



AVOIDING DANGEROUS CLIMATE CHANGE

International Symposium on the Stabilisation of greenhouse gas concentrations

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The International Scientific Steering Committee

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Foreword

The International Symposium on Stabilisation of Greenhouse Gas Concentrations – Avoiding Dangerous Climate Change - took place, at the invitation of the British Prime Minister Tony Blair and under the sponsorship of the UK Department for Environment, Food and Rural Affairs (Defra), at the Met Office, Exeter, United Kingdom, on 1-3 February 2005.

The conference discussed the long-term implications of different levels of climate change for different sectors and for the world as a whole. Major themes included key vulnerabilities of the climate system and critical thresholds, socio-economic effects, both globally and regionally, emission pathways to climate stabilisation and technological options available to achieve stabilisation levels.

The conference brought together over 200 participants from some 30 countries, mainly including scientists, and representatives from international organisations and national governments. The conference offered a unique opportunity for scientists to exchange views on the consequences and risks presented to the natural and human systems as a result of changes in the world's climate, and on the pathways and technologies to limit GHG emissions and atmospheric concentrations.

This report, prepared by the International Scientific Steering Committee (ISSC), summarises findings as presented at the conference. I am very grateful to the ISSC for their many suggestions and contributions.

The Chair

Dennis Tirpak

Summary

The Third Assessment Report (2001) of the IPCC (TAR) reviewed in depth all the scientific, technical and socio-economic aspects of climate change. It concluded that there was strong evidence that climate change due to human emissions of greenhouse gases was already occurring and that future emissions of greenhouse gases were likely to raise global temperatures by between 1.4 and 5.8 C during this century, with a wide range of impacts on the natural world and human society.

Building on the TAR, the conference on *Avoiding Dangerous Climate Change*, considered three scientific questions relating to stabilising greenhouse gas concentrations in the atmosphere at levels which would avoid dangerous anthropogenic climate change. These questions were:

1. For different levels of climate change what are the key impacts, for different regions and sectors and for the world as a whole?
2. What would such levels of climate change imply in terms of greenhouse gas stabilisation concentrations and emission pathways required to achieve such levels?
3. What options are there for achieving stabilisation of greenhouse gases at different stabilisation concentrations in the atmosphere, taking into account costs and uncertainties?

The findings presented at the conference addressed different aspects of these questions.

Assessment of Impacts

Compared with the TAR there is greater clarity and reduced uncertainty about the impacts of climate change across a wide range of systems, sectors and societies. In many cases the risks are more serious than previously thought. As noted in the TAR, a global temperature increase of up to 1 C may be beneficial for a few regions and sectors such as high latitude areas and agriculture. A number of new impacts were identified that are potentially disturbing. One example is the recent change that is occurring in the acidity of the ocean. This is likely to reduce the capacity to absorb CO₂ from the atmosphere and affect the entire marine food chain.

A number of critical temperature levels and rates of change relative to pre-industrial times were noted. These vary for the globe, specific regions and sensitive ecosystems. For example, a regional increase above present levels of 2.7 C¹ may be a threshold that triggers melting of the Greenland ice-cap, while an increase in global temperatures of about 1 C is likely to lead to extensive coral bleaching. In general, surveys of the literature suggest increasing damage if the globe warms about 1 to 3 C above current levels. Serious risk of large scale, irreversible system disruption, such as reversal of the land carbon sink and possible destabilisation of the Antarctic ice sheets is more likely above 3 C. Such

¹ This would be associated with a global temperature rise of about 1.5 C above present or about 2 C above pre-industrial temperature

levels are well within the range of climate change projections for the century. While a clear temperature threshold has not been identified for shutdown of the Atlantic thermohaline circulation, studies were presented suggesting that a shutdown becomes more likely with increasing temperature. In this context, some felt that it would be useful to agree upon a set of critical thresholds that we should aim not to cross. Others noted it would be difficult to objectively choose such a level.

The impacts of climate change are already being observed in a variety of sectors. Ecosystems are already showing the effects of climate change. Changes to polar ice and glaciers and rainfall regimes have already occurred. While consistent with model projections the links to anthropogenic climate change need to be investigated further.

Many climate impacts, particularly the most damaging ones, will be associated with an increased frequency or intensity of extreme events. This is an important area for further work since many studies do not explicitly take into account the effects of extremes, although it is known that such extremes pose significant risks to human well being. The heat-wave that affected Europe in 2003 is a prime example.

Adaptive capacity is highly important to lessening the potential future dangerous effects of climate change. In some sectors and systems this capacity may be sufficient to delay or avoid much potential damage, though in others it is quite limited.

The capacity to adapt is closely related to technological ability, income levels and form of governance in a country. Adaptation and alternative development pathways need to be taken into account in developing strategies to avoid dangerous anthropogenic climate change. This was seen as particularly important if the potential impacts of climate change in Africa are to be avoided.

Climate sensitivity and emission pathways

It is possible to decouple the assessment of different levels of stabilisation from consideration of the question of what is dangerous. The conference thus explored separately the emission pathways associated with different greenhouse gas stabilisation levels and different global temperature limits. It is helpful to take into account uncertainty in the sensitivity of the climate system to greenhouse forcing by presenting pathways in probabilistic terms. There is evidence that the sensitivity is now likely to be higher than quoted in the TAR, however observational data may constrain the range.

