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INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE

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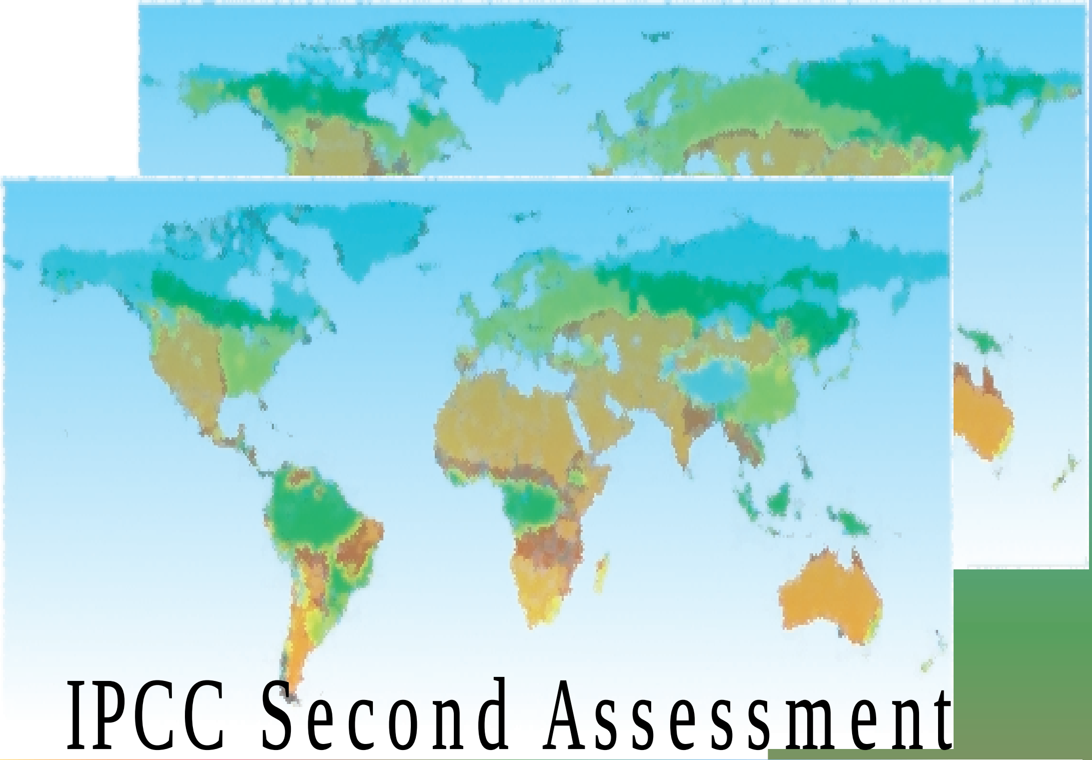

IPCC Second Assessment
Climate Change 1995

A REPORT OF THE

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PREFACE

The Intergovernmental Panel on Climate Change (IPCC) was jointly established by the World Meteorological Organization and the United Nations Environment Programme in 1988, in order to: (i) assess available scientific information on climate change, (ii) assess the environmental and socio-economic impacts of climate change, and (iii) formulate response strategies. The IPCC First Assessment Report was completed in August 1990 and served as the basis for negotiating the UN Framework Convention on Climate Change. The IPCC also completed its 1992 Supplement and *Climate Change 1994: Radiative Forcing of Climate Change and An Evaluation of the IPCC IS92 Emission Scenarios* to assist the Convention process further.

In 1992, the Panel reorganized its Working Groups II and III to assess, respectively, the impacts and response options, and the social and economic aspects of climate change. It committed itself to completing its Second Assessment in 1995, not only updating the information on the same range of topics as in the First Assessment, but also including the new subject area of technical issues related to the socio-economic aspects of climate change. We applaud the IPCC for producing its Second Assessment Report (SAR) as scheduled. We are convinced that the SAR, as the earlier IPCC reports, would become a standard work of reference, widely used by policymakers, scientists and other experts.

As usual in the IPCC, success in producing this report has depended upon the enthusiasm and cooperation of numerous busy scientists and other experts worldwide. We are exceedingly pleased to note here the very special efforts made by the IPCC in ensuring the participation of scientists and other experts from the developing and transitional economy countries in its activities, in particular in the writing, reviewing and revising of its reports. The scientists and experts from the developed, developing and transitional economy countries have given of their time very generously, and governments have supported them, in the enormous intellectual and physical effort required, often going substantially beyond reasonable demands of duty. Without such conscientious and professional involvement, the IPCC would be greatly impoverished. We express to all these scientists and experts, and the governments who supported them, our sincere appreciation for their commitment.

We take this opportunity to express our gratitude to the following individuals for nurturing another IPCC report through to a successful completion:

- Prof. Bolin, the Chairman of the IPCC, for his able leadership and skilful guidance of the IPCC;
- the Vice-Chairmen of the IPCC, Prof. Yu. A. Izrael (Russian Federation) and Dr A. Al-Gain (Saudi Arabia);
- the Co-Chairmen of Working Group I, Dr L.G. Meira Filho (Brazil) and Sir John Houghton (UK); the Vice-Chairmen of the Working Group, Dr Ding Yihui (China), Dr H. Grassl and later Prof. D. Ehhalt (Germany) and Dr A.B. Diop (Senegal);
- the Co-Chairmen of Working Group II, Dr R. T. Watson (USA) and Dr M.C. Zinyowera (Zimbabwe); the Vice-Chairmen of the Working Group, Dr O. Canziani (Argentina), Dr M. Petit (France), Dr S. K. Sharma (India), Mr H. Tsukamoto (Japan), Prof. P. Vellinga (the Netherlands), Dr M. Beniston (Switzerland) Dr A. Hentati and later Dr J. Friaa (Tunisia) and Ing. (Mrs) M. Perdomo (Venezuela);
- the Co-Chairmen of Working Group III, Dr J.P. Bruce (Canada) and Dr Hoesung Lee (Republic of Korea); the Vice-Chairmen of the Working Group, Prof. R. Odingo (Kenya) and Dr T. Hanisch and later Dr L. Lorentsen (Norway);
- the Regional Representatives in the IPCC Bureau, Dr A. Adejokun (Nigeria for Africa), Dr H. Nasrallah (Kuwait for Asia), Dr F. Fajardo Moros (Cuba for North and Central America and the Caribbean), Dr N. Sabogal and later Dr K. Robertson (Colombia for South America), Dr J. Zillman (Australia for Southwest Pacific) and Dr M. Bautista Perez (Spain for Europe);
- Dr B. Callander, the Head of the Technical Support Unit of Working Group I and his staff, Ms K. Maskell, Mrs J.A. Lakeman and Mrs F. Mills, and those who provided additional assistance, namely, Dr N. Harris (European Ozone Research Co-ordinating Unit, Cambridge, UK) and Dr A. Kattenberg (Royal Netherlands Meteorological Institute);
- Dr R. H. Moss, the Head of the Technical Support Unit of Working Group II and his staff, interns or volunteers, namely, Mr S. Agarwala, Mr D.J. Dokken, Mr S. Greco, Ms D. Hagag, Ms S. MacCracken, Ms F. Ormond, Ms M. Taylor, Ms A. Tenney and Ms L. Van Wie;
- Dr E. Haites, the Head of the Technical Support Unit of Working Group III and his staff Ms L. Lawson and Ms V. Dreja;
- and Dr N. Sundararaman, the Secretary of the IPCC and his staff in the IPCC Secretariat, the late Mr S. Tewungwa, Mrs R. Bourgeois, Ms C. Ettori and Ms C. Tanikie.

G.O.P. Obasi
Secretary-General
World Meterological Organization

Ms E. Dowdeswell
Executive Director
United Nations Environment Programme

FOREWORD

The IPCC completed its Second Assessment Report (SAR) in December 1995. The SAR consists of four parts:

- the IPCC Second Assessment Synthesis of Scientific-Technical Information Relevant to Interpreting Article 2 of the UN Framework Convention on Climate Change;
- the Report of Working Group I of the IPCC, the Science of Climate Change, with a Summary for Policymakers (SPM);
- the Report of Working Group II of the IPCC, Scientific-Technical Analyses of Impacts, Adaptations and Mitigation of Climate Change, with SPM;
- the Report of Working Group III of the IPCC, the Economic and Social Dimensions of Climate Change, with SPM.

The IPCC Second Assessment Synthesis and the Summaries for Policymakers of the three Working Groups constitute the Report of the IPCC (1995). They are published in this volume and available in the six UN languages, namely, Arabic, Chinese, English, French, Russian and Spanish. The Reports of the Working Groups, with their respective SPMs, are available in English only and each is separately published commercially.

We take this opportunity, because of much misinformation and misunderstanding on the subject, to inform the reader on how the IPCC conducts its assessments.

1. The Panel at the outset decides the content, broken down into chapters, of the report of each of its Working Groups. A writing team of three to six experts (on some rare occasions, more) is constituted for the initial drafting and subsequent revisions of a chapter. Governments and intergovernmental and non-governmental organizations are requested to nominate individuals with appropriate expertise for consideration for inclusion in the writing teams. The publication record of the nominees and other relevant information are also requested. Lists of such individuals are compiled from which the writing team is selected by the Bureau of the Working Group concerned (i.e., the Co-Chairmen and the Vice-Chairmen of the Working Group). The IPCC requires that at least one member of each writing team be from the developing world.

2. The reports are required to have a Summary for Policymakers (SPM). The SPM should reflect the state-of-the-art understanding of the subject matter and be written in a manner that is readily comprehensible to the non-specialist. Differing but scientifically or technically well-founded views should be so exposed in the reports and the SPMs, if they cannot be reconciled in the course of the assessment.

3. The writing teams draft the chapters and the material for inclusion in the SPMs. The drafts are based on literature published in peer-reviewed journals and reports of professional organizations such as the International Council of Scientific Unions, the World Meteorological Organization, the United Nations Environment Programme, the World Health Organization and the United Nations Food and Agriculture Organization. Sometimes, the IPCC holds workshops to collect information that is otherwise not readily available; this is particularly done to encourage information-gathering on and in the developing countries.

4. Each draft chapter is sent to tens of experts worldwide for expert review. The reviewers are also chosen from nominations made by governments and organizations. The mandated time for this review is six weeks. The draft, revised in the light of the comments received, is sent to governments and organizations for their technical review. The mandated time for this (second) review is also six weeks. In some cases, the expert and government reviews are conducted simultaneously when the time factor would not permit sequential reviews.

5. The draft is revised a second time in the light of the reviews received from governments and organizations. It is then sent to governments (and organizations) one month in advance of the session of the Working Group which would consider it. The Working Group approves the SPM line by line and accepts the underlying chapters; the two together constitute the Report of the Working Group. It is not practical for the Working Group to approve its Report which usually runs to two hundred pages or more. The meaning of the term acceptance in this context is that the underlying chapters and the SPM are consistent with each other.

6. When the Working Group approves the SPM, selected members of the writing teams — from the developing as well as the developed worlds — are present and the text of the SPM is revised at the session with their concurrence. Thus, in reality, the Reports of the Working Groups are written and revised by experts and reviewed by other experts.

7. The Report of the Working Group (with the approved SPM) is sent to governments and organizations one month before the session of the IPCC which would consider it for acceptance.

8. The reader may note that the IPCC is a fully intergovernmental, scientific-technical body. All States that are Members of the United Nations and of the World Meteorological Organization are Members of the IPCC and its Working Groups. As such, governments approve the SPMs and accept the underlying chapters, which are, as stated earlier, written and revised by experts.

The IPCC Second Assessment Synthesis was drafted by a Drafting Team constituted under the chairmanship of the Chairman of the

IPCC. It underwent expert and government reviews simultaneously. It was approved line by line by the IPCC at its Eleventh Session (Rome, 11-15 December 1995).

May we reiterate that the reports of the IPCC and of its Working Groups contain the factual basis of the issue of climate change, gleaned from available expert literature and further carefully reviewed by experts and governments. In total more than two thousand experts worldwide participate in drafting and reviewing them. Governments of the world approve/accept them for their scientific-technical content. The final product is written by experts selected worldwide and accepted by governments sitting in plenary sessions.

We also take this opportunity to record the sad loss of a valued member of the IPCC Secretariat. Mr Samuel Tewungwa, who passed away in January 1996, was seconded by the United Nations Environment Programme to the Secretariat. His good cheer and good humour and dedication to duty are, and will be, much missed.

