THE ROYAL SOCIETY

Climate change: *what we know and what we need to know*

Report of a Royal Society meeting held in December 2001

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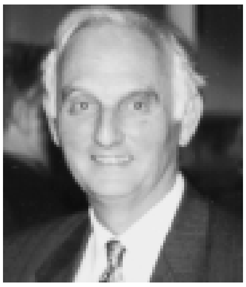
Foreword by Sir John Houghton CBE FRS

Chair of the Royal Society Steering Group for the climate change meeting



Early in 2001, the Intergovernmental Panel on Climate Change (IPCC) published the main part of its Third Assessment Report (TAR) of human induced climate change. It is in three volumes, each up to 1000 pages long, covering respectively the Scientific Basis[1]; Impacts, Adaptation and Vulnerability[2]; and Mitigation[3]. Several thousand scientists from many countries were involved in writing and reviewing material for the report. The thorough and comprehensive nature of the assessment is further illustrated by the many thousands of references to the scientific literature. In September 2001, as a further part of the TAR, the IPCC published a Synthesis Report[4] that brings together the main results of the other volumes in answering nine specific policy related questions.

Because of the significance of the TAR to the understanding of the science (natural science and social science) of human induced climate change, the Royal Society held a two-day meeting in London in December 2001 to present and to discuss the main findings of the TAR. One hundred and sixty-five people attended including many leading experts, a diverse group representing natural science, economics and other social science, industry, business and policy. A good proportion of the meeting was devoted to questions, discussion and comment.

One of the main aims of the meeting was to identify priority areas in all the disciplines where further research is needed. Another was to see whether such a broadly based meeting could result in an overall perspective regarding the likely threat from human induced climate change and regarding the action that should be taken.

The sense of the meeting was clear and in general upbeat. Although human induced climate change was recognised as a serious issue, the technologies to address it are potentially available and appropriate adaptation and mitigation policies could be put in place provided that the political will exists and social behaviour can adjust. Two particular things are necessary for adequate progress to be made. First, that experts from all the disciplines work closely together towards the solutions and secondly, above all, that there be strong commitment from all concerned. Scientists have already demonstrated a large measure of commitment, for instance through the work of the IPCC. Senior representatives from industry at the meeting demonstrated how industries are beginning to take up the challenge of climate change and the opportunities it presents. The UK government has taken a leading role in international negotiations on the issue but was urged by participants to demonstrate stronger commitment in terms of action. It was also pointed out that for governments to feel confident about action, their confidence needs to be shared by the public at large, which points to the need for a much better informed public – a substantial challenge for the media and those involved in education.

The report that follows briefly describes some of the main results from the IPCC report as presented to the meeting and summarises the main conclusions and challenges that emerged from the discussions.

Summary

1 In December 2001 the Royal Society held a two-day meeting to discuss the findings of the recently published Third Assessment Report (TAR) of the Intergovernmental Panel on Climate Change (IPCC). Scientists, policy makers, and representatives of industry, business and non-governmental organisations were invited to discuss the current knowledge of climate change issues and what decision makers still need to know in order to tackle the problems. The result of this discussion was an almost unanimous recognition that human-induced climate change will have serious consequences but is potentially manageable providing that all countries and sectors are committed to adequate strategies for mitigation and adaptation.

2 Since the industrial revolution one of the most important greenhouse gases in the atmosphere, carbon dioxide, has increased by 33%. The global mean surface temperature has also risen in the last two decades, reaching its highest level during the last 140 years. The IPCC concluded that most of the observed warming over this period was due to human activities.

3 Whilst there is no doubt that increasing greenhouse gas emissions contribute to climate change, the range of results from climate models makes it difficult to predict just how serious this will be. This is because of large uncertainties in the modelling of the global climate system and in the prediction of the world's future socio-economic development. Improved ability to predict both near-term and long-term patterns of climate change is needed, including changes in the frequency and probability of extreme weather events, in order to help society plan and adapt to climate change impacts.

4 Changes in mean climate, climate variability and extreme weather events will have adverse impacts on water resources, agriculture, health, forests, coastal zones and biodiversity. Global impacts are expected to be negative overall, even if greenhouse gas concentrations are stabilised in the near future. There will be major differences in impacts between regions, with negative impacts providing further stresses for populations already suffering from poverty, water shortage, and inadequate public health.

5 Many regions and populations are already beyond acceptable thresholds of exposure to climatic risk.There is a need to develop the scientific understanding of vulnerability and adaptation. Techniques and tools for enhancing adaptation should be flexible since past adaptations may not be an accurate guide to the future. It was suggested that in future the IPCC should focus more on regional assessments that involve stakeholders in the assessment process. It should also involve development organisations in building adaptive capacity.

6 Society must decide how to develop a synergy between development and the controlling of climate change. Adaptation and mitigation measures need to be embedded in new strategies for sustainable development. In order to meet the lower range of stabilisation targets, developing countries need to take part in measures to mitigate their greenhouse gas emissions whilst still having the opportunity to develop. A possible way of achieving this would be via sustainable development agreements with technical and financial support for developing countries to encourage low emissions.

7 For the UK, a 60% reduction in carbon dioxide emissions by 2050 is technologically achievable but there are a host of economic, social and institutional obstacles. Removal of these obstacles should be a priority. Fundamental structural changes in energy systems will be required. A combination of taxes, emissions trading and programmes that create incentives was suggested.

8 Model projections indicate that overall long-term global GDP growth is not significantly affected by mitigation actions towards stabilisation. However, costs and benefits of mitigation vary widely across sectors, countries and development paths and for some the costs may be significant. Costs are expected to be lower if mitigation measures and frameworks are planned and adopted at an early stage.

9 Numerous technical and economic opportunities exist for energy efficiency improvements. There is an urgent need for increased research and development of low-carbon technologies. The high cost and insufficient availability of these technologies remain barriers to their introduction. Nuclear energy and geological or biological carbon sequestration were suggested as having potentially important roles in controlling greenhouse gas emissions in the near to medium term, once issues such as public confidence, safety and effectiveness have been resolved.

10 Climate change will not be effectively managed until individuals and communities recognise that their behaviour can make a difference. All sectors of society need to adopt 'carbon thinking' and carbon-accounting needs to be incorporated into institutional and regulatory systems.

11 A key challenge is to develop a clear, equitable, realistic international framework for the much larger reductions in emissions that will be required post-Kyoto and to apply principles of international and intergenerational equity in policy formulation.

Contents

Preparation of this report

This is a report of a meeting held by the Royal Society in London on the 12 and 13 December 2001. This document summarises the ideas expressed at the meeting and does not necessarily represent the views of the Royal Society.

