CARBON TRUST

Making business sense of climate change

The Climate Change Challenge 1: Scientific evidence and implications

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Foreword

Climate change is emerging as a major challenge for modern society. Government, business, and wider society will all be affected and all have a role to play in tackling it. This report is the first in a series of Carbon Trust reports that are designed to help businesses in particular to understand the nature of the challenge, why and how governments are acting to address it, and what the implications may be. The reports are subject to both internal and external international review.

This report summarises the nature of the problem. It explains the fundamental science and the accumulating evidence that climate change is real and needs to be addressed. It also explains the future potential impacts, including the outstanding uncertainties.

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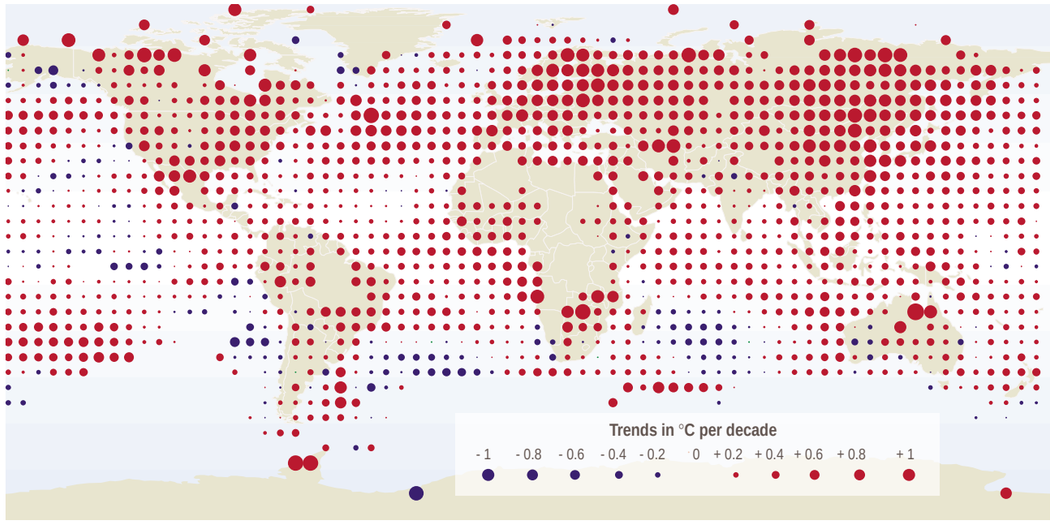
Chart 1. Temperature changes around the world in the last quarter of the 20th century



Large-scale warming of both the land and ocean surface occurred in the last quarter of the 20th century, with the largest increases over mid and high latitudes of North America, Europe and Asia. The pattern, including faster warming over land than oceans and faster near the poles than equator, is consistent with that expected from greenhouse-gas warming.

Source: Intergovernmental Panel on Climate Change, Third Assessment, Climate Change 2001: Synthesis Report (Figure 2-6b)

Is climate change real?

Emissions of various gases from industrial and other human activities are changing our atmosphere. 'Climate change' encapsulates the wide variety of accompanying impacts on temperature, weather patterns and other natural systems. Despite decades of research, important things remain uncertain, but much is also now established beyond reasonable doubt.

The fundamental science of climate change

The fundamentals of climate change have long been well understood because they involve the same basic physics that keeps the earth habitable. Heat-trapping 'greenhouse gases' in the atmosphere (of which the two most important are water vapour and carbon dioxide, CO_2) let through short-wave radiation from the sun but absorb the long-wave heat radiation coming back from the Earth's surface and re-radiate it. These gases act like a blanket - and keep the surface and the lower atmosphere about 33 deg. C warmer than it would be without them. The Earth's greenhouse blanket is a good balance between the extremes of our neighbours: Mars, exposed without any greenhouse gases, is a frozen wasteland; whilst Venus remains trapped in a dense blanket of hot CO_2.

Primarily through the burning of fossil fuels, and long-term deforestation, humans have been increasing the concentration of CO_2 and other greenhouse gases in the atmosphere since the industrial revolution began, thickening the greenhouse blanket.

The world has been warming

Surface warming in recent decades is established beyond doubt. So too is cooling of the stratosphere (the layer above the main 'blanket'), as would be expected from greenhouse warming that traps more heat near the surface. Direct temperature records back to the middle of the last century are considered to be reliable enough to establish that recent temperatures are warmer than any since direct measurements began - all of the 10 warmest years have occurred since 1990, including each year since 1995.

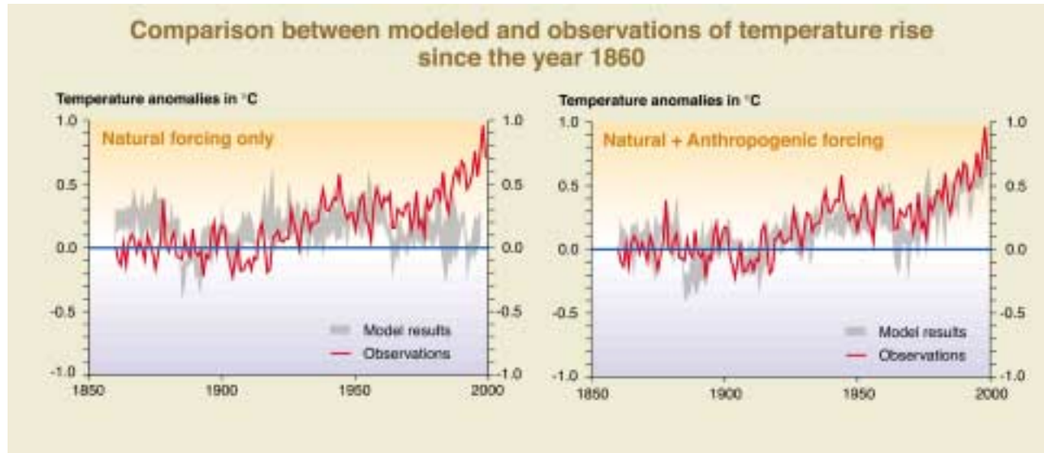
During the middle of the 20th Century there was a plateau in global temperatures with decline in the northern hemisphere. This was due at least partly to other pollutants (notably sulphur) temporarily blocking sunlight and masking the underlying trend. Since the 1980s, the clean-up of sulphur emissions (to avoid acid rain damage) has reduced this masking, and the underlying, long-term greenhouse warming has emerged more clearly. Better accounting for these and other factors can now generate a good fit between the observed temperature trend and the results of computer simulations that incorporate these multiple factors (Chart 2).

A wide variety of 'proxy indicators' (such as tree rings, coral layering, glacier records, etc.) give a high confidence that the warming observed is unprecedented for at least the past 1000-2000 years (see also Annex). Indeed it appears that global average temperatures have varied by less than half a degree C for thousands of years, and probably during the entire post Ice-Age period during which human civilisation has developed, so that recent years are probably the warmest seen for more than 100,000 years.