N. Sundararaman
Secretary of the IPCC

B. Bolin
Chairman of the IPCC

IPCC SECOND ASSESSMENT SYNTHESIS OF SCIENTIFIC-TECHNICAL INFORMATION RELEVANT TO INTERPRETING ARTICLE 2 OF THE UN FRAMEWORK CONVENTION ON CLIMATE CHANGE

ADDRESSING THE UNFCCC ARTICLE 2

1

1.1 Following a resolution of the Executive Council of the World Meteorological Organization (July 1992), the IPCC decided to include an examination of approaches to Article 2, the Objective of the UN Framework Convention on Climate Change (UNFCCC), in its work programme. It organized a workshop on the subject in October 1994 in Fortaleza, Brazil, at the invitation of the Government of Brazil. Thereafter, the IPCC Chairman assembled a team of lead authors (listed at the end of this report in the Appendix) under his chairmanship to draft the Synthesis. The team produced the draft which was submitted for expert and government review and comment. The final draft Synthesis was approved line by line by the IPCC at its eleventh session (Rome, 11-15 December 1995), where representatives of 116 governments were present as well as 13 intergovernmental and 25 non-governmental organizations. It may be noted for information that all Member States of the World Meteorological Organization and of the United Nations are Members of the IPCC and can attend its sessions and those of its Working Groups. The Synthesis presents information on the scientific and technical issues related to interpreting Article 2 of the UNFCCC, drawing on the underlying IPCC Second Assessment Report. Since the Synthesis is not simply a summary of the IPCC Second Assessment Report, the Summaries for Policymakers of the three IPCC Working Groups should also be consulted for a summary of the Second Assessment Report.

1.2 During the past few decades, two important factors regarding the relationship between humans and the Earth's climate have become apparent. First, human activities, including the burning of fossil fuels, land-use change and agriculture, are increasing the atmospheric concentrations of greenhouse gases (which tend to warm the atmosphere) and, in some regions, aerosols (microscopic airborne particles, which tend to cool the atmosphere). These changes in greenhouse gases and aerosols, taken together, are projected to change regional and global climate and climate-related parameters such as temperature, precipitation, soil moisture and sea level. Second, some human communities have become more vulnerable[1] to hazards such as storms, floods and droughts as a result of increasing population density in sensitive areas such as river basins and coastal plains. Potentially serious changes have been identified, including an increase in some regions in the incidence of extreme high-temperature events, floods and droughts, with resultant consequences for fires, pest outbreaks, and ecosystem composition, structure and functioning, including primary productivity.

1.3 Scientific and technical assessments of climate change and its impacts have been conducted by the Intergovernmental Panel on Climate Change (IPCC). The First Assessment, published in 1990, provided a scientific and technical base for the UN Framework Convention on Climate Change (UNFCCC) which was open for signature at the Earth Summit in Rio in 1992.

1.4 The ultimate objective of the UNFCCC, as expressed in Article 2 is:

> "... stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system. Such a level should be achieved within a time-frame sufficient to allow ecosystems to adapt naturally to climate change, to ensure that food production is not threatened and to enable economic development to proceed in a sustainable manner".

1.5 The challenges presented to the policymaker by Article 2 are the determination of what concentrations of greenhouse gases might be regarded as "dangerous anthropogenic interference with the climate system" and the charting of a future which allows for economic development which is sustainable. The purpose of this synthesis report is to provide scientific, technical and socio-economic information that can be used, *inter alia*, in addressing these challenges. It is based on the 1994 and 1995 reports of the IPCC Working Groups.

1.6 The report follows through the various matters which are addressed in Article 2. It first briefly summarizes the degree of climate change — the "interference with the climate system" — which is projected to occur as a result of human activities. It then goes on to highlight what we know about the vulnerabilities of ecosystems and human communities to likely climate changes, especially in regard to agriculture and food production and to other factors such as water availability, health and the impact of sea-level rise which are important considerations for sustainable development. The task of the IPCC is to provide a sound scientific basis that would enable policymakers to better interpret dangerous anthropogenic interference with the climate system.

1.7 Given current trends of increasing emissions of most greenhouse gases, atmospheric concentrations of these gases will increase through the next century and beyond. With the growth in atmospheric concentrations of greenhouse gases, interference with the climate system will grow in magnitude and the likelihood of adverse impacts from climate change that could be judged dangerous will become greater. Therefore, possible pathways of future net emissions were considered which might lead to stabilization at different levels and the general constraints these imply. This

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[1] Vulnerability defines the extent to which climate change may damage or harm a system. It depends not only on a system's sensitivity but also on its ability to adapt to new climatic conditions.

consideration forms the next part of the report and is followed by a summary of the technical and policy options for reducing emissions and enhancing sinks of greenhouse gases.

1.8 The report then addresses issues related to equity and to ensuring that economic development proceeds in a sustainable manner. This involves addressing, for instance, estimates of the likely damage of climate change impacts, and the impacts, including costs and benefits, of adaptation and mitigation. Finally, a number of insights from available studies point to ways of taking initial actions (see the section on Road Forward) even if, at present, it is difficult to decide upon a target for atmospheric concentrations, including considerations of time-frames, that would prevent "dangerous anthropogenic interference with the climate system".

1.9 Climate change presents the decision maker with a set of formidable complications: considerable remaining uncertainties inherent in the complexity of the problem, the potential for irreversible damages or costs, a very long planning horizon, long time lags between emissions and effects, wide regional variations in causes and effects, an irreducibly global problem, and a multiple of greenhouse gases and aerosols to consider. Yet another complication is that effective protection of the climate system requires international cooperation in the context of wide variations in income levels, flexibility and expectations of the future; this raises issues of efficiency and intra-national, international and intergenerational equity. Equity is an important element for legitimizing decisions and promoting cooperation.

1.10 Decisions with respect to Article 2 of the UNFCCC involve three distinct but interrelated choices: stabilization level, net emissions pathway and mitigation technologies and policies. The report presents available scientific and technical information on these three choices. It also notes where uncertainties remain regarding such information. Article 3 of the UNFCCC identifies a range of principles that shall guide, *inter alia*, decision-making with respect to the ultimate objective of the Convention, as found in Article 2. Article 3.3[2] provides guidance, *inter alia*, on decision-making where there is a lack of full scientific certainty, namely that the Parties should:

> "take precautionary measures to anticipate, prevent or minimize the causes of climate change and mitigate its adverse effects. Where there are threats of serious or irreversible damage, lack of full scientific certainty should not be used as a reason for postponing such measures, taking into account that policies and measures to deal with climate change should be cost effective so as to ensure global benefits at the lowest possible cost. To achieve this, such policies and measures should take into account different socio-economic contexts, be comprehensive, cover all relevant sources, sinks and reservoirs of greenhouse gases and adaptation and comprise all economic sectors. Efforts to address climate change may be carried out cooperatively by interested Parties."

The Second Assessment Report of the IPCC also provides information in this regard.

1.11 The long time-scales involved in the climate system (e.g., the long residence time of greenhouse gases in the atmosphere) and in the time for replacement of infrastructure, and the lag by many decades to centuries between stabilization of concentrations and stabilization of temperature and mean sea level, indicate the importance for timely decision-making.

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[2] Kuwait registered its objection to quoting only subparagraph 3 of Article 3 and not the Article in its entirety.

ANTHROPOGENIC INTERFERENCE WITH THE CLIMATE SYSTEM

2

Interference to the present day

2.1 In order to understand what constitutes concentrations of greenhouse gases that would prevent dangerous interference with the climate system, it is first necessary to understand current atmospheric concentrations and trends of greenhouse gases, and their consequences (both present and projected) to the climate system.

2.2 The atmospheric concentrations of the greenhouse gases, and among them, carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O), have grown significantly since pre-industrial times (about 1750 A.D.): CO_2 from about 280 to almost 360 ppmv[3], CH_4 from 700 to 1720 ppbv and N_2O from about 275 to about 310 ppbv. These trends can be attributed largely to human activities, mostly fossil-fuel use, land-use change and agriculture. Concentrations of other anthropogenic greenhouse gases have also increased. An increase of greenhouse gas concentrations leads on average to an additional warming of the atmosphere and the Earth's surface. Many greenhouse gases remain in the atmosphere — and affect climate — for a long time.

2.3 Tropospheric aerosols resulting from combustion of fossil fuels, biomass burning and other sources have led to a negative direct forcing and possibly also to a negative indirect forcing of a similar magnitude. While the negative forcing is focused in particular regions and subcontinental areas, it can have continental to hemispheric scale effects on climate patterns. Locally, the aerosol forcing can be large enough to more than offset the positive forcing

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[3] ppmv stands for parts per million by volume; ppbv stands for parts per billion (thousand million) by volume. Values quoted are for 1992.

due to greenhouse gases. In contrast to the long-lived greenhouse gases, anthropogenic aerosols are very short-lived in the atmosphere and hence their radiative forcing adjusts rapidly to increases or decreases in emissions.

2.4 Global mean surface temperature has increased by between about 0.3 and 0.6°C since the late 19th century, a change that is unlikely to be entirely natural in origin. The balance of evidence, from changes in global mean surface air temperature and from changes in geographical, seasonal and vertical patterns of atmospheric temperature, suggests a discernible human influence on global climate. There are uncertainties in key factors, including the magnitude and patterns of long-term natural variability. Global sea level has risen by between 10 and 25 cm over the past 100 years and much of the rise may be related to the increase in global mean temperature.

2.5 There are inadequate data to determine whether consistent global changes in climate variability or weather extremes have occurred over the 20th century. On regional scales there is clear evidence of changes in some extremes and climate variability indicators. Some of these changes have been toward greater variability, some have been toward lower variability. However, to date it has not been possible to firmly establish a clear connection between these regional changes and human activities.

Possible consequences of future interference

2.6 In the absence of mitigation policies or significant technological advances that reduce emissions and/or enhance sinks, concentrations of greenhouse gases and aerosols are expected to grow throughout the next century. The IPCC has developed a range of scenarios, IS92a-f, of future greenhouse gas and aerosol precursor emissions based on assumptions concerning population and economic growth, land-use, technological changes, energy availability and fuel mix during the period 1990 to 2100[4]. By the year 2100, carbon dioxide emissions under these scenarios are projected to be in the range of about 6 GtC[5] per year, roughly equal to current emissions, to as much as 36 GtC per year, with the lower end of the IPCC range assuming low population and economic growth to 2100. Methane emissions are projected to be in the range 540 to 1170 Tg[6] CH_4 per year (1990 emissions were about 500 Tg CH_4); nitrous oxide emissions are projected to be in the range 14 to 19 Tg N per year (1990 emissions were about 13 Tg N). In all cases, the atmospheric concentrations of greenhouse gases and total radiative forcing continue to increase throughout the simulation period of 1990 to 2100.

2.7 For the mid-range IPCC emission scenario, IS92a, assuming the "best estimate" value of climate sensitivity[7] and including the effects of future increases in aerosol concentrations, models project an increase in global mean surface temperature relative to 1990 of about 2°C by 2100. This estimate is approximately one-third lower than the "best estimate" in 1990. This is due primarily to lower emission scenarios (particularly for CO_2 and CFCs), the inclusion of the cooling effect of sulphate aerosols, and improvements in the treatment of the carbon cycle. Combining the lowest IPCC emission scenario (IS92c) with a "low" value of climate sensitivity and including the effects of future changes in aerosol concentrations leads to a projected increase of about 1°C by 2100. The corresponding projection for the highest IPCC scenario (IS92e) combined with a "high" value of climate sensitivity gives a warming of about 3.5°C. In all cases the average rate of warming would probably be greater than any seen in the last 10,000 years, but the actual annual to decadal changes would include considerable natural variability. Regional temperature changes could differ substantially from the global mean value. Because of the thermal inertia of the oceans, only 50-90% of the eventual equilibrium temperature change would have been realized by 2100 and temperature would continue to increase beyond 2100, even if concentrations of greenhouse gases were stabilized by that time.

2.8 Average sea level is expected to rise as a result of thermal expansion of the oceans and melting of glaciers and ice-sheets. For the IS92a scenario, assuming the "best estimate" values of climate sensitivity and of ice melt sensitivity to warming, and including the effects of future changes in aerosol concentrations, models project an increase in sea level of about 50 cm from the present to 2100. This estimate is approximately 25% lower than the "best estimate" in 1990 due to the lower temperature projection, but also reflecting improvements in the climate and ice melt models. Combining the lowest emission scenario (IS92c) with the "low" climate and ice melt sensitivities and including aerosol effects gives a projected sea-level rise of about 15 cm from the present to 2100. The corresponding projection for the highest emission scenario (IS92e) combined with "high" climate and ice-melt sensitivities gives a sea-level rise of about 95 cm from the present to 2100. Sea level would continue to rise at a similar rate in future centuries beyond 2100, even if concentrations of greenhouse gases were stabilized by that time, and would continue to do so even beyond the time of stabilization of global mean temperature. Regional sea-level changes may differ from the global mean value owing to land movement and ocean current changes.