Our thanks go to the Steering Group who advised on the programme of the meeting and the contents of this report. The Steering Group comprised Sir John Houghton FRS (then Co-chair, IPCC Working Group 1) Chair, Dr Terry Barker (Department of Applied Economics, University of Cambridge), Dr Thomas Downing (Stockholm Environment Institute, Oxford), Dr David Griggs (Hadley Centre for Climate Prediction and Research, Met Office), Prof Michael Grubb (Imperial College & University of Cambridge), Prof Brian Hoskins FRS (Department of Meteorology, University of Reading), Prof Mike Hulme (Tyndall Centre for Climate Change Research), Lord Hunt of Chesterton FRS (Department of Space and Climate Physics, University College London), Prof Martin Parry (Jackson Environment Institute, UEA). The meeting was organised and the report produced by the secretariat of the Royal Society: Miss Marisa Goulden and Dr Rachel Quinn.

Our particular thanks go to the speakers and discussants at the meeting. The programme for the meeting is reproduced at the back of this report. Details of the speakers, the presentations and the list of participants are available on the Royal Society website at http://www.royalsoc.ac.uk/policy/cur_clim.htm#clim_meet

The meeting and this report make an important addition to the Royal Society's existing work on the subject of climate change, which includes the statement on the 'Science of Climate Change' published jointly by 16 National Academies of Science from all parts of the world in the journal *Science* in May 2001. Further details are available on the Royal Society web site as indicated above.

The IPCC 2001 Third Assessment Report[1] and Synthesis Report[2] are available on the IPCC website at http://www.ipcc.ch

1 Introduction

What do we know about climate change? What more do we need to know? What action should we be taking? Scientists, policy makers, and representatives of industry, business and non-governmental organisation discussed answers to these questions in a two-day meeting at the Royal Society in London in December 2001. The findings of the Intergovernmental Panel on Climate Change's (IPCC) Third Assessment Report (TAR)[1, 2, 3,] published in 2001, were presented and discussed by experts involved in its compilation and key players representing diverse sectors likely to be affected both by the impacts of climate change and by measures to control it. The result of this discussion was an impressive consensus that the issue of climate change is serious but potentially manageable and all sectors need to be committed to working out adequate strategies for mitigation and adaptation. This report presents a summary of the key issues and challenges that emerged from the meeting and is not necessarily an expression of the views of the Royal Society.

Figure 1 below describes the relationship between the key themes that are covered in this report.

Climate is influenced by concentrations of greenhouse gases (discussed in Section 2). Changes in climate will have an impact on human and natural systems, which may be lessened by natural or planned adaptation (discussed in Section 3). Severe climate change impacts are likely to influence the development of local and global economies and will require society to adapt. The socio-economic development paths followed by developed and developing countries will determine their use of energy and land and hence the emissions of greenhouse gases that cause climate change. Measures taken to mitigate (lessen) emissions have the potential to reduce future concentrations of greenhouse gases (discussed in Sections 4 and 5). Scenarios of future greenhouse gas emissions have been developed and used by the IPCC to describe a range of possible future development paths. These have been used to model possible future climate change (as discussed in Section 2). Section 6 discusses how communication might be improved to best engage society in efforts to tackle climate change. The conclusions presented in Section 7 contain key challenges identified at the meeting and some over-arching reflections from the participants.

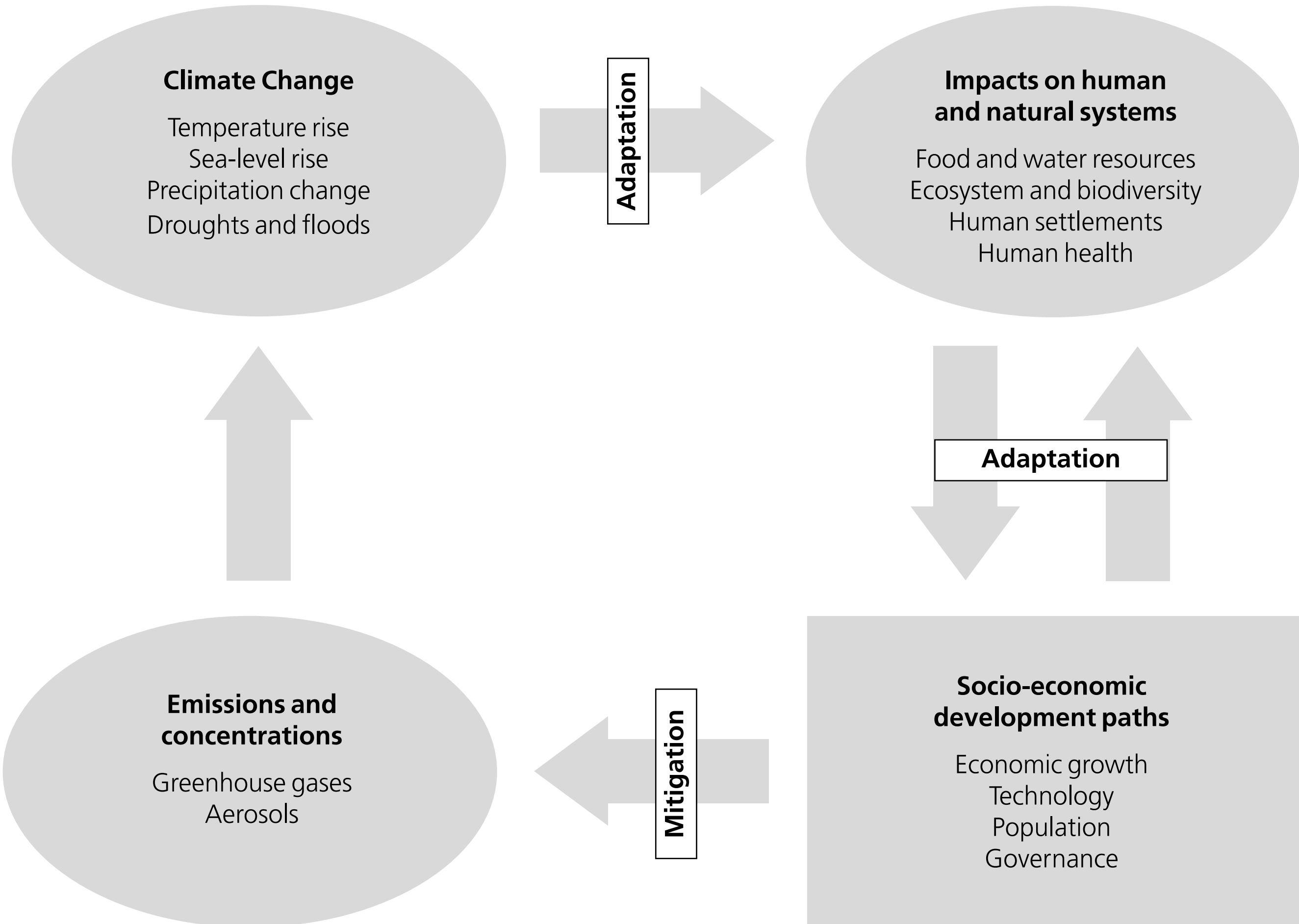


Figure 1 This shows the relationship between the main aspects of climate change that have been discussed in this report. The clock-wise arrows show the cycle of cause and effect and the anti-clockwise arrow shows society's response to climate change impacts (adapted from IPCC Synthesis Report 2001[4], with permission).