There is a range of emission pathways that could be followed theoretically to avoid different temperature levels. Probability analysis provides a quantitative estimate of the risk that a particular temperature level would not be exceeded. For example, limiting warming to 2 C above pre-industrial levels with a relatively high certainty requires the equivalent concentration of CO₂ to stay below 400 ppm. Conversely, if concentrations were to rise to 550 ppm CO₂ equivalent, then it is unlikely that the global mean temperature increase would stay below 2 C. Limiting climate change to 2 C above pre-industrial implies limiting the atmospheric concentration of all greenhouse gases. Based on new insights into the

uncertainty ranges of climate sensitivity, a stabilisation at 450 ppmv CO₂ equivalent would imply a medium likelihood (~50%) of staying below 2 C warming. In many cases this would mean that concentrations would peak before stabilising, though whether this could be achieved practically was not considered.

Different models suggest that delaying action would require greater action later for the same temperature target and that even a delay of 5 years could be significant. If action to reduce emissions is delayed by 20 years, rates of emission reduction may need to be 3 to 7 times greater to meet the same temperature target. Coupled carbon-cycle GCM simulations showed the importance of considering the future of natural sources and sinks of carbon when determining how to achieve given CO₂ stabilisation levels.

Technological options

The IEA World Energy Outlook 2004 predicts that CO₂ emissions will increase by 63% over 2002 levels by 2030. This is generally consistent with the IPCC emission scenarios, published in 2000. This means that the world will, in the absence of urgent and strenuous mitigation actions in the next 20 years, almost certainly be committed to a temperature rise of between about 0.5 C and 2 C relative to today by 2050.

Technological options for significantly reducing emissions over the long term already exist. Large reductions can be attained, using a portfolio of options whose costs are likely to be smaller than previously considered. Sustainable development strategies can make low-level stabilisation easier. There are no magic bullets; a portfolio of options is needed and excluding any options will increase costs. Multi-gas strategies, emission trading, optimal timing and strong technology development, diffusion and trading are all required to keep costs of low-level stabilisation relatively low. Inclusion of technological learning in models suggests that projected costs of such reductions can be reduced by over half. To make required action more specific and transparent, the challenges could be broken down into discrete wedges, covering for example energy efficiency, nuclear energy, low-emission transport fuels and fossil fuel power plants with CO₂ capture and storage.

Globalisation and market forces will drive the developing countries to follow the same pattern practiced by the developed countries. Demonstrated energy efficiency improvements under the present market system in industrialised countries are not enough to offset increases in demand caused by economic growth in developing countries, although some developing countries have shown much higher improvement rates over certain periods. Efficiency improvements and alternative energy supply such as nuclear and renewables are of priority for developing countries to contribute their share to the effort of stabilisation.

Major investment is needed now in both mitigation and adaptation. The first is essential to minimise future impacts and the latter is essential to cope with impacts which cannot be avoided in the near to medium term.

Report of the conference by the Steering Committee

Introduction

The International Conference on Stabilisation of Greenhouse Gases – Avoiding Dangerous Climate Change took place, at the invitation of the British Prime Minister Tony Blair and under the sponsorship of the UK Department for Environment, Food and Rural Affairs (Defra), at the Met Office, Exeter, United Kingdom, on 1-3 February 2004.

The conference brought together over 200 participants from some 30 countries, mainly scientists and representatives from international universities, organisations, and national governments. The conference offered a unique opportunity for scientists to exchange views on the consequences and risks presented to natural and human systems as a result of changes in the world's climate.

The conference discussed the long-term implications of different levels of climate change for different sectors and for the world as a whole. Major themes included key vulnerabilities of the climate system and critical thresholds, socio-economic effects, both globally and regionally, emission pathways to stabilise greenhouse gases and technological options to achieve stabilisation level.

This report by the Steering Committee is designed to give an overview of the key issues arising, but should not be seen as an exhaustive report. Readers are encouraged to look at the papers and presentations which have been placed on the conference website at www.stabilisation2005.com

Keynote speech

Dr Pachauri, chairman of the IPCC noted that “dangerous” climate change requires a value judgment but that these should be based on the principles of universal human rights and the needs of future generations, as exemplified in Sustainable Development. However, science can provide essential information on impacts and damage, taking into account socio-economic dimensions.

He considered the issues relevant to the use of thresholds in defining dangerous climate change such as initial conditions, marginal impacts and damage, costs of impacts, irreversibility and adaptation. He noted that it would be important to consider who would be affected and the time scale for dangerous effects to become apparent. He also asked whether a temperature target would capture various dimensions of dangerous, whether a global target would represent dangers at the local level, how concentrations are related to temperature and what trajectories were appropriate.

He noted current changes related to warming, and the scale of impacts which are anticipated, including the impact of extremes. He also noted the potential for major changes to the climate system, which could overwhelm our response strategies, including breakdown of the thermohaline circulation, disintegration of the West Antarctic Ice Sheet, a shift in mean climate towards an El Nino like state, reduced carbon sink capacity, methane release from hydrates, and a rearrangement of biome distributions.