2.9 Confidence is higher in the hemispheric-to-continental scale projections of coupled atmosphere-ocean climate models than in the regional projections, where confidence remains low. There is more confidence in temperature projections than hydrological changes.

2.10 All model simulations, whether they were forced with increased concentrations of greenhouse gases and aerosols or with increased concentrations of greenhouse gases alone, show the following features: greater surface warming of the land than of the sea in winter; a maximum surface warming in high northern

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[4] See Table 1 in the Summary for Policymakers of IPCC Working Group II.

[5] To convert GtC (gigatonnes of carbon or thousand million tonnes of carbon) to mass of carbon dioxide, multiply GtC by 3.67.

[6] Tg: teragram is 10^{12} grams.

[7] In IPCC reports, climate sensitivity usually refers to long-term (equilibrium) change in global mean surface temperature following a doubling of atmospheric equivalent CO_2 concentration. More generally, it refers to the equilibrium change in surface air temperature following a unit change in radiative forcing (°C/Wm^{-2}).

latitudes in winter, little surface warming over the Arctic in summer; an enhanced global mean hydrological cycle, and increased precipitation and soil moisture in high latitudes in winter. All these changes are associated with identifiable physical mechanisms.

2.11 Warmer temperatures will lead to a more vigorous hydrological cycle; this translates into prospects for more severe droughts and/or floods in some places and less severe droughts and/or floods in other places. Several models indicate an increase in precipitation intensity, suggesting a possibility for more extreme rainfall events. Knowledge is currently insufficient to say whether there will be any changes in the occurrence or geographical distribution of severe storms, e.g., tropical cyclones.

2.12 There are many uncertainties and many factors currently limit our ability to project and detect future climate change. Future unexpected, large and rapid climate system changes (as have occurred in the past) are, by their nature, difficult to predict. This implies that future climate changes may also involve "surprises". In particular, these arise from the non-linear nature of the climate system. When rapidly forced, non-linear systems are especially subject to unexpected behaviour. Progress can be made by investigating non-linear processes and subcomponents of the climatic system. Examples of such non-linear behaviour include rapid circulation changes in the North Atlantic and feedbacks associated with terrestrial ecosystem changes.

SENSITIVITY AND ADAPTATION OF SYSTEMS TO CLIMATE CHANGE

3

3.1 This section provides scientific and technical information that can be used, *inter alia*, in evaluating whether the projected range of plausible impacts constitutes "dangerous anthropogenic interference with the climate system", as referred to in Article 2, and in evaluating adaptation options. However, it is not yet possible to link particular impacts with specific atmospheric concentrations of greenhouse gases.

3.2 Human health, terrestrial and aquatic ecological systems, and socio-economic systems (e.g., agriculture, forestry, fisheries and water resources) are all vital to human development and well-being and are all sensitive to both the magnitude and the rate of climate change. Whereas many regions are likely to experience the adverse effects of climate change — some of which are potentially irreversible — some effects of climate change are likely to be beneficial. Hence, different segments of society can expect to confront a variety of changes and the need to adapt to them.

3.3 Human-induced climate change represents an important additional stress, particularly to the many ecological and socio-economic systems already affected by pollution, increasing resource demands, and non-sustainable management practices. The vulnerability of human health and socio-economic systems — and, to a lesser extent, ecological systems — depends upon economic circumstances and institutional infrastructure. This implies that systems typically are more vulnerable in developing countries where economic and institutional circumstances are less favourable.

3.4 Although our knowledge has increased significantly during the last decade and qualitative estimates can be developed, quantitative projections of the impacts of climate change on any particular system at any particular location are difficult because regional-scale climate change projections are uncertain; our current understanding of many critical processes is limited; systems are subject to multiple climatic and non-climatic stresses, the interactions of which are not always linear or additive; and very few studies have considered dynamic responses to steadily increasing concentrations of greenhouse gases or the consequences of increases beyond a doubling of equivalent atmospheric CO_2 concentrations.

3.5 Unambiguous detection of climate-induced changes in most ecological and social systems will prove extremely difficult in the coming decades. This is because of the complexity of these systems, their many non-linear feedbacks, and their sensitivity to a large number of climatic and non-climatic factors, all of which are expected to continue to change simultaneously. As future climate extends beyond the boundaries of empirical knowledge (i.e., the documented impacts of climate variation in the past), it becomes more likely that actual outcomes will include surprises and unanticipated rapid changes.

Sensitivity of systems

Terrestrial and aquatic ecosystems

3.6 Ecosystems contain the Earth's entire reservoir of genetic and species diversity and provide many goods and services including: (i) providing food, fibre, medicines and energy; (ii) processing and storing carbon and other nutrients; (iii) assimilating wastes, purifying water, regulating water runoff, and controlling floods, soil degradation and beach erosion; and (iv) providing opportunities for recreation and tourism. The composition and geographic distribution of many ecosystems (e.g., forests, rangelands, deserts, mountain systems, lakes, wetlands and oceans) will shift as individual species respond to changes in climate; there will likely be reductions in biological diversity and in the goods and services that ecosystems provide society. Some ecological systems may not reach a new equilibrium for several centuries after the climate achieves a new balance.

This section illustrates the impact of climate change on a number of selected ecological systems.

3.7 **Forests**: Models project that as a consequence of possible changes in temperature and water availability under doubled equivalent[8] CO_2 equilibrium conditions, a substantial fraction (a global average of one-third, varying by region from one-seventh to two-thirds) of the existing forested area of the world will undergo major changes in broad vegetation types — with the greatest changes occurring in high latitudes and the least in the tropics. Climate change is expected to occur at a rapid rate relative to the speed at which forest species grow, reproduce and re-establish themselves. Therefore, the species composition of forests is likely to change; entire forest types may disappear, while new assemblages of species and hence new ecosystems may be established. Large amounts of carbon could be released into the atmosphere during transitions from one forest type to another because the rate at which carbon can be lost during times of high forest mortality is greater than the rate at which it can be gained through growth to maturity.

3.8 **Deserts and desertification**: Deserts are likely to become more extreme — in that, with few exceptions, they are projected to become hotter but not significantly wetter. Temperature increases could be a threat to organisms that exist near their heat tolerance limits. Desertification — land degradation in arid, semi-arid and dry sub-humid areas resulting from various factors, including climatic variations and human activities — is more likely to become irreversible if the environment becomes drier and the soil becomes further degraded through erosion and compaction.

3.9 **Mountain ecosystems**: The altitudinal distribution of vegetation is projected to shift to higher elevation; some species with climatic ranges limited to mountain tops could become extinct because of disappearance of habitat or reduced migration potential.

3.10 **Aquatic and coastal ecosystems**: In lakes and streams, warming would have the greatest biological effects at high latitudes, where biological productivity would increase, and at the low-latitude boundaries of cold- and cool-water species ranges, where extinctions would be greatest. The geographical distribution of wetlands is likely to shift with changes in temperature and precipitation. Coastal systems are economically and ecologically important and are expected to vary widely in their response to changes in climate and sea level. Some coastal ecosystems are particularly at risk, including saltwater marshes, mangrove ecosystems, coastal wetlands, sandy beaches, coral reefs, coral atolls and river deltas. Changes in these ecosystems would have major negative effects on tourism, freshwater supplies, fisheries and biodiversity.

Hydrology and water resources management

3.11 Models project that between one-third and one-half of existing mountain glacier mass could disappear over the next hundred years. The reduced extent of glaciers and depth of snow cover also would affect the seasonal distribution of river flow and water supply for hydroelectric generation and agriculture. Anticipated hydrological changes and reductions in the areal extent and depth of permafrost could lead to large-scale damage to infrastructure, an additional flux of carbon dioxide into the atmosphere, and changes in processes that contribute to the flux of methane into the atmosphere.

3.12 Climate change will lead to an intensification of the global hydrological cycle and can have major impacts on regional water resources. Changes in the total amount of precipitation and in its frequency and intensity directly affect the magnitude and timing of runoff and the intensity of floods and droughts; however, at present, specific regional effects are uncertain. Relatively small changes in temperature and precipitation, together with the non-linear effects on evapotranspiration and soil moisture, can result in relatively large changes in runoff, especially in arid and semi-arid regions. The quantity and quality of water supplies already are serious problems today in many regions, including some low-lying coastal areas, deltas and small islands, making countries in these regions particularly vulnerable to any additional reduction in indigenous water supplies.

Agriculture and forestry

3.13 Crop yields and changes in productivity due to climate change will vary considerably across regions and among localities, thus changing the patterns of production. Productivity is projected to increase in some areas and decrease in others, especially the tropics and subtropics. Existing studies show that on the whole, global agricultural production could be maintained relative to baseline production in the face of climate change projected under doubled equivalent CO_2 equilibrium conditions. This conclusion takes into account the beneficial effects of CO_2 fertilization but does not allow for changes in agricultural pests and the possible effects of changing climatic variability. However, focusing on global agricultural production does not address the potentially serious consequences of large differences at local and regional scales, even at mid-latitudes. There may be increased risk of hunger and famine in some locations; many of the world's poorest people — particularly those living in subtropical and tropical areas and dependent on isolated agricultural systems in semi-arid and arid regions — are most at risk of increased hunger. Global wood supplies during the next century may become increasingly inadequate to meet projected consumption due to both climatic and non-climatic factors.

Human infrastructure

3.14 Climate change clearly will increase the vulnerability of some coastal populations to flooding and erosional land loss. Estimates put about 46 million people per year currently at risk of flooding due to storm surges. In the absence of adaptation measures, and not taking into account anticipated population growth, 50-cm sea-level rise would increase this number to about 92 million; a 1-meter sea-level rise would raise it to about 118 million.

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[8] See paragraph 4.17 for a description of "equivalent CO_2".

Studies using a 1-meter projection show a particular risk for small islands and deltas. This increase is at the top range of IPCC Working Group I estimates for 2100; it should be noted, however, that sea level is actually projected to continue to rise in future centuries beyond 2100. Estimated land losses range from 0.05% in Uruguay, 1.0% for Egypt, 6% for the Netherlands and 17.5% for Bangladesh to about 80% for the Majuro Atoll in the Marshall Islands, given the present state of protection systems. Some small island nations and other countries will confront greater vulnerability because their existing sea and coastal defense systems are less well established. Countries with higher population densities would be more vulnerable. Storm surges and flooding could threaten entire cultures. For these countries, sea-level rise could force internal or international migration of populations.

Human health

3.15 Climate change is likely to have wide-ranging and mostly adverse impacts on human health, with significant loss of life. Direct health effects include increases in (predominantly cardio-respiratory) mortality and illness due to an anticipated increase in the intensity and duration of heat waves. Temperature increases in colder regions should result in fewer cold-related deaths. Indirect effects of climate change, which are expected to predominate, include increases in the potential transmission of vector-borne infectious diseases (e.g., malaria, dengue, yellow fever and some viral encephalitis) resulting from extensions of the geographical range and season for vector organisms. Models (that entail necessary simplifying assumptions) project that temperature increases of 3-5°C (compared to the IPCC projection of 1-3.5°C by 2100) could lead to potential increases in malaria incidence (of the order of 50–80 million additional annual cases, relative to an assumed global background total of 500 million cases), primarily in tropical, subtropical and less well-protected temperate-zone populations. Some increases in non-vector-borne infectious diseases — such as salmonellosis, cholera and giardiasis — also could occur as a result of elevated temperatures and increased flooding. Limitations on freshwater supplies and on nutritious food, as well as the aggravation of air pollution, will also have human health consequences.

3.16 Quantifying the projected impacts is difficult because the extent of climate-induced health disorders depends on numerous coexistent and interacting factors that characterize the vulnerability of the particular population, including environmental and socio-economic circumstances, nutritional and immune status, population density and access to quality health care services. Hence, populations with different levels of natural, technical and social resources would differ in their vulnerability to climate-induced health impacts.