2 Climate change science

What we know: a summary of the findings of the IPCC Third Assessment Report (TAR)[1]

Since the beginning of the industrial revolution carbon dioxide in the atmosphere has increased by 33% to a level that has not been exceeded over the last 420,000 years and likely not during the past 20 million years. Methane in the atmosphere has doubled and nitrous oxide increased by 15%. These increases have resulted primarily from the burning of fossil fuels, with additional contributions from deforestation and changes in land management practices. These activities all add to the atmosphere's greenhouse effect (see Box 1) and tend to warm the Earth's surface.

The global mean average surface temperature has risen in the last two decades and has reached its highest level during the last 140 years – the period of the instrumental record. Analyses of data from the northern hemisphere show that the increase in temperature during the 20th Century is likely to be the largest of any century during the last 1000 years.

This temperature rise over the last 50 years is broadly accounted for by anthropogenic forcing (changes to the earth's radiation balance) due to the increases in greenhouse gases together with some cooling caused by sulphate particles from increased sulphur dioxide emissions, and some small natural forcing (from volcanoes and changes in solar radiation). The IPCC concluded therefore that most of the observed warming over this period was due to human activities.

Carbon dioxide concentrations are projected to increase from the current level of 368ppm (parts per million) to between 540ppm and 1000ppm over the next 100 years, depending on the assumptions made regarding future emissions of greenhouse gases. As a result of this increase in carbon dioxide, temperatures are predicted to rise relative to today's values by between 1.4 to 5.8°C. (This range in values is a result of the different climate models and emissions scenarios used in many predictions). Based on palaeoclimate data, the rate of increase is likely to be without precedent during at least the last 10,000 years. Landmasses are expected to warm more than the ocean, and high latitudes more than the tropics.

Although less certain, projections from models generally show increased precipitation in the high latitudes of both hemispheres and in the tropics. In parts of the sub-tropics, for instance in southern Africa and the southern Mediterranean region, model projections show precipitation decreases. In other sub-tropical regions there is little consistency among models concerning precipitation change.

Changes in extreme weather events will tend to have more impact than changes in the mean. Projections are for more hot days and heat waves, and higher minimum temperatures with fewer cold days and frosty days over nearly all land areas. More intense precipitation events are projected and changes in patterns may occur with respect to both geographical area and frequency. In some areas there are likely to be both more floods and more droughts. For tropical cyclones, some areas are expected to experience increases in peak wind intensity and in mean and peak precipitation intensities.

The global average sea level is projected to increase over the next 100 years by between 9 and 88 cm for the full range of emissions scenarios. The main causes of the rise are thermal expansion of ocean water and melting of glaciers. Because of the long time response of the deep oceans, even if climate change were stabilised now, the

Box 1 The greenhouse effect

The basic scientific understanding of changes in climate is that they are driven by changes in the incoming solar radiation or by changes in the outgoing infrared radiation from the earth's surface or atmosphere. In the absence of clouds, the atmosphere is relatively transparent to solar radiation, letting much of it through so that it warms the Earth's surface. Much of the infrared radiation emitted by the surface, however, is absorbed by 'greenhouse gases' present in the atmosphere causing some heat to be retained. This 'greenhouse' property of the atmosphere acts as a blanket over the surface leading to it being warmer than it would otherwise be. Without this effect the Earth's surface would be 20 to 30°C colder and much less suitable for life as we know it.

The main greenhouse gases in the atmosphere are water vapour, carbon dioxide, ozone, methane and nitrous oxide. Any increase in the atmospheric concentration of any of these gases because of human activities (eg the burning of fossil fuels) leads to an enhanced greenhouse effect. Any changes, in solar radiation or in the greenhouse properties of the atmosphere, whether natural or anthropogenic, result in what is known as *radiative forcing* and will lead to climate change.

expansion of oceans would continue at about the same rate for many centuries. The major ice sheets in Antarctica and Greenland are not expected to make a significant contribution to sea level rise in the short term since melting around their edges is roughly matched by increased snowfall. However, ice sheet models predict that a local warming of greater than 3°C, if sustained for millennia, would lead to virtually a complete melting of the Greenland ice sheet with a resulting sea level rise of about 7 metres.

What is our confidence in the science and what more do we need to know?

The causes of climate change

As explained in Box 1, any changes in solar radiation or in the greenhouse properties of the atmosphere can be expected to lead to climate change. The most important greenhouse gas, water vapour, is not directly influenced by human activity on the global scale. However, marked increases in the other two major greenhouse gases, carbon dioxide and methane, have been attributed to human activity such as the burning of fossil fuels since the beginning of the industrial revolution.

Changes in solar radiation have been directly measured from satellite instruments since the 1970s; on longer time scales changes have been inferred from other indicators of solar behaviour. One possible way in which solar ultra-violet radiation can influence the climate is through changes in stratospheric ozone (in the upper part of the atmosphere) that in turn could affect the tropospheric climate (in the lower part of the atmosphere).

Variations in volcanic activity can also cause climate change. Sulphate aerosols (microscopic airborne particles or droplets) formed from volcanic gases act mainly to cool the surface because of the interception of solar radiation. There is still substantial uncertainty in the detailed radiative forcing (see Box 1) due to regional changes in types and amounts of aerosols, which may have either a direct or an indirect influence on climate through their impacts on clouds.

Despite uncertainty over factors such as aerosols and clouds, the IPCC concluded that radiative forcing due to observed and expected increases in greenhouse gases in the 20th and 21st century is almost certainly substantially larger than the forcing due to other factors.