Finally he noted the inertia in the climate system and time taken for mitigation actions to impact on temperatures and sea levels, and the importance of mitigation in furthering sustainable development goals and maximising co- benefits of mitigation and implementing no regrets options.

Session 1a - Key vulnerabilities of the climate system and critical thresholds

As a result of anthropogenic greenhouse gas emissions, key components of the climate system are put under stress and may respond in an abrupt and irreversible way. Schneider emphasised this high impact general risk in his conceptual overview of “dangerous” climate change issues. He also portrayed the respective roles of scientists and policymakers in this complex arena. In particular, he introduced the notion of Type I errors (exaggerated precautionary action based on ultimately unfounded concerns) and Type II errors (insufficient hedging action delaying measures while waiting for the advent of overwhelming evidence). Schneider suggested ways out of this dilemma using recently developed probabilistic analyses (constructing, for instance, a cumulative density function for the IPCC TAR’s burning embers diagram). His observations were underpinned by a series of more-specific presentations addressing possible critical thresholds and tipping points in physical and biological systems.

Rapley focussed on the Antarctic ice sheet and its relationship with sea-level. He presented new data-based results that cast further doubts on the stability of the West

Antarctic ice sheet. The melting of the ice shelves, such as Larsen B which has been continuously present since the last ice-age, may be leading to a speed up of some glaciers, by a factor of 2–6, in a “cork out of bottle” effect. These processes need to be incorporated in advanced ice-sheet models. The extents to which anthropogenic warming or natural variability are contributing to these changes is unknown.

Lowe addressed the Greenland ice sheet which, if it melted would raise the global average sea-level by around 7 metres. Lowe reported on a model ensemble experiment based on the IPCC finding that local warming of more than 2.7 C would start the ice sheet to contract. Using a range of models and of emissions scenarios leading to CO₂ stabilisation between 450 ppm and 1000 ppm, the study demonstrates that the trigger point could be reached within the next few decades. In fact, even with stabilisation at 450 ppm, 5% of the models and scenarios lead to a complete and irreversible meltdown, although this would take place over millennia.

A package of three papers was dedicated to the stability of the North-Atlantic Thermohaline Circulation (THC). Schlesinger presented a novel assessment based on probability distributions for crucial system parameters and a spectrum of possible policy interventions. He estimated using a simplified model that business as usual emissions generates a 2 in 3 chance of a THC collapse in the next 200 years. Challenor presented results, based on a massive ensemble study, using a medium-complexity model and Bayesian techniques. The study suggests a 30% possibility of THC shutdown by the end of this century. The ensemble has not been weighted by comparison with observations, although the parameter values were obtained from a previous model fit. Wood showed from a model simulation that the cooling effect of a hypothetical THC shutdown in 2050 would more than outweigh global warming in and around the N Atlantic. He demonstrated the feasibility of ensembles of GCMs to quantify the likelihood of THC collapse, noting that no GCM in IPCC TAR or since showed a shutdown by 2100. He noted that further modelling experiments and observation data are essential for more robust answers.

Turley presented new data showing the marked acidification of the oceans due to atmospheric carbon dioxide enrichment. This acidification may result in drastic changes in marine ecosystem structure and biogeochemical cycling with major impacts on the ocean carbon fluxes and the ability of the oceans to buffer further emissions of CO₂.

The papers presented in this session illustrate why the term “global warming” is inadequate to describe the changes we can expect in the Earth System. We should not focus on temperature alone but on the anticipated shifts in climate variability, for example, with an increase in the frequency and severity of extreme events. As suggested, we have to consider systems risks such as the release of carbon from oceans, forests and permafrost, or the possibility of a rapid decline of Arctic sea ice. Addressing climate change will involve balancing uncertainties and understanding the dangers associated with delayed action.

Our understanding of the Earth System is still incomplete and the models need to be improved. For example, while we have a good sense of how much the sea level would rise if the Greenland ice sheet were to disappear, we do not fully understand the time frame in which this might happen. Similarly, while we believe the THC behaviour can be

represented as a hysteresis curve we do not know its precise shape or where we are presently on it. Although this limits the ability to identify critical levels, nevertheless, our present knowledge, from palaeoclimatic data and from models, suggest a somewhat greater risk than expressed in the IPCC 3rd Assessment Report and is certainly sufficient to indicate the possibility of “tipping points” that we should strive to avoid.

Session 1b - Impacts Overview

Papers presented by Parry, Izrael, and Smith, and discussion led by Houghton, illustrated from different perspectives the extent to which tools are now emerging to support decision making in relation to the impacts of climate change.

Parry stressed that key impacts and thresholds are affected by choice of scale, sector and adaptive capacity. Indications from the “Fast-Track” project are that stabilisation at 750 ppm does not avoid most “dangerous” effects, whilst stabilisation at 550 ppm avoids some but not all dangerous climate change. Choice of development pathway (for example, IPCC SRES B2) can be as important as specific mitigation strategy.

Izrael proposed tentative limits of a temperature rise of 2.5 C for the globe and 4 C for the Arctic, 1 m sea-level rise, with CO₂ limited to 550-700 ppmv. Global mitigation costs should not exceed 1-2% of the increase in GDP.