Technology and policy options for adaptation

3.17 Technological advances generally have increased adaptation options for managed systems. Adaptation options for freshwater resources include more efficient management of existing supplies and infrastructure; institutional arrangements to limit future demands/promote conservation; improved monitoring and forecasting systems for floods/droughts; rehabilitation of watersheds, especially in the tropics; and construction of new reservoir capacity. Adaptation options for agriculture — such as changes in types and varieties of crops, improved water-management and irrigation systems, and changes in planting schedules and tillage practices — will be important in limiting negative effects and taking advantage of beneficial changes in climate. Effective coastal-zone management and land-use planning can help direct population shifts away from vulnerable locations such as flood plains, steep hillsides and low-lying coastlines. Adaptive options to reduce health impacts include protective technology (e.g., housing, air conditioning, water purification and vaccination), disaster preparedness and appropriate health care.

3.18 However, many regions of the world currently have limited access to these technologies and appropriate information. For some island nations, the high cost of providing adequate protection would make it essentially infeasible, especially given the limited availability of capital for investment. The efficacy and cost-effective use of adaptation strategies will depend upon the availability of financial resources, technology transfer, and cultural, educational, managerial, institutional, legal and regulatory practices, both domestic and international in scope. Incorporating climate-change concerns into resource-use and development decisions and plans for regularly scheduled investments in infrastructure will facilitate adaptation.

ANALYTICAL APPROACH TO STABILIZATION OF ATMOSPHERIC CONCENTRATIONS OF GREENHOUSE GASES

4

4.1 Article 2 of the UN Framework Convention on Climate Change refers explicitly to “stabilization of greenhouse gas concentrations”. This section provides information on the relative importance of various greenhouse gases to climate forcing and discusses how greenhouse gas emissions might be varied to achieve stabilization at selected atmospheric concentration levels.

4.2 Carbon dioxide, methane and nitrous oxide have natural as well as anthropogenic origins. The anthropogenic emissions of these gases have contributed about 80% of the additional climate forcing due to greenhouse gases since pre-industrial times (i.e., since about 1750 A.D.). The contribution of CO_2 is about 60% of this forcing, about four times that from CH_4.

4.3 Other greenhouse gases include tropospheric ozone (whose chemical precursors include nitrogen oxides, non-methane hydrocarbons and carbon monoxide), halocarbons[9] (including HCFCs and HFCs) and SF_6. Tropospheric aerosols and tropospheric ozone are inhomogeneously distributed in time and space and their atmospheric lifetimes are short (days to weeks). Sulphate aerosols are amenable to abatement measures and such measures are presumed in the IPCC scenarios.

4.4 Most emission scenarios indicate that, in the absence of mitigation policies, greenhouse gas emissions will continue to rise during the next century and lead to greenhouse gas concentrations that by the year 2100 are projected to change climate more than that projected for twice the pre-industrial concentrations of carbon dioxide.

Stabilization of greenhouse gases

4.5 All relevant greenhouse gases need to be considered in addressing stabilization of greenhouse gas concentrations. First, carbon dioxide is considered which, because of its importance and complicated behaviour, needs more detailed consideration than the other greenhouse gases.

Carbon dioxide

4.6 Carbon dioxide is removed from the atmosphere by a number of processes that operate on different time-scales. It has a relatively long residence time in the climate system — of the order of a century or more. If net global anthropogenic emissions[10] (i.e., anthropogenic sources minus anthropogenic sinks) were maintained at current levels (about 7 GtC/yr including emissions from fossil-fuel combustion, cement production and land-use change), they would lead to a nearly constant rate of increase in atmospheric concentrations for at least two centuries, reaching about 500 ppmv (approaching twice the pre-industrial concentration of 280 ppmv) by the end of the 21st century. Carbon cycle models show that immediate stabilization of the concentration of carbon dioxide at its present level could only be achieved through an immediate reduction in its emissions of 50-70% and further reductions thereafter.

4.7 Carbon cycle models have been used to estimate profiles of carbon dioxide emissions for stabilization at various carbon dioxide concentration levels. Such profiles have been generated for an illustrative set of levels: 450, 550, 650, 750 and 1000 ppmv. Among the many possible pathways to reach stabilization, two are illustrated in Figure 1 for each of the stabilization levels of 450, 550, 650 and 750 ppmv, and one for 1000 ppmv. The steeper the increase in the emissions (hence concentration) in these scenarios, the more quickly is the climate projected to change.

4.8 Any eventual stabilized concentration is governed more by the accumulated anthropogenic carbon dioxide emissions from now until the time of stabilization, than by the way those emissions change over the period. This means that, for a given stabilized concentration value, higher emissions in early decades require lower emissions later on. Cumulative emissions from 1991 to 2100 corresponding to these stabilization levels are shown in Table 1, together with the cumulative emissions of carbon dioxide for all of the IPCC IS92 emission scenarios (see Figure 2 below and Table 1 in the Summary for Policymakers of IPCC Working Group II for details of these scenarios).

4.9 Figure 1 and Table 1 are presented to clarify some of the constraints that would be imposed on future carbon dioxide emissions, if stabilization at the concentration levels illustrated were to be achieved. These examples do not represent any form of recommendation about how such stabilization levels might be achieved or the level of stabilization which might be chosen.

4.10 Given cumulative emissions, and IPCC IS92a population and economic scenarios for 1990-2100, global annual average carbon dioxide emissions can be derived for the stabilization scenarios on a per capita or per unit of economic activity basis. If the atmospheric concentration is to remain below 550 ppmv, the future global annual average emissions cannot, during the next century, exceed the current global average and would have to be much lower before and beyond the end of the next century. Global annual average emissions could be higher for stabilization levels of 750 to 1000 ppmv. Nevertheless, even to achieve these latter stabilization levels, the global annual average emissions would need to be less than 50% above current levels on a per capita basis or less than half of current levels per unit of economic activity[11].

4.11[12] The global average annual per capita emissions of carbon dioxide due to the combustion of fossil fuels is at present about 1.1 tonnes (as carbon). In addition, a net of about 0.2 tonnes per capita are emitted from deforestation and land-use change. The average annual fossil fuel per capita emission in developed and transitional economy countries is about 2.8 tonnes and ranges from 1.5 to 5.5 tonnes. The figure for the developing countries is 0.5 tonnes ranging from 0.1 tonnes to, in some few cases, above 2.0 tonnes (all figures are for 1990).

4.12[13] Using World Bank estimates of GDP (gross domestic product) at market exchange rates, the current global annual average emission of energy-related carbon dioxide is about 0.3 tonnes per thousand 1990 US dollars output. In addition, global net emissions from land-use changes are about 0.05 tonnes per thousand US dollars of output. The current average annual energy-

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[9] Most halocarbons, but neither HFCs nor PFCs, are controlled by the Montreal Protocol and its Adjustments and Amendments.

[10] For the remainder of Section 4, “net global anthropogenic emissions” (i.e., anthropogenic sources minus anthropogenic sinks) will be abbreviated to “emissions”.

[11] China registered its disagreement on the use of carbon dioxide emissions derived on the basis of a per unit economic activity.

[12] The Panel agreed that this paragraph shall not prejudge the current negotiations under the UNFCCC.

[13] The Panel agreed that this paragraph shall not prejudge the current negotiations under the UNFCCC.

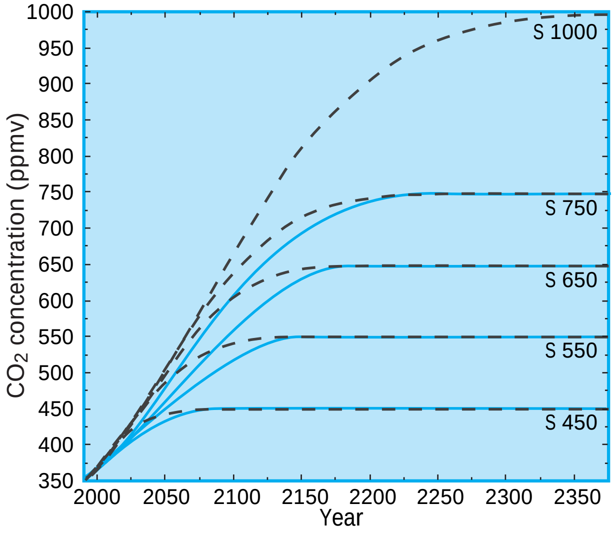

Figure 1 (a). Carbon dioxide concentration profiles leading to stabilization at 450, 550, 650 and 750 ppmv following the pathways defined in IPCC (1994) (solid curves) and for pathways that allow emissions to follow IS92a until at least the year 2000 (dashed curves). A single profile that stabilizes at a carbon dioxide concentration of 1000 ppmv and follows IS92a emissions until at least the year 2000 has also been defined. Stabilization at concentrations of 450, 650 and 1000 ppmv would lead to equilibrium temperature increases relative to 1990[14] due to carbon dioxide alone (i.e., not including effects of other greenhouse gases (GHGs) and aerosols) of about 1°C (range: 0.5 to 1.5°C), 2°C (range: 1.5 to 4°C) and 3.5°C (range: 2 to 7°C), respectively. A doubling of the pre-industrial carbon dioxide concentration of 280 ppmv would lead to a concentration of 560 ppmv and doubling of the current concentration of 358 ppmv would lead to a concentration of about 720 ppmv.

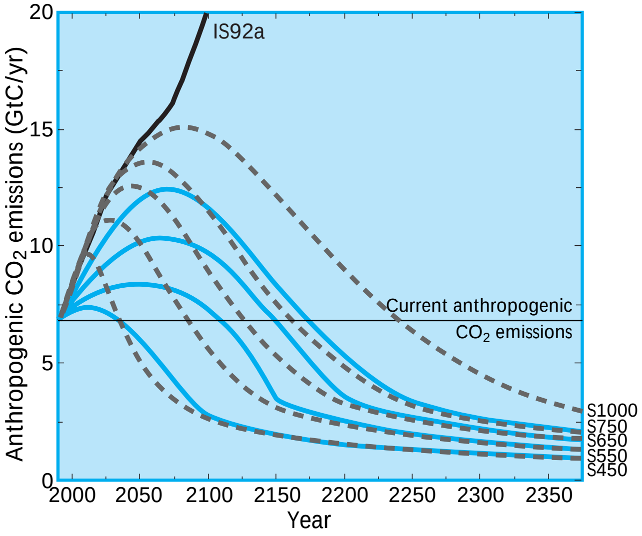

Figure 1 (b). Carbon dioxide emissions leading to stabilization at concentrations of 450, 550, 650, 750 and 1000 ppmv following the profiles shown in (a) from a mid-range carbon cycle model. Results from other models could differ from those presented here by up to approximately ± 15%. For comparison, the carbon dioxide emissions for IS92a and current emissions (fine solid line) are also shown.

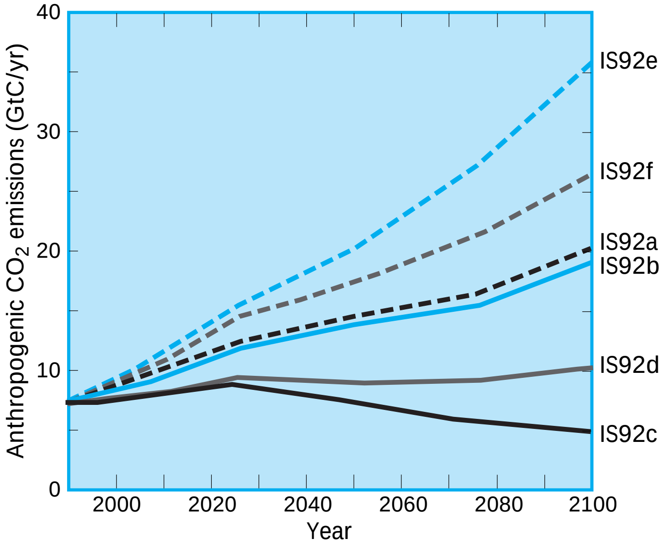

Figure 2. Annual anthropogenic carbon dioxide emissions under the IS92 emission scenarios (see Table 1 in the Summary for Policymakers of IPCC Working Group II for further details).

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[14] These numbers do not take into account the increase in temperature (0.1 to 0.7°C) which would occur after 1990 because of CO_2 emissions prior to 1990.

