Setting a long-term climate objective

A paper for the International Climate Change Taskforce

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Summary

The United Nations Framework Convention on Climate Change (UNFCCC) remains the fundamental basis for international action to address climate change. Its ultimate objective, as stated in Article 2, is to 'prevent dangerous anthropogenic interference with the climate system.' However, ten years after the Convention came into force, that objective remains undefined. This paper argues that defining it is now a matter of urgency and makes recommendations on how such a definition could be achieved.

The case for setting a long-term objective

Setting a long-term objective is needed to guide, catalyse and evaluate policy-making on climate change, and to shape decisions by the business and investment communities. Without agreement on where we want to be in the long-term the next round of commitments under the Kyoto Protocol or the UNFCCC – negotiations on which are due to begin in 2005 – risk being seriously inadequate. Further deferment of the task could foreclose the possibility of achieving climatic options for the future, with potentially disastrous implications.

The scientific uncertainties involved mean that setting a long-term objective is undoubtedly a challenge. But certainty is rarely a precondition for action in policy-making: many key decisions are taken in the face of incomplete evidence, including those relating to national security. Moreover, science has a key role in informing the process, particularly in identifying critical thresholds to be avoided that can form the basis of a political consensus. The sooner the discussion starts, the faster potential differences can be addressed, and the quicker an agreement may be reached.

Specifying an objective

A long-term climate change objective would need, if met, to prevent dangerous anthropogenic interference with the climate system. A review of the findings of the IPCC's Third Assessment Report and other peer-reviewed publications finds that a threshold appears to exist above which the extent and magnitude of impacts are likely to increase significantly and may widely be considered as being dangerous.

Beyond that threshold, the damage to ecosystems appears to grow significantly: 95 per cent of coral reefs are unlikely to recover; other highly bio-diverse ecosystems and sources of regional climatic stability, such as the Amazon rainforest, are likely to be lost forever, and the planet's soils and forests are projected to become a net source of carbon. Also, beyond that threshold, projections show agricultural losses extending to the world's largest exporters of food; the additional number of people at risk of water scarcity jumping by 2 billion; and global net economic losses taking place. That threshold appears to be no higher than a global average warming of 2°C above pre-industrial levels.

While uncertainty remains, existing information enables a well considered and balanced judgement to be made on the basis of the precautionary principle. This paper consequently concludes that global average temperature rise should be prevented from exceeding 2°C above pre-industrial levels. This should be regarded as an upper limit from which temperature should be reduced as rapidly as possible – this is important to increase the probability of preserving the Greenland ice sheet, whose decay would result in a sea level rise of about six to seven metres, and prevent large positive feedbacks from the carbon cycle, which could cause an extra 3°C rise in temperature.

Limiting global mean warming to 2°C does represent an ambitious objective. Global average surface temperature has already risen by 0.8° between 1860 and 2004, and it will rise further still whatever action is taken to reduce emissions due to climatic inertia. However, the 2°C

objective does command a wide range of support including from the European Union's Environment Council and the CEO of BP.

The implications for concentrations and emissions

Establishing what it would take to meet the 2°C objective is a task rife with uncertainty. We do not know how sensitive the climate system will be to different levels of greenhouse gases in the atmosphere, nor do we know how much of the cooling effect caused by aerosols will be lost as they are reduced. Yet we cannot assume that these uncertainties will be resolved for the best. When so much is at stake, responsible leadership requires preparing for the worst.

Consequently, to have an 80 per cent chance of keeping global average temperature rise below 2°C, this paper concludes that greenhouse gas concentrations would need to be prevented from exceeding 450-500ppm CO_2-equivalent in the next 50 years and thereafter should rapidly be reduced to about 400ppm CO_2-equivalent. If, in attempting to achieve that, non-CO_2 emissions are as significantly constrained as CO_2, levels of CO_2 alone would probably need to be stabilised at about 360ppm.

Atmospheric concentrations of CO_2 already reached 376ppm in 2003. For concentrations to be brought down, human emissions over the century would need to amount to less than the total absorbed by the natural world over that period. Assuming a natural carbon sink of 4 billion tons of carbon (GtC) per year, that would leave a budget of about 380 GtC that could be emitted from 2000-2100. That in turn could be achieved by reducing global CO_2 emissions annually by about 2.5 per cent in absolute terms from 2010. For the medium term, that would imply global emission reductions of 15 per cent below 2000 levels or 10 per cent below 1990 levels by 2020. For the longer term, it would imply global emission reductions of about 60 per cent by 2050 and of about 90 per cent by 2100.

For developed countries, the reductions would need to be steeper to allow for a rise in prosperity and emissions in the developing world. For the United Kingdom, for example, reductions in CO_2 emissions would need to be in the order of about 40 per cent below 1990 levels by 2020 and about 90 per cent by 2050.

The implications of this paper's assessment are undoubtedly challenging both politically and economically. But the task is achievable, especially if emissions of non-CO_2 gases, particularly methane and tropospheric ozone, and black carbon, are slashed, in addition to achieving major reductions in CO_2 emissions from fossil fuel use, and a major emphasis is placed on reducing land-use emissions.

Operationalising an objective

An international consensus urgently needs to be built in favour of a long-term climate objective. If the uncertainties involved were to prevent such a consensus from being reached, a hedging strategy should be adopted in which medium-term action is taken to keep a range of stabilisation options within reach, including those consistent with having a high probability of limiting warming to 2°C, such as 400ppm CO_2-equivalent. That would enable long-term options to be re-assessed as new knowledge becomes available, without making it impossible to meet an ambitious objective if a consensus is finally reached that it was necessary to do so.

A pre-condition of being able to build any consensus on a long-term objective or a related hedging strategy is that political discussions on the issue are initiated. The logical place for negotiations to take place is under the UNFCCC, where an agreement would bind all countries and guide national positions in negotiations on post-2012 commitments. However, if such a proposal were to be tabled now, conditions may not yet be conducive enough for a successful outcome to be possible. First, discussions need to take place outside the UN process, aimed at building a significant group of countries in favour of a specific long-term objective or hedging strategy, and/or of negotiating such an agreement under the UNFCCC. If either outcome, having being sought, proves impossible to reach, governments should be encouraged to initiate a domestic process to come to a national agreement on a long-term objective. Any objective that emerges from such multilateral or domestic processes should then shape positions taken in the next round of negotiations on commitments under the UNFCCC, as well as domestic climate and energy policy as it is decided.

The UK government, together with members of the EU and other interested governments, should place a high priority on achieving agreement on the options outlined, especially during the UK's presidencies of the G8 and EU in 2005. Once a process for agreeing an objective was agreed, the case for limiting temperature rise to 2°C should be made vigorously, on the basis of the impacts that would be avoided. To be acceptable, it would require a political and financial package aimed at involving more countries in future mitigation efforts in a way that is demonstrably fair to all, and increased funding for mitigation and adaptation activities in the developing world.

The very process of attempting to develop a long-term objective could at least help educate governments and the public alike about the risks their countries are facing from climate change, as well as highlight the scale and urgency of the problem, thereby helping to generate political will and serving as a catalyst for action.

Introduction

The United Nations Framework Convention on Climate Change (UNFCCC) remains the ultimate basis for international action to address the problem of climate change. Ratified by 189 countries representing 98 per cent of the world's population, it commands universal support and its legitimacy is unquestioned.

The ultimate objective of the Convention, as stated in Article 2, is to achieve 'stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system.'

Of all the hundreds of multilateral treaties that exist on myriad issues, few other agreements have a long-term objective that is as far-reaching in its implications. Yet, ten years after the Convention entered into force and thirty years since the expert community began examining the issues involved, that objective remains undefined.

This paper will argue that defining the Convention's ultimate objective is now a matter of urgency and it will make recommendations on how it could be achieved. It will suggest ways of specifying or quantifying a global, long-term objective to guide action to mitigate climate change, and recommend how it could be operationalised politically, including by making use of Britain's presidency of the G8 in 2005.

It does so on the basis of an analysis of much of the literature that has been published over the past ten years on setting long-term limits to global warming, as well as interviews with fifty-five experts and policy-makers in over a dozen developed and developing countries of importance in the international climate change negotiations.

1. The case for a long term objective

Members of the International Taskforce on Climate Change agreed at their meeting in Windsor UK in March 2004 that the Taskforce should make a recommendation on a global, long-term objective to guide action on climate change. The case for doing so is persuasive.

Each of the countries that have ratified the UN Framework Convention on Climate Change has a legal obligation to fulfil its ultimate objective to stabilize greenhouse gas concentrations at a level that would prevent dangerous human interference with the climate. To achieve that goal satisfactorily requires defining what constitutes such dangerous interference and setting a global objective to avoid it.

Before undertaking any journey, it is essential to know the destination. The multi-decade journey of mitigating climate change is no different. In the words of Michael Zammit Cutajar, speaking as the Executive Secretary of the UNFCCC in 2001, defining a long-term objective for avoiding dangerous climate change is necessary to 'give a sense of where the whole international community should be heading' (Lee, 2001). This applies as much to the direction of efforts made under the UNFCCC as to domestic policy-making, where the definition of a long-term objective is necessary to catalyse, guide and evaluate near and medium term action on climate change.

Defining a long-term objective is also necessary to shape near- and medium-term decisions by the business and investment communities, particularly where investments in energy systems are being made that will have a lifetime of several decades. It would also give industry a more certain environment in which to attract necessary investment than one in which only short-term targets are in place.

Specifying a long-term objective would also help communicate a sense of the scale of the challenge of mitigating climate change to the public, whose level of engagement in the mitigation process needs to be increased. By setting out the scale of the challenge, a long-term objective might also help make it harder for policy-makers to avoid addressing the problem in the near-term, and encourage earlier action than would otherwise be the case, which would be more equitable for future generations.

Defining a long-term objective is not only necessary but urgent. Further deferment prevents the possibility of adopting adequate near and medium term emission reduction targets. That in turn risks foreclosing the possibility of achieving climatic options for the future, with potentially disastrous implications for coming generations. Further delay could make it impossible to prevent concentrations of greenhouse gases reaching levels that would result in dangerous increases in temperature or sea level rise, that could in turn breach critical climatic thresholds, causing far-reaching and possibly irreversible change.