Natural fluctuations can certainly affect global temperatures, but scientists have been unable to identify natural factors that could explain either the degree or the pattern of the surface warming and stratosphere cooling observed over recent decades. In addition, climate change models predict that greenhouse warming should be greater over land than over the oceans, and greater near the poles than the equator. This is what has been observed (Chart 1, page 2).

Understanding is still incomplete. The causes of slight mid-atmosphere cooling near the equator remain uncertain, and debate continues as to whether there is any discrepancy between the long-standing surface records and more recent, more disparate satellite-based temperature measurements (see Annex). But the fundamentals are clear and supported by a long list of other accumulating impacts.

Chart 2. Global temperature changes since 1860



These figures show average global surface temperature as measured (red line), compared to estimates from a computer simulation, respectively without (left) and with (right) the effects of human emissions included.

Source: Reproduced from Intergovernmental Panel on Climate Change, Third Assessment, Synthesis Report, 2001 (Figure SPM-2).

Other observed indicators and impacts of our changing climate

The list of observed changes other than temperature and sea-level is growing rapidly. These include 'the thawing of permafrost, later freezing and earlier break-up of ice on rivers and lakes, lengthening of mid to high-latitude growing seasons, poleward and altitudinal shifts of plant and animal ranges, declines of some plant and animal populations, and earlier flowering of trees, emergence of insects, and egg-laying in birds'.[1]

Perhaps the most clear, prominent and consistent indicator is the retreat of mountain glaciers (e.g. Chart 3) which has been a worldwide phenomenon. Impacts on ice are also clear around the poles. The Arctic ice cap is shrinking, whilst in Antarctica, massive calving of the Larsen Ice Shelf combined with rapid rise in local temperatures around the Antarctic peninsula – still incompletely understood - has led scientists to predict its complete disappearance within decades. Another widely-observed impact is the 'bleaching' of coral reefs caused at least in part by rising sea-surface temperatures.

Changes in extreme weather events potentially have the greatest impacts on humans, but since by definition they occur infrequently, trends are hard to prove. Warming increases evaporation and precipitation, and both aggregate rainfall and occurrences of 'heavy precipitation events' in northern mid-latitudes (e.g. Europe and the US) - the principal cause of flooding - have increased in recent decades. In tropical regions, the potential for more intense hurricanes and typhoons increases in a warmer world, but the data are sufficiently sparse and complex that the observational trend remains in dispute.

The impact on some other extremes is better established. Many areas (including the UK) have seen fewer long cold spells and more long hot spells, in ways that are consistent with the predictions of climate models. But unlike the general trends of temperature, ice and sea level, it may always be questionable to attribute any one particular weather event to climate change, because all weather events have multiple causes. So the question 'was X due to climate change?' cannot be answered simply – whether X was last year's record temperature in the UK (which for the first time ever exceeded 100 deg.F), droughts in the US, or the devastating floods of Central Europe. But science may increasingly be able to estimate 'how much have past emissions increased the risk of such events?' – and the chances, at least of extremes such as these, are rising.

Insurance data (Chart 4) show a dramatic rise in the economic costs due to extreme weather events, though a major part of this is probably due to changes in demographics, property valuation and insurance practices.

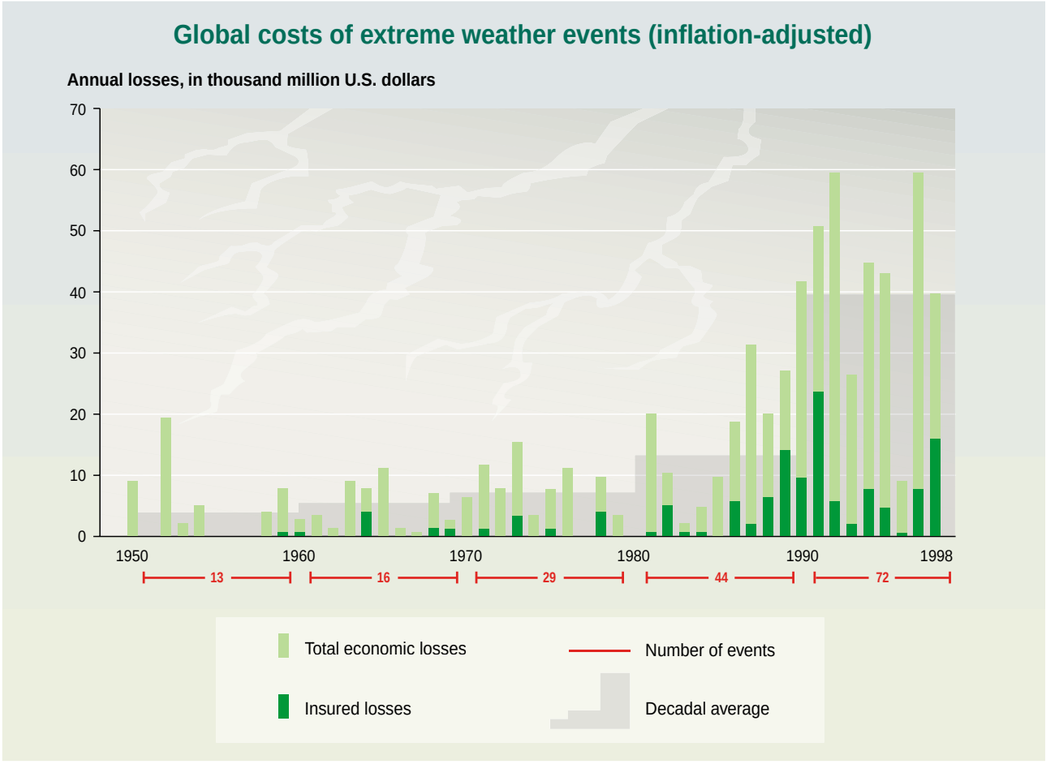
[1]Cited from IPCC Third Assessment, Climate Change 2001, Report on Impacts, Adaptation and Vulnerability (Policymakers Summary).

Chart 3. Alpine Glacier: comparison of present to 1900
Pasterze Glacier in Kärtnen, Austria

A. Circa 1900
Photo Source: Munich Society for Environmental Research

B. Recent

Chart 4. Global costs of extreme weather events (inflation-adjusted) since 1950



The economic losses from catastrophic weather events have risen globally 10-fold since the 1950s, after accounting for inflation. Part of the trend is linked to growing wealth and population, which increases economic vulnerability to extreme events, and part is linked to regional climatic factors (eg. changes in precipitation and flooding).

Source: Intergovernmental Panel on Climate Change, Third Assessment, Climate Change 2001: Synthesis report (Figure 2-7)

To disentangle the climate-change-induced component, a recent study by the British Meteorological Office looked at trends in the number of gales. Based on data from 28 pressure measurement sites they found an increase in UK storminess since 1970 both in the Autumn period October-December, and in the Spring period January-March, though the latter peaked in the late 1980s. There is also (wave-height) evidence that the beginning of the 20th Century was similarly stormy, however, so the debate about greenhouse impacts on storms in mid-latitudes continues.