	Accumulated carbon dioxide emissions 1991 to 2100 (GtC)[§]	
IS92 scenarios		
c	770	
d	980	
b	1430	
a	1500	
f	1830	
e	2190	
Stabilization case	For profiles A*	For profiles B†
450 ppmv	630	650
550 ppmv	870	990
650 ppmv	1030	1190
750 ppmv	1200‡	1300‡
1000 ppmv	—	1410‡

§ For comparison, emissions during the period 1860 to 1994 amounted to about 360 GtC, of which about 240 GtC were due to fossil-fuel use and 120 GtC due to deforestation and land-use change.
* As in IPCC (1994) — see Figure 1 (a) (solid curves).
† Profiles that allow emissions to follow IS92a until at least the year 2000 — see figure 1 (a) (dashed curves).
‡ Concentrations will not stabilize by 2100.

Table 1. Total anthropogenic carbon dioxide emissions accumulated from 1991 to 2100 inclusive (GtC) for the IS92 scenarios (see Table 1 in the Summary for Policymakers of IPCC Working Group II) and for stabilization at various levels of carbon dioxide concentration following the two sets of pathways shown in Figure 1 (a). The accumulated emissions leading to stabilization of carbon dioxide concentration were calculated using a mid-range carbon cycle model. Results from other models could be up to approximately 15% higher or lower than those presented here.

related emissions per thousand 1990 US dollars output, evaluated at market exchange rates, is about 0.27 tonnes in developed and transitional economy countries and about 0.41 tonnes in developing countries. Using World Bank estimates of GDP at purchasing power parity exchange rates, the average annual energy-related emissions per thousand 1990 US dollars output is about 0.26 tonnes in developed and transitional economy countries and about 0.16 tonnes in developing countries.[15]

Methane

4.13 Atmospheric methane concentrations adjust to changes in anthropogenic emissions over a period of 9 to 15 years. If the annual methane emissions were immediately reduced by about 30 Tg CH_4 (about 8% of current anthropogenic emissions), methane concentrations would remain at today's levels. If methane emissions were to remain constant at their current levels, methane concentrations (1720 ppbv in 1994) would rise to about 1820 ppbv over the next 40 years.

Nitrous oxide

4.14 Nitrous oxide has a long lifetime (about 120 years). In order for the concentration to be stabilized near current levels (312 ppbv in 1994), anthropogenic sources would need to be reduced immediately by more than 50%. If emissions of nitrous oxide were held constant at current levels, its concentration would rise to about 400 ppbv over several hundred years, which would increase its incremental radiative forcing by a factor of four over its current level.

Further points on stabilization

4.15 Stabilization of the concentrations of very long-lived gases, such as SF_6 or perfluorocarbons, can only be achieved effectively by stopping emissions.

4.16 The importance of the contribution of CO_2 to climate forcing, relative to that of the other greenhouse gases, increases with time in all of the IS92 emission scenarios (a to f). For example, in the IS92a scenario, the CO_2 contribution increases from the present 60% to about 75% by the year 2100. During the same period, methane and nitrous oxide forcings increase in absolute terms by a factor that ranges between two and three.

4.17 The combined effect of all greenhouse gases in producing radiative forcing is often expressed in terms of the equivalent concentration of carbon dioxide which would produce the same forcing. Because of the effects of the other greenhouse gases, stabilization at some level of equivalent carbon dioxide concentration implies maintaining carbon dioxide concentration at a lower level.

4.18 The stabilization of greenhouse gas concentrations does not imply that there will be no further climate change. After stabilization is achieved, global mean surface temperature would continue to rise for some centuries and sea level for many centuries.

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[15] These calculations of emissions per unit of economic activity do not include emissions from land-use changes or adjustments to reflect the informal economy.

TECHNOLOGY AND POLICY OPTIONS FOR MITIGATION

5

5.1 The IPCC Second Assessment Report (1995) examines a wide range of approaches to reduce emissions and enhance sinks of greenhouse gases. This section provides technical information on options that could be used to reduce anthropogenic emissions and enhance sinks of the principal greenhouse gases with a view to stabilizing their atmospheric concentrations; however, this analysis does not attempt to quantify potential macroeconomic consequences that may be associated with mitigation.

5.2 Significant reductions in net greenhouse gas emissions are technically possible and can be economically feasible. These reductions can be achieved by utilizing an extensive array of technologies and policy measures that accelerate technology development, diffusion and transfer in all sectors, including the energy, industry, transportation, residential/commercial and agricultural/forestry sectors.

5.3 The degree to which technical potential and cost-effectiveness are realized is dependent on initiatives to counter lack of information and overcome cultural, institutional, legal, financial and economic barriers which can hinder diffusion of technology or behavioural changes.

5.4 By the year 2100, the world's commercial energy system in effect will be replaced at least twice, offering opportunities to change the energy system without premature retirement of capital stock; significant amounts of capital stock in the industrial, commercial, residential and agricultural/forestry sectors will also be replaced. These cycles of capital replacement provide opportunities to utilize new, better performing technologies.

Energy demand

5.5 The IPCC projects (IPCC 1992; IPCC 1994) that without policy intervention, there could be significant growth in emissions from the industrial, transportation and commercial/residential buildings sectors. Numerous studies have indicated that 10-30% energy efficiency gains above present levels are feasible at negative[16] to zero cost in each of the sectors in many parts of the world through technical conservation measures and improved management practices over the next two to three decades. Using technologies that presently yield the highest output of energy services for a given input of energy, efficiency gains of 50–60% would be technically feasible in many countries over the same time period. Achieving these potentials will depend on future cost reductions, the rate of development and implementation of new technologies, financing and technology transfer, as well as measures to overcome a variety of non-technical barriers. Because energy use is growing worldwide, even replacing current technology with more-efficient technology could still lead to an absolute increase in greenhouse gas emissions in the future. Technologies and measures to reduce greenhouse gas emissions in energy end-use sectors include:

- *Industry*: improving efficiency; recycling materials and switching to those with lower greenhouse gas emissions; and developing processes that use less energy and materials.
- *Transportation*: the use of very efficient vehicle drive-trains, lightweight construction and low-air-resistance design; the use of smaller vehicles; altered land-use patterns, transport systems, mobility patterns and lifestyles; and shifting to less energy-intensive transport modes; and the use of alternative fuels and electricity from renewable and other fuel sources which do not enhance atmospheric greenhouse gas concentrations.
- *Commercial/residential*: reduced heat transfers through building structures and more-efficient space-conditioning and water supply systems, lighting and appliances.

Energy supply

5.6 It is technically possible to realize deep emissions reductions in the energy supply sector within 50 to 100 years using alternative strategies, in step with the normal timing of investments to replace infrastructure and equipment as it wears out or becomes obsolete. Promising approaches, not ordered according to priority, include:

(*a*) Greenhouse gas reductions in the use of fossil fuels
  - More-efficient conversion of fossil fuels (e.g., combined heat and power production and more-efficient generation of electricity);
  - Switching to low-carbon fossil fuels and suppressing emissions (switching from coal to oil or natural gas, and from oil to natural gas);
  - Decarbonization of flue gases and fuels and carbon dioxide storage (e.g., removal and storage of CO_2 from the use of fossil fuel feedstocks to make hydrogen-rich fuels);
  - Reducing fugitive emissions, especially of methane, in fuel extraction and distribution.

(*b*) Switching to non-fossil fuel sources of energy
  - Switching to nuclear energy (if generally acceptable responses can be found to concerns such as about reactor safety, radioactive-waste transport and disposal, and nuclear proliferation);
  - Switching to renewable sources of energy (e.g., solar, biomass, wind, hydro and geothermal).

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[16] Negative cost means an economic benefit.

Integration of energy system mitigation options

5.7 The potential for greenhouse gas emission reductions exceeds the potential for energy use efficiency because of the possibility of switching fuels and energy sources, and reducing the demand for energy services. Even greater energy efficiency, and hence reduced greenhouse gas emissions, could be attained with comprehensive energy source-to-service chains.

5.8 To assess the potential impact of combinations of individual measures at the energy systems level, "thought experiments" exploring variants of a low-CO_2 emitting energy supply system were described. These variants illustrate the *technical* possibility of deep reductions in CO_2 emissions from the energy supply system within 50 to 100 years using alternative strategies. These exercises indicate the *technical* possibility of reducing annual global emissions from 6 GtC in 1990 to about 4 GtC in 2050 and to about 2 GtC by 2100. Cumulative CO_2 emissions from 1990 to 2100 would range from about 450 GtC to about 470 GtC in these constructions, thus keeping atmospheric concentrations below 500 ppmv.

5.9 Costs for integrated energy services relative to costs for conventional energy depend on relative future energy prices, which are uncertain within a wide range, and on the performance and cost characteristics assumed for alternative technologies. However, within the wide range of future energy prices, one or more of the variants would plausibly be capable of providing the demanded energy services at estimated costs that are approximately the same as estimated future costs for current conventional energy. It is not possible to identify a least-cost future energy system for the longer term, as the relative costs of options depend on resource constraints and technological opportunities that are imperfectly known, and on actions by governments and the private sector. Improving energy efficiency, a strong and sustained investment in research, and development and demonstration to encourage transfer and diffusion of alternative energy supply technologies are critical to deep reductions in greenhouse gas emissions. Many of the technologies being developed would need initial support to enter the market and to reach sufficient volume to lower costs to become competitive.

5.10 Market penetration and continued acceptability of different energy technologies ultimately depend on their relative cost, performance (including environmental performance), institutional arrangements, and regulations and policies. Because costs vary by location and application, the wide variety of circumstances creates initial opportunities for new technologies to enter the market. Deeper understanding of the opportunities for emissions reductions would require more detailed analysis of options, taking into account local conditions.

Industrial process and human settlement emissions

5.11 Large reductions are possible in some cases in process-related greenhouse gases including CO_2, CH_4, N_2O, halocarbons and SF_6, released during manufacturing and industrial processes, such as production of iron, steel, aluminum, ammonia, cement and other materials. Measures include modifying production processes, eliminating solvents, replacing feedstocks, materials substitution, increased recycling and reduced consumption of greenhouse gas-intensive materials. Capturing and utilizing methane from landfills and sewage treatment facilities, and lowering the leakage rate of halocarbon refrigerants from mobile and stationary sources, also can lead to significant greenhouse gas emission reductions.

Agriculture, rangelands and forestry

5.12 Beyond the use of biomass fuels to displace fossil fuels, the management of forests, agricultural lands and rangelands can play an important role in reducing current emissions of carbon dioxide, methane and nitrous oxide, and enhancing carbon sinks. A number of measures could conserve and sequester substantial amounts of carbon (approximately 60-90 GtC in the forestry sector alone) over the next 50 years. In the forestry sector, measures include sustaining existing forest cover; slowing deforestation; natural forest regeneration; establishment of tree plantations; promoting agroforestry. Other practices in the agriculture sector could reduce emissions of other greenhouse gases such as methane and nitrous oxide. In the forestry sector, costs for conserving and sequestering carbon in biomass and soil are estimated to range widely but can be competitive with other mitigation options.

Policy instruments

5.13 The availability of low carbon technologies is a prerequisite for, but not a guarantee of, the ability to reduce greenhouse gas emissions at reasonable cost. Mitigation of emissions depends on reducing barriers to the diffusion and transfer of technology, mobilizing financial resources, supporting capacity building in developing countries and countries with economies in transition, and other approaches to assist in the implementation of behavioural changes and technological opportunities in all regions of the globe. The optimum mix of policies will vary from country to country, depending upon energy markets, economic considerations, political structure and societal receptiveness. The leadership of national governments in applying these policies will contribute to responding to the adverse consequences of climate change. Policies to reduce net greenhouse gas emissions appear more easily implemented when they are designed to also address other concerns that impede sustainable development (e.g., air pollution, soil erosion). A number of policies, many of which might be used by individual nations unilaterally, and some of which may be used by groups of countries and would require regional or international agreement, can facilitate the penetration of less greenhouse gas-intensive technologies and modified consumption patterns. These include, *inter alia* (not ordered according to priority):

- Putting in place appropriate institutional and structural frameworks;

- Energy pricing strategies — for example, carbon or energy taxes and reduced energy subsidies;
- Phasing out those existing distortionary policies which increase greenhouse gas emissions, such as some subsidies and regulations, non-internalization of environmental costs, and distortions in agriculture and transport pricing;
- Tradable emissions permits;
- Voluntary programmes and negotiated agreements with industry;
- Utility demand-side management programmes;
- Regulatory programmes including minimum energy-efficiency standards, such as for appliances and fuel economy;
- Stimulating research, development and demonstration to make new technologies available;
- Market pull and demonstration programmes that stimulate the development and application of advanced technologies;
- Renewable energy incentives during market build-up;
- Incentives such as provisions for accelerated depreciation and reduced costs for consumers;
- Education and training; information and advisory measures;
- Options that also support other economic and environmental goals.