High urgency is of the essence because it takes time to have an impact on the climate system. Carbon dioxide and certain other greenhouse gases have long residence times in the atmosphere. That means that the levels we allow them to reach, together with the warming and sea level rise that results, cannot be reversed easily or rapidly. Both warming and sea level rise lag well behind rises in concentrations of greenhouse gases: by at least a few decades in the case of warming and by several centuries-to-millennia for sea level rise. Achieving socio-economic and technological change also takes time. Hence the more we delay defining a long-term objective to guide that change, the longer it will take to achieve, and the greater the risk that it won't be achieved in time.

Now is also the time to define a long-term objective because of the likelihood of negotiations beginning in 2005 on a new round of commitments under the Kyoto Protocol or the Convention. Without agreement on where we want to be in the long-term, of what we are trying to avoid, the next round of commitments risk being seriously inadequate. Emission reduction commitments made at Kyoto were largely based on the short-term political and economic grounds of ‘what we can manage’, without reference to a long-term objective for avoiding dangerous climate change. As a result, commitments were relatively modest and almost certainly inadequate to address the scale of the challenge we face.

Mini-steps such as these, based on ‘muddling through’, may seem sufficient at the time, but even a series of them may not get us to where we need to be to avoid dangerous interference with the climate without reference to an end goal.

Setting a long-term objective is undoubtedly a challenge. Substantial uncertainties remain about the science on which the objective would be based, which could be used to prevent or delay agreement. But certainty is rarely a precondition for action in policy-making: many key decisions are taken in the face of incomplete evidence, including those relating to national security. Moreover, strategies based on waiting for uncertainties to be resolved will not necessarily make an agreement easier to strike: while we wait, concentrations of greenhouse gases will rise, requiring far steeper emission reductions in the future, which would be much harder to agree to politically and much harder to achieve without serious economic disruption.

Agreeing a long-term objective on the basis of avoiding dangerous interference with the climate may also be challenging because of possible differences in interpretation of what is dangerous, based on where people live, what impacts they will experience, what capacity they have to adapt and what they value. Nevertheless, science has a key role in informing the process, particularly in identifying critical thresholds to be avoided that can form the basis of a political consensus. Differences in views will arise. But the sooner the discussion starts, the faster those potential differences can be addressed, and the quicker an agreement has a chance of being reached.

2. Specifying an objective

A long-term climate change objective would need, if met, to 'prevent dangerous anthropogenic interference with the climate system,' as stipulated by the UNFCCC. To specify that objective, this paper attempts to establish what rise in temperature is likely to cause impacts which might be considered dangerous. It then aims to establish if it is possible to identify a concentration level of greenhouse gases in the atmosphere that would be likely to allow us to avoid exceeding that temperature rise, and what level and pathway of emission reductions would keep us within that limit.

a) Impacts and temperature

Any amount of climate change could be described as being dangerous. Every life, species or culture lost because of climate change is one too many. For some communities, climate change is already dangerous, and for others, some level of harm is now inevitable. By specifying a long-term objective, we are essentially deciding how much more to accept and how much more will be too risky to tolerate.

To assist in defining such a limit, this paper describes the impacts projected for a range of temperature scenarios. In so doing, it aims to discover any temperature thresholds above which the extent and magnitude of impacts increase significantly; become irreversible and impossible to adapt to and spread across large regions or are distributed across regions globally and may be considered dangerous by all.

Article 2 of the UNFCCC provides a set of criteria to guide us in making these judgements. It states that stabilization of greenhouse gas concentrations 'should be achieved 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.'

Consequently, this paper will examine the impacts on ecosystems, food production and economic development projected for different increases in temperature. The paper also briefly reviews impacts on water availability which is closely linked to food security, human health and coastal flooding. It also explores possible temperature thresholds for abrupt or non-linear changes in climate, which would constitute highly dangerous and essentially irreversible impacts arising from climate change.

The findings presented here are based on those published in the IPCC's Third Assessment Report (TAR) and other peer-reviewed publications. Much of the information on ecosystems, food, water and development is drawn from an extensive review of the literature conducted for the German Advisory Council on Global Climate Change (Hare 2003). Also, unless otherwise stated, rises in temperature described relate to the global average over the pre-industrial level (this taken as the global average temperature in1861, the first year for which we have acurate thermometer records).

Impacts on ecosystems of linear change in climate

Harm to ecosystems and species will arise from their inability to move or adapt to projected changes in temperature and warming-induced changes in rainfall, extreme weather events, sea level rise and the spread of pests and diseases.

Coral reefs

Coral reefs are the ecosystem with the second highest level of biodiversity in the world, and are an important source of nutrition and income to many developing countries both from the fish they are home to and the tourism they generate. As global warming takes place, increases in water temperature cause corals to eject their algae (in a process known as coral bleaching), resulting, if sustained, in their eventual death.

1°C: Coral reefs move into a high risk zone (Hare 2003).
1–2°C: Coral bleaching is likely to become much more frequent, with slow or no recovery, especially in the Indian Ocean south of the equator, where extinction is likely (Sheppard 2003).
2–3°C: Coral reefs projected to bleach annually in many regions. 95% are unlikely to recover if 2°C is exceeded (Hoegh-Guldberg 1999).

Coastal wetlands

The droughts and sea-level rise caused by temperature rises will adversely affect coastal wetlands which span the Earth and are home to an abundance of bird species.

1°C: Risk of damage is low for most (Hare 2003).
1–2°C: Moderate to large losses likely for a few vulnerable systems, such as the UNESCO World Heritage-listed Kakadu wetlands of Australia and the Sundarbans of Bangladesh which may both suffer 50% losses (Nicholls *et al.* 1999).
2–3°C: Mediterranean, Baltic and US wetlands could suffer 50% losses, and the complete loss of the Kakadu and Sundarbans is likely. An increase of 2.4°C would destroy over 10% of global coastal wetland area (Hulme *et al.* 1999).
3.4°C 22% of coastal wetland area worldwide would be destroyed (Hulme *et al.* 1999).

Other ecosystems

Other ecosystems will undergo major changes as a result of being unable to adapt principally to increases in temperature and altered water availability.

1°C: The biodiversity hotspot of the Succulent Karoo in South Africa, home to 2,800 endemic plants, as well as the highland tropical forests of Queensland in Australia enter a high risk zone (Midgley *et al.* 2003).
1–2°C: The Karoo, together with some Arctic and Alpine ecosystems are likely to experience large or severe damage (Hannah *et al.* 2002). The highland tropical forests of Queensland are projected to halve in area, and moderate to large losses of boreal forest are likely in China (Ni 2002).
2–3°C: The Amazon forest, the ecosystem with the highest level of biodiversity globally, is likely to suffer possibly irreversible damage resulting in its collapse (Cowling *et al.* 2003). The Succulent Karoo risks being eliminated (Hannah *et al.* 2002). China's boreal forests face a 70% reduction in area (Ni 2002). Canadian Low Arctic tundra, Taiga and Russian coastal tundra face a 70–77% loss (Malcolm *et al.* 2002). Alpine ecosystems in mainland Australia are likely to be on the brink of disappearance (Busby 1988 and Brereton *et al.* 1995). The forests of North Queensland are likely to see the extinction of endemic vertebrate species (Hilbert *et al.* 2001). European alpine ecosystems will be at or above their tolerance limits for warming (Theurillat and Guisan 2001, and Kundzewicz *et al.* 2001).

Impacts on human populations of linear change in climate

Food scarcity

Damage to crops and livestock is expected from increasing heat stress, droughts, extreme weather events, heavy rains, hail storms, a rise in agricultural pests and the growth of invasive weeds in response to increases in global temperature.

1°C: About 10 million more people at risk of hunger and/or under-nourishment over the twenty-first century. In the tropics, many developing countries are likely to experience small declines in growth of crop yields, while agriculture in almost all developed countries will benefit (Parry *et al*. 2001).
1–2°C: The number of people at risk of hunger triples by the 2080s (Parry *et al.* 2001).
2–3°C: Risk of damage increases significantly, with some models showing losses in North America, Russia and Eastern Europe (Parry *et al.* 1999). By the 2080s, for a 3°C warming, one models shows 65–75 million more people at risk of hunger (Fisher *et al.* 2001).
3–4°C: 80–125 million more people at risk of hunger (Fisher *et al.* 2001). In Australia, whole regions are likely to be put out of production at 4°C (Fisher *et al.* 2001).

Studies also indicate that for every 1°C rise in the Tropics, crop yields there could decline by as much as 10%, as rising temperatures damage the ability of crops, including rice, maize and wheat, to flower and set seed. Billions of people across the tropics depend on such crops for their survival (UNEP 2001).

Sustainable economic development

Economic damage will arise from changes driven by increases in temperature, such as increased heat-waves, droughts, rainfall, floods, storms, and sea level rise.

1°C: Net losses are likely for a significant number of developing countries (Tol 2002).
2°C: A few to several percentage points of GDP in net losses is projected for developing countries, and in excess of several percentage points for some regions, particularly Africa (Tol 2002).
2–3°C: The likelihood of global net economic losses increases, arising from market losses in important sectors in most regions in both developed and developing countries (Hare 2003).

Water scarcity

Increases in temperature will make fresh-water become more scarce, as a result of increased evaporation, the decline of glacier-fed rivers, increased demand for irrigation in agriculture, and declines in precipitation over some land areas as atmospheric circulations are displaced or altered. This trend will be heightened by very large city populations by 2080 in China and India becoming newly at risk.

1°C: 400-800 million additional people in water shortage regions.
1–2°C: 1.5 billion additional people in water shortage regions.
2–5°C: 2.4–3.1 billion additional people at risk of water shortage.
2.5–3°C 3.1–3.5 billion additional people at risk of water shortage.
(Arnell b 2000, and Parry *et al.* 2001).

Health threats

As well as malnutrition and dehydration, rises in temperature are projected to increase heat stroke and asthma, injuries from extreme wind events, and vector and water borne diseases such as malaria and diarrhoea, both of which are considered here.