Smith suggested there are many levels of potentially dangerous anthropogenic interference, given the complexity of climate change impacts and scales at which it is felt. It may be desirable to establish a goal which stabilises concentrations at as low a level as feasible, which can be revisited in the light of improvements in scientific understanding, the capacity to reduce emissions or as values change. This should recognise that impacts below the goal may still be dangerous and will need to be the focus of adaptation. To be broadly accepted and meaningful, any process to determine a target should be transparent, and incorporate public values and perceptions.

Papers during this session demonstrated the need to take into account both incremental and non linear impact processes, and the interactions between them, as well as the way in which climate and other human induced stresses operate in combination. The consequences of climate change vary with scale, from global to community level, and between regions. How to respond is a function not only of scientific understanding but also of values, which themselves vary between different communities, and over time as knowledge advances. Moreover as climate changes, societies will also be changing. New technologies are likely to emerge, new discoveries will be made and population shifts will occur. Forecasting such changes is extremely difficult but climate change impacts analyses must take into account, to the extent possible, changes to societies and how they will adapt.

Nevertheless, there is a growing understanding of how to assess climate vulnerabilities for humans and ecosystems, how to frame the associated risks, and how to aggregate likely damage across regions and sectors. Many uncertainties remain; but our sense of what is

known and what is not known is growing, as is our confidence in presenting this in an integrated form to policymakers.

The notion of resilience is an important concept. Societies that are more resilient to exogenous change in general will be better able to adapt to climate induced stresses. Climate change would put many more people at risk of malaria, for example. But this number was small in relation to the total number at risk. In that case, climate change is simply an additional reason to intensify public health measures to deal with or eliminate malaria.

Session 1c Key vulnerabilities for Ecosystems and Biodiversity

In this session the impacts of climate change on the carbon cycle and ecosystems were considered. Cox presented an analysis of the modelled transition from carbon sink to carbon source in the terrestrial biosphere. He noted that such feedbacks have been an important consideration in developing the newest generations of GCMs which include the key processes of photosynthesis, respiration and vegetation dynamics and their responses to changes in CO₂ and climate. His work noted that the high range of uncertainty in the relevant parameters, but concluded that there was a significant probability of shift from carbon sink to source in the terrestrial environment before the year 2100 under business-as-usual emissions scenarios.

Lewis discussed the role of tropical forests in the global carbon cycle. He showed partly on the basis of permanent plot studies, how remaining forest is currently an important sink, while ongoing deforestation is still an important source. However, remaining forest could become a major source of CO₂ under business as usual scenarios, leading to rapid atmospheric CO₂ concentration increases, this century. He also noted that observed biodiversity changes, not included in the GCMs, could exacerbate such a trend.

Leemans noted that the large increases in the number of studies published in the literature provides evidence of ecosystems changes; 21 papers were available to the IPCC TAR and now there are over a thousand. He emphasised that studies focusing on species specific responses depict more impacts than traditional impact assessments focusing on long-range shifts of biomes. His survey showed very widespread and immediate phenological, species range shifts and whole food- web responses, including insects, birds, pathogens, lichens and trees, as a result of climate change. He also noted that ecosystems may respond more strongly to changes in extreme weather events than average climate and proposed that the rate be limited to 0.5 C per century instead of the commonly suggested 2 C above pre-industrial levels.

Lanchberry argued that, on the basis of ecological effects and the observed inability of some natural ecosystems to adapt, atmospheric concentrations of greenhouse gases can be considered to be already too high. He pointed out alterations to species ranges, ecosystem loss and the unpredictability of subsequent impacts arising from changes in one key species. He highlighted work in the North Sea on seabird populations, and noted that climate impacts on plankton abundance may have resulted in a substantial reduction in

sand eel numbers – a key feed species for many seabirds. This shortage has been independently indicated by Danish sand eel fisheries where 2003/4 catches were half the typical catch.

Summarising these four presentations, Prentice noted a common theme which applied equally to studies focused on biodiversity the carbon cycle, namely, that observations of various kinds – including range shifts, phenology, atmospheric measurements and whole eco-system measurements – generally confirm current understanding of the first-order environmental controls on ecological processes as encapsulated in current models. However he observed that the interaction of these processes with land-use is less well understood, although land-use change is now a major driver of ecosystem changes in most parts of the world. Finally although some presentations had suggested specific climatic thresholds related to ecosystem effects, he noted that many such effects did not lend themselves easily to the definition of thresholds and might be better treated through a quantitative analysis based on multiple metrics.

Session 1d - Socio-economic effects – key vulnerabilities for water resources, ecosystems, agriculture, coastal settlements and health.

In this session presentations focused on the science behind determination of key magnitudes, rates and aspects of timing related to the estimated effects of climate change.

Patwardhan suggested that key vulnerabilities, as measured in terms of socio-economic outcomes could provide useful information for countries to arrive at a well-informed judgment about what might be considered as dangerous levels or rates of climate change. He noted that climate change may be either a triggering effect on events which may have been pre-conditioned by other forces, or be an underlying cause in itself. But even in its causative role climate change most frequently occurs as one of a set of multiple stresses. It is therefore necessary to consider a quite complex set of interactions between climate and non-climate factors affecting future human and biophysical systems. As a result, it may be difficult to draw a direct relation between outcomes that matter, and rates and levels of climate change.