The distinction between climate and weather is itself a bit like that between sea-level and waves. Sea-level sets average conditions which vary locally according to tides and coastline, but even understanding all these does not mean one can easily pick out trends from individual waves, or predict them in detail. But the complexities and uncertainties around climate change should not obscure the basic facts. The fundamental mechanics of climate change are well understood; the world is warming; and much of the warming is due to human emissions of greenhouse gases. The next sections explain why climate changes seem set to accelerate in the future, and the varied impacts this may bring.

Box 1: Why is projecting climate change so complex?

Although the basic mechanisms of climate change are straightforward, the final consequences for temperature and specific impacts can be extremely hard to quantify. Warmer average temperatures mean that more water evaporates; this can multiply the original effect through water vapour's own greenhouse forcing, but also generates more clouds, which affect heat transfer in various ways. Melting ice may leave darker surfaces that increase the heat absorbed at the surface, but the faster hydrological cycle may also increase snowfall. In addition, pollutants other than greenhouse gases can influence climate, regionally and globally, for example by scattering sunlight. The role of the oceans, which store vast amounts of heat and move it around in ocean currents, is also complex.

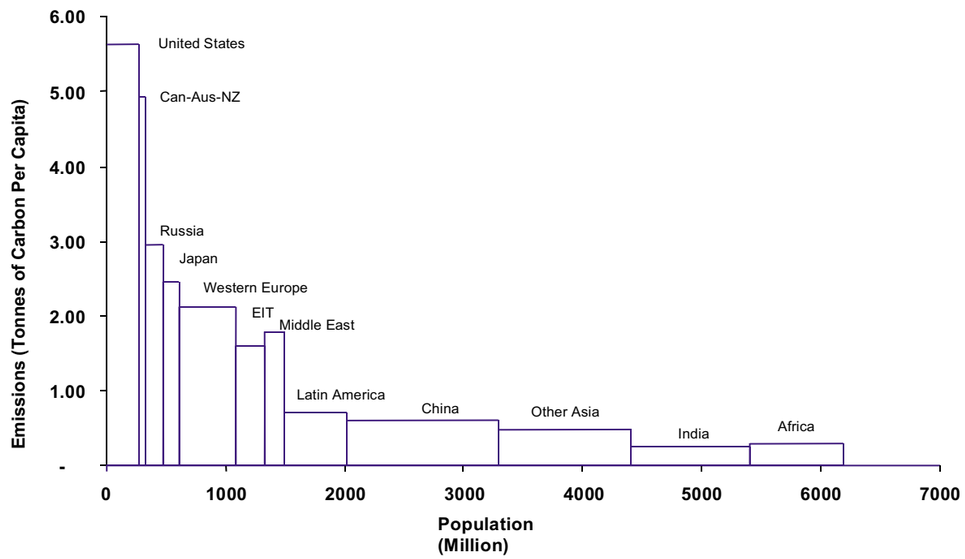
This introduces some deep uncertainties into efforts to quantify climate change. Greenhouse gases will in aggregate warm the surface, but by how much and how fast only becomes clearer as the warming signal emerges more and more clearly from amidst all the other influences. Even then, it is very hard to disentangle the effect of the oceans' thermal inertia from the actual 'climate sensitivity' - slow warming may be a sign either of low atmospheric sensitivity, or it may show that decades more unavoidable climate change remains pent up in the slowly warming oceans.

The chaotic nature of weather itself (as opposed to the 'climate envelope') makes regional climate changes and extreme events even harder to predict, and scientists are only slowly moving towards greater confidence about such effects.

Projecting climate change

Projecting future climate change is a complex and evolving science. There are important intrinsic scientific uncertainties (see 'Why is projecting climate change so complex?'), to which must be added uncertainties in future emissions. Despite the emerging efforts to limit emissions, these are widely projected to grow not least because of the huge international disparities as indicated in Chart 5. Per capita emissions in the industrialised countries are typically as much as ten times the average in the more populous developing countries, particularly Africa and the Indian subcontinent. If industrialised countries are struggling to limit their emissions, it is hard to see rapid emissions growth in the rest of world being curtailed, as developing countries aspire to follow the same kind of fossil-fuel based economic development. The potential for global emissions growth is thus huge, even if and as leading countries start to embark upon more serious action.

Chart 5. CO_2 emissions in different regions in 2000, per capita and population



The chart shows the global distribution of CO_2 emissions in terms of three major indices: emissions per capita (height of each block); population (width of each block); and total emissions (product of population and emissions per capita = area of block). Per capita emissions in the industrialised countries are currently as much as ten times the average in developing countries, particularly Africa and the Indian subcontinent.

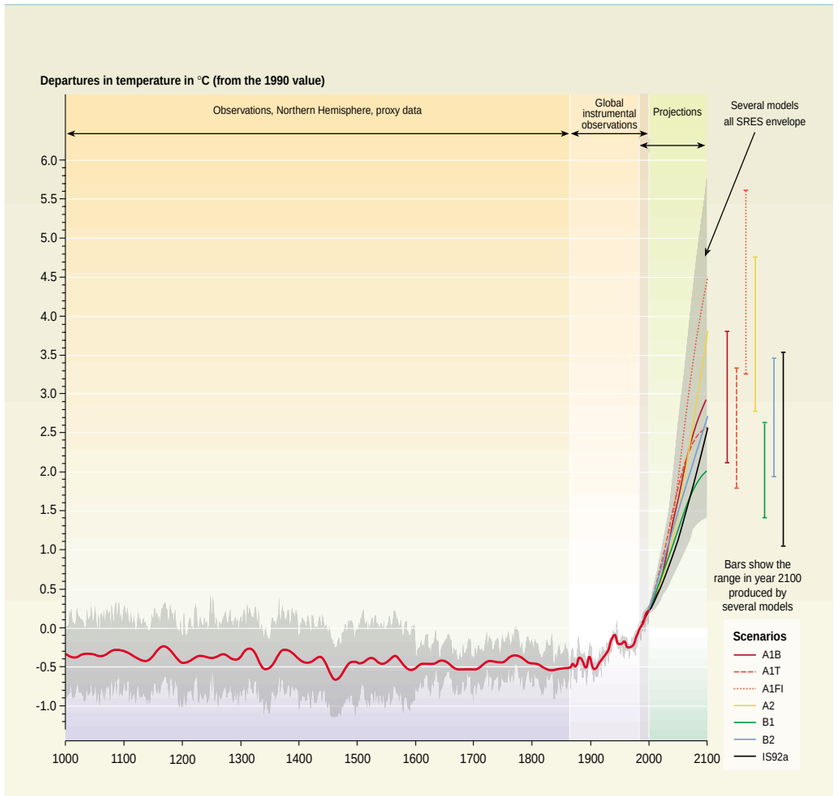
Source: Author, with data from US Energy Information Administration, http://www.eia.doe.gov/iea/

The main estimates of global temperature change produced to date, from a wide set of scenarios by the Intergovernmental Panel on Climate Change (see Annex) are illustrated and compared against the past 1000 years in Chart 6. This projects that global temperature will increase by 1.5 to 5.8 deg.C by the end of the century; the latter number is comparable to the rise that occurred between ice age and pre-industrial temperatures.