Climate change in the twentieth century: observations and modelling

There is little doubt that the globally averaged surface temperature rose by some 0.6°C over the 20th century. The magnitude of the surface warming is consistent with that expected from both simple theory and complex models. The results from models are now generally consistent with the observed temperature record, and point to the early century warming being partly associated with natural factors and the later warming being mostly due to anthropogenic activity.

In the stratosphere, increased greenhouse gases lead to cooling which is well described by climate models. At lower levels in the troposphere, models tend to show similar warming to that at the surface. However, observations from satellite data do not agree well with the model results. The reason for this is not well understood, although it should be noted that these satellite observations are only available for a relatively short time scale.

Predicting future climate change

Predicting future climate change requires a sequence of steps, each with associated uncertainties. First, emissions of greenhouse gases and aerosols need to be specified. Their dependence on unknown socio-economic behaviour is tackled by using scenarios designed to produce a range that is indicative rather than definitive. In reality feedbacks are likely to occur, for example climate change is likely to influence socio-economic behaviour. The IPCC TAR used a wider range of scenarios, representing different socio-economic development pathways, than the previous IPCC reports.

The next step is to determine what the impact of these emissions will be on the composition of the atmosphere. Until very recently this was calculated in a separate model but the most recent calculations have included the carbon cycle as an interactive part of the climate model. A suggestion from the first of these calculations is that climate may be more sensitive with this interaction included.

Climate models still show a wide range of sensitivity to increasing carbon dioxide concentrations. Whilst there is no doubt that increasing greenhouse gas emissions will cause adverse impacts, the range of results from climate models makes it difficult to predict just how serious these will be. Further, it was suggested at the meeting that current models might underestimate the atmospheric circulation response. The complex and non-linear climate models show a surprisingly linear response. This could lead us to underestimate the possibility that the climate might change very rapidly at some point in the future, once certain unknown thresholds have been passed. For example some scientists are investigating the potential for rapid methane release. It has also been suggested that changes in land cover, such as large scale planting of forests, may have an effect on climate by altering the reflective property of the earth's surface.

There was agreement that the latest climate models are able to reproduce the long-term temperature record more accurately than previously. However, uncertainties in climate model results remain significant and arise both from the models themselves and the choice of emissions scenarios used. Improvements have been made in the quantification of uncertainties in climate models but these have not been significantly reduced, the largest remaining problem being the uncertainty in the feedback from clouds. It was suggested that uncertainties arising from the choice of emissions scenarios are of a similar magnitude to those arising from the climate models, when global average temperatures are modelled. Conversely, where climate models are used to predict patterns of climate change (eg precipitation), the uncertainties arising from the models dominate.

To describe climate change in terms of global averages provides only limited information. Most of the impacts of climate change depend on changes in regional climate or on changes in the natural variability of climate, including extreme weather events. Will we see changes in climate patterns such as the El Niño or the Indian Monsoon? Will there be an increase in extreme winds in Europe? To answer questions like these we will need to improve our ability to predict changes in the probability distributions of climate and weather phenomena. In order to do this we will need to use a large amount of computing power to perform many calculations with improved and higher resolution climate models. The models will need to use starting conditions which describe the current state of the climate system as accurately as possible so that they can provide the best possible forecast of the first decade or so, as well as better forecasts further into the future. It was suggested that near-term predictions are particularly needed in order to motivate institutions to plan for climate impacts. Uncertainties arising in these predictions need to be quantified in order for them to be useful in risk assessments.

Box 2 The Intergovernmental Panel on Climate Change (IPCC)

The IPCC was formed in 1988 jointly by two United Nations bodies, the World Meteorological Organisation and the United Nations Environment Programme. Its mandate was to prepare authoritative assessments of human induced climate change covering the fundamental science, the likely impacts on human communities and ecosystems, and the policy options including economic, technical, social and political aspects.

In the preparation of its reports, the IPCC has involved a wide range of scientists from many countries, including many of the world's leading climate scientists. Wide ownership of its reports has therefore been achieved by the international scientific community. To ensure accuracy and quality, the reports have been subjected to extensive review procedures. The involvement of government representatives in the preparation of the summaries for policymakers that accompany each report has ensured their relevance to policy formation and has also meant that governments have felt ownership of the reports.

The IPCC's first assessment was prepared in 1990. The achievement of such a broad scientific consensus provided a firm basis for agreement by the world's governments to the United Nations Framework Convention on Climate Change (UNFCCC) at the Earth Summit in Rio de Janeiro in 1992. Subsequent comprehensive IPCC reports have been published in 1995 and 2001. These and a number of additional special reports have continued to inform the UNFCCC process.

3 Impacts and adaptation

What we know: a summary of the findings of the IPCC Third Assessment Report (TAR)[2]

Global impacts
Changes in mean climate conditions and also in climate variability and extreme weather events will have adverse impacts on water resources, agriculture, health, forests, coastal zones and biodiversity. There will be impacts from climate change on a global scale and they are expected to have an adverse effect overall, even if greenhouse gas concentrations are stabilised in the near future. Impacts around the world are likely to be substantial, providing further stresses for populations already suffering from poverty, water shortage, and inadequate public health. There will be major differences in impacts between regions, with negative impacts particularly likely for Africa and Southern Asia. Strategies will be required for both adaptation to these impacts and to achieve stabilisation of greenhouse gases in order to limit future adverse impacts.

The IPCC TAR presented a qualitative risk assessment of reasons for concern about projected climate change impacts. This consisted of an analysis of the effects of different degrees of climate change (described by global temperature increase for the range of IPCC scenarios) on five key reasons for concern. For low levels of climate change we would expect to see damage or loss of threatened natural systems, uneven distribution of impacts with lowest income groups negatively impacted, and damages from increased probability of extreme weather events. These types of impact would become increasingly adverse at higher levels of climate change. At high levels of climate change we would also expect global impacts to be adverse overall (negative impacts outweigh positive ones) and we would see an increased probability of large-scale one-off events occurring, such as the melting of the west Antarctic ice sheet or changes in global ocean circulation systems.

Ecosystems
Many ecosystems will be significantly disturbed by climate change because they are unable to adapt to the rate of change. Key issues in forested areas, for example, would be fire, drought, pest infestation and invasions of exotic species. Coral reefs are particularly sensitive to temperature rise and their sensitivity is further compounded by polluted land run-off and over-fishing. Many reefs that are critical to the livelihood of islanders for fish and tourism are already seriously threatened.