5.14 The choice of measures at the domestic level may reflect objectives other than cost-effectiveness such as meeting fiscal targets. If a carbon or carbon-energy tax is used as a policy instrument for reducing emissions, the taxes could raise substantial revenues and how the revenues are distributed could dramatically affect the cost of mitigation. If the revenues are distributed by reducing distortionary taxes in the existing system, they will help reduce the excess burden of the existing tax system, potentially yielding an additional economic benefit (double dividend). For example, those of the European studies which are more optimistic regarding the potential for tax recycling, show lower and, in some instances, slightly negative costs. Conversely, inefficient recycling of the tax revenues could increase costs. For example, if the tax revenues are used to finance government programmes that yield a lower return than the private sector investments foregone because of the tax, then overall costs will increase. The choice of instruments may also reflect other environmental objectives such as reducing non-greenhouse pollution emissions or increasing forest cover or other concerns such as specific impacts on particular regions or communities.

EQUITY AND SOCIAL CONSIDERATIONS

6

6.1 Equity considerations are an important aspect of climate change policy and of the Convention and in achieving sustainable development[17]. Equity involves procedural as well as consequential issues. Procedural issues relate to how decisions are made while consequential issues relate to outcomes. To be effective and to promote cooperation, agreements must be regarded as legitimate, and equity is an important element in gaining legitimacy.

6.2 Procedural equity encompasses process and participation issues. It requires that all Parties be able to participate effectively in international negotiations related to climate change. Appropriate measures to enable developing country Parties to participate effectively in negotiations increase the prospects for achieving effective, lasting and equitable agreements on how best to address the threat of climate change. Concern about equity and social impacts points the need to build endogenous capabilities and strengthen institutional capacities, particularly in developing countries, to make and implement collective decisions in a legitimate and equitable manner.

6.3 Consequential equity has two components: the distribution of the costs of damages or adaptation and of measures to mitigate climate change. Because countries differ substantially in vulnerability, wealth, capacity, resource endowments and other factors listed below, unless addressed explicitly, the costs of the damages, adaptation and mitigation may be borne inequitably.

6.4 Climate change is likely to impose costs on future generations and on regions where damages occur, including regions with low greenhouse gas emissions. Climate change impacts will be distributed unevenly.

6.5 The intertemporal aspects of climate change policy also raise questions of intergenerational equity because future generations are not able to influence directly the policies being chosen today that could affect their well-being, and because it might not be possible to compensate future generations for consequent reductions in their well-being. Discounting is the principal analytical tool economists use to compare economic effects that occur at different points in time. The choice of discount rate is of crucial technical importance for analyses of climate change policy, because the time horizon is extremely long and mitigation costs tend to come much earlier than the benefits of avoided damages. The higher the discount rate, the less future benefits and the more current costs matter in the analysis.

6.6 The Convention recognizes in Article 3.1 the principle of common but differentiated responsibilities and respective

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[17] In common language equity means “the quality of being impartial” or “something that is fair and just”.

capabilities. Actions beyond "no regrets[18]" measures impose costs on the present generation. Mitigation policies unavoidably raise issues about how to share the costs. The initial emission limitation intentions of Annex I Parties represent an agreed collective first step of those parties in addressing climate change.

6.7 Equity arguments can support a variety of proposals to distribute mitigation costs. Most of them seem to cluster around or combine approaches: equal per capita emission allocations and allocations based on incremental departures from national baseline emissions (current or projected). The implications of climate change for developing countries are different from those for developed countries. The former often have different urgent priorities, weaker institutions and are generally more vulnerable to climate change. However, it is likely that developing countries' share of emissions will grow further to meet their social and developmental needs. Greenhouse gas emissions are likely to become increasingly global, even whilst substantial per-capita disparities are likely to remain.

6.8 There are substantial variations both among developed and developing countries that are relevant to the application of equity principles to mitigation. These include variations in historical and cumulative emissions, current total and per-capita emissions, emission intensities and economic output, projections of future emissions and factors such as wealth, energy structures and resource endowments.

6.9 A variety of ethical principles, including the importance of meeting people's basic needs, may be relevant to addressing climate change, but the application of principles developed to guide individual behaviour to relations among states is complex and not straightforward. Climate change policies should not aggravate existing disparities between one region and another nor attempt to redress all equity issues.

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[18] "No regrets" measures are those whose benefits, such as reduced energy costs and reduced emissions of local/regional pollutants equal or exceed their cost to society, *excluding* the benefits of climate change mitigation. They are sometimes knows as "measures worth doing anyway".

ECONOMIC DEVELOPMENT TO PROCEED IN A SUSTAINABLE MANNER

7

7.1 Economic development, social development and environmental protection are interdependent and mutually reinforcing components of sustainable development, which is the framework for our efforts to achieve a higher quality of life for all people. The UNFCCC notes that responses to climate change should be coordinated with social and economic development in an integrated manner with a view to avoiding adverse impacts on the latter, taking into full account the legitimate priority needs of developing countries for the achievement of sustainable development and the eradication of poverty. The Convention also notes the common but differentiated responsibilities and respective capabilities of all Parties to protect the climate system. This section reviews briefly what is known about the costs and benefits of mitigation and adaptation measures as they relate, *inter alia*, to the sustainability of economic development and environment.

Social costs of climate change

7.2 Net climate change damages include both market and non-market impacts as far as they can be quantified at present and, in some cases, adaptation costs. Damages are expressed in net terms to account for the fact that there are some beneficial impacts of climate change as well, which are, however, dominated by the damage costs. Non-market impacts, such as human health, risk of human mortality and damage to ecosystems, form an important component of available estimates of the social costs of climate change. The estimates of non-market damages, however, are highly speculative and not comprehensive and are thus a source of major uncertainty in assessing the implications of global climate change for human welfare.

7.3 The assessed literature quantifying total damages from 2 to 3°C warming provides a wide range of point estimates for damages given the presumed change in atmospheric greenhouse gas concentrations. The aggregate estimates tend to be a few per cent of world GDP, with, in general, considerably higher estimates of damage to developing countries as a share of their GDP. The aggregate estimates are subject to considerable uncertainty, but the range of uncertainty cannot be gauged from the literature. The range of estimates cannot be interpreted as a confidence interval given the widely differing assumptions and methodologies in the studies. Aggregation is likely to mask even greater uncertainties about damage components. Regional or sectoral approaches to estimating the consequences of climate change include a much wider range of estimates of the net economic effects. For some areas, damages are estimated to be significantly greater and could negatively affect economic development. For others, climate change is estimated to increase economic production and present opportunities for economic development. Equalizing the value of a statistical life at the level typical of that in developed countries would increase monetized damages several times, and would further increase the share of the developing countries in the total damage estimate. Small islands and low-lying coastal areas are particularly vulnerable. Damages from possible large-scale catastrophes, such as major changes in ocean circulation, are not reflected in these estimates.

Benefits of limiting climate change

7.4 The benefits of limiting greenhouse gas emissions and enhancing sinks are: (*a*) the climate change damages and adaptation costs avoided; and (*b*) the indirect economic and environmental benefits associated with the relevant policies — such as reductions in other pollutants jointly produced with greenhouse gases, biological diversity conserved and technological innovation driven by climate change response.

Adaptation costs

7.5 Many options are available for adapting to the impacts of climate change and thus reducing the damages to national economies and natural ecosystems. Adaptive options are available in many sectors, ranging from agriculture and energy to health, coastal zone management, off-shore fisheries and recreation. Some of these provide enhanced ability to cope with the current impacts of climate variability. Systematic estimates of the costs of adaptation to cope with impacts on agriculture, human health, water supplies and other changes are not available. Where adaptation measures are technically feasible, costs of adaptation, for example to sea-level rise, could be prohibitively expensive for some countries without external assistance.

Mitigation costs and benefits

7.6 The costs of stabilizing atmospheric concentrations of greenhouse gases at levels and within a time-frame which will prevent dangerous anthropogenic interference with the climate system will be critically dependent on the choice of emissions time path, consumption patterns, resource and technology availability and the choice of policy instruments. The cost of the abatement programme will be influenced by the rate of capital replacement, the discount rate and the effect of research and development. Failure to adopt policies as early as possible to encourage efficient replacement investments at the end of the economic life of plant and equipment (i.e., at the point of capital stock turnover) impose an economic cost to society. Implementing emissions reductions at rates that can be absorbed in the course of normal stock turnover is likely to be cheaper than enforcing premature retirement now. The choice of abatement paths thus involves balancing the economic risks of rapid abatement now against the risks of delay. Mitigation measures undertaken in a way that capitalize on other environmental benefits could be cost-effective and enhance sustainable development. Movement of polluting activities which lead to an increase in global greenhouse gas emissions can be lessened through coordinated actions of groups of countries.

7.7 While very few studies of the costs to stabilize atmospheric concentrations of greenhouse gases have been published, some estimates of the costs of various degrees of emissions reductions are available in the literature. Mitigation cost estimates vary widely, depending upon choice of methodologies, underlying assumptions, emission scenarios, policy instruments, reporting year, etc.

7.8 Despite significant differences in views, there is agreement that energy efficiency gains of perhaps 10-30% above baseline trends over the next two to three decades can be realized at negative to zero net cost. With longer time horizons, which allow a more complete turnover of capital stocks and which give research, development and demonstration, and market transformation policies a chance to impact multiple replacement cycles, this potential is much higher. The magnitude of such "no regrets" potential depends upon the existence of substantial market or institutional imperfections that prevent cost-effective emission reduction measures from occurring. The key question is then the extent to which such imperfections and barriers can be removed cost-effectively by policy initiatives.

7.9 **OECD countries**: Although it is difficult to generalize, top-down[19] analyses suggest that the costs of substantial reductions below 1990 CO_2 emissions levels could be as high as several per cent of GDP. In the specific case of stabilizing emissions at 1990 levels, most studies estimate that annual costs in the range of minus 0.5 per cent of GDP (equivalent to a gain of about $60 billion in total for OECD countries at today's GDP levels) to plus 2 per cent of GDP (equivalent to a loss of about $240 billion) could be reached over the next several decades. However, studies also show that appropriate timing of abatement measures and the availability of low-cost alternatives may substantially reduce the size of the overall bill. Some bottom-up studies show that the costs of reducing emissions by 20% in developed countries within two to three decades are negligible to negative. Other bottom-up studies suggest that there exists a potential for absolute reductions in excess of 50% in the longer term, without increasing and perhaps even reducing total energy system costs.

7.10 **Countries with economies in transition**: The potential for cost-effective reductions in energy use is apt to be considerable but the realizable potential will depend upon what economic and technological development path is chosen, as well as the availability of capital to pursue different paths. A critical issue is the future of structural changes in these countries that are apt to change dramatically the level of baseline emissions and the emission reduction costs.

7.11 **Developing countries**: Analyses suggest that there may be substantial low-cost fossil fuel carbon dioxide emission reduction opportunities for developing countries. Development pathways that increase energy efficiency, promote alternative energy technologies, reduce deforestation and enhance agricultural productivity and biomass energy production can be economically beneficial. To embark upon this pathway may require significant international cooperation and financial and technology transfer. However, these are likely to be insufficient to offset rapidly increasing emissions baselines, associated with increased economic growth and overall welfare. Stabilization of carbon dioxide emissions is likely to be costly.

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[19] See Box 1 in the Summary for Policymakers of IPCC Working Group III for a discussion of top-down and bottom-up models.

7.12 Cost estimates for a number of specific approaches to mitigating emissions or enhancing sinks of greenhouse gases vary widely and depend on site-specific characteristics. This is true for renewable energy technologies, for example, as well as carbon sequestration options. The latter could offset as much as 15-30% of 1990 global energy-related emissions each year in forests for the next 50 years. The costs of carbon sequestration, which are competitive with source control options, differ among regions of the world.

7.13 Control of emissions of other greenhouse gases, especially methane and nitrous oxide, can provide significant cost-effective opportunities in some countries. About 10% of anthropogenic methane emissions could be reduced at negative or low cost using available mitigation options for such methane sources as natural gas systems, waste management and agriculture. Costs differ between countries and regions for some of these options.

Subsidies, market imperfections and barriers

7.14 The world economy and indeed some individual national economies suffer from a number of price distortions which increase greenhouse gas emissions, such as some agricultural and fuel subsidies and distortions in transport pricing. A number of studies of this issue indicate that global emissions reductions of 4-18 % together with increases in real incomes are possible from phasing out fuel subsidies.