An illustration of this was given by Arnell in relation to effects on water supply. He noted that three key variables need analysis regarding their future trend: demand (dependant on population and its income level), vulnerability (dependant on income level and governance), and resource supply (in part dependant on climate change). Even without climate change, water stress is expected to increase, especially in C. Asia, N. Africa and the drier parts of China. Projected changes in climate are likely to alter the magnitude of stress and the timing of water stress. Arnell explored the effect of different development pathways (as reflected in SRES projections of population and GDP) on possible future impacts of climate change. Increases in water stress are likely to be higher under an A2 than a B2 scenario primarily because of higher vulnerability under A2, not because of difference in climate forcing.

Hare illustrated results from an expert review of extensive literature across several systems and sectors. He used a four-fold risk scale (from not significant to severe, according to the proportion of damage expected). He concluded that the point of large damage (20-50 per cent) varies considerably from one exposure unit to another. In most ecosystems it appears to be below 2 C above pre-industrial; but in some systems it may not occur even above 3 C. In general he concluded (and this is confirmed in other studies) that up to 1 C increase in mean global temperature is likely to be associated with damages in developing countries and with some benefits in developed countries, but beyond this point net damage is likely to increase in all areas.

Much of the analysis of potential impacts has been derived from modelling studies using input data from GCMs and statistical downscaling. These have been limited by the use of mean (for example, monthly) changes in values, and assumptions of a stationary climate. New work with process-based crop models, specifically designed to be coupled to GCMs, enable analysis of changes in CO₂, climate and extremes (for example, high temperature events that can reduce yields, such as the stress on wheat when temperature exceeds 31 C). They also include land-surface feedbacks to be considered. Challinor showed how his process-based crop model coupled to the Hadley climate model can be used to explore the effects of changes including extremes on crop productivity.

The importance of adaptive responses in affecting key vulnerabilities was stressed by Nicholls, using the example of coastal flooding due to sea level rise. Considerable differences in the estimated future numbers at risk derive from assuming either: constant protection of coasts, or evolving protection or enhanced protection. And, assuming enhanced protection in a B2 world, additional risk levels due to climate change are almost wholly avoided. This confirms the conclusions reported by Parry and Arnell (see above) that different levels of vulnerability and wealth in various development pathways greatly affect the ability to delay or avoid 'dangerous' effects; and that choice of development pathway can be an effective response to climate change (e.g. SRES B2 avoids most dangerous effects). This is especially relevant, since Nicholls pointed out that stabilisation cannot avoid all additional risk from future flooding due to the 'commitment' to sea-level rise in the ocean system.

In the health sector, Kovats et al. stressed the role of climate variability, and the possible effects on this of climate change. Much of the incidence of climate-related disease outbreak is due to particular weather events, sometimes in combination and also in relation to conditioning non-climate factors. In some cases the relationship appears quite clear (e.g. diarrhoea incidence in Peru increases by about 8% per degree C). In other cases it will require analysis from new coupled biophysical-climate models of the kind described by Challinor et al.

In discussion it was emphasised that the ability of society to adapt is central to a consideration of future 'dangerous' effects. Some current impact assessments do not give sufficient attention to this.

Some conclusions from this session can be summarised as follows.

- Analysis of adaptive capacity is central to any determination of potential future critical or “dangerous” effects from climate change. In some sectors and systems this capacity may be sufficient to delay or avoid much potential damage; in others it is quite limited.
- The capacity to adapt is closely related to aspects of future society such as technological ability, level of income and type of governance. For example, impacts under SRES B2 development pathways appear to be much less than under A2.
- Vulnerability (or exposure levels) may also vary considerably between, for example, the A2 and B2 worlds and this evidently greatly affects the nature of possible future impacts, whether ‘dangerous’ effects occur, and at what time.
- It follows from the above that a) adaptation and b) choice of development pathway are key potential strategies in avoiding ‘dangerous’ climate change.
- Mitigation cannot avoid considerable impacts in the near and medium term, and other strategies such as adaptation will be necessary as a consequence, as part of a mixed adaptation-mitigation response to climate change.
- Finally, new research tools such as coupled impacts-climate models offer the opportunity of analysing the effects of occurrence of ‘dangerous’ weather events rather than simply ‘dangerous’ climate change.

Session 1e - Regional perspectives: Polar regions, Mid-latitudes, Tropics and Sub-tropics

Folkestad discussed the impacts of temperature rise in the Arctic. He pointed out that the Arctic has been warming at a rate of about 0.5 C per decade (although others commented that Arctic temperatures were as warm in the 1940s as they are today). Using a range of GCMs they showed that the timeframe within which the global temperature might rise to 2 C above pre-industrial level was between 2026 and 2060. Such a rise could be equivalent to 3.2 to 6.6 C increase in the Arctic temperature. Their paper also showed that for each 1 C warming, perennial ice in the Arctic Ocean decreases by about 1.5 million km². The work suggested that such changes will have major impacts on ice living animals, but also important social and economic consequences for indigenous people.