Some of the big, persistent trends indicated for example in glaciers, which embody a lot of inertia also due to past warming, can already be projected with confidence. The snows of Kilimanjaro, for example, already much shrunk, are expected to disappear entirely within the next few decades - it is already too late to avert this (Chart 7). Glaciers and sea ice will continue to shrink, and there may be no Arctic sea ice in summer by the end of this century. The Antarctic ice sheet, being in a much colder climate, is less likely to lose mass, not withstanding some shrinking ice shelves around it.

Existing zones of preferred vegetation and associated crops will migrate towards the poles, requiring farming practices and ecosystems to adapt. However, many species and ecosystems have limited scope to move, because of a wide variety of barriers. The most comprehensive study to date estimates that about a quarter of the world's known animals and plants - more than a million species - will eventually die out because of the warming projected to take place in the next fifty years.

Chart 6. Projected temperature change compared to past 1000 years



The chart shows projected changes in global temperature (relative to 1990) for this century compared to the record since 1000 (northern hemisphere proxy data only available for period before 1860, direct global measurements since then). The lines show (past) the 50-year averaged and (future) projected temperatures associated with the various emission scenarios of the IPCC (see Annex) assuming average climate sensitivity. The grey zones illustrate (past) estimated uncertainties in measurements, and (future) in temperature projections arising from combination of different scenarios and climate sensitivities.

Source: Intergovernmental Panel on Climate Change, Third Assessment Synthesis Report (Figure. SPM-10b)

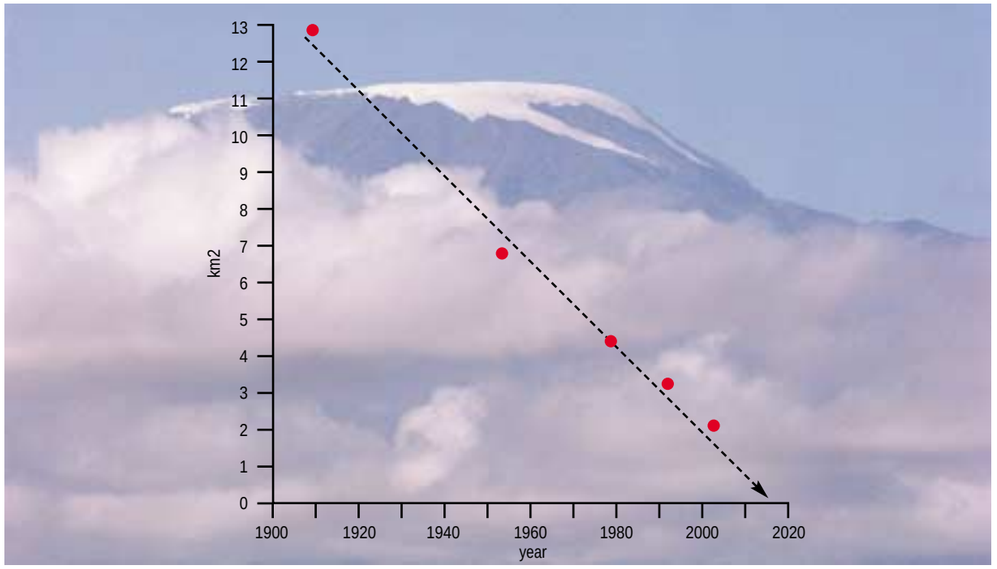
Box 2: What about Europe - why do some talk about UK cooling?

In the global climate, Europe is an anomaly. Northern Europe in particular, despite being at similar latitude to Newfoundland, is far warmer because of the Gulf Stream - the ocean current system known as the North Atlantic Thermohaline Circulation (together with associated wind patterns). This draws heat from the tropics (and in fact more widely) in the warm surface waters, and releases it in the north-east Atlantic to give Europe the mild conditions to which it has become accustomed. The warm water floats on the cold and more dense returning currents beneath, but evaporation makes the surface water progressively cooler and more salty and hence heavier, and when it has cooled enough, it sinks under its own weight, powering the continued circulation.

However, the faster hydrological cycle and accelerated melting of ice with global warming - particularly from Greenland and a number of large Siberian rivers - dilutes the surface waters and is thus expected to slow the oceanic circulation. Under most simulations, the net effect would be to slow down projected warming in the North Atlantic region.

But the thermohaline circulation appears to have cut off during ice ages – and indeed this shutdown probably helps to switch the world between ice-age and non ice-age states. Furthermore, it happened rapidly – in a matter of a few years – possibly associated with the collapse of ice sheets or ice barriers. Scientists do not understand the mechanisms well, but current modelling studies do not suggest a collapse of the thermohaline circulation this century.

Chart 7. The snows of Kilimanjaro



The picture shows Kilimanjaro with (superimposed) a graph showing the decline in ice cover during the 20th century and projection of its disappearance by c.2020.

Data Source: Prof. Lonnie Thompson Byrd Polar Research Center, Ohio State University 1090. Alverson et al., Science 293:47

Specific impacts and human risks

In addition to the broad physical and biological trends of warming and glacier retreat, sea-level rise, and the migration and loss of species and ecosystems, other predicted impacts of climate change are many and varied, and as research continues and experience begins to accumulate the list grows longer.

Combined with the probability of changing storm patterns, rising sea levels could have huge consequences for hundreds of millions of people living in coastal cities; delta regions such as the Nile Delta, lower Bangladesh, and parts of Florida, may be intrinsically difficult or impossible to protect.

Scientists rate the following other changes to be very likely (with more than 90% confidence):[2]

- Higher maximum temperatures, with more hot days and heat waves over nearly all land areas. This would increase heat-related deaths, as well as heat-related stresses on crops, livestock, etc.;
- Higher minimum temperatures, fewer cold days, frost days and cold waves over nearly all land areas. This would reduce cold-related deaths and crop and livestock-related stresses associated with frost and other cold conditions. The balance between this and the first set of effects obviously depends on the starting conditions, but also on the rate and degree of change. Tentative estimates predict net agricultural gains for the US and Europe for equilibrium global changes up to 2.5 deg.C (this does not include transitional effects), the balance becomes negative for greater changes; and
- More intense precipitation events, resulting in increased floods, landslide, avalanche, and mudslide damage, with increased soil erosion and increased flood run-off.

The following changes are rated as likely (with confidence greater than two-thirds):

- Summer drying over most mid-latitude continental interiors and associated risk of drought;
- More intense tropical cyclones (in terms of both wind and rainfall);
- Intensified droughts and floods associated with the Pacific El Niño events, in many different regions; and
- More variable Asian summer monsoon, obviously of particular relevance to the half the world's population that live in China, India and surrounding countries.

Two regional examples help to illustrate possible consequences. Summer drying and heatwaves in and around the Mediterranean could further stress water supplies in some regions that are already politically sensitive and heavily dependent upon irrigation for agriculture. The suffering could also drive expanded migration into northern Europe which might itself come under growing pressure from increased floods and heatwaves.