7.15 Progress has been made in a number of countries in cost-effectively reducing imperfections and institutional barriers in markets through policy instruments based on voluntary agreements, energy efficiency incentives, product efficiency standards and energy efficiency procurement programmes involving manufacturers and utility regulatory reforms. Where empirical evaluations have been made, many have found that the benefit-cost ratio of increasing energy efficiency was favourable, suggesting the practical feasibility of realizing “no regrets” potentials at negative net cost.

Value of better information and research

7.16 The value of better information about the processes, impacts of and responses to climate change is likely to be great. Analysis of economic and social issues related to climate change, especially in developing countries, is a high priority for research. Further analysis is required concerning effects of response options on employment, inflation, trade, competitiveness and other public issues.

THE ROAD FORWARD

8

8.1 The scientific, technical, economic and social science literature does suggest ways to move forward towards the ultimate objective of the Convention. Possible actions include mitigation of climate change through reductions of emissions of greenhouse gases and enhancement of their removal by sinks, adaptation to observed and/or anticipated climate change, and research, development and demonstration to improve our knowledge of the risks of climate change and possible responses.

8.2 Uncertainties remain which are relevant to judgement of what constitutes dangerous anthropogenic interference with the climate system and what needs to be done to prevent such interference. The literature indicates, however, that significant “no regrets” opportunities are available in most countries and that the risk of aggregate net damage due to climate change, consideration of risk aversion and the precautionary approach, provide rationales for actions beyond “no regrets”. The challenge is not to find the best policy today for the next 100 years, but to select a prudent strategy and to adjust it over time in the light of new information.

8.3 The literature suggests that flexible, cost-effective policies relying on economic incentives and instruments as well as coordinated instruments, can considerably reduce mitigation or adaptation costs, or can increase the cost-effectiveness of emission reduction measures. Appropriate long-run signals are required to allow producers and consumers to adapt cost-effectively to constraints on greenhouse gas emissions and to encourage investment, research, development and demonstration.

8.4 Many of the policies and decisions to reduce emissions of greenhouse gases and enhance their sinks, and eventually stabilize their atmospheric concentration, would provide opportunities and challenges for the private and public sectors. A carefully selected portfolio of national and international responses of actions aimed at mitigation, adaptation and improvement of knowledge can reduce the risks posed by climate change to ecosystems, food security, water resources, human health and other natural and socio-economic systems. There are large differences in the cost of reducing greenhouse gas emissions, and enhancing sinks, among countries due to their state of economic development, infrastructure choices and natural resource base. International cooperation in a framework of bilateral, regional or international agreements could significantly reduce the global costs of reducing emissions and lessening emission leakages. If carried out with care, these responses would help to meet the challenge of climate change and enhance the prospects for sustainable economic development for all peoples and nations.

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SUMMARY FOR POLICYMAKERS:

THE SCIENCE OF CLIMATE CHANGE

IPCC WORKING GROUP I

SUMMARY FOR POLICYMAKERS: THE SCIENCE OF CLIMATE CHANGE

Considerable progress has been made in the understanding of climate change[1] science since 1990 and new data and analyses have become available.

1. GREENHOUSE GAS CONCENTRATIONS HAVE CONTINUED TO INCREASE

Increases in greenhouse gas concentrations since pre-industrial times (i.e., since about 1750) have led to a positive *radiative forcing*[2] of climate, tending to warm the surface and to produce other changes of climate.

- The atmospheric concentrations of greenhouse gases, *inter alia*, carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) have grown significantly: by about 30%, 145%, and 15%, respectively (values for 1992). These trends can be attributed largely to human activities, mostly fossil-fuel use, land-use change and agriculture.
- The growth rates of CO_2, CH_4 and N_2O concentrations were low during the early 1990s. While this apparently natural variation is not yet fully explained, recent data indicate that the growth rates are currently comparable to those averaged over the 1980s.
- The direct radiative forcing of the long-lived greenhouse gases (2.45 Wm^{-2}) is due primarily to increases in the concentrations of CO_2 (1.56 Wm^{-2}), CH_4 (0.47 Wm^{-2}) and N_2O (0.14 Wm^{-2}) (values for 1992).
- Many greenhouse gases remain in the atmosphere for a long time (for CO_2 and N_2O, many decades to centuries), hence they affect radiative forcing on long time-scales.
- The direct radiative forcing due to the CFCs and HCFCs combined is 0.25 Wm^{-2}. However, their *net* radiative forcing is reduced by about 0.1 Wm^{-2} because they have caused stratospheric ozone depletion which gives rise to a negative radiative forcing.
- Growth in the concentration of CFCs, but not HCFCs, has slowed to about zero. The concentrations of both CFCs and HCFCs, and their consequent ozone depletion, are expected to decrease substantially by 2050 through implementation of the Montreal Protocol and its Adjustments and Amendments.
- At present, some long-lived greenhouse gases (particularly HFCs (a CFC substitute), PFCs and SF_6) contribute little to radiative forcing but their projected growth could contribute several per cent to radiative forcing during the 21st century.
- If carbon dioxide emissions were maintained at near current (1994) levels, they would lead to a nearly constant rate of increase in atmospheric concentrations for at least two centuries, reaching about 500 ppmv (approaching twice the pre-industrial concentration of 280 ppmv) by the end of the 21st century.
- A range of carbon cycle models indicates that stabilization of atmospheric CO_2 concentrations at 450, 650 or 1000 ppmv could be achieved only if global anthropogenic CO_2 emissions drop to 1990 levels by, respectively, approximately 40, 140 or 240 years from now, and drop substantially below 1990 levels subsequently.
- Any eventual stabilized concentration is governed more by the accumulated anthropogenic CO_2 emissions from now until the time of stabilization than by the way those emissions change over the period. This means that, for a given stabilized concentration value, higher emissions in early decades require lower emissions later on. Among the range of stabilization cases studied, for stabilization at 450, 650 or 1000 ppmv, accumulated anthropogenic emissions over the period 1991 to 2100 are 630 GtC[3], 1030 GtC and 1410 GtC, respectively (± approximately 15% in each case). For comparison the corresponding accumulated emissions for IPCC IS92 emission scenarios range from 770 to 2190 GtC.
- Stabilization of CH_4 and N_2O concentrations at today's levels would involve reductions in anthropogenic emissions of 8% and more than 50% respectively.
- There is evidence that tropospheric ozone concentrations in the Northern Hemisphere have increased since pre-industrial times because of human activity and that this has resulted in a positive radiative forcing. This forcing is not yet well characterized, but it is estimated to be about 0.4 Wm^{-2} (15% of that from the long-lived greenhouse gases). However, the observations of the most recent decade show that the upward trend has slowed significantly or stopped.

2. ANTHROPOGENIC AEROSOLS TEND TO PRODUCE NEGATIVE RADIATIVE FORCINGS

- Tropospheric aerosols (microscopic airborne particles) resulting from combustion of fossil fuels, biomass burning and other sources have led to a negative direct forcing of about 0.5 Wm^{-2}, as a global average, and possibly also to a negative indirect forcing of a similar magnitude. While the negative forcing is focused in particular regions and subcontinental areas, it can have continental to hemispheric scale effects on climate patterns.
- Locally, the aerosol forcing can be large enough to more than offset the positive forcing due to greenhouse gases.

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[1] Climate change in IPCC Working Group I usage refers to any change in climate over time whether due to natural variability or as a result of human activity. This differs from the usage in the UN Framework Convention on Climate Change where "climate change" refers to a change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods.

[2] A simple measure of the importance of a potential climate change mechanism. Radiative forcing is the perturbation to the energy balance of the Earth-atmosphere system (in Watts per square metre [Wm^{-2}]).

[3] 1 GtC = 1 billion tonnes of carbon.

- In contrast to the long-lived greenhouse gases, anthropogenic aerosols are very short-lived in the atmosphere, hence their radiative forcing adjusts rapidly to increases or decreases in emissions.

3. CLIMATE HAS CHANGED OVER THE PAST CENTURY

At any one location, year-to-year variations in weather can be large, but analyses of meteorological and other data over large areas and over periods of decades or more have provided evidence for some important systematic changes.

- Global mean surface air temperature has increased by between about 0.3 and 0.6°C since the late 19th century; the additional data available since 1990 and the re-analyses since then have not significantly changed this range of estimated increase.
- Recent years have been among the warmest since 1860, i.e., in the period of instrumental record, despite the cooling effect of the 1991 Mt Pinatubo volcanic eruption.
- Night-time temperatures over land have generally increased more than daytime temperatures.
- Regional changes are also evident. For example, the recent warming has been greatest over the mid-latitude continents in winter and spring, with a few areas of cooling, such as the North Atlantic ocean. Precipitation has increased over land in high latitudes of the Northern Hemisphere, especially during the cold season.
- Global sea level has risen by between 10 and 25 cm over the past 100 years and much of the rise may be related to the increase in global mean temperature.
- There are inadequate data to determine whether consistent global changes in climate variability or weather extremes have occurred over the 20th century. On regional scales there is clear evidence of changes in some extremes and climate variability indicators (e.g., fewer frosts in several widespread areas; an increase in the proportion of rainfall from extreme events over the contiguous states of the USA). Some of these changes have been toward greater variability; some have been toward lower variability.
- The 1990 to mid-1995 persistent warm-phase of the *El Niño*-Southern Oscillation (which causes droughts and floods in many areas) was unusual in the context of the last 120 years.

4. THE BALANCE OF EVIDENCE SUGGESTS A DISCERNIBLE HUMAN INFLUENCE ON GLOBAL CLIMATE

Any human-induced effect on climate will be superimposed on the background "noise" of natural climate variability, which results both from internal fluctuations and from external causes such as solar variability or volcanic eruptions. Detection and attribution studies attempt to distinguish between anthropogenic and natural influences. "Detection of change" is the process of demonstrating that an observed change in climate is highly unusual in a statistical sense, but does not provide a reason for the change. "Attribution" is the process of establishing cause and effect relations, including the testing of competing hypotheses.

Since the 1990 IPCC Report, considerable progress has been made in attempts to distinguish between natural and anthropogenic influences on climate. This progress has been achieved by including effects of sulphate aerosols in addition to greenhouse gases, thus leading to more realistic estimates of human-induced radiative forcing. These have then been used in climate models to provide more complete simulations of the human-induced climate-change 'signal'. In addition, new simulations with coupled atmosphere-ocean models have provided important information about decade to century time-scale natural internal climate variability. A further major area of progress is the shift of focus from studies of global-mean changes to comparisons of modelled and observed spatial and temporal patterns of climate change.

The most important results related to the issues of detection and attribution are:

- The limited available evidence from proxy climate indicators suggests that the 20th century global mean temperature is at least as warm as any other century since at least 1400 A.D. Data prior to 1400 are too sparse to allow the reliable estimation of global mean temperature.
- Assessments of the statistical significance of the observed global mean surface air temperature trend over the last century have used a variety of new estimates of natural internal and externally-forced variability. These are derived from instrumental data, palaeodata, simple and complex climate models, and statistical models fitted to observations. Most of these studies have detected a significant change and show that the observed warming trend is unlikely to be entirely natural in origin.
- More convincing recent evidence for the attribution of a human effect on climate is emerging from pattern-based studies, in which the modelled climate response to combined forcing by greenhouse gases and anthropogenic sulphate aerosols is compared with observed geographical, seasonal and vertical patterns of atmospheric temperature change. These studies show that such pattern correspondences increase with time, as one would expect, as an anthropogenic signal increases in strength. Furthermore, the probability is very low that these correspondences could occur by chance as a result of natural internal variability only. The vertical patterns of change are also inconsistent with those expected for solar and volcanic forcing.
- Our ability to quantify the human influence on global climate is currently limited because the expected signal is still emerging from the noise of natural variability, and because there are uncertainties in key factors. These include the magnitude and patterns of long-term natural variability and the time-evolving pattern of forcing by, and response to, changes in concentrations of greenhouse gases and aerosols, and land surface changes. Nevertheless, the balance of evidence suggests that there is a discernible human influence on global climate.

5. CLIMATE IS EXPECTED TO CONTINUE TO CHANGE IN THE FUTURE

The IPCC has developed a range of scenarios, IS92a-f, of future greenhouse gas and aerosol precursor emissions based on assumptions concerning population and economic growth, land-use, technological changes, energy availability and fuel mix during the period 1990 to 2100. Through understanding of the global carbon cycle and of atmospheric chemistry, these emissions can be used to project atmospheric concentrations of greenhouse gases and aerosols and the perturbation of natural radiative forcing. Climate models can then be used to develop projections of future climate.