Steffen and co-authors examined southern hemisphere perceptions of dangerous climate change, which are clearly necessary to complete our global picture. He showed that the distribution of rainfall over Australia has changed markedly over the past 50 years, with both large increases and decreases. Rainfall in SW Australia underwent a 15% decrease in the mid-70s, while at this time crop yields were increased due to changes in practices. However, at the same time stream flow decreased by 50%; as a consequence Perth is already water constrained. This case study showed how the same change in climate can have dramatically different consequences for different sectors. Changing SSTs and decreasing ocean pH have a marked effect on coral bleaching events; if these become too frequent coral reefs will be unable to recover. There is a lack of knowledge linking the impact of longer-term climate change with the behaviour of major climate features such as ENSO and ocean circulation. Steffen stated that for Australia there was a significant risk of further decreases in rainfall, leading to more severe and more prolonged droughts. They emphasised that the rate of change might be more important than the magnitude of the

change and that changes in water availability will be as important as the changes in temperature per se.

Harasawa showed how climatic changes had brought about an increase in extreme events in Asia in recent years. For example there were 10 typhoons in Japan during 2004. Large proportions of the Japanese coastal population are at risk with a 1 m rise in sea level. Other observed impacts included changes in the beech forests, water stresses and human health. There are indications that in India there will be increased water stress due to climate change that will affect crops such as rice and wheat. The paper called for more research to better understand the geographical scope and magnitude of expected impacts, and to try and identify critical thresholds in different sectors.

Nyong highlighted the vulnerability of Africa to climate change; 70% of the least-developed countries are in Africa. This high vulnerability is a result not just of climatic factors, but of other stresses such as drought, disease and conflict. These impacts and vulnerabilities will be felt strongly in the water resources, agriculture, fisheries and health sectors. Under climate change scenarios, the work showed that the majority of crops will decrease in yield, that the area suitable for malaria in southern Africa will double and coral reefs will be lost due to bleaching, bringing associated impacts on the tourism industry. The paper included a call for more capacity building on adaptation in Africa, including the use of appropriate technologies, integration of indigenous knowledge and improved access to available funding.

Vogel and Nyong highlighted the linkages between climate change and development in Africa. They noted the key links between climate change and food security, water resources and other health factors. They emphasised that climate change will affect the achievement of the Millennium Development Goals. The paper called for more research at the climate/development nexus, in particular on the need to balance trade-offs between adaptation options.

Hayhoe presented an impact assessment for California based on two different climate change scenarios, but noted the difficulty in estimating future amounts of precipitation. California is a large climate-sensitive region with a wide variety of ecosystems. Primary findings showed that temperature could rise up to 4 C locally under a low emissions scenario and up to 8 C under a higher emissions scenario, and impacts on the region varied significantly between scenarios. As such, this approach could be applied to other regions around the world as a starting point from which to assess how risk of "dangerous" impacts scales with emissions. Hayhoe highlighted the importance of region-specific climate impact assessments covering a range of future scenarios to inform decision makers of potential "dangerous" impacts and the outcome of alternative GHG emission and stabilisation choices.

In discussing the session, Huq indicated the need for more regional scale models, which requires the ability to downscale to the local/national level. In particular, he highlighted the need for local models of politically relevant regions such as Small Island Developing States (SIDS) and Least Developed Countries (LDCs). These are the most vulnerable according to UNFCCC (Article 4.8) and therefore very relevant for specific efforts at targeted regional

impacts assessments. However there is a requirement for further research in each of the important regions. It will also be necessary to compare the results from regional studies with the global analyses to check consistency.

Working paper on the impacts literature

Warren introduced a working paper, commissioned by Defra, consisting of a number of tables of impacts. These presented different categories of impacts as a function of global temperature and sea level rise. She explained the rationale behind this work and the need to present possible impacts of climate change in an accessible way for policy makers. She also requested participants to provide feedbacks, including some positive, to enable her to improve the draft tables.

Session 2 – Emission pathways and climate sensitivity

This session considered the probabilities of exceeding different concentrations on temperatures given alternative pathways.

Mastrandrea and Meinshausen proposed a probabilistic approach to climate sensitivity as an appropriate method to inform policy makers of the risks of exceeding levels of Dangerous Anthropogenic Interference (DAI) for various stabilisation levels. Examples of such DAIs used are, for example, EU 2 C stabilisation target and a DAI index based on an equal weighting of the IPCC TAR reasons of concern (Mastrandrea). Meinshausen used a set of different published PDFs for indicating the risk of exceeding temperature targets for various stabilisation levels.

The constructed probability density functions indicate that the range of climate sensitivity (CS) values is much wider than suggested by the IPCC, in particular the probability of high values. While the most likely level of temperature change for double CO₂ is 2-4 C above pre-industrial more extreme change cannot be ruled out. Stainforth's exploration of uncertainty inherent in GCM modelling using distributed computational power showed that the response to even a relatively low stabilisation level (doubled CO₂) could be as much as 11 C above pre-industrial level.

Stainforth and Allen highlighted that there are problems with constraining climate sensitivity on the basis of observational data and that the various PDFs are determined by subjective expert judgements in their construction. Analyses of transient responses seem to indicate that the uncertainty in the CS is less important on the shorter timeframe of stabilisation than equilibrium responses. Allen suggested an alternative approach would be to consider the more well-constrained relationship between cumulative emissions and maximum temperature change.