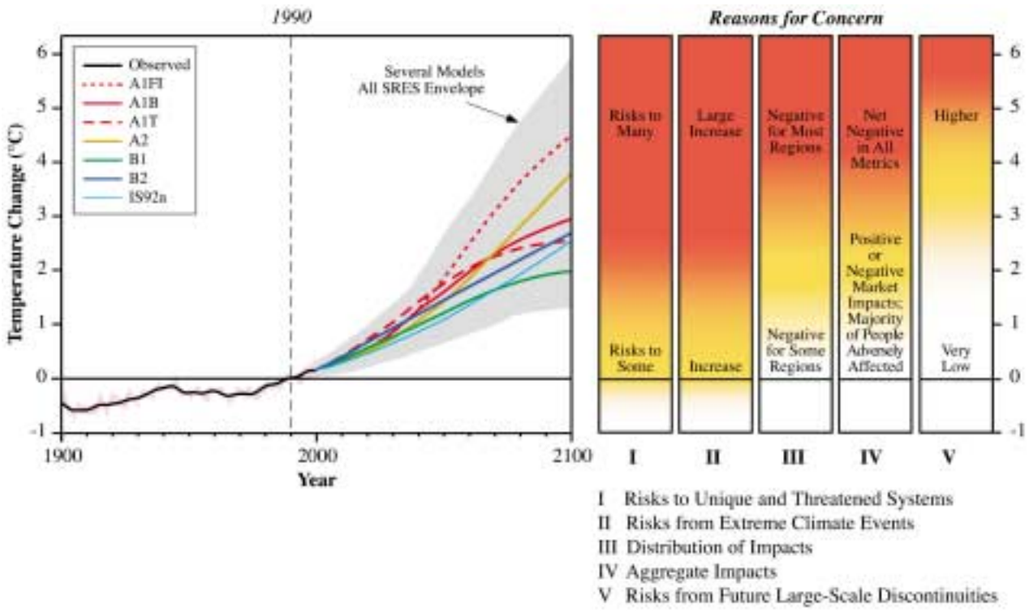
On the Indian subcontinent, Bangladesh and north-east India could face a number of diverse pressures: rising seas and storms inundating the Ganges delta region; a more variable monsoon undermining the agricultural foundations that feed a quarter of a billion people; and changing patterns of river flow as climate change impacts the Himalayan glaciers that feed the rivers, with corresponding international tensions across already volatile borders.

[2]This list is drawn from the IPCC 3rd Assessment, Report on Impacts, Adaptation, and Vulnerability, Table SPM-1.

These are just tentative examples; the possible human consequences of climate change are only just beginning to be seriously considered. A particularly complex consideration is that whilst most scientific studies have focused upon the possible impacts of a *warmer* world, most human impacts may flow from the nature of a *warming* world, in which change - often hard to predict at the local level - may be the most difficult characteristic for societies to handle. Farming practices, water industries, and innumerable other social and infrastructural systems designed for the last century's climate will not necessarily adapt easily to the accelerating change now in prospect, particularly as some of the underlying natural systems are also pressured by global economic and population growth.

The impacts of projected climate changes have been summarised in terms of five risk categories (Chart 8). This suggests that even at the most optimistic end of projections, some unique and threatened ecosystems will disappear and some regions will be exposed to adverse impacts. In the mid range, many unique systems may be at risk and the impact of extreme events would rise, with the developing countries hurt the most although impact on the aggregate global economy could still be modest. Changes towards the upper end pose risks to all and the risk of large-scale abrupt disruptions becomes significant.

Chart 8. Five risk indicators associated with projected global temperatures changes



The chart shows how the projected range of temperature changes for this century (left hand panel) would affect the risks posed in terms of five generic 'reasons for concerns' (right hand panel). In the columns, white indicates neutral or small impacts, yellow indicates negative impacts for some systems or low risk, and red means negative impacts or risks that are more widespread and/or greater. The five columns concern (i) risks to unique and threatened ecosystems, (ii) the risks from extreme climate events; (iii) the risks posed to specific regions, with only the most vulnerable being affected in the white/yellow zone but most in the red zone; (iv) the aggregated impact on the global economy, and (v) the risk from large-scale climatic discontinuities (such as collapse of ocean circulation patterns). The assessment took account only of the magnitude, not the rate, of change.

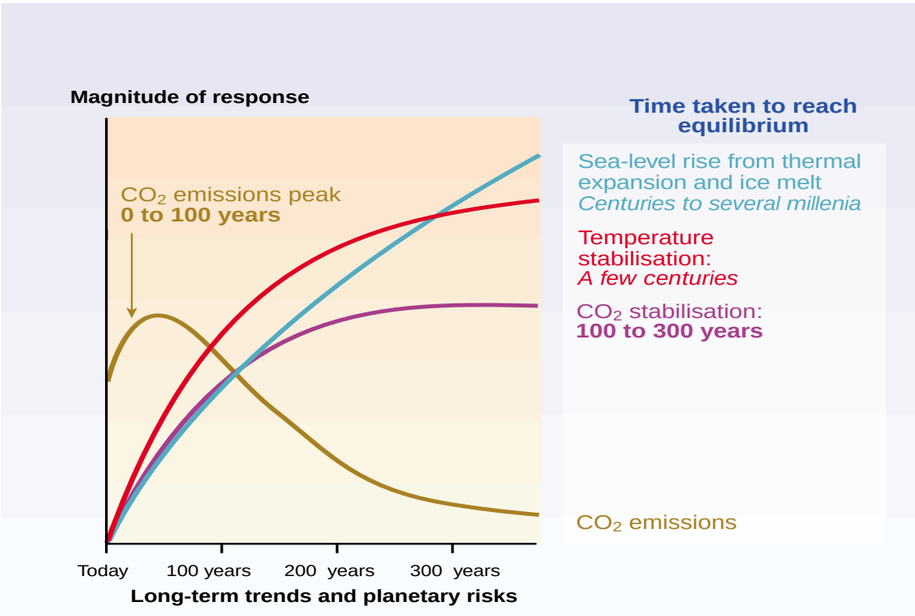
Source: Intergovernmental Panel on Climate Change, Third Assessment, Report on Impacts, Adaptation, and Vulnerability, (Figure SPM-2)

Long term trends and planetary risks

One fundamental characteristic of the climate problem is the inertia involved. Atmospheric greenhouse gas concentrations will not stabilise until global greenhouse gas emissions are reduced to a small fraction of today's levels, which few expect before the end of the century. Even after the atmosphere stabilises, other effects will continue to accumulate.

Global temperatures will continue to rise for decades as the oceans slowly adjust to the higher heat input. Sea levels will rise due to both thermal expansion and ice melt – effects which will accumulate over hundreds to thousands of years respectively (see Chart 9): over centuries, sea levels would rise many metres if and as the Greenland and/or west Antartic ice sheets disintegrate. Emission choices over the next few decades (which will affect emissions and concentrations for decades beyond that) will thus do much to determine [sea] temperatures for centuries, and ultimate sea-level rise by some metres.