Malaria
1°C: 160-230 million additional people at risk.
2°C: Up to 275 million additional people at risk.
3°C: 280–340 million additional people at risk.

(Figures from Parry *et al.* 2001, for temperature rise relative to 1961–90 average.)

Diarrhoeal illness
Estimated to grow by 3–8% per degree C temperature rise, as water scarcity associated with temperature rise reduces the scope for personal hygiene (WBGU 2003).

Coastal flooding

Increases in temperature will cause sea levels to rise as a result of the expansion of sea water as it heats up and the melting of land ice cover (excluding ice sheet collapse).

1°C: 20 million additional people at risk
2°C: 30 million additional people at risk
3°C: 80 million additional people at risk

(Figures from Parry *et al.* 2001, for temperature rise relative to 1961–90 average.)

Non-linear or abrupt changes in climate

Abrupt climate change refers to a large and rapid shift in climate, relating, for example, to changes in temperature, precipitation or sea level, affecting large regions or the whole planet, which can persist for centuries or millennia. It could be so abrupt or severe that damages would be very high and adaptation almost impossible (IPCC 2001a). It would thus represent a devastating risk to humankind and ecosystems.

Evidence shows that the Earth's climate system has sensitive thresholds, and if these are exceeded, the climate system can jump rapidly from one stable operating mode to a totally different one, 'just as the slowly increasing pressure of a finger eventually flips a switch and turns on a light' (US National Academy of Sciences 2002).

There have been repeated instances of large and abrupt climate changes over the last 100,000 years, including local warmings as great as 16°C (28°F) occurring, sometimes in just a decade (US National Academy of Sciences 2002).

In the past, abrupt change has been triggered by natural causes. Today, human-induced temperature rise increases the probability of crossing a critical threshold and triggering an abrupt change in climate (Alley *et al.* 2003). Were this to happen, even if the impact were only experienced in the distant future, it would unquestionably constitute 'dangerous anthropogenic interference' with the climate system. Consequently, this paper explores whether any temperature-related thresholds can be identified beyond which such events could be triggered.

West Antarctic Ice Sheet collapse

The disintegration of the West Antarctic Ice Sheet (WAIS) would cause an irreversible rise in sea level of 4–6 metres, over time scales ranging from a few hundred to a thousand years (IPCC 2001b). It would destroy coastal settlements worldwide and threaten the existence of many of the world's largest cities such as London and New York. A large portion of the world's population which lives by the sea would have to be moved and trillions of dollars of infrastructure would be lost. If the WAIS were to collapse, it would present a problem of universal risk.

The IPCC finds that substantial sea level rise from this source is 'very unlikely during the 21st century', although it acknowledges that 'its dynamics are still inadequately understood, especially for projections on longer time-scales' (IPCC 2001a).

Because of this uncertainty, the IPCC's calculations for the twenty-first century concerning the WAIS are based mainly on the gradual effects of changes in snowfall, evaporation and melting, whereas ice-sheet disintegration is likely to be driven by highly non-linear processes and feedbacks (Hansen 2004).

With global warming, the most likely mechanism for the WAIS' collapse would be the loss of the large floating ice shelves that are thought to buttress the landed ice of the continental interior. The WAIS is known as a 'marine' ice sheet because its grounded base lies far below sea level. This is a significant source of instability, as is the fact that the bed of the ice sheet slopes downward into the continental interior from shallower margins on the continental shelf. Unlike an ice sheet whose bed slopes upwards, where melting would be slowed as the ice sheet retreats inland, a marine ice sheet is thought to be intrinsically unstable once fringing ice shelves have collapsed and deep ocean warming begins to melt the base of the ice stream. It is thought that once this happens, uncontained collapse or disintegration would occur.

Recent observation of much higher than expected 'basal' melting of ice shelves around Antarctica (Rignot and Jacobs 2002) and of accelerating loss of continental ice from one of the main drainage basins (the Amundsen sea sector) of the WAIS (Thomas *et al.* 2004), indicate a higher vulnerability than is implied based only on surface warming models of ice shelf disintegration. It should be noted that an uncontained collapse of this sector of the WAIS alone would raise sea levels by around 1.0–1.5 metres and could have considerable consequences for the stability of both the WAIS itself and for the main ice streams of the East Antarctic.

Once an ice sheet begins to collapse, its demise can be rapid and impossible to stop (Hansen 2004). The time scales involved are not known, but range between 200 and a thousand years, implying rates of sea level rise as high as 2–3 metres per century. Moreover, recent developments in satellite observation techniques have helped demonstrate that the discharge ice streams are much deeper than originally thought, which could reduce the timescale associated with ice sheet collapse significantly.

The WAIS is thought to have collapsed at least once in the last 1.3 million years, most likely during a warm period about 400,000 years ago, and proxy data indicates that global average temperatures then may not have been more than 2°C above today's (Oppenheimer 1998). Other estimates suggest that disintegration could ultimately be committed from a global mean increase of about 3°C, which would represent a local mean of 10°C (O'Neill & Oppenheimer 2002). Ocean and surface warming sufficient to threaten the fringing ice shelves could occur with a global warming of about 2.5°C.

The preconditioning of ice sheets for accelerated break-up may take a long time (Hansen 2004), although the conditions for it could be created by warming occurring in the twenty-first century (IPCC 2001b). Disintegration itself might not occur for many centuries, although shorter timescales have not been ruled out (O'Neill & Oppenheimer 2002). Even if it disintegrates within 500–700 years, the contribution to sea level rise would reach 0.6–1.2 metres per century, which would likely exceed the adaptive capacity of most coastal structures and ecosystems (Oppenheimer 1998).

To avoid this threat, James Hansen, the director of NASA's Goddard Institute for Space Studies, suggests that the highest prudent level of additional global warming is not more than about 1°C, based on the paleoclimatic evidence (Hansen 2004).

Michael Oppenheimer, of the Department of Geosciences at Princeton University, and Brian O'Neill of the Center for Environmental Studies at Brown University, argue that a limit of 2°C above global average temperature in 1990 is justified to protect the WAIS, 'taking a precautionary approach because of the very large uncertainties involved,' (O'Neill and Oppenheimer 2002). However, this analysis did not address the question of deep ocean warming and the melting of ice shelves from beneath.

Greenland ice sheet decay

The complete decay of the Greenland ice sheet would result in a sea level rise of about 6–7 metres (IPCC 2001a) over a millennium or so. Unlike the WAIS, the Greenland ice sheet is not intrinsically unstable as it is not marine in character and drains through quite narrow channels. Therefore the maximum rates of decay that are thought possible are the equivalent of about 0.5 metres of sea level rise per century, with the rate of decay being controlled by the degree of warming.

The IPCC concludes that 'a local warming of larger than 3°C, if sustained for millennia, would lead to virtually a complete melting of the Greenland ice sheet' (IPCC 2001). This would occur as the melting of the Greenland ice sheet would exceed the snowfall, causing the ice sheet to contract and eventually be eliminated, raising global average sea level over 1,000 years. If greater warming occurs, mass will be lost faster and the ice sheet is likely to disappear (Gregory *et al.* 2004).

Local warming over Greenland is estimated by models to be between 1.3 and 3 times higher than the global mean warming (IPCC 2001a). The melting that results is further enhanced because as snow and ice are lost there is a reduction in the albedo effect: the reflection of sunlight which is absorbed instead, accelerating melting. Increased absorption of sunlight also results from the presence of black-carbon aerosols and melt-water which blacken ice sheets, further accelerating warming. Hence, if local mean warming is assumed to be double the global mean, a 1.5°C rise in global average temperature over pre-industrial levels, if sustained, would lead to the melting of the entire Greenland ice sheet.

Furthermore, it appears that additional effects may cause the process to occur more rapidly. Greenland is already losing ice at an accelerating rate which far exceeds model estimates and cannot be explained by recent warming alone. It appears to be caused by a much more rapid ice stream flow from the interior of Greenland than has been predicted by models. The mechanism for this appears to be warming related, as cracks develop on the discharge glaciers in summer that result in melt-water from the surface lubricating the bed of the discharge ice streams (Zwally *et al.* 2002).

Shutdown of the thermohaline circulation

The thermohaline circulation system is a global ocean current. Part of it, generally known as the Gulf Stream, brings warm tropical water to the North Atlantic, warming Northern and Western Europe by several degrees and increasing precipitation across the region and beyond. The system can be affected by increases in temperature and freshwater infusion, to the extent that the system could weaken or shutdown.

Were it to cease abruptly, the North Atlantic region would cool by 3°C to 5°C within 5-10 years and stay cooler for decades to centuries, enough in isolation to produce winters twice as cold as the worst winters on record in the eastern United States in the past century (Gagosian 2003) and jeopardise the region's ability to feed and support current population levels. Substantial adverse consequences for agriculture have also been projected as far afield as Africa and India. In an interdependent world, no economy would be immune from the consequences. It should be noted, however, that it is still uncertain if any regional cooling resulting from a shutdown would be counteracted by regional warming due to increased greenhouse gases.

Evidence from deep-sea sediments and ice-sheet cores shows that the thermohaline circulation has slowed and shut down several times in the past, stopping heat delivery to the North Atlantic and causing significant cooling throughout the region, as well as widespread droughts throughout the world (Gagosian 2003). Examples include the 5°C plunge in temperatures in the North Atlantic region about 12,700 years ago in the Younger Dryas period, which lasted for 1,300 years (Gagosian 2003).

For the twenty-first century, the IPCC concludes that most models show a weakening of the thermohaline circulation resulting in a reduction of heat transport into high latitudes of Europe (IPCC 2001a). Beyond 2100, some models suggest a complete and possibly irreversible shutdown if the temperature increase is large and applied long enough (IPCC 2001a).

Some models show the threat of a complete shutdown increases beyond a global mean warming of 4–5°C, but this remains very uncertain (IPPC 2001b). O'Neill and Oppenheimer conclude that a limit of 3°C global average warming over 100 years above 1990 levels is warranted to avert a shutdown of the thermohaline circulation (O'Neill & Oppenheimer 2002).