The pathways associated with meeting climate targets were explored by several of the speakers.

Den Elzen noted the importance of considering the non-CO₂ gases and aerosols when analysing pathways. Tol showed that rapid reductions of global greenhouse gas emissions will lead to an initial increase in temperature due to aerosol reductions, although there was no discussion of the fact that reduced aerosol emissions were likely with or without reduced CO₂ emissions. Jones showed that carbon cycle feedbacks currently underestimated will have significant impacts on future pathways by requiring 20-30% greater emissions cuts to meet 550 ppmv CO₂ stabilisation goals, and changes in optimal trajectories. Climate-carbon cycle feedbacks are also critical in determining the feasibility of “overshoot” scenarios which may rely on natural carbon sinks to reduce CO₂ levels to the stabilisation target.

Meinshausen and Den Elzen considered the likelihood of overshooting the EU target of 2 C above pre-industrial level and indicated that there was a relatively high risk of exceeding the target when stabilising at 550 ppm CO₂ equivalent, and even some risk at 400 ppm and referred to studies that show that there is already a risk that the target will be exceeded even on current levels. The dependence of such outcomes on the PDFs used was noted. Meinshausen also showed that the risk of overshoot a temperature target can be reduced by letting concentrations peak (and then decrease) before they are stabilised.

They further considered the cuts needed to meet the EU target and indicated that emissions would need to peak around 2015, with subsequent decreases by 2050 dependent on the eventual stabilisation level (-10% for stabilising at 550 ppmv CO₂, e.g. and about 15% more for each 50 ppmv lower stabilisation target). In the case of low stabilisation targets (400–500 ppmv CO₂ equivalent), concentrations temporarily exceed the target levels before they return to their ultimate stabilisation targets by 2150. This overshoot is needed due to the short timeframes for adjustment and the present concentrations.

They, and others, highlighted the consequences of delaying action on climate change. Meinshausen showed that delays are possible but result in the need to increase reduction rates by approximately 1% for each five year delay. Kallbekken showed that a 20-year delay of action could result in required rates of emission reduction of 3-7 times greater than that required for a more immediate response to meet the same temperature target. Den Elzen also indicated the regional implications of stabilisation pathways, because that is important when considering cost and feasibility aspects.

Tol stated that no objective definition of dangerous interference is possible. Using a cost-benefit framework he suggested that only moderate mitigation levels are justifiable. He also pointed at the possible risk that too rapid mitigation, reducing economic growth, could increase vulnerability and climate change impacts in developing countries.

The discussion on climate sensitivity focused on the problems in defining PDFs and possible alternatives. A discussion on pathways included the importance of considering the rates of temperature change. In the discussion it was acknowledged that the costs and economic effects of stabilisation pathways, and the additional risks related to overshooting scenarios need to be considered.

Session 3 - Technology options for achieving stabilisation of greenhouse gases at different stabilisation concentrations in the atmosphere, taking into account costs and uncertainties

Metz noted that low-level stabilisation would not require totally new technologies such as nuclear fusion and that sustainable development strategies and corresponding behavioural attitudes would make low-level stabilisation easier. He pointed out that there are no magic bullets; a portfolio of options is needed and excluding any options will increase costs. Multi-gas strategies, emission trading, optimal timing and strong technology development, diffusion and trading are all required to keep costs of low-level stabilisation relatively low. A big problem for low-level stabilisation is overcoming the many political, social and behavioural barriers to implementing mitigation options. Co-benefits (development, security, environment) are important for costs and acceptability.

Socolow introduced the concept of the stabilisation wedge as a useful unit for discussing climate stabilisation. Each wedge is equivalent to 1 Gt C/yr of emissions savings in 2054, achieved by a single strategy that will not occur without deliberate attention to global carbon. He suggested that seven wedges would establish a path to stabilisation at a concentration less than double the pre-industrial concentration. This new framework also considers wedges of energy efficiency, nuclear energy and carbon capture and storage. The wedges concept permits discussion of cost, pace, risk and trade-offs associated with climate change. The framework could contribute new elements to global carbon policy, promoting internationally coordinated commercialisation of low-carbon technology.

Akimoto and Tomoda evaluated the costs and technological options by region for various CO₂ emissions reduction targets using their world energy systems model, which covers 77 regions over a 100-year time-span. Three case studies were covered by the evaluation: no climate policy; stabilisation at 550 ppmv CO₂; and stabilisation at 450 ppmv CO₂. They considered that the most cost effective stabilisation option would be made up of a mix of technological options, that the marginal cost of CO₂ reduction in 2100 is about 120 and 290 US\$/tC for 550 and 450 ppmv respectively, and that carbon capture and storage is important, especially for developed countries, to reduce the costs in both stabilisation cases.

Edmonds addressed the energy technology implications of limiting climate change in the year 2100 to 2 C relative to pre-industrial.

An Integrated Assessment Model (MiniCam and MAGICC) was used to simulate the future up to 2095, with a full physical model plus demography, land resource constraints and energy technology. Cost minimisation with full trading was assumed. The reference used was the IPCC SRES B-2 scenario.