Chart 9. Accumulating impacts of climate change over the long term



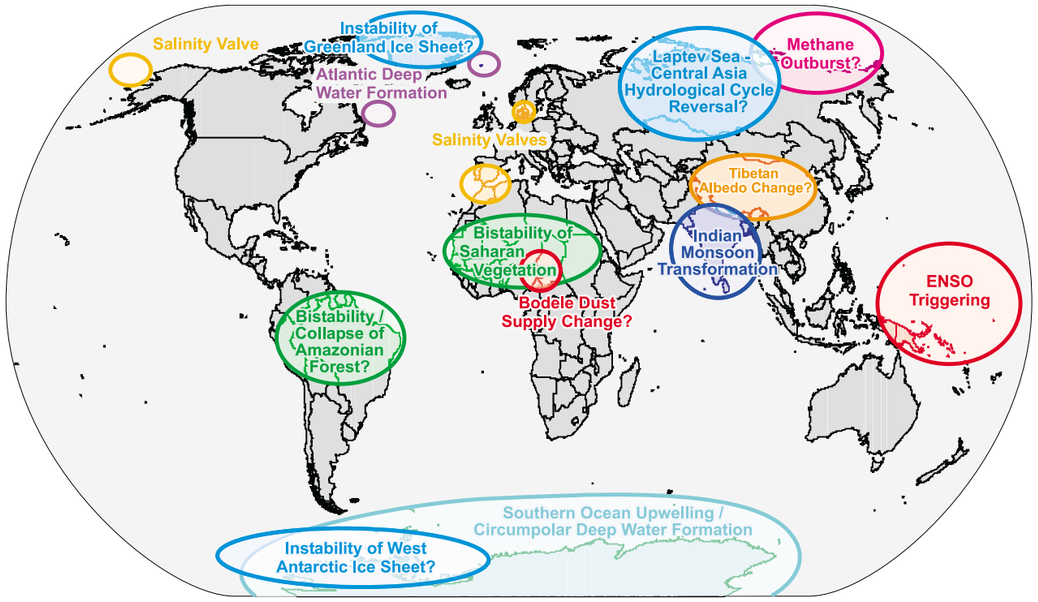
The chart shows how key aspects of climate change will continue to accumulate long after global emissions are reduced even to low levels. Temperatures would continue to rise slowly for a few centuries as the oceans continued to warm; but sea level rise would continue for hundreds to thousands of years, due to the continuing impact on ice sheets in addition to thermal expansion of the oceans. The impact on species might also continue for centuries as the effects on ecosystem viability play out (not shown).

Source: Adapted from the Intergovernmental Panel on Climate Change, Third Assessment Synthesis Report, (Figure SPM-5)

In addition, scientists studying the interaction between different components of the climate system, and related natural systems, express concern about various possible instabilities. The North Atlantic ocean circulation is the best known (see Box 2), but is by no means the only example. Some studies question the stability of monsoon patterns particularly on the Indian subcontinent. The UK Hadley Centre projects that climate changes over Amazonia will lead to loss of the rainforest, and greater carbon emissions from soils as temperature increases, which then feeds more carbon back into the atmosphere and amplifies the warming. Another feedback effect is that thawing permafrost in the far north is likely to release pent-up methane (another and potent greenhouse gas) - perhaps the most likely near-term such danger. Other very long-term possibilities include the collapse of the west Antarctic ice sheet, and the release of huge amounts of methane currently locked on the sea bed.

There are inherent uncertainties about such systems; the dynamics that keep them stable, and their limits, are not well understood. When it comes to such big questions about complex systems, uncertainty is endemic. But especially given the inertia in all these systems, by the time the limits are understood - they may already be crossed, possibly with dramatic consequences.

Chart 10: Potentially sensitive 'switch point' areas in which local effects might trigger larger-scale changes



The chart shows regions in which specific local phenomena may result in points of sensitivity for larger-scale and possibly rapid changes in regional or global climatic conditions.

Source: J. Schellnhuber and H. Held, adapted from 'How Fragile is the Earth System?, in J. Briden, and T. Downing, T.(Eds.), Managing the Earth: the Eleventh Linacre Lectures, Univ. Press., Oxford (2002).

How has the world responded and what are the options?

Climate change is no longer a new issue. After scientific consensus on the fundamentals emerged from a series of international workshops during the 1980s, governments led by the Reagan Administration established the Intergovernmental Panel on Climate Change (IPCC) in 1988 to help them understand and build some international consensus on the nature of the problem. The IPCC has been termed the 'most extensive and carefully-constructed international advisory process in history' (see Annex).

The IPCC's first report, in 1990, confirmed the basic scientific cause for concern and thus laid the basis for negotiation of an international treaty to start combating the problem. This emerged as the UN Framework Convention on Climate Change (UNFCCC), signed at the Rio Earth Summit in 1992. In negotiating and ratifying the UNFCCC, virtually all countries in the world agreed certain basic principles, including that:

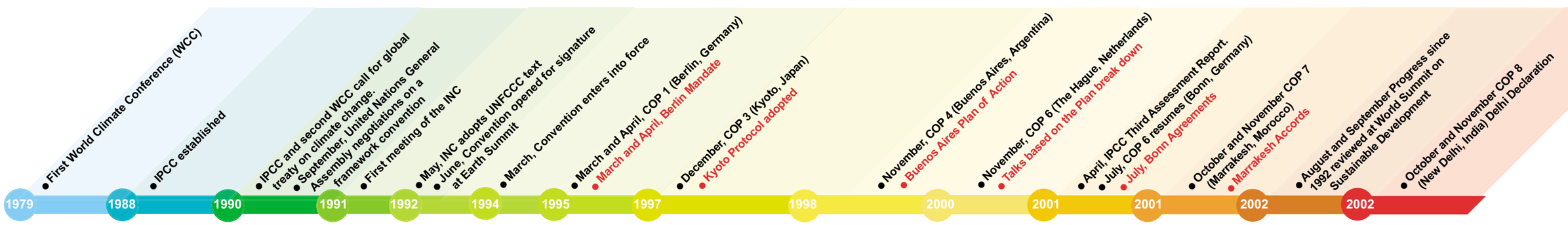
- Remaining scientific uncertainties should not be used as a reason for inaction;
- Action should aim to stabilise atmospheric greenhouse gas concentrations 'at a level that would prevent dangerous anthropogenic interference with the climate system within a time-frame sufficient to allow ecosystems to adapt naturally to climate change, to ensure that food production is not threatened and to enable economic development to proceed in a sustainable manner'; and that
- Action should be based on 'common but differentiated responsibilities' between countries, with industrialised countries taking the lead in tackling the problem.

The Convention established an annual Conference of Parties (COP) to oversee its implementation, and embodied a non-binding initial goal that industrialised countries should aim to return their emissions to 1990 levels as a first step.