Water resources
There will be regional differences in changes in water availability with increases expected in high latitudes and Southeast Asia and decreases expected in central Asia, Mediterranean countries, southern Africa and Australia. There are already 19 water-stressed countries mainly in Africa and the Middle East and climate change will be an additional stress, particularly in those areas that are already highly stressed. The frequency and magnitude of flooding could increase in many regions. Projections are based on modelled changes in precipitation, which are less certain than modelled temperature changes.

Food production
Cereal production is likely to decrease from 2020 to 2080 in Africa, Latin America, the Middle East and India. Production may increase in the middle and high latitudes of the Northern Hemisphere so that globally there would be no significant decrease in the 2050s. But by 2080 there could be a global decrease. Regional disparity in food production is likely to be more of a problem than decreases in global production. Globally there is enough food today but it is unequal access to it that causes hunger and famine and this will be exacerbated by climate change.

Health
There will be both positive and negative impacts of climate change on human health. Mortality will decrease with fewer cold spells in winter, but there are likely to be more deaths related to extreme weather such as heat waves, storms, floods and droughts. There may also be impacts from changes in the occurrence of infectious diseases (eg dengue and malaria) due to an extension of the regions of potential transmission.

Sea level rise
Rising sea levels will affect low–lying countries and many islands. For instance, a 1m rise could inundate 17% of Bangladesh where tens of millions of people now live and reduce its rice-growing land by 50%.

What more do we need to know?

The IPCC TAR has made breakthroughs in three main areas of the assessment of climate change impacts: the detection of trends in present impacts; a qualitative risk assessment of impacts; and an overview of adaptation frameworks and issues. However, in each case it was felt that further evaluation of the underlying methodologies is required.

Whilst it is clear that global impacts will be realised, little is known about projected impacts under different socio-economic world futures or how mitigation efforts might change these impacts. Despite a decade of global assessments, it is difficult to balance the global burden of impacts against targets for reducing greenhouse gas emissions. This is due to issues such as the different time trajectories used, a lack of common means for valuing impacts, and the difficulty of incorporating questions of equity.

The following suggestions were made for key areas needing further progress:

- potential risks of large-scale extreme events – it is likely that most impacts will be caused by alteration of the frequency or severity of extreme weather events, where society's capacity to adapt is most limited. Up until now impact studies have concentrated on mean climate conditions but greater understanding of extreme weather events should be considered in the next assessment report that the IPCC produces.
- mega-vulnerabilities – research is needed to understand the cumulative effects of additional stresses (eg AIDS) on climate impacts and adaptation.
- the potential contributions of public sector and private actions to adapt to climate change.

Many see the task ahead for the IPCC to be to develop further our scientific understanding of vulnerability and adaptation. It was suggested that this should be tackled within a broad discipline of 'sustainability science', which would encourage the integration of climate change issues into development policy. This would allow research on climate change impacts and adaptation to be more closely linked to the fields of risk assessment, disaster preparedness and adaptive environmental management with a focus on current conditions. It would provide development planners with more useful near-term climate scenarios (eg10 to 20 years), something not yet provided by the IPCC.

Research into the impacts of climate change needs to include the study of adaptation processes and look at how exposure and vulnerabilities across sectors and at the local level relate to regional and global processes. Both opportunities and constraints will need to be considered. These processes will be dynamic and responsive to many stresses in addition to climate change, eg the effects of global economic systems and AIDS. The links between impacts, adaptation and mitigation need to be explored at a local level.

It was suggested that vulnerability indices need to be developed and applied to regions and that planning to build adaptive capacity should begin with those regions showing the highest vulnerability. Techniques and tools for enhancing adaptation should be flexible since past adaptations may not be an accurate guide to the future. For instance, past weather statistics are unlikely to be suitable for planning new infrastructure. There was a call for scientists to provide models, which could comprise both of global change and local variability components, to help decision-making in different sectors.

Many regions and populations are already beyond acceptable thresholds of exposure to climatic risks. In order to reduce the impact of present climatic disasters as well as future extreme weather events it was suggested that the IPCC should focus more on regional participatory assessments and involve development organisations (including international agencies, academic networks and nongovernmental organisations) in building adaptive capacity.

Climate change will increase the challenges the world faces in providing enough food, energy, clean water, and sanitation for everyone in a healthy environment. 'This is not just an environmental issue,' said Dr Robert Watson (the then Chair of the IPCC), 'but a development issue'.

Box 3 Update on international climate change policy

The United Nations Framework Convention on Climate Change (UNFCCC) was endorsed by 186 countries during and subsequent to the 1992 Earth Summit in Rio de Janeiro. Its aim was to achieve stabilisation of greenhouse gases in the atmosphere that would prevent dangerous anthropogenic interference with the climate system. This treaty is the primary political response to scientific warnings about climate change.

The Kyoto Protocol set out targets for emissions reductions for developed countries and was adopted by parties to the UNFCCC in 1997. At the most recent Conference of the Parties (COP) to the UNFCCC, held in Marrakech in November 2001, the parties (countries) confirmed their intention to ratify the treaty and bring it into force by the end of 2002. 55% of those countries signed up to the UNFCCC, representing at least 55% of the developed world's emissions, need to ratify the Kyoto Protocol in order to bring it into force. This is still achievable despite the USA's well-publicised refusal to ratify.

Major advances at Marrakech included decisions on most of the rules for implementing Kyoto and the setting up of funds for capacity building and adaptation in developing countries. These decisions followed a ministerial statement which stressed that climate change is a development issue and linked to poverty alleviation and social development.

4 Mitigation

Stabilisation of the atmosphere

The objective of the United Nations Framework Convention on Climate Change (UNFCCC) agreed by the world's nations at the Earth Summit in Rio de Janeiro in 1992 is stated as the stabilisation of the concentrations of greenhouse gases in the atmosphere at a level that would prevent 'dangerous interference with the climate system' and that is also consistent with sustainable development. The aim of mitigation measures is to achieve stabilisation particularly of carbon dioxide (the most significant greenhouse gas associated with anthropogenic climate change) and therefore to avoid the worst impacts of climate change.

The IPCC Third Assessment Report (TAR)[3] details the rise in concentrations of greenhouse gases in the atmosphere since the pre-industrial era and estimates that they will continue to rise in the 21st century by an amount between 75 and 350% from pre-industrial levels (depending on the world's future economic development). Mitigation efforts are required to stabilise greenhouse gas levels by reducing sources of emissions and enhancing sinks. More than half of the increase in greenhouse gases up until now has come from the industrialised nations. The Kyoto Protocol requires mitigation by industrial countries, but the problem is such that in order to achieve long-term stabilisation, developing countries will also eventually need to control their greenhouse gas emissions (see Box 4). In discussing a range of future scenarios the TAR refers to a number of indicative stabilisation levels of carbon dioxide concentrations of between 450ppm and 1000ppm, compared to today's level of 368ppm and pre-industrial concentrations of 280ppm.