Some interesting conclusions were obtained. The portfolio of technological options to meet a 2 C above pre-industrial level limit included a multigas approach and a substantial share of CO₂ capture and storage. Costs of this strategy are lower than estimated for similar constraints in the past. Global emissions peak before 2020 and decline to about 3 GtC/year by the end of the century.

Barker and Warren addressed the question of the costs of atmospheric stabilisation of CO₂, by coupling the E3MG energy-environment-economy model to a simple climate model (MAGICC). The approach is based on new concepts in the modelling of induced technological change (ITC) and thus provides new insights into the costs of stabilisation. A baseline scenario is compared with three others in which carbon taxes with revenue recycling are applied to achieve stabilisation of carbon dioxide concentrations at three different levels by 2100. The study showed that the projected cost of mitigation could be more than halved if technological learning is taken into account.

Zhou described current trends of world development. Technology innovation in developed countries lead technology change across the world. Globalisation and market forces drive the developing countries to follow the same pattern practiced by the developed countries. Up to now, higher per capita GDP correlated with higher carbon emission, although higher GDP also leads to lower carbon intensity. He noted that if per capita emissions can not be decreased significantly in the developed world, there is no way to achieve any of the stabilisation targets. Moreover, energy efficiency improvements under the present market system are not enough to offset increases in demand caused by economic growth, although China has shown significantly higher efficiency improvement rates in the recent past. Thus we need, it was suggested, to create a new low-emission model of global development with the developed countries taking the lead. Efficiency improvements and alternatives of supplies such as nuclear and renewables are of priority for developing country to contribute their share to the effort of stabilisation.

Read reviewed the efficacy of bio-energy with carbon storage (BECS) as a technology for reducing emissions. He noted that this technology has negative emissions and could be important for rapid deployment in case of a threat of abrupt climate change. He suggested that the first stage of such a scheme (having low or possibly negative costs, depending on oil prices, and yielding numerous ancillary benefits) should be embarked on without delay. This is because it has long lead times and needs to be well advanced in preparation for the costly second stage, which would be undertaken urgently in the event that abrupt climate change becomes imminent. If the second stage, linking CCS technology to bioenergy, needs to be implemented, then the pre-industrial level of 280 ppm is attainable by around 2060, with lower levels later on if needed to compensate for non-CO₂ greenhouse gases.

Gibbins *et al* reviewed the scope for future carbon capture and storage (CCS) technologies for achieving CO₂ emissions reductions from electricity generation in the United Kingdom. Among the conclusions, the research team suggest that large (approx. 45%) reductions in CO₂ emissions from UK electricity generation could be achieved by as early as 2020 by including CCS in the mitigation strategy. The team also conclude that CCS technologies have considerable potential for future emissions reductions globally, and that making new power plants at least “capture ready”, if not actually built to capture CO₂ from the outset, is particularly important in economies where large numbers of new power plants are being built.

Session 4: Research requirements

The chairman Schellnhuber opened the session with a strategic comment on the research needs concerning the two main issues of the conference. Regarding the scientific underpinning of political perceptions of “dangerous climate change”, he suggested to focus on a shortlist of critical Earth System elements (e.g., Greenland ice sheet, methane clathrates). This might require to focus resources over the next 5-10 years through a fast-track initiative or even a Manhattan Project-type activity. The identification of just one or two major critical thresholds might already be sufficient to define robust temperature targets.

By way of contrast, the chairman recommended to pursue a broad research portfolio approach regarding climate-change management through mitigation and adaptation measures. Rather than relying on the discovery of a “magic bullet”, one should generate a diversity of technological, institutional and socioeconomic options for overcoming the multiple real-world barriers to climate protection.

Patwardan sketched three research areas he felt were particularly in need of more work. Firstly he explained that we have made progress in understanding adaptation and now we need to be able to quantify it. He indicated that we need impact models that can both quantify the impacts and also design the response. Secondly, he suggested that a good strategy would be action research, learning as we develop and validate conceptual models. Finally, he noted the need for capacity building in developing countries with sustainable long term investment. This would include an open source approach to modelling and tools.

Schneider concluded that the scientific community should be a policy aware, but not a policy prescriptive community. He suggested a risk management framework to explore the wide range of approaches and assess probabilities. He suggested that we should use PDFs where possible, as cost benefit analyses result in too specific arbitrary results. Schneider concluded that future research should use coupled models to find emerging behaviours, and that scientists should talk across communities, both scientific and policy.

Metz suggested that we need to understand our implementation process and identify why things are so difficult. One important solution is to encourage the development of climate change science from within developing countries. We also need to understand more about how technology development and diffusion occur.

Hare said that current models are inadequate to explain some of the rapid changes in ice sheets observed global and indicated the need for more accurate models. We also need more research into the response of circum polar deep water to climate change. He reiterated the need for coupled climate systems to assess the risk of events such as the release of methane hydrates from the ocean.

Stone reiterated the need for systematic observations of the climate. While, Read advocated learning-by-doing in the development of a global bio-energy industry, with world

trade in liquid biofuels and which in turn would benefit the development of global bio-energy through applied research.