Destabilisation of methane hydrates

Methane hydrates are ice-like solids consisting of water and mostly methane gas that are stable at high pressures and low temperatures, below the sea floor of every continental margin on Earth. They contain the equivalent of 10,000 billion tonnes of carbon: over 10 times more than the amount of carbon currently in the atmosphere. If temperatures around them warm enough, hydrates can melt, releasing their methane, a greenhouse gas 20 times more powerful than CO_2, greatly boosting global warming.

The release of as much as 1,200 billion tons of methane from gas hydrates is thought to have triggered the dramatic increase in temperature of 5°C, lasting 100,000 years, that occurred in the early Eocene Period 55 million years ago (Maslin 2004). The release of methane from hydrates may also have triggered the rapid increase in temperature of 6°C that occurred at the end of the Permian era 250 million years ago, which provoked the extinction of 95 percent of the world's species (Benton 2003).

Researchers at the University of Wyoming calculate that a 5°C temperature increase at the sea floor could result in a release of about 2,000 billion tonnes of methane (Holbrook *et al.* 2004).

Unpublished model calculations by the Hadley Centre, however, suggest that at current predicted rates of warming, sea level will rise fast enough to counter the effects of the warming, keeping the majority of marine gas hydrates stable (Maslin 2004). But this may not be the case for hydrates in shallow marine settings, as in the high Arctic, which could be widely destabilised by warming (Nisbet 2002). Here, warming in excess of 4°C could start causing methane to be released, while 10°C could result in large amounts of methane release (Nisbet 2002).

Moreover, if the current rate of warming increases, perhaps because of other positive feedback processes, temperature may rise more than sea level, causing ocean gas hydrates to break down more widely, releasing methane in the process (Maslin 2004).

Transformation of the terrestrial biosphere into a net source of carbon

Global warming may also be accelerated by the impact of rising temperatures on the biosphere. The natural world currently absorbs about half of human carbon emissions from fossil fuels: about half of that is absorbed by the oceans and the other half by the terrestrial biosphere. However, the higher temperatures rise, the faster soil organisms respire, converting organic matter to CO_2, and the more likely tropical forests are to dry out and die. These processes would mean that soils and forests are less able to store and absorb CO_2, and instead of doing so, become responsible for a net release of it, leaving more CO_2 in the atmosphere and thereby accelerating global warming.

Hadley Centre models project an abrupt transformation of the terrestrial biosphere to a net source of CO_2 instead of a sink for it when global average temperature rises by 2°C above pre-industrial levels (Cox *et al.* 2000, and Jenkins 2003).

Under a business-as-usual emissions scenario, by the last quarter of this century, the terrestrial biosphere would have emitted all the man-made carbon it took up over the past 150 years, even without taking into account the effects of deforestation and other land use changes (Jenkins 2003). This would add to the atmosphere the equivalent of two-thirds of the amount of CO_2 currently there (Cox *et al.* 2000).

By 2100, this source of CO_2 from the land would almost balance the amount of CO_2 absorbed by the oceans, so that there would no longer be a net absorption of human CO_2 emissions by the natural world. The amount of CO_2 in the atmosphere would increase, therefore, at about the same rate as human emissions (Cox *et al.* 2000). Consequently, instead of a 5°C average rise in land temperature by 2100, this feedback would produce a massive 8°C rise in temperature (Cox *et al.* 2000).

Conclusion

The preceding overview indicates that damages will occur even at a low level of warming. But there does appear to be a threshold above which the extent and magnitude of impacts are likely to increase significantly, to the extent to which they may widely be considered as being dangerous and to pose an unacceptable risk.

Beyond that threshold, the damage to ecosystems appears to grow significantly, with 95 per cent of coral reefs unlikely to recover, other highly bio-diverse ecosystems and sources of regional climatic stability, such as the Amazon rainforest, are likely to be lost forever, and the biosphere is projected to become a net source of carbon. Also beyond that threshold, projections show agricultural losses extending to the world's largest exporters of food; the additional number of people at risk of water scarcity jumping by 2 billion; and global net economic losses taking place.

That threshold appears to be no higher than a warming of 2°C above the pre-industrial level. While there is less clarity about what level of warming will trigger abrupt changes in climate, it does appear likely that limiting warming to 2°C would preserve the West Antarctic Ice Sheet, the thermohaline circulation, and the stability of the majority of methane hydrates. If temperature can be reduced below a peak of 2°C, it would also increase the possibility of preventing the loss of the Greenland ice sheet.

Consequently, this paper recommends that global average temperature rise should be prevented from exceeding 2°C above the pre-industrial level. This should be regarded as an upper limit from which temperature should be reduced as rapidly as possible.

The precautionary approach

Considerable areas of uncertainty remain. But existing information does enable a well considered and balanced judgement to be made on the basis of the precautionary principle, as stipulated by the UNFCCC, whose Article 3.3 states:

'The Parties should take precautionary measures to anticipate, prevent or minimize the causes of climate change and mitigate its adverse effects. Where there are threats of serious or irreversible damage, lack of full scientific certainty should not be used as a reason for postponing such measures…'

Adoption of the precautionary principle is this debate is particularly appropriate because humans have no experience of this degree of global climate change (see below). We also have a duty to adopt the precautionary approach for the sake of future generations, to whom we have a responsibility to provide living conditions and life prospects at least as good as those we have had ourselves.

It is clear that the higher the peak temperature rises, the greater the risk to both human and natural systems. Therefore, respect for the precautionary principle should lead us to accept the lowest plausible value for a temperature threshold.

Support for a limit of 2°C

A wide range of opinion supports this approach. It includes the British Secretary of State for the Environment, Food and Rural Affairs, Margaret Beckett, who has said: 'Given the predicted dire consequences and irreversibility of climate change, we should be guided by the precautionary approach as set out in the UNFCCC. In my view, this means adhering to a course of action that will keep temperatures to no more than 2°C above pre-industrial levels' (Beckett 2003).

From the business community, Sir John Browne, CEO of BP has said: 'There is a very strong case for precautionary action and I believe the aim of that action should be to limit any increase in the world's temperature to 2 degrees Celsius' (Baer 2004).

The objective of limiting temperature rise to 2°C has also been endorsed by a number of relevant organisations including: the European Union's Environment Council; the Enquete Commissions of the German Bundestag; the Germany Advisory Council on Global Change; the Association Of Small Island States (AOSIS); the Government of the Philippines; The Advisory Group on Greenhouse Gases; the North-South Dialogue on Equity in the Greenhouse; and Climate Action Network International.

Recognising that 2°C is not 'safe'

Limiting warming to 2°C does represent an ambitious objective. Global average surface temperature has already risen by 0.8° above between 1860 and 2004 (UK Met Office 2004). And it will rise further (over possibly hundreds of years) even if the atmospheric concentration of greenhouse gases were frozen at today's levels immediately, due to the inertia of the climate system (Hadley Centre 2003).

However, it is important to understand that a 2°C rise itself is not 'safe', and does not represent an ideal to be reached, but rather an upper limit which must not be exceeded. A 2°C warming would be a magnitude of warming greater than any that human civilisation has ever experienced (IPCC 2001b). We would need to return to the Milocene era, some 5–25 million years ago, to find a climate that is warmer than today's by more than 2°C (IPCC 2001b). Modern man, meanwhile, is only thought to have entered into existence about 120,000 years ago.

Furthermore, the IPCC is clear that even at levels of warming of less than 2°C, many countries, particularly in the developing world, are vulnerable, and are likely to face net economic losses because of a lower capacity to respond and adapt (IPCC 2001b). Already, global average warming of 0.8°C is responsible for dangerous impacts for some communities, including the populations of some small island states where sea levels are rising, and of the high Arctic where melting permafrost is causing the widespread subsidence of homes and roads (Lynas 2004).

Ecosystems, too, are already at risk, and many coral reefs, most glaciers, and some Arctic and other sensitive ecosystems are unlikely to survive a sustained period of global warming of 2°C. The Greenland ice sheet is unlikely to be able to do so either and positive feedbacks from the carbon cycle would be probable as well. Consequently, it would be important to try to limit the period of peak warming, by reducing global average temperature after peaking as rapidly as possible.

b) Concentrations and emissions

Understanding what would prevent global average temperature from rising above 2°C over pre-industrial levels is a complex task. Many factors affect temperature and large uncertainties exist about their exact contribution. Taking those uncertainties into account, and without focusing on economic considerations, this paper aims to provide an honest assessment of what it would take to stand a good chance of meeting the 2°C objective. In particular, the paper focuses on the constraints that would be needed on the atmospheric concentration and emissions of carbon dioxide, taking into consideration the effect of other greenhouse gases and uncertainties relating to the sensitivity of the climate system and the effect of aerosols.

The factors driving temperature change

Global temperature is decided by the energy balance of the planet: the amount of incoming energy versus outgoing energy. The equilibrium between the two that existed at the start of the industrial era is now being altered, or 'forced', by several different factors, so-called 'radiative forcings', most of which have a human cause.

'Positive forcings' increase the amount of energy at the Earth's surface above the previous equilibrium, largely by preventing outgoing terrestrial radiation being lost to space, thereby causing warming. 'Negative forcings' decrease the amount of energy at the Earth's surface, largely by reflecting solar radiation away, causing cooling.

Over the twentieth Century, positive forcings have been greater than negative ones, and they are projected to carry on being so. The most important positive forcings are increased levels of greenhouse gases in the atmosphere: carbon dioxide (which is responsible for the single largest positive forcing), methane, halocarbons (such as CFCs), and nitrous oxide. Other, smaller positive forcings arise from increased levels of black carbon, tropospheric ozone, and solar irradiance.

Combined, these exceed the effect of negative forcings, which is nonetheless considerable. The most important negative forcings are increased levels of aerosols (microscopic liquid or solid particles in the air), largely from sulphur dioxide emissions, which have a direct reflective effect and a very uncertain, indirect reflective effect through cloud modification. Other, smaller negative forcings arise from land cover change; depleted levels of stratospheric ozone; increased levels of aerosols from biomass burning; mineral dust; and natural volcanic aerosols.