What is dangerous climate change?

Determining exactly what is 'dangerous interference with the climate system' in order to decide how best to manage climate change is not a simple task. It was suggested that this is not a scientific process but a value judgement for society to make. However, it must be informed by scientific and technical information. There are various methods used by economists for attaching a price to risks like climate change. An example of this is cost-benefit analysis, which attempts to balance gains (eg increased yield of crops in northern latitudes) against losses (eg increased deaths and damage from flooding in Bangladesh) in order to determine whether climate change causes a net gain or loss. Such calculations are not easy to make and this approach has not proved to be generally acceptable to governments and society. In practice governments have chosen to follow the precautionary principle with the setting of targets for emissions reductions, as in the Kyoto Protocol. Some of those at the meeting felt this to be the best way to proceed in making decisions on climate change management, at least in the short term. It was suggested that climate change management decisions should be informed by a new generation of models, known as integrated assessment models, which describe all aspects of the climate system and the human and natural factors that influence it. These models can be used to calculate the emissions limits needed in order to remain within certain critical thresholds beyond which climate impacts are considered unacceptable.

How can we achieve stabilisation?

The IPCC TAR presents an optimistic view that both short-term (Kyoto) goals and atmospheric stabilisation of greenhouse gases in the longer term can be achieved by much increased efficiency in the generation and use of energy and by the development of low-carbon technologies. However, there are some discrepancies in the predictions of models that assess technological developments and those that model the macro-economic effects of mitigation. It is widely recognised that there are many obstacles to the take-up of low-carbon technologies. These technologies and suggestions of how their take-up might be encouraged are covered in more detail in Section 5 and Box 5.

The Royal Commission on Environmental Pollution suggested in its 2000 report[5] that the UK needs to reduce its emissions (from 2000 levels) by 60% by 2050 in order to prevent carbon dioxide concentrations from exceeding 550ppm. This figure was arrived at using the much-debated 'contraction and convergence' approach, which would allow developed countries' emissions to decrease progressively from their current high levels and allow developing countries' emissions to increase as their economies grow, before progressively decreasing to the same per capita level as for developed countries.

It was felt that a 60% reduction in carbon dioxide emissions by 2050 is technologically achievable but that there are a host of economic, social and institutional obstacles. Fundamental structural changes in energy systems will be required in order to control emissions. There are calls for simple regulatory frameworks that will kick-start the process of reduction in emissions. These policies should apply to transport and other sectors, as well as the energy intensive industries. A combination of taxes, emissions trading and programmes that create incentives was suggested. It was pointed out that policies should be forward-looking and describe the policy goals so that the market could dictate the best means of achieving them. An industry representative commented that resistance from business could turn into creativity once policies had been introduced.

How much will climate change mitigation cost?

Model projections indicate that overall long-term global growth paths commonly measured by growth in Gross Domestic Product (GDP) are not significantly affected by mitigation actions towards stabilisation. For 2100, for example, the global costs of mitigation appear to be small compared to the projected growth in GDP. This appears to be the case for all stabilisation levels (including 450ppm), all development pathways and all models. However, costs and benefits of mitigation vary widely across sectors, countries and development paths; for some sectors and countries the costs may be significant.

Costs are expected to be lower if mitigation measures are planned and frameworks adopted at an early stage. It was argued that there are substantial opportunities for reducing the costs of mitigation. By implementing technological advances global emissions may be reduced by 2020 to their 2000 level at costs below US$100 per tonne carbon-equivalent, with half the reduction at no cost. Other cost savings can be derived from opportunities for creating ancillary benefits (eg reduced local pollution and improved health from non-fossil fuel burning devices) and double-dividend policies that may give net short-term economic benefits. Modelling suggests that international emission-permit trading schemes could reduce the costs of mitigation by about half.

In order to assess the costs of mitigation accurately, information is still needed on the costs and availability of low-emissions technology and the methods and costs of removing barriers to implementation of these technologies. Further progress is needed on quantified cost estimates that reconcile different approaches (eg top-down, bottom-up), include ancillary benefits and allow for policy-induced technological change. These estimates are needed at sectoral, global and regional levels.

It was concluded that obstacles to climate change mitigation are primarily political rather than economic and plenty of examples could be found where economic growth had occurred without increased levels of emissions. Removal of these obstacles should be a priority. It was emphasized that development and climate change could not be separated but must be considered together.

Box 4 Equity and sustainable development

There was strong agreement that climate change will have a disproportionate impact on the world's poor, particularly in developing countries. It is also widely recognised that developing countries need to take part in measures to mitigate their greenhouse gas emissions, whilst still having the opportunity to develop, in order for the lower range of stabilisation targets to be met (eg 450ppm).

There is considerable debate about how and when developing countries should adopt emissions reductions targets under the Kyoto Protocol/UNFCCC. International and intergenerational equity considerations are seen as key to decisions on this matter. Some felt that the IPCC Third Assessment Report[2,3] had not addressed equity issues sufficiently but others suggested that this is a political issue and as such it is outside the remit of the IPCC's work.

Differing principles such as the need for development, equal rights, capability of paying, and the historical contribution to the problem (polluter pays principle) have dominated discussion up until now. It was noted that politically acceptable solutions might not be able to incorporate all these principles. Some argue that the vulnerability of a nation to climate change impacts should be taken into consideration when assessing which nations should have the responsibility for mitigation action.

Various options for regimes designed to limit global climate change were discussed. These include multi-stage approaches with increasing participation; contraction and convergence; and sustainable development agreements (commitments to encourage low emissions and sustainable development with technical and financial support). It was suggested that the sustainable development approach would be the most attractive to developing countries but agreements could be complex, controversial and difficult to manage.

5 Energy technologies

Numerous technical and economic opportunities exist for energy efficiency improvements, particularly in the final conversion step from fuel to energy services (eg from a gas burning boiler to a warm comfortable home). Opportunities also exist for new renewable energy sources to increase their contribution to world energy sources (from 2% in 1998). For example, it was noted that solar photovoltaics and grid-connected wind installed capacities are growing at a rate of 30% a year globally. Demand for wind energy currently outstrips supply in some countries, such as the Netherlands, and future opportunities exist for offshore wind farms. The successful development of fuel cells would facilitate the introduction of hydrogen as an energy carrier. Fuel cells are receiving intense attention, especially for transportation, because they offer high efficiency and the additional benefit of near-zero local air pollution, although their contribution to greenhouse gas mitigation efforts will depend on the source of energy used to manufacture the hydrogen.

