 30 years time the summer of 2003 will become Europe's average summer. By the latter part of this century it will seem cool [31].

CONCLUSION

While categorical proof is not possible, the level of evidence that the world is warming due to human activities is more than sufficient to take action. It is now clearly demonstrable that the risk of serious climate change is sufficiently great and that the benefits of action far outweigh those of inaction.

Climate change has no regard for international boundaries and every part of the world will be affected. The worst fallout will be experienced in the world's poorest countries, which have contributed least to the problem and are both the most vulnerable and the least able to adapt. It is a truly global problem that requires truly global solutions. The earlier we start the more options we will have, the lower the risks and costs, and the greater the chance of success.

I believe climate change is the biggest single global challenge that we face. Our success or failure in taking the steps necessary to tackle it now, and over the next couple of decades, will play out for centuries to come. If unchecked, and if we fail to adapt, it has the potential to be catastrophic. It is a serious problem and solving it will not be easy. But, with commitment and innovation, it can be done.

References

[1] Siegenthaler U *et al* (2005), Stable Carbon Cycle–Climate Relationship During the Late Pleistocene *Science* 310, 1313-1317

[2] Radiative climate forcing by long-lived greenhouse gases: the NOAA annual greenhouse gas index (2005), http://www.cmdl.noaa.gov/aggi/

[3] Climate Change and the Greenhouse Effect, A briefing from the Hadley Centre, December (2005) p16 (and references therein)

[4] Stern Review: The Economics of Climate Change (2006), p3

[5] Augustin L *et al (*EPICA community members) (2004), Eight glacial cycles from an Antarctic ice core, *Nature* 429, 623-628

[6] Climatic Research Unit (2005) http://www.cru.uea.ac.uk

[7] Brohan P *et al* (2006), Uncertainty estimates in regional and global observed temperature changes: a new dataset from 1850, *Journal of Geophysical Research* 111, D12106

[8] USGS Repeat Photography Project, http://www.nrmsc.usgs.gov/repeatphoto/overview.htm

[9] Soden BJ *et al* (2005), The Radiative Signature of Upper Tropospheric Moistening, *Science* 310, 841-844

[10] IPCC Third Assessment Report: Climate Change (2001), updated by Hadley Centre, Met Office

[11] Lean J, Beer J and Bradley R (2005), Reconstruction of solar irradiance since 1610: Implications for climate change, Geophys. Res. Letts 22, 3195-3198

[12] Barnett TP *et al* (2005), Penetration of Human-Induced Warming into the World's Oceans, *Science* 309, 284-287

[13] US Climate Change Science Program, Temperature Trends in the Lower Atmosphere: Steps for Understanding and Reconciling Differences (April 2006)

[14] Murphy J *et al* (2004), Quantification of modelling uncertainties in a large ensemble of climate change simulations*, Nature,* 430, 768-772

[15] Stern Review: The Economics of Climate Change

[16] IPCC Fourth Assessment Report: Climate Change (2007) (WG1 report)

[17] For example, Stainforth DA *et al* (2005), Uncertainty in predictions of the climate response to rising levels of greenhouse gases, *Nature* 433, 403-406

[18] Johns RC *et al* (2003), Anthropogenic climate change for 1860 to 2100 simulated with the HadCM3 model under updated emissions scenarios, Clim. Dyn. 20, 583-612

[19] Cabanes C, Cazenave A and Le Provost C (2001), Sea Level Rise During Past 40 Years Determined from Satellite and in Situ Observations, *Science* 294, pp. 840 - 842

[20] Stabilising climate to avoid dangerous climate change — a summary of relevant research at the Hadley Centre, Hadley Centre (January 2005)

[21] Gornitz V (2000), Coastal Populations, Topography, and Sea Level Rise, NASA GISS Science Brief, http://www.giss.nasa.gov/research/briefs/gornitz_04/

[22] Nicholls RJ and Mimura N (1998), Regional issues raised by sea level rise and their policy implications. Climatic Research 11, 15-18.

[23] Warren R (2006), Impacts of Global Climate Change at Different Annual Mean Global Temperature Increases, Avoiding Dangerous Climate Change, p93-131

[24] Barnett TP, Adam JC and Lettenmaier JP (2005), Potential impacts of a warming climate on water availability in snow-dominated regions, *Nature* 438, 303-309

[25] Arnell NW (2006), Climate Change and Water Resources: A Global Perspective, Avoiding Dangerous Climate Change, p167-176

[26] Patz et al (2005), Impact of regional climate change on human health, *Nature* 438, 310-317

[27] Millennium Ecosystem Assessment (2005), Ecosystems and Human Well-being: Biodiversity Synthesis. World Resources Institute, Washington, DC

[28] Thomas, CD *et al* (2004), Extinction risk from climate change, *Nature* 427, 145-148

[29] US State Department Website

[30] House of Lords Economic Affairs Committee (June 2005), Minutes of Evidence, Annex 4

[31] Stott PA, Stone DA and Allen MR (2004), Human contribution to the European heat wave of 2003, *Nature* 432, 610-614

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ISBN 978 0 901469 61 8

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