To prevent global average temperature rising above 2°C, the most significant positive forcings clearly need to be constrained. The question is: by how much?

The role of carbon dioxide

Of all the positive forcings, carbon dioxide (CO_2) has the greatest effect. The rise in the accumulation or concentration of CO_2 in the atmosphere is responsible for 60% of the increase in radiative forcing of greenhouse gases from 1750–2000 (IPCC, 2001a).

CO_2 concentrations have risen by over a third since pre-industrial times: from 280ppm (280 molecules of CO_2 per million molecules of dry air) to 376ppm in 2003 (Keeling 2004). Atmospheric concentrations of CO_2 have risen as humans have been emitting more CO_2 than the natural world has absorbed, mostly through burning fossil fuels, but also through land-use change, especially deforestation. As emissions rise, while natural removals remain fairly constant, more CO_2 accumulates in the atmosphere, where it can remain for an average of 200 years. The IPCC estimates that about 3.2 billion tonnes of carbon per year are thus accumulating in the atmosphere.

That in turn is producing a rise in CO_2 concentrations. In the 1980s and 1990s, atmospheric CO_2 concentrations rose by about 1.5ppm per year (IPCC 2001a), and from 2001–2003, they have risen by an alarming average of 2ppm (Keeling 2004). By 2100, concentrations could lie between 490ppm and 1260ppm (IPCC 2001a) if little or no deliberate mitigating action is taken, depending on different estimates of economic and population growth rates, technological change and diffusion rates, as well as the sensitivity of the climate system to radiative forcings (see below).

To stop concentrations of CO_2 rising, inflows and outflows of CO_2 in the atmosphere (the amount emitted and the amount removed from it) must be matched, and if CO_2 concentrations are to be reduced, outflows must exceed inflows.

The problem of climate sensitivity

Identifying the level at which CO_2 concentrations would need to be stabilized and the extent to which emissions of CO_2 reaching the atmosphere would need to be reduced to keep within the 2°C limit is complicated by the issue of climate sensitivity.

Climate sensitivity is the degree to which the climate system as a whole is affected by or responds to radiative forcings, such as increasing CO_2. It is generally measured by the increase in global average surface temperature reached at equilibrium, that is when it stops rising over a period of hundreds of years, if the atmospheric concentration of CO_2 were to rise to twice the pre-industrial level (560ppm).

The answer is very uncertain. The IPCC puts it at between 1.5 and 4.5°C (IPCC 2001 a). In other words, if the climate system turns out to have a low sensitivity, 560ppm of CO_2 would produce a rise in temperature of 1.5°C, but if sensitivity is high, the rise would be 4.5°C. Moreover, since 2001, other studies have concluded that there is a significant probability that the climate sensitivity could exceed 4.5°C (Baer 2004; Stainforth *et al.* 2005). To complicate matters further, it is possible that climate sensitivity is not constant.

This degree of uncertainty exists because of our poor understanding of many of the components of the climate system and our inability to model all the feedbacks between them. We still don't know exactly what radiative effect will result from the impact of increased forcings, such as higher levels of CO_2, upon atmospheric water content and cloud cover, both of which have a significant effect on temperature.

Temperature ranges for different concentration levels

Reflecting the uncertainty about climate sensitivity, the IPCC's projections of what global mean surface temperature would result from different concentration levels of CO_2 in the atmosphere include a range of possible outcomes (IPCC 2001a).

- CO_2 stabilisation at 450ppm would produce a mean surface temperature change above 1990 levels of 1.5 to 3.9°C at equilibrium.
- CO_2 stabilisation at 550ppm would produce a mean surface temperature change above 1990 levels of 2.0 to 5.0°C at equilibrium.
- CO_2 stabilisation at 750ppm would produce a mean surface temperature change above 1990 levels of 2.8 to 7.0°C at equilibrium;.
- CO_2 stabilisation at 1000ppm would produce a mean surface temperature change above 1990 levels of 3.5 to 8.7°C at equilibrium.

For each of these scenarios, the IPCC does not only consider the radiative effect of CO_2 alone, but also an additional contribution from other greenhouse gases. The assumed accompanying increase in radiative forcing is equivalent to that occurring with an additional 28 per cent in the final CO_2 concentrations (IPCC 2001a).

Of all the stabilisation options considered here by the IPCC, it is clear that only one, the option of stabilising CO_2 at 450ppm, would keep final temperature rise fairly close to 2°C over pre-industrial levels, and then, only if climate sensitivity is low.

Probability of different concentration levels keeping temperature rise below 2°C

To obtain a clearer guide, it is possible to establish the likelihood that climate sensitivity lies in any particular range, or the probability distribution of the climate sensitivity, defined mathematically as a probability density function (PDF). From that, it is possible to establish the probability that different concentration levels of greenhouse gases (whose collective radiative effect can be measured as an equivalent of CO_2) would prevent temperature from rising by more than 2°C.

When a median is taken of several PDFs based on different temperature ranges for climate sensitivity by the IPCC and others (see Appendix 1), it shows:

- To have an 80 per cent chance of limiting temperature rise to below 2°C, greenhouse gas concentrations (together with all the other radiative forcing agents) would need to add up to a net warming no greater than what would be associated with a CO_2 concentration of about 400ppm (CO_2-equivalent).

Similar calculations (Baer 2004) also show that a concentration level of:

- 450ppm CO_2-equivalent has a 50 per cent chance of staying below 2°C;
- 550ppmv CO_2-equivalent has a 10-20 per cent chance of staying under 2°C;
- 650ppmv CO_2-equivalent has a 3-10 per cent chance of staying under 2°C

In IPCC terminology, this means that 400ppm CO_2-equivalent is 'likely' to limit temperature rise to below 2°C, whereas there is less than a 'medium likelihood' that 450ppm would do so, and it is 'unlikely' for 550ppm and 'very unlikely' for 650ppm.

The implications for concentrations of CO_2

These calculations are based on the effect of all radiative forcings, not only CO_2. That is significant because the radiative forcing caused by greenhouse gases other than CO_2 is substantial. Methane, nitrous oxide and halocarbons are responsible for 40 percent of the radiative effect of all greenhouse gases over the twentieth century (IPCC 2001a).

The contribution that greenhouse gases other than CO_2 make to radiative forcing today is roughly equivalent to 100ppm of CO_2 (IPCC 2001a), although their full effect is masked by the impact of aerosols (see below). Their contribution to future radiative forcing depends on how much we reduce emissions of these gases.

In this regard, the second most powerful greenhouse gas, methane, can be removed from the atmosphere in almost a decade, unlike CO_2 which may persist for an average of 200 years. Concentration levels of methane, therefore, respond rapidly to emissions reductions.

Hence, if a concentration level of 400ppm CO_2-equivalent were aimed for, and if we assume that in attempting to achieve it, non-CO_2 emissions would be as significantly constrained as CO_2, levels of CO_2 alone would probably need to be at about 360ppm.

Losing the cooling effect of aerosols

An additional layer of uncertainty is created by the effect of reducing sulphate aerosols. These pollutants are created by the same process that is responsible for CO_2 emissions: burning fossil fuels. Sulphate aerosols are already being reduced as traditional air pollution is being controlled. But as action to mitigate climate change accelerates, these aerosols will be reduced further, roughly linearly with CO_2.

As noted earlier, aerosols have a direct reflective effect and a very uncertain, indirect reflective effect through cloud modification. Both have a cooling effect on global climate which masks some of the warming we should be experiencing today.

The loss of the direct reflective effect from reduced burning of fossil fuels may be cancelled out partially or fully by the simultaneous removal of black carbon (or soot) and tropospheric ozone, which are also a product of burning fossil fuels and have a warming effect (IPCC 2001a). However, the loss of the very large and uncertain effect of aerosols on clouds may cause substantial warming, as this process may be offsetting as much radiative forcing as 150ppm of CO_2-equivalent (IPCC 2001a).

The 'overshoot, peak & decline' scenario

The likely loss of any of the cooling effect of aerosols greatly strengthens the case for stabilising greenhouse gas concentrations at a low level. However, as concentrations of CO_2 already reached 376ppm in 2003 and the current contribution of other greenhouse gases (and aerosols) could take net forcings close to 400ppm CO_2-equivalent, it is already possible that temperature will increase by 2°C.

Furthermore, given the slow nature of the political response so far to the need for emission reductions, even under fairly optimistic reduction scenarios, concentrations could rise to 450 or 500ppm CO_2-equivalent, or more, before being stabilised.

However, it should still be possible to limit eventual temperature rise to close to 2°C as long as the peak concentration level is not far above 400ppm CO_2-equivalent, is not reached slowly and declines rapidly. The further the peak concentration overshoots 400ppm CO_2-equivalent, the harder it will be to bring the concentration level back down towards it again. And the slower the peak concentration is reached and brought down, the closer we will come to the equilibrium temperature implied for that peak, and the harder and slower it will be for global temperature to fall below it.

To limit temperature rise to 2°C, therefore, concentrations should not peak higher than 450ppm and certainly not more than 500ppm CO_2-equivalent in the next 50 years, and should fairly rapidly be reduced to 400ppm CO_2-equivalent thereafter.

The implications for a 100 year carbon budget

Stabilising concentrations at any level requires defining an allowable amount of carbon that can be emitted between now and some point in the future. To stabilise greenhouse gas concentrations at 400ppm CO_2-equivalent by 2100, concentrations of CO_2 would probably need to be stabilised at about 360ppm. As that would require concentrations to fall below where they are today, human emissions over the century would need to amount to less than the total absorbed by the natural world over that period, so that more carbon leaves the atmosphere than enters it, bringing concentration levels down.

Currently, the net amount absorbed by the natural world is 3-5 billion tonnes of carbon (GtC) per annum: ~2 GtC by the oceans and 1–3 GtC by the biosphere, depending on differing estimates about rates of deforestation (Prentice *et al.* 2001; Houghton 2003; House *et al.* 2003). With a moderately precautionary approach, it is reasonable to assume a natural carbon sink of 4 GtC per year. There remains significant uncertainty about whether this level of sink is likely to be maintained, but if it were, it would represent a sink of 400 GtC over a hundred years.