The high cost and insufficient availability of these low-carbon technologies remain barriers to their introduction. Improved technology from research and automation will provide large reductions in costs in many of these technologies. There is an urgent need for increased research and development of low-carbon technologies. It was suggested that this should be achieved by bringing in private financing, expanding the market for it and redirecting subsidies away from conventional energy. In the UK the Carbon Trust will promote low-carbon industrial and public sectors by supporting innovation and best practice programmes.

The role of nuclear energy was raised at the meeting and some saw this to be particularly important in the transition from fossil fuels to a sustainable energy economy.

The sequestration of carbon, which involves the capture of carbon dioxide from power stations and subsequent storage in underground geological formations, was also discussed. It was suggested that this could perform a bridging role by reducing the damage caused by the continued burning of fossil fuels whilst alternative sources of energy are being developed. It was argued that the price of fossil fuels should include the cost of carbon sequestration in order to encourage the market to develop alternatives such as renewable energy technologies. Some of the major issues that must be addressed if this technology is to make an impact on carbon dioxide emissions are the cost of carbon dioxide capture, the safety and security of storage, and public acceptability. The biological storage of carbon in plants and soil (also known as 'carbon sinks') might also provide an interim measure of reducing carbon dioxide concentrations in the atmosphere. However, it was recommended that measures to enhance carbon sinks should not divert resources away from the restructuring of energy since they are likely to provide only a limited and temporary solution.

Box 5 Carbon thinking

Many argue that we have a sufficient understanding of climate change to take action, but ask why it is that individuals fail to do so in their own lives? Some felt that there is a need for improved understanding of human values and what drives our choices. It was suggested that it is difficult to build strong public support for a long-term goal where action now benefits future generations and that financial or legal incentives are necessary to get individuals to change their behaviour.

There is wide agreement that all sectors of society need to adopt 'carbon thinking'. An obvious way to do this would be to attach a value to carbon emissions. This will internalise the environmental costs and alert organisations to their hidden assets or liabilities. This will also encourage individuals and organisations to recognise that they will need to adapt to an unstable climate. It was suggested that consumer behaviour would change if regulations are forward looking and as long as industry delivers what the consumer wants. Regulation, economic measures, technology and behaviour should all be considered and addressed as a package rather than in isolation.

6 How should we communicate climate change?

Efforts to manage climate change will not succeed until we are able to convey the idea that individual behaviour can make a difference. Education and communication will have a key role to play and it was suggested that the media continues to be an effective way for scientists to reach the general public. Other stakeholders such as Local Authorities and environmental pressure groups also have an important role in communicating climate change science.

It was recognised that communicating climate change issues is not easy because there are long lead times and the issues are uncertain and complex. However, the science can provide compelling arguments that the public can accept once they have reached a threshold of engagement. Scientists and communicators were urged to avoid claiming certainty where there is none. The point was made that communication will only succeed by telling the story clearly, correctly and repeatedly in different ways and regularly arguing for the need to reduce emissions (for example by explaining the target of a 60% reduction in the long term as recommended by the Royal Commission on Environmental Pollution). It was suggested that editors have often tended to prefer to focus on the victims of policies inspired by climate science and tried to instil drama into the debate by highlighting the conflict between climate sceptics and the mainstream.

Local authorities can communicate the need for action by example. Effective ways of communication will be informed by research into the understanding of the risks of climate change, involving social scientists and risk psychologists.

7 Conclusions

The IPCC's Third Assessment Report (TAR) of 2001[1, 2, 3, 4] represents a major advance in our scientific understanding of climate change. The presentations and discussion at the Royal Society meeting highlighted the major advances in knowledge presented in the TAR and produced many suggestions of knowledge gaps that still need to be addressed. The following key ideas and challenges for science and society were identified:

Challenges for science and technology

- There are still large scientific uncertainties associated with predicting future climate change, particularly where predictions concern climate patterns, such as the frequency of extreme weather events, rather than mean climate conditions. Long-term predictions of climate change will always remain uncertain because of the difficulty in predicting which development scenario we will follow. **Improved ability to predict both near term and long-term patterns of climate change is needed, including changes in the frequency and probability of extreme weather events, in order to help society plan and adapt to climate change impacts.**

- It is technically feasible to control greenhouse gas emissions. Opportunities exist for energy efficiency improvements and renewable energy technologies. Nuclear energy and geological or biological carbon sequestration can perform important roles in controlling greenhouse gas emissions in the near to medium term, providing that issues such as public confidence, safety and effectiveness can be resolved. **There is an urgent need for increased research and development of low carbon technologies.**

Challenges for society

- **A key challenge for society is how to develop a synergy between development and the management of climate change. Adaptation and mitigation measures need to be embedded in new strategies for sustainable development.**

- The definition of dangerous climate change, the level of emissions that we wish to avoid, is not a purely scientific process. It is a value judgement to be made by political discussion and negotiation but informed by science and technology.

- Uncertainties are already assimilated into decision-making in most areas of life - certainly in business planning. **We need to incorporate carbon-accounting into business planning and adaptive thinking into our institutional and regulatory systems.**

- Many regions and populations are already beyond acceptable thresholds of exposure to climatic risks and action is needed to help reduce the impact of present climatic disasters as well as future extreme weather events. **A major effort should be made to build adaptive capacity, beginning in those regions that are most vulnerable to climate change impacts. Climate impact research and adaptation planning should be integrated into development policy and development organisations need to be involved in building adaptive capacity**.

- Impacts, benefits and costs will be distributed unevenly within and between societies. This questions our political vision of how we want the future to look. **A key challenge is to apply principles of international and intergenerational equity in the formulation of policy nationally and internationally**.

- Solutions to climate change mitigation exist technically and economically, but the inertia of social systems is preventing their implementation through a whole collection of barriers. We need to overcome these obstacles, which are largely political rather than economic. **The key question is how to effect fundamental structural changes in energy systems.**

- Even though we have a significant amount of understanding about climate change, individuals still fail to take action. **We need to improve our understanding of human values and choices and what drives them. We need to communicate effectively that individual behavior can make a difference. Carbon accounting, that is attaching a value to all carbon emissions, could be used to achieve this.**

- **A key and immediate challenge is to develop a clear, equitable, realistic international framework for the much larger reductions in emissions that will be required post-Kyoto.**

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Programme

Wednesday 12 December 2001

Introduction and welcome
Sir John Houghton FRS (Co-chair, IPCC Working Group 1)

Session 1 Has the climate changed and why?