The IPCC's Second Assessment, completed in 1995, concluded not only that climate change was being observed, but for the first time that the balance of evidence suggested a 'discernible human influence' in the observed changes – moving it from the realm of scientific theory to hard evidence of emerging impacts. This, and the evident failure of most industrialised countries to start delivering on the non-binding 'first-step' aim of the Convention, was a prime reason for countries to move towards specific, legally binding, emission targets under the Kyoto Protocol.

The IPCC continued to a Third Assessment in 2001 which strengthened the scientific foundations, reporting 'new and stronger evidence' of human-induced climate change, and added much detail about potential regional impacts. However, the decision by the incoming Bush administration to reject Kyoto, and continued prevarication about the Treaty by Russia, has led to an increasing search for other approaches.

Given the background of steadily strengthening evidence, it is not credible simply to continue waiting for outstanding scientific uncertainties to be resolved. Such uncertainties concern not the fundamentals of whether there is a problem, but the specifics of what the impacts will be in particular regions and how fast they will accumulate. Reducing these uncertainties is likely to be a slow business, and some are only likely to be resolved as accumulating impacts themselves strengthen the statistical basis upon which evaluation of trends in extreme weather events, for example, ultimately rest. Unfortunately, because of the inertia in the natural systems involved (particularly the oceans and ice sheets), by the time such evidence emerges clearly above the noise of natural fluctuations there are decades more climate change already pent up and unavoidable. Waiting for more evidence is in effect committing to accept ongoing and accelerating climate change.



Source: UNFCCC, Caring for the Climate Guide

Can we just adapt to climate change?

One approach is to focus chiefly upon adapting to climate change, reducing or abandoning efforts to limit emissions as being just too difficult. Substantial adaptation now appears unavoidable: as is apparent from the previous discussion, quite a lot of climate change is already pent up and can no longer be avoided.

Initially, the main impacts of climate change are a slight aggravation of existing weather fluctuations. Victims of extreme weather events - storms, floods, droughts, etc - have no choice but to adapt as best they can after the event. Many adverse impacts can however be reduced by *anticipatory* adaptation, making preparations against such extreme events.

There are however several limitations to relying on adaptation as the prime strategy. It can be very hard to predict exactly what one is trying to adapt to. Sea level rise is relatively predictable but the storm surges that actually inflict the coastal damage are not, except in the broad sense of emerging statistical averages and very short-term warnings, so coastal preparations have to be extensive and costly in advance. In these circumstances, retreat - often in practice after the fact - may be more realistic.

It should be possible for temperate regions to adapt to conditions that are both hotter and wetter if these can be predicted, but impacts of both may be dictated mostly by the extremes that would be hard to predict.

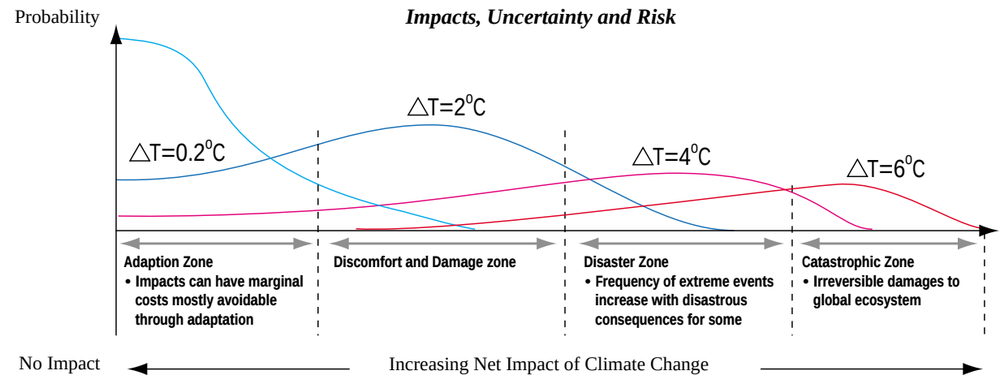
Adapting in others parts of the world may be still more difficult and this raises issues of equity between those responsible for most of the impacts (predominantly the rich nations) and those likely to suffer the most. The brunt of climate impacts are likely to fall on developing countries that have less capacity to cope with the consequences, less capacity to invest in long-term preparatory adaptation, and also have done little to cause the climate problem in the first place.

There are also impacts that can hardly be mitigated by adaptation. Some coastal deltas and swamp habitats may be impossible to protect against rising sea levels. Nothing can stop the melting of mountain glaciers, the loss of mountain ecosystems, or the bleaching of coral reefs due to warmer waters. And probably not much can be done to prevent some other ecosystems and species dying out as climatic zones shift.

But perhaps the biggest problem with an 'adapt-only' strategy is the extent to which it may simply store up more trouble for the future. Chart 11 highlights more explicitly the message of the 'risk' diagram (Chart 8): specific impacts may be very uncertain but the greater (and more rapid) the global temperature rise, the higher will be the probability of more severe damages.
The great majority of scientists believe that the most dramatic potential planetary impacts of climate change - like the collapse of the North Atlantic ocean current system or disintegration of major land-based polar ice sheets (which would raise sea levels by many metres) - can still be avoided. After a few more decades of unchecked emissions growth, that might simply no longer be possible.

No business or government expects to take decisions knowing everything for certain, and climate change embodies the same dilemmas on a global and long term scale. Policymaking nearly always requires judgement in the fact of uncertainty and climate change is no different. Taking no action is itself a decision. Adaptation will certainly be required, but is not credibly an alternative to tackling the root problem of rising global emissions. That is the big challenge explored in subsequent reports in this series.

Chart 11. Changing probabilities of climate damages as temperature rise increases: schematic illustration



The diagram illustrates in general terms how the probability of different kinds of impacts might change as the global temperature change increases. For low global temperature changes, adaptation can probably cope with most of the changes. As the temperate change increases, the probability of higher damages and the difficulty of adapting increases. The changes predicted towards the end of this century in the absence of mitigation action substantially increase the risk of 'disastrous' impacts, though other outcomes remain possible.

Source: Intergovernmental Panel on Climate Change, Second Assessment Report, Climate Change 1995: Economic and Social Dimensions

Annex: Science assessment, the Intergovernmental Panel on Climate Change, and recent debates

The science of climate change is complex and many aspects have been contested, particularly by those reluctant to see action to limit emissions. This Annex indicates how governments internationally have sought to establish robust facts on which to base decision-making, and the nature of recent debates.

As explained previously in the section 'How has the world responded?' (page 15), in the late 1980s governments responded to the rising chorus of scientific concern by establishing the Intergovernmental Panel on Climate Change (IPCC). This was designed to assess critically the state of knowledge and thereby help to foster a common understanding of robust facts about climate change. In many ways it is the most elaborate and carefully designed international advisory process ever created.

For the IPCC assessments, leading scientists from around the world are selected to form writing teams which then assess the state of knowledge as expressed in the published, peer-reviewed literature. The draft chapters are in turn sent out for review by a combination of the scientific community and diverse stakeholders - in fact, almost anyone who wishes can request drafts and submit comments for consideration. A revised draft is then sent out for combined government and peer review. An additional element built into the IPCC Third Assessment was the use of Review Editors, whose job is to ensure that all review comments are considered and that their treatment - including reasons if comments are rejected - are recorded.