That would leave a budget of about 380 GtC that could be emitted from 2000–2100 if we were to stabilise CO_2 concentrations at 360ppm by 2100 (see Appendix 2). Total annual carbon emissions from human sources today amount to 7–8 GtC: 6.5 GtC from burning fossil fuels and 1–2 GtC from land use change. Hence, for comparison, if we continued emitting at today's levels, 700–800 GtC would be emitted by 2100, which is in the ballpark of the budget associated with a concentration of 550ppm. The budget for 360ppm CO_2 is about half that, indicating the scale of the challenge.

The implications for emission reductions

There are any number of different pathways and timelines for meeting a carbon budget. It is possible to stay within a carbon budget by allowing increases in emissions in the near-term followed by very steep cuts. The benefits of deferring action, it can be argued, are that it allows for technology development and avoids the premature replacement of expensive capital stock, such as power plants, which would make emissions abatement cheaper. It could also be argued that we shall be wealthier in the future and thus better able to afford rapid decarbonisation.

However, this is an extremely high risk strategy. Any benefits seem likely to be outweighed by the drawbacks. Deferring action would:

- require a steeper and more abrupt reduction in emissions and a much more rapid technological transition (after having locked in carbon-intensive technologies), which could be financially and politically costlier, possibly prohibitively so;
- shift the burden on to other generations and increase the risk that necessary measures would be avoided and targets continuously pushed back, by which time it could be too late to prevent dangerous climate change;
- result in a larger and faster rate of initial warming and sea level rise compared to early action, as well as an abrupt spike in temperature from a more rapid loss of the cooling effect of aerosols, making it harder for human and natural systems to adapt;
- make revising a long-term objective in light of new information about the extent of climate change or the capacity of sinks to take up our carbon much harder.

Initiating early action, on the other hand, would stimulate technological development more rapidly, which is necessary because of the inertia in the energy system, bringing costs down more rapidly in the process, and it would allow society to keep its options open. It clearly constitutes the more precautionary approach.

To reflect that approach in meeting a carbon budget of 380 GtC associated with having a high probability of limiting temperature rise to below 2°C, a scenario could be envisaged in which global emissions peaked at 10per cent above 2000 levels by 2010 and thereafter were reduced by 2.5 per cent below 2000 levels in absolute terms annually. That would imply a 15 per cent reduction in global emissions below 2000 levels by 2020; a 35 per cent reduction by 2030; a 50 per cent reduction by 2040; a 60 per cent reduction by 2050; an 80 per cent reduction by 2080; and a 90 per cent reduction by 2100 (see Appendix 3).

Using the Kyoto baseline year for this scenario, global emissions would peak at 16 per cent above 1990 levels by 2010, fall by about 10 per cent below 1990 levels by 2020; 30 per cent by 2030; 45 per cent by 2040; 57 per cent by 2050; 80 per cent by 2080; and 90 per cent by 2100 (see Appendix 3).

For comparison, if reductions did not begin until 2020, emissions would need to fall by about 4 per cent per year to stay within the same budget, at greater cost in terms of payment for the mitigation effort and the effects of a higher rise in peak forcings.

Under either scenario, developed countries would need to make steeper reductions to allow for a rise in prosperity and emissions in the developing world. For the United Kingdom, for example, that would mean cuts in CO_2 emissions of close to 40 per cent below 1990 levels by 2020 and close to 90 per cent by 2050 (see Appendix 4).

Conclusion

Establishing what it would take to prevent global average temperature rising beyond 2°C above pre-industrial levels, and thereby avoid impacts from climate change that may widely be considered as being dangerous, is a task that is rife with uncertainty. We simply do not know how sensitive the climate system will be to different levels of greenhouse gases in the atmosphere, nor do we know how much of the cooling effect caused by aerosols will be lost as they are reduced, nor exactly how much carbon the natural world will continue to absorb in decades to come.

Uncertainty requires precaution

Yet we cannot assume that any one of the uncertainties involved will be resolved for the best. When so much is at stake, responsible leadership requires preparing for the worst. That is the basis upon which costly efforts are made to protect national security from military or terrorist threats today, however remote, and prevention of dangerous climate change should not be treated any differently. Indeed, as parties to the UNFCCC, governments are legally required to adopt the precautionary principle in addressing climate change when there is a lack of full scientific certainty. Hence, whatever temperature objective may be agreed, corresponding concentration and emission objectives need to be based on the possibility that climate sensitivity is at the high end of the range. Assuming otherwise has no justification.

An honest assessment

Consequently, to have a high chance of keeping global average temperature rise below 2°C, this paper concludes that greenhouse gas concentrations would need to be prevented from exceeding 450-500ppm CO_2-equivalent in the next 50 years, and thereafter, should rapidly be reduced to about 400ppm CO_2-equivalent. That could be achieved by reducing global CO_2 emissions annually by about 2.5 per cent in absolute terms from 2010. For the medium term, that would require global emission reductions of 15 per cent below 2000 levels or 10 per cent below 1990 levels by 2020.

It should be stressed that meeting the 2°C objective by stabilising concentrations at 550ppm, as the European Council, the UK's Royal Commission on Environmental Pollution and the CEO of BP have implied, could only possibly occur if climate sensitivity is low. Its chances of achieving the task are therefore low.

It should also be noted that in the longer term, concentrations may need to be reduced further than 400ppm if some models are correct and climate sensitivity is not constant, or if ice sheet instability emerges, or if limiting sea level rise becomes a priority.

Addressing the challenge

The implications of this paper's assessment are undoubtedly challenging both politically and economically. But the task is achievable through substantial increases in energy efficiency and renewable energy generation to reduce emissions of CO_2 from fossil fuel use and by much greater action to reduce land-use emissions. That will need to be matched by measures to slash emissions of other greenhouse gases, particularly methane and tropospheric ozone, and black carbon.

Rapid reductions of land-use emissions from the destruction of forests and soils would allow us to reach the same CO_2 stabilisation objective without as great a reduction in fossil fuel use and therefore without as great an increase in warming arising from reduced aerosols. It would also preserve the terrestrial carbon sink, whose strength will be vital if atmospheric concentration levels are to be brought down.

What we cannot afford to do is wait for absolute proof before adopting a strategy. That would effectively close down the option of stabilising at a low level, as concentrations would rise too far to be reduced in time to avoid possible dangerous change. It would lock in risk and pass on the burden to future generations, whose chances of avoiding dangerous climate change are lessened with every year of delay.

3. Operationalising an objective

To avoid dangerous climate change and fulfil the ultimate objective of the UNFCCC, it is a matter of urgency that an international consensus be built in favour of a long-term climate objective. That objective, this paper concludes, should be to limit global average temperature rise to 2°C over pre-industrial levels, by stabilising greenhouse gas concentrations and reducing emissions as outlined earlier in the paper.

Alternatively, if the uncertainties involved were to prevent such a consensus from being reached, a hedging strategy should be adopted in which medium-term action is taken to keep a range of stabilisation options within reach. Those should include options consistent with having a high probability of limiting warming to 2°C, including 400ppm CO_2-equivalent. Such a strategy would enable long-term options to be re-assessed as new knowledge becomes available, without making it impossible to meet an ambitious objective if a consensus is finally reached that it was necessary.

A pre-condition of standing a chance of building an international consensus on either of these options is that political discussions on the issue are initiated. This section explores which fora and which strategies might best be suited to that task, and it considers how possible obstacles might be overcome. This section also explores how a long-term climate objective could be operationalised at a national level if a multilateral consensus were to prove impossible to reach.

a) UNFCCC negotiations on a long-term objective?

Arguments in favour

The UNFCCC is the logical framework under which to have an organised discussion about long-term climate objectives in the context of Article 2. The task of agreeing a long-term objective or a related hedging strategy requires a political negotiation, representing the voices of the wealthy and the poor, from the developed and developing worlds, and the UN is the most appropriate forum for that. Decisions taken would be legally binding and would guide future national commitments and policy.

A mandate for negotiations on the issue of long-term objectives would need to be tabled by a coalition of countries, preferably from among those that are the most vulnerable to climate change to maximise the mandate's legitimacy, and agreed upon. Discussions could take place under the review of the adequacy of commitments under the UNFCCC, thereby allowing non-Kyoto parties to take part, if so desired. In addition, clear modalities for the talks could be decided in advance, with agreement, for example, on what criteria to use and what climate sensitivity to apply.

Arguments against

However, the problems associated with this approach are likely to be substantial. The first hurdle would be obtaining agreement on a mandate for such negotiations. Opposition is likely to be based on the belief that any internationally agreed long-term objective might result in potentially far-reaching obligations. For developing countries in particular, caps of any kind are often thought to hinder development. Moreover, OPEC countries, who usually chair and control the group of 77 developing countries (G77) at the climate negotiations, are likely to use their resources to try to block any motion they believe would reduce their output or revenue. Even sympathetic governments may say that they would not want to start talks on this issue until 2007, when the IPCC's Fourth Assessment Report is due to be published.

Even if a mandate to negotiate a multilateral agreement on a long-term objective under the UNFCCC were obtained, the scientific uncertainties involved could provide ample opportunity for many years of disagreement and delay, possibly diverting a limited pool of negotiating energy and providing an excuse for inaction, on the basis that no new short-term targets could be agreed until the long-term objective was decided.

Possible solutions

To increase their chance of success, much critical groundwork would need to be achieved in advance of any negotiations, focusing in particular on building support for the implementation of Article 2 to avoid a North–South divide in the talks. That would require intensifying contacts and multiplying confidence-building measures with G77 countries; efforts to increase the scientific and technical capacity of developing countries to define their vulnerability to climate change; and the provision of further assistance to improve developing countries' negotiating capacity.

It would also require agreement to be reached on holding concurrent negotiations on issues relating to pressing concerns of developing countries, including finance for clean development and adaptation, and equitable principles for future burden sharing. Outside of the climate policy arena, progress is also likely to require greater recognition of developing country concerns by the EU and US in world trade talks.