Chair: Prof Brian Hoskins FRS (University of Reading)

- *Radiative forcing of climate*
  Prof Joanna Haigh (Imperial College, London)
  Discussant: Prof John Grace (University of Edinburgh)

- *Climate of the 20th Century*
  Dr Myles Allen (Department of Physics, Oxford University)
  Discussant: Prof Paul Valdes (University of Reading)

- *Patterns of climate change*
  Dr Tim Palmer (European Centre for Medium-Range Weather Forecasts, Reading)
  Discussant: Prof Brian Hoskins FRS (University of Reading)

Session 2 How will climate change this century?

Chair: Dr David Griggs (Hadley Centre, Met Office)

- *Emission scenarios*
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- *How reliable are global climate models?*
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  Discussant: Prof Julia Slingo (University of Reading)

Session 3 Impacts and adaptation

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- *Key areas of vulnerability*
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Session 4 Mitigation and stabilisation
Chair: Sir Eric Ash (Vice-President and Treasurer, Royal Society)

- *Mitigating climate change: an overview of the potential for technologies and policies*
  Prof Michael Grubb (Imperial College Centre for Environmental Technology)

- *Costs of emission limitations - a macroeconomic view*
  Dr Terry Barker (Cambridge University)
  Discussant: Mr Tom Burke (Visiting Professor, Imperial College)

- *Cutting edge technologies: Renewable energy and energy efficiency technologies*
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- *CO_2 storage technologies*
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Thursday 13 December 2001

Session 5 The Intergovernmental Panel on Climate Change

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  Sir John Houghton FRS (Co-chair, IPCC Working Group 1)

- *Summary of IPCC Synthesis Report*
  Dr Robert T Watson (Chair IPCC, Chief Scientist & Director, ESSD The World Bank)

- *Update on the UNFCCC process*
  Ms Claire Parker (Secretariat of the UNFCCC)

Session 6 Sustainable climate change: challenges at the international level

Chair: Prof Michael Grubb (Imperial College Centre for Environmental Technology)

- *What is a sustainable level of climate change?*
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- *How might global efforts be distributed?*
  Dr Bert Metz (National Institute of Public Health and the Environment, The Netherlands)

- *The corporate contribution to sustainable climate change*
  Sir Mark Moody-Stuart (former Chairman of the Royal Dutch/Shell Group)

- *The international framework*
  Mr Henry Derwent (Department for Environment, Food & Rural Affairs)

  Discussants:
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  Ms Ute Collier (WWF UK)

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  Discussants:
  Mr Daniel Waller (Association for the Conservation of Energy)
  Mr Adrian Ham (British Nuclear Industry Forum)

- *Managing the dangers*
  Mr Chris Newton (Environment Agency)
  Discussants:
  Dr Paul Jefferiss (Royal Society for the Protection of Birds)
  Dr Peter Baxter (Dept of Community Medicine, University of Cambridge)

- *Communicating climate change science*
  Mr Roger Harrabin (Environment Correspondent, BBC Today Programme)

  Discussants:
  Mr Steve Waller (Improvement and Development Agency)
  Mr Steve Sawyer (Greenpeace International)

Session 8 Discussion: What do we still need to know?

- *What are the gaps in our understanding of climate change?*

- *Do they prevent us from identifying and achieving a sustainable level of climate change?*

- *What strategies will best address these gaps in our knowledge?*

- *How can these strategies be implemented?*

  Panel Chair: Prof David King FRS (Chief Scientific Adviser & Head of OST)
  Panel members:
  Prof Michael Grubb (Imperial College Centre for Environmental Technology)
  Sir John Houghton FRS (Chair IPCC WG 1)
  Dr Mike Hulme (Tyndall Centre for Climate Change Research)
  Dr Bert Metz (National Institute of Public Health and the Environment, The Netherlands)
  Sir Mark Moody-Stuart (former Chairman of the Royal Dutch/Shell Group)

Closing Remarks

Lord May of Oxford (President of the Royal Society)

Details of the speakers, the presentations and the list of participants are available on the Royal Society website at http://www.royalsoc.ac.uk/policy/cur_clim.htm#clim_meet

Other recent Royal Society reports

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The health effects of depleted uranium munitions (8 page summary of Parts I and II 6/02, March 2002 ISBN 085403 5753, *Part II* 150 page document 5/02, March 2002 £17.50 ISBN 0 85403 574 5, *Part I* 88 page document 06/01,22 May 2001, £17.50 ISBN 0 85403 3540)

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Response to a consultation by HM Treasury and the Inland Revenue on R&D tax credits for larger companies (2 pages, submitted, 10/02, January 2002)

Response to the Policy Commission on the future of farming and food. (4 page response to the Policy Commission, 22/01, October 2001)

Response to the consultation on DEFRA's aims and objectives. (2 page response to DEFRA consultation, 21/01, September 2001)

Royal Society response to PIU Energy project scoping note. (5 page response to cabinet office consultation, 20/01, September 2001)

The role of land carbon sinks in mitigating global climate change (2 page summary, 11/01, July 01, ISBN 0 85403 561 3 and 32 page document, 10/01, July 01, ISBN 0 85403 562 1)

European Commission's white paper 'Strategy for a future chemicals policy' (5 page response to the inquiry by the House of Lords European Union Committee, 19/01, July 2001)

The second stage of the quinquennial review of the Research Councils (17 page response to OST consultation 13/01, July 01)

Draft code of practice for scientific advisory committees (3 page response to OST consultation 14/01, July 01)

Stem cells research-second update (4 page response to the inquiry by the House of Lords Science and Technology Committee 09/01, June 2001 ISBN 0 85403 560 5)

Transmissible spongiform encephlopathies (11 page statement 08/01, 5 June 2001)

The use of genetically modified animals (46 page document 05/01, 21 May 2001, ISBN 0 85403 556 7)

The Science of Climate Change (2 page joint statement from 16 scientific academies, 17 May 2001)

Quinquennial Review of Royal Botanic Gardens, Kew (4-page response to MAFF's public consultation, document 04/01, submitted 6 April 2001)

The future of Sites of Special Scientific Interest (SSSIs) (21-page document, 01/01, February, ISBN 0 85403 5524)

Response to House of Commons Environmental Audit Committee Inquiry into Renewable Energy (5-page letter, 29 January 2001)

Transgenic plants in world agriculture (19-page full report, 08/00, July 2000, ISBN 0 85403 5443)
Transgenic plants in world agriculture (2-page summary, 09/00, July 2000)

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