Leading scientists from the different chapters then draft two summaries of the findings - a detailed technical summary, which remains under the authority of the scientists as authors, and a policymakers' summary. The latter is then handed to a governmental plenary at which governmental representatives negotiate line-by-line their acceptance of or changes to the draft text, with the lead author scientists present to challenge them if they consider the changes proposed to be scientifically inaccurate.

Through this elaborate process, governments effectively 'sign up' to a statement of knowledge that is considered to be robust and accepted by consensus - and which thereby forms an agreed intellectual backdrop for political negotiations on what to do about it.

Given the political import of the IPCC's findings, it is not surprising that its reports have been subjected to attacks and attempts to undermine its conclusions. Perhaps the most famous concerned the conclusions of the Second Assessment Report (1995) of 'discernible human influence' in observed climatic changes. Some US lobby groups both attacked the process and sought to undermine the US scientist Ben Santer who conducted the seminal 'fingerprint analysis' of observed changes in the early 1990s. His findings have since been reinforced by numerous other 'fingerprint' studies, leading the Third Assessment (2001) to strengthen its findings with 'new and stronger evidence that most of the warming observed over the last 50 years is attributable to human activities'.

Upon coming into office, President Bush expressed scepticism about the science of climate change and established a committee of US scientists, with relatively strong representation of sceptics, to again evaluate the IPCC findings. The committee broadly endorsed the IPCC's findings, whilst placing more emphasis upon the uncertainties particularly with respect to quantified projections of future changes.

The most widely-cited attack on the scientific consensus since then has been the publication of a paper that questioned estimates of pre-1860 temperatures. This argued in particular that available proxy indicators suggested a late mediaeval warm period - challenging the 'hockey stick' shaped long-term temperature record (Chart 6) - and implying by analogy that the current warming could be due to natural (perhaps solar-induced) variation, at least to a far greater degree than the IPCC considered. The credibility of this analysis was considerably undermined after it was revealed that peer reviews pointing to serious scientific errors in the paper had been ignored, whereupon the Editor-in-Chief and four members of the Editorial Board of the journal concerned resigned. The debate about the precision of mediaeval temperature estimates rumbles on, however, strained by the now politicised nature of what at root is a highly complex technical discussion over the reliability and weighting of over 100 proxy indicators.

A few scientists (including the co-author of the critique of the mediaeval temperature studies) have highlighted the possible role of solar variations. Obviously, fluctuations in solar output can affect the Earth's temperature, but the size of the direct effect is small compared to the radiative impact of accumulating greenhouse gases. There is some speculation about possible indirect solar effects, but in addition to the mechanisms being unclear it remains hard to see how anything like this could explain the observed upper atmosphere cooling. Nor is there evidence of recent solar activity so exceptional as to explain recent temperatures, and it would seem a remarkable coincidence should solar output surge just as greenhouse gases are accumulating.

The recent temperature record itself has been criticised. Queries about the influence of 'urban heat island' effects have been raised for many years and exhaustively and conclusively addressed (for example through consideration of remote and sea-based measurements). More recently, critics have pointed to apparent discrepancies between surface and satellite-based temperature measurements. Most scientists regard the more recent and quite disparate satellite measurements as being less reliable and subject to a range of problems (including satellite drift); assessments by the US National Academy of Sciences, as well as the IPCC, have concluded that the near-surface warming recorded by thermometers is undoubtedly real and that correction of satellite data for early calibration problems supports this conclusion. Again, debate over the details continues.

Another critique, given prominence by The Economist, attacked the scenarios of future emissions that informed the IPCC's predictions of future climate change. Two economists argued that the IPCC had made excessively high projections of economic growth in the developing world because it had used market exchange rates in comparing economies instead of exchange rates corrected for variations in purchasing powers. The IPCC authors responded that their assessment reflected the scenarios literature available at the time and that in fact they had made purchasing power corrections, to the extent they considered feasible.

It is clear that purchasing power corrections would change projected economic growth rates. It is less clear the extent to which any such corrections would affect emission projections - exchange rate adjustments as economies mature would indeed affect economic growth as measured in international terms, but of course would not in themselves change physical emissions. The fundamental driving forces of global emissions growth are readily apparent from Chart 5, and indeed most other criticisms of the IPCC scenarios have been simply that they span such a very wide range. It remains hard to see how debates about the valuation of exchange rates between countries could fundamentally alter the basic issues surrounding the projections of growing emissions and associated climatic changes. Nevertheless, the debate reinforced the fact that prediction is not an exact science (which is why the IPCC uses a range of scenarios), and that there are differing views about how quickly the pressures for emissions growth will play out - and whether and how fast efforts to curtail emissions can catch up so as to lead ultimately to global emission reductions.

About the Carbon Trust

The Carbon Trust is a business-led, government-backed independent company. It was established to help UK business and public sectors understand and manage the risks and opportunities associated with climate change. It works with these sectors to support the transition to a low carbon economy in the UK, though programmes which help organisations to reduce their emissions and to invest strategically in low-carbon technologies. For further information, see www.thecarbontrust.co.uk

Sources of further information

This report combines information from many sources and was subject to wide-spread review by diverse international scientists. Specific technical queries seeking clarification or verification of any statements in the report can be submitted to michael.grubb@thecarbontrust.co.uk

Summaries of the scientific reviews conducted through the Intergovernmental Panel on Climate Change are all available from www.ipcc.ch The full Assessment Reports are published by Cambridge University Press. These contain exhaustive references to the enormous and diverse literature on climate change.

In the UK, which chaired the science working group of the IPCC for the first three IPCC Assessments, the Hadley Centre at the Meteorological Office is one of the world's foremost scientific climate science research groups. Its website, http://www.met-office.gov.uk/research/hadleycentre contains extensive source data and overviews, as well as links to many other centres of information. In the UK these include the Climate Change Impacts Programme which addresses climate change impacts and adaptation issues.

Internationally, another leading centre is the Carbon Dioxide Information Analysis Centre, based at the US Oak Ridge National Laboratory. Its website http://cdiac.esd.ornl.gov/ gives links to the major US research centres on climate change science.

The UN Environment Programme hosts a general website on climate change with material ranging from basic explanations to the results of UN scientific programmes and links on diverse aspects of the issue, at http://climatechange.unep.net Information on national and international responses to climate change are brought together through the UNFCCC. Its website, www.unfccc.int, includes links to the reports submitted by governments on their national programmes.

Finally, there are innumerable websites of individuals and organisations promoting various views of the issue. The website www.aip.org/history/climate/ contains a fascinating and excellent overview of the historical evolution of climate change science. One of the leading scientists has developed a website covering a wealth of material, including his experience of media treatment of the issue and reference and web links to the various contributions to controversies covered in the Annex to this report (http://stephenschneider.stanford.edu).

Information sources concerning technology and policy responses will be summarised in the subsequent reports in this series.