If China, India and Brazil as well as a coalition of least developed countries could be persuaded to support negotiations on a long-term objective, they could take on resistance from OPEC. Backed up by an unambiguous, high level political message to Saudi Arabia from major industrialised countries, its opposition could be neutralised. It would also clearly be important for any leadership group to build bridges to members of the Umbrella Group, including the US, Canada, Japan and Australia.

The negotiations could be aided by being framed clearly as being about long-term objectives, not commitments or targets. And the provision in the UNFCCC for a five yearly review of adequacy could reduce potential conflict over scientific uncertainty by providing a ready-made mechanism to ensure any long-term objective can be revised in light of new scientific information or dramatic changes in climate. Also, a hedging strategy could be pursued, as outlined above, which would avoid the need to agree on a specific long-term objective at this stage if it proved impossible, but would keep open the option of meeting any number of objectives in the future.

Without sufficient backing, however, it appears unlikely that a near-term negotiation on long-term objectives under the UNFCCC could proceed or prove worthwhile.

b) Building a coalition of countries in favour of a long-term objective

A distinct though complementary strategy would be to build a coalition of countries in support of a long-term objective or hedging strategy, using bilateral and multilateral channels. If a powerful enough coalition was built, conducive conditions might then be met for talks to be initiated at the UNFCCC. Alternatively, any agreement could be used to guide the development of national commitments and policy to mitigate climate change. Moreover, the attempt to pursue such a strategy alone could encourage governments to focus on the science, scale, and urgency of the problem.

The UK's G8 Presidency

The G8 could be a very useful forum to forge agreement in favour of a long-term objective or hedging strategy. It may be easier to engage G8 countries in discussion on this issue without the pressure of negotiating with 189 countries at this stage, especially if discussion is undertaken by heads of government and not at junior level. It will also be important to invite major developing countries like China, India and Brazil to take part in these discussions, and some of the most vulnerable countries too.

The UK Government has already indicated that it hopes to make long-term objectives a focus of its work on climate change in 2005 when it holds the G8 Presidency. The meeting announced by the Prime Minister on the science of climate change to be hosted by the Hadley Centre in February 2005 will provide a useful opportunity to discuss the issue. Any conclusions should inform the discussion by G8 heads of state on the issue, which the UK Government should work to ensure takes place.

If a process towards agreeing a long-term objective can be reached, the UK Government should work to build support for the 2°C objective and the medium-term action on CO_2 emissions necessary to meet it, which this paper concludes requires a cut in global CO_2 emissions of 10 per cent below 1990 levels by 2020.

That would require a major effort of persuasion by the UK Government and the Prime Minister, aimed at convincing other governments of the merits of the 2°C objective on the basis of the impacts that it would avoid. It is also likely to require a political and financial package to accompany it. That would need to include the outline of a global plan to involve more countries in the mitigating or burden sharing effort in the future in a way that is demonstrably fair to all parties. It should also demonstrate an increase in willingness among industrialised countries to fund mitigation and adaptation activities in the developing world.

If agreement could not be reached on a specific objective at the G8, governments should be persuaded at least to accept the importance of agreeing a long-term objective or strategy and a timetable to secure agreement on one.

Likely positions of the G8 and major developing countries

If such an approach were pursued, the UK would likely find **France** and **Germany** as G8 allies (although **Italy** is unlikely to be supportive). To build momentum before the G8 summit, the UK should work with its European allies to ensure that the EU Council reaffirms its 1996 decision to support the 2°C objective and specify what that means, at the EU leaders' Spring 2005 Council meeting.

It is hard to predict with certainty what the positions of other G8 members would be on this issue. However, as far as the **United States of America** is concerned, there is a small chance that President Bush might be persuaded to engage. One of Bush's central arguments in rejecting the Kyoto Protocol was that it didn't relate to the science and didn't involve any long-term destination. Moreover, in 2002, Bush reaffirmed the commitment of the United States to the UNFCCC and its ultimate objective. However, it should also be noted that he subsequently stated that 'No one can say with any certainty what constitutes a dangerous level of warming, and therefore what level must be avoided' (O'Neil and Oppenheimer 2002).

Of the different type of objectives, a temperature objective might be the least offensive to the US, unlike an objective based on emission reductions. The discussion would also need to be billed as an attempt to identify an 'aspirational' goal.

The governments of Canada, Japan and Russia have yet to take a position on a global long-term objective. Nevertheless, **Canada** might not have a problem taking part in a substantial discussion about it at the G8. It is already discussing long-term emission targets domestically, and any agreement at the G8 would afford it the chance of making grand, progressive statements on the international stage without necessarily having to follow up with immediate implementation, which would be attractive.

Work is ongoing in **Japan**, meanwhile, investigating the issue, with conclusions from one group, the Committee on Global Environment, likely to be published before the end of 2004. A discussion may therefore be possible, although it should be noted that the Ministry of Economy, Trade and Industry takes a sceptical view of targets, unless the US and developing countries are signed up, due to competitiveness concerns.

There is also some indication that **Russia** may be open to a discussion on long-term objectives. The high politics, and thus policy on the issue could change quickly, depending on Presidential intervention, as has been the case with regards to Russian ratification of the Kyoto Protocol.

With regards to the positions of the governments of the major developing countries that could be asked to participate in discussions on this issue at the G8, there appears to be scope for dialogue with China, India and Brazil. An academic study programme is underway in **China** on defining Article 2 of the UNFCCC, and China might envisage a combination of a temperature and a concentration objective. However, it would also be likely to seek an equitable framework (based on per capita allocation of emission entitlements, as well as some level of historical accountability for the problem) as a condition of China taking part in burden sharing, and China is also likely to want to have such discussions in the context of the UN.

India may not find a temperature-based objective impossible to accept, as long as it did not involve any allocation of commitments. And it is possible that **Brazil** could agree to a long-term objective of 2°C. But it would likely be opposed to a concentration target, because it feels it would imply short-term commitments.

There is therefore clearly scope for a potentially useful discussion on long-term objectives during the UK's Presidency of the G8. However, it will be very important to maintain momentum after the G8 process ends, by making use of other political events throughout the year and identifying what can be achieved at each.

Countries that may be willing to be part of a larger informal coalition

Whatever emerges from the G8 process, any discussion on long-term objectives should be extended to as many countries as possible, not least to reduce the suspicion or hostility with which countries might treat any outcome if and when it is brought to the FCCC, if the initial discussion takes place outside it and they were not involved.

If the US or other countries prove unwilling to take part, the task of building a wider coalition of countries in favour of a long-term objective or strategy should proceed without them. Countries that could usefully be engaged with in the process include:

- members of the EU (although perhaps not many of the newest members);
- possibly New Zealand, Norway and Switzerland;
- the largest industrialising countries with the most progressive positions on climate change: Mexico, Argentina and South Korea;
- Latin American countries, who are fairly vulnerable to climate change, are not responsible for large emissions, and have adopted a renewable energy target;
- a large number of least developed countries who are highly vulnerable to climate change, including Tanzania, Mali, Uganda and Bangladesh;
- members of the Alliance of Small Island States, including Samoa, Tuvalu and the countries of the Caribbean.

Most governments in Africa ought to be among the most willing partners in such a coalition. However, it is hard to find people to engage with and take the issue seriously in much of

Africa. Consequently, a dialogue needs to be opened with African leaders to help them recognise the scale of threats they face from climate change, through regional impact assessments and capacity building for negotiations.

If the largest developing country emitters, particularly China, India and Brazil, could be persuaded to join such a coalition, the impact would be very significant. However, the challenge is unlikely to be met without substantial trust-building first.

If such a strategy succeeds, and a critical mass of support is reached in favour of a specific long-term objective or hedging strategy, or the need to agree one on a specific timetable, it might then be possible to initiate formal discussions at the UNFCCC.

c) Forging a domestic consensus on a long-term objective

If a multilateral consensus on a long-term climate objective or strategy proves impossible to reach, governments should be encouraged to initiate a process aimed at forging a domestic consensus on what a long-term objective should be. They should then ensure that it is reflected in their national commitments as part of the post-2012 international climate negotiations or simply to inform domestic policy.

A bottom-up identification of current and future risks could be initiated in individual countries. Discussion could take place in national parliaments, where legislators are likely to be more sensitive to risk issues than administrations, especially in the US. Parliamentary enquiries or hearings could be held, and a clear recommendation made.

It could also involve scientists, environment and development organisations, and businesses, each examining what impacts would be considered as being dangerous as the basis of an objective. The process could also be made more participatory by involving the public, through citizen’s juries and focus groups, including normally excluded voices and vulnerable groups.

The very process of trying to develop a long-term objective could help educate governments and the public alike about the risks their countries are facing from climate change, helping to generate political will and acting as a catalyst for action.

Members of the G8 could commit to initiating such a process domestically, in the absence of a common agreement on a specific long-term objective or strategy at the G8, and it could build the foundations for an eventual multilateral negotiation.

Conclusion

The issue of setting long-term limits to global warming has been discussed among experts for thirty years. If the ultimate objective of the UNFCCC is to be fulfilled and dangerous climate change avoided, it is time that political discussions on it begin.

The ideal solution would be for negotiations to take place under the UNFCCC, concluding in an international agreement that binds all countries to meeting a common objective and guides national positions in negotiations on the next phase of the Kyoto Protocol. However, if such a proposal were to be tabled immediately, conditions may not be conducive enough yet for a successful outcome to be possible.

First, discussions need to take place outside the UN process, aimed at building a significant group of countries in favour of a specific long-term objective or hedging strategy, and/or of negotiating such an agreement at the UNFCCC. If either outcome, having being sought, proves impossible to reach, governments should be encouraged to initiate a domestic process to come to a national agreement on a long-term objective. Any objective that emerges from such multilateral or domestic processes should then shape positions taken in the next round of negotiations on commitments at the UNFCCC, as well as domestic climate and energy policy as it is decided.

With the UK's Presidencies of the G8 and EU in 2005 and a government in office in the UK that is willing to take the initiative on this issue, a rare opportunity exists to see discussions on such options initiated multilaterally at the highest levels. The UK government, joined or supported by members of the EU and other interested governments, should place a high priority on achieving agreement on the options outlined. Furthermore, if a process for agreeing an objective can be agreed, the case for limiting temperature rise to 2°C should be made vigorously.

Whatever option is deemed most favourable, the task of defining a long-term objective needs to be raised up the political agenda and discussed, not least during the UK's Presidency of the G8 in 2005. If we are to avoid the prospect of dangerous climate change, it is an issue that we can no longer afford to ignore.

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Appendices

Appendix 1*

Probability Calculations

Tables 1 and 2 (below) show the implications for temperature stabilization targets of seven different plausible PDFs (probability density functions) for the climate sensitivity. The seven PDFs are described below.

Table 1 shows the value of the 50th, 60th, 70th, 80th, 90th, 95th and 99th percentiles for each PDF, in degrees C; for example, for the first PDF, IPCC uniform, it is 80 per cent likely that the equilibrium temperature will be at or under 3.9ºC.

Table 2 shows the radiative forcing, in CO_2-equivalent, associated with various probabilities of staying below the 2ºC line at equilibrium. For example, again for the first PDF (IPCC Uniform), an 80 per cent chance of staying below 2ºC requires stabilization at or below 398 ppm CO2 equivalent.

Table 1

PDF THRESHOLD (°C)	50	60	70	80	90	95	99
IPCC Uniform	3.0	3.3	3.6	3.9	4.2	4.4	4.5
IPCC Normal 90	3.0	3.3	3.6	4.0	4.5	4.9	5.7
IPCC Normal 95	3.0	3.2	3.5	3.8	4.2	4.5	5.1
IPCC Normal 98	3.0	3.2	3.4	3.6	4.0	4.2	4.7
Wigley Lognormal	2.6	2.8	3.1	3.4	4.0	4.5	5.7
TAR GCMs	3.5	3.7	4.0	4.3	4.7	5.0	5.6
Andronova and Schlesinger	2.0	2.8	3.6	4.7	6.8	9.4	15.0
MIN	2.0	2.8	3.1	3.4	4.0	4.2	4.5
MEDIAN	3.0	3.2	3.6	3.9	4.2	4.5	5.6
MAX	3.5	3.7	4.0	4.7	6.8	9.4	15.0

Table 2

2° CO_2e MAX (ppm)	50	60	70	80	90	95	99
IPCC Uniform	443	424	410	398	388	383	380
IPCC Normal 90	443	425	410	395	380	370	356
IPCC Normal 95	443	428	416	403	389	380	366
IPCC Normal 98	443	431	420	408	395	387	373
Wigley Lognormal	476	455	436	417	394	379	356
TAR GCMs	414	404	395	385	375	367	356
Andronova and Schlesinger	552	459	411	375	342	322	305
MIN	414	404	395	375	342	322	305
MEDIAN	443	428	411	398	388	379	356
MAX	552	459	436	417	395	387	380

About the PDFs.

The first five PDFs are based on alternative interpretations of the IPCC's estimate that the climate sensitivity is between 1.5 and 4.5ºC. The IPCC declined in the TAR to put any further qualifications on the shape of the probablility distribution. The five interpretations are:

1) Uniform: an equal probability of every temperature between 1.5 and 4.5ºC, and no probability that it is outside that range;
2) IPCC Normal 90: a normal (bell shaped) distribution, with a mean of 3.0ºC, and 90 per cent of the distribution between 1.5º and 4.5º. This implies a standard deviation of 1.15, and a 5 per cent probability that the value is >4.5ºC.
3) IPCC Normal 95: the same as 2, but with a smaller standard deviation, so that 95 per cent of the distribution is between 1.5º and 4.5º, and a 2.5 per cent probability that the value is >4.5ºC.
4) IPCC Normal 98: the same as 2 and 3, but with a still smaller standard deviation, so that 98 per cent (actually 97.7 per cent) of the distribution is between 1.5º and 4.5º. Technically this defines the 1.5º and 4.5º boundaries as being exactly two standard deviations from the mean.
5) TAR GCMs: In Table 9.4 of the report of Working Group I in the Third Assessment Report, the IPCC reports the mean and standard deviation of the climate sensitivity in the 15 GCMs whose results are reported.
6) Wigley Lognormal: Another way to define a PDF to fit a specified range is as a lognormal distribution, which is similar to a normal distribution except that it implies the natural logarithm of the independent variable is normally distributed rather than the independent variable itself. By contrast with the normal distribution, the mean is shifted to the left, and the right hand 'tail' is longer. Wigley and Raper (2001) defined a lognormal which has 90 per cent of the distribution between 1.5º and 4.5ºC, and a median of 2.6ºC.
7) Andronova and Schlesinger (2001) compared the results of a simple model with historical climate data to produce a Bayesian estimate of the climate sensitivity. Compared with the IPCC range, the median is relatively low (2.0ºC) and the right hand tail is very large (more than 20 per cent is over 2.5ºC).

It's important to note that there is no 'correct' PDF for the climate sensitivity. Unlike the PDF for (say) flipping a coin, there is no underlying 'population' of results, from which climate sensitivity is a particular realisation. Rather, a PDF represents a subjective estimation of the strength of evidence for various possible values. For a more complete discussion, see Morgan and Henrion (1990).

It's also important to note that the 'min, median and max' will be determined by which PDFs are included. There are several other PDFs for the climate sensitivity that have been published, some generally 'higher' and some generally 'lower' than the IPCC-based PDFs (Baer 2004).

References

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Appendix 2

A carbon budget corresponding to stabilisation at 360ppm CO2

The formula for working out a 100 year carbon budget is: target concentration level minus concentration level at start of budget period / 0.47 + 100*average sink.

For a budget period of 2000 to 2100, a target concentration of 360ppm CO_2, a concentration level of 370ppm CO_2 in 2000, and an average annual sink of 4 billion tons of carbon (GtC), the budget calculation is: 360-370 / 0.47 + 400 = 378.72 GtC

Appendix 3*

Global emission reduction scenarios to achieve stabilisation at 360ppm CO_2

The following tables assume that fossil fuel emissions were 6.1 GtC in 1990, 6.6 GtC in 2000 and rise at 1 per cent per year until stabilization, and that land use emissions were constant at 1 GtC annually from 1990 until the year in which they start to decline, at which point they decline at the same rate as fossil fuel emissions.

Table 1. 2.5% annual decline starting in 2010

Year	Tot CO_2 emissions (GtC)	Atmos CO_2 (ppm)	CO_2 (pct of 1990)	CO_2 (pct of 2000)	Cum CO_2 (from 2000)	Avg Sink
1990	7.1	354	100	93	0	0.0
2000	7.6	369	107	100	0	4.2
2010	8.3	387	116	109	79	4.2
2020	6.5	402	91	85	153	4.2
2030	5	410	71	66	211	4.1
2040	3.9	413	55	52	256	4.1
2050	3.1	410	43	40	291	4.1
2060	2.4	404	33	31	319	4.1
2070	1.9	396	26	24	340	4.1
2080	1.4	386	20	19	357	4.0
2090	1.1	374	16	15	369	4.0
2100	0.8	360	12	12	380	4.0

Table 2. Stabilization in 2010, 4.05% annual decline starting in 2020

Year	Tot CO_2 emissions (GtC)	Atmos CO_2 (ppm)	CO_2 (pct of 1990)	CO_2 (pct of 2000)	Cum CO_2 (from 2000)	Avg Sink
1990	7.1	354	100	93	0	0.0
2000	7.6	369	107	100	0	4.2
2010	8.3	387	116	109	79	4.2
2020	8.3	406	116	109	162	4.2
2030	6	422	85	80	236	4.1
2040	4	427	57	53	287	4.1
2050	2.7	424	38	35	321	4.1
2060	1.8	416	25	24	343	4.1
2070	1.2	405	17	16	358	4.1
2080	0.8	391	11	10	368	4.0
2090	0.5	376	7	7	375	4.0
2100	0.3	360	5	5	380	4.0

Appendix 4 **

Emission reduction scenarios for the UK to 2050 consistent with longer-term global stabilisation at 360ppm CO_2

Table 1: Global emissions peak in 2010

Year	UK				World			
	Population (millions)	Total CO_2 emissions (MtC)	Change in total CO_2 emissions from 1990	Per capita CO_2 emissions (tC)	Population (billions)	Total CO_2 emissions (GtC)	Change in total CO_2 emissions from 1990	Per capita CO_2 emissions (tC)
1990	57	165	-	2.9	5.3	7.1	-	1.3
2000	59	153	-7%	2.6	6.1	7.6	+7%	1.2
2010	61	132	-20%	2.2	6.8	8.3	+16%	1.2
2020	64	105	-36%	1.6	7.5	6.5	-8%	0.9
2050	65	22	-87%	0.3	9.2	3.1	-56%	0.3

Table 2: Global emissions peak in 2020

Year	UK				World			
	Population (millions)	CO_2 emissions (MtC)	Change in total CO_2 emissions from 1990	Per capita CO_2 emissions (tC)	Population (billions)	CO_2 emissions (GtC)	Change in total CO_2 emissions from 1990	Per capita CO_2 emissions (tC)
1990	57	165	-	2.9	5.3	7.1	-	1.3
2000	59	153	-7%	2.6	6.1	7.6	+7%	1.2
2010	61	132	-20%	2.2	6.8	8.3	+17%	1.2
2020	64	104	-37%	1.6	7.5	8.3	+17%	1.1
2050	65	19	-88%	0.3	9.2	2.7	-62%	0.3

These tables are based on a global emissions budget to stabilise atmospheric CO_2 concentrations at 360 ppm CO_2 by 2100 (see appendix 3), with global emissions peaking in 2010 (table 1) and 2020 (table 2). Population projections to 2050 for the UK are from the Government Actuary Department and those for the world are from the US Census Bureau. The table also assumes the UK Government's target for a 20 per cent reduction in total UK CO_2 emissions by 2010 is met, steady reduction in UK emissions between 2010 and 2050 takes place, and convergence on equal per capita emissions occurs between countries in 2050.

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