- The increasing realism of simulations of current and past climate by coupled atmosphere-ocean climate models has increased our confidence in their use for projection of future climate change. Important uncertainties remain, but these have been taken into account in the full range of projections of global mean temperature and sea-level change.
- For the mid-range IPCC emission scenario, IS92a, assuming the "best estimate" value of climate sensitivity[4] and including the effects of future increases in aerosol, models project an increase in global mean surface air temperature relative to 1990 of about 2°C by 2100. This estimate is approximately one-third lower than the "best estimate" in 1990. This is due primarily to lower emission scenarios (particularly for CO_2 and the CFCs), the inclusion of the cooling effect of sulphate aerosols, and improvements in the treatment of the carbon cycle. Combining the lowest IPCC emission scenario (IS92c) with a "low" value of climate sensitivity and including the effects of future changes in aerosol concentrations leads to a projected increase of about 1°C by 2100. The corresponding projection for the highest IPCC scenario (IS92e) combined with a "high" value of climate sensitivity gives a warming of about 3.5°C. In all cases the average rate of warming would probably be greater than any seen in the last 10,000 years, but the actual annual to decadal changes would include considerable natural variability. Regional temperature changes could differ substantially from the global mean value. Because of the thermal inertia of the oceans, only 50-90% of the eventual equilibrium temperature change would have been realized by 2100 and temperature would continue to increase beyond 2100, even if concentrations of greenhouse gases were stabilized by that time.
- Average sea level is expected to rise as a result of thermal expansion of the oceans and melting of glaciers and ice-sheets. For the IS92a scenario, assuming the "best estimate" values of climate sensitivity and of ice-melt sensitivity to warming, and including the effects of future changes in aerosol, models project an increase in sea level of about 50 cm from the present to 2100. This estimate is approximately 25% lower than the "best estimate" in 1990 due to the lower temperature projection, but also reflecting improvements in the climate and ice-melt models. Combining the lowest emission scenario (IS92c) with the "low" climate and ice-melt sensitivities and including aerosol effects gives a projected sea-level rise of about 15 cm from the present to 2100. The corresponding projection for the highest emission scenario (IS92e) combined with "high" climate and ice-melt sensitivities gives a sea-level rise of about 95 cm from the present to 2100. Sea level would continue to rise at a similar rate in future centuries beyond 2100, even if concentrations of greenhouse gases were stabilized by that time, and would continue to do so even beyond the time of stabilization of global mean temperature. Regional sea-level changes may differ from the global mean value owing to land movement and ocean current changes.
- Confidence is higher in the hemispheric-to-continental scale projections of coupled atmosphere-ocean climate models than in the regional projections, where confidence remains low. There is more confidence in temperature projections than hydrological changes.
- All model simulations, whether they were forced with increased concentrations of greenhouse gases and aerosols or with increased concentrations of greenhouse gases alone, show the following features: greater surface warming of the land than of the sea in winter; a maximum surface warming in high northern latitudes in winter, little surface warming over the Arctic in summer; an enhanced global mean hydrological cycle, and increased precipitation and soil moisture in high latitudes in winter. All these changes are associated with identifiable physical mechanisms.
- In addition, most simulations show a reduction in the strength of the north Atlantic thermohaline circulation and a widespread reduction in diurnal range of temperature. These features too can be explained in terms of identifiable physical mechanisms.
- The direct and indirect effects of anthropogenic aerosols have an important effect on the projections. Generally, the magnitudes of the temperature and precipitation changes are smaller when aerosol effects are represented, especially in northern mid-latitudes. Note that the cooling effect of aerosols is not a simple offset to the warming effect of greenhouse gases, but significantly affects some of the continental scale patterns of climate change, most noticeably in the summer hemisphere. For example, models that consider only the effects of greenhouse gases generally project an increase in precipitation and soil moisture in the Asian summer monsoon region, whereas models that include, in addition, some of the effects of aerosols suggest that monsoon precipitation may decrease. The spatial and temporal distribution of aerosols greatly influences regional projections, which are therefore more uncertain.
- A general warming is expected to lead to an increase in the occurrence of extremely hot days and a decrease in the occurrence of extremely cold days.
- Warmer temperatures will lead to a more vigorous hydrological cycle; this translates into prospects for more severe droughts and/or floods in some places and less severe droughts and/or floods in other places. Several models indicate an increase in precipitation intensity, suggesting a possibility for more extreme rainfall events. Knowledge is currently insufficient to say whether there will be any changes in the occurrence or geographical distribution of severe storms, e.g., tropical cyclones.
- Sustained rapid climate change could shift the competitive balance among species and even lead to forest dieback, altering the terrestrial uptake and release of carbon. The magnitude is uncertain, but could be between zero and 200 GtC over the next one to two centuries, depending on the rate of climate change.

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[4] In IPCC reports, climate sensitivity usually refers to the long-term (equilibrium) change in global mean surface temperature following a doubling of atmospheric equivalent CO_2 concentration. More generally, it refers to the equilibrium change in surface air temperature following a unit change in radiative forcing ($°C/Wm^{-2}$).

6. THERE ARE STILL MANY UNCERTAINTIES

Many factors currently limit our ability to project and detect future climate change. In particular, to reduce uncertainties further work is needed on the following priority topics:

- Estimation of future emissions and biogeochemical cycling (including sources and sinks) of greenhouse gases, aerosols and aerosol precursors and projections of future concentrations and radiative properties.
- Representation of climate processes in models, especially feedbacks associated with clouds, oceans, sea ice and vegetation, in order to improve projections of rates and regional patterns of climate change.
- Systematic collection of long-term instrumental and proxy observations of climate system variables (e.g., solar output, atmospheric energy balance components, hydrological cycles, ocean characteristics and ecosystem changes) for the purposes of model testing, assessment of temporal and regional variability, and for detection and attribution studies.

Future unexpected, large and rapid climate system changes (as have occurred in the past) are, by their nature, difficult to predict. This implies that future climate changes may also involve “surprises”. In particular, these arise from the non-linear nature of the climate system. When rapidly forced, non-linear systems are especially subject to unexpected behaviour. Progress can be made by investigating non-linear processes and sub-components of the climatic system. Examples of such non-linear behaviour include rapid circulation changes in the North Atlantic and feedbacks associated with terrestrial ecosystem changes.

SUMMARY FOR POLICYMAKERS:

SCIENTIFIC-TECHNICAL ANALYSES OF IMPACTS, ADAPTATIONS AND MITIGATION OF CLIMATE CHANGE

IPCC WORKING GROUP II

SUMMARY FOR POLICYMAKERS: SCIENTIFIC-TECHNICAL ANALYSES OF IMPACTS, ADAPTATIONS AND MITIGATION OF CLIMATE CHANGE

1. SCOPE OF THE ASSESSMENT

The charge to Working Group II of the Intergovernmental Panel on Climate Change (IPCC) was to review the state of knowledge concerning the impacts of climate change on physical and ecological systems, human health and socio-economic sectors. Working Group II also was charged with reviewing available information on the technical and economic feasibility of a range of potential adaptation and mitigation strategies. This assessment provides scientific, technical and economic information that can be used, *inter alia*, in evaluating whether the projected range of plausible impacts constitutes "dangerous anthropogenic interference with the climate system," as referred to in Article 2 of the United Nations Framework Convention on Climate Change (UNFCCC), and in evaluating adaptation and mitigation options that could be used in progressing towards the ultimate objective of the UNFCCC (see Box 1).

BOX 1. ULTIMATE OBJECTIVE OF THE UNFCCC (ARTICLE 2)

"...stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system. Such a level should be achieved within a time-frame sufficient to allow ecosystems to adapt naturally to climate change, to ensure that food production is not threatened, and to enable economic development to proceed in a sustainable manner."

2. NATURE OF THE ISSUE

Human activities are increasing the atmospheric concentrations of greenhouse gases — which tend to warm the atmosphere —and, in some regions, aerosols — which tend to cool the atmosphere. These changes in greenhouse gases and aerosols, taken together, are projected to lead to regional and global changes in climate and climate-related parameters such as temperature, precipitation, soil moisture and sea level. Based on the range of sensitivities of climate to increases in greenhouse gas concentrations reported by IPCC Working Group I and plausible ranges of emissions (IPCC IS92; see Table 1), climate models, taking into account greenhouse gases and aerosols, project an increase in global mean surface temperature of about 1–3.5°C by 2100 and an associated increase in sea level of

Table 1. Summary of assumptions in the six IPCC 1992 alternative scenarios.

Scenario	*Population*	*Economic Growth*	*Energy Supplies*
IS92a,b	World Bank 1991 11.3 billion by 2100	1990–2025: 2.9% 1990–2100: 2.3%	12,000 EJ conventional oil 13,000 EJ natural gas Solar costs fall to $0.075/kWh 191 EJ of biofuels available at $70/barrel*
IS92c	UN Medium-Low Case 6.4 billion by 2100	1990–2025: 2.0% 1990–2100: 1.2%	8,000 EJ conventional oil 7,300 EJ natural gas Nuclear costs decline by 0.4% annually
IS92d	UN Medium-Low Case 6.4 billion by 2100	1990–2025: 2.7% 1990–2100: 2.0%	Oil and gas same as IS92c Solar costs fall to $0.065/kWh 272 EJ of biofuels available at $50/barrel
IS92e	World Bank 1991 11.3 billion by 2100	1990–2025: 3.5% 1990–2100: 3.0%	18,400 EJ conventional oil Gas same as IS92a,b Phase out nuclear by 2075
IS92f	UN Medium-High Case 17.6 billion by 2100	1990–2025: 2.9% 1990–2100: 2.3%	Oil and gas same as IS92e Solar costs fall to $0.083/kWh Nuclear costs increase to $0.09/kWh

*Approximate conversion factor: 1 barrel = 6 GJ.

Source: IPCC, 1992: *Climate Change 1992: The Supplementary Report to the IPCC Scientific Assessment.* Section A3, prepared by IPCC Working Group I [J.T. Houghton, B.A. Callander and S.K. Varney (eds.)] and WMO/UNEP. Cambridge University Press, Cambridge, UK, 200 pp.

about 15–95 cm. The reliability of regional-scale predictions is still low and the degree to which climate variability may change is uncertain. However, potentially serious changes have been identified, including an increase in some regions in the incidence of extreme high-temperature events, floods and droughts, with resultant consequences for fires, pest outbreaks, and ecosystem composition, structure and functioning, including primary productivity.

Human health, terrestrial and aquatic ecological systems, and socio-economic systems (e.g., agriculture, forestry, fisheries and water resources) are all vital to human development and well-being and are all sensitive to changes in climate. Whereas many regions are likely to experience the adverse effects of climate change — some of which are potentially irreversible — some effects of climate change are likely to be beneficial. Hence, different segments of society can expect to confront a variety of changes and the need to adapt to them.

Policymakers are faced with responding to the risks posed by anthropogenic emissions of greenhouse gases in the face of significant scientific uncertainties. It is appropriate to consider these uncertainties in the context of information indicating that climate-induced environmental changes cannot be reversed quickly, if at all, due to the long time-scales associated with the climate system (see Box 2). Decisions taken during the next few years may limit the range of possible policy options in the future because high near-term emissions would require deeper reductions in the future to meet any given target concentration. Delaying action might reduce the overall costs of mitigation because of potential technological advances but could increase both the rate and the eventual magnitude of climate change, hence the adaptation and damage costs. Policymakers will have to decide to what degree they want to take precautionary measures by mitigating greenhouse gas emissions and enhancing the resilience of vulnerable systems by means of adaptation. Uncertainty does not mean that a nation or the world community cannot position itself better to cope with the broad range of possible climate changes or protect against potentially costly future outcomes. Delaying such measures may leave a nation or the world poorly prepared to deal with adverse changes and may increase the possibility of irreversible or very costly consequences. Options for adapting to change or mitigating change that can be justified for other reasons today (e.g., abatement of air and water pollution) and make society more flexible or resilient to anticipated adverse effects of climate change appear particularly desirable.

3. VULNERABILITY TO CLIMATE CHANGE

Article 2 of the UNFCCC explicitly acknowledges the importance of natural ecosystems, food production and sustainable economic development. This report addresses the potential *sensitivity*, *adaptability* and *vulnerability* of ecological and socio-economic systems — including hydrology and water resources management, human infrastructure and human health — to changes in climate (see Box 3).

Human-induced climate change adds an important new stress. Human-induced climate change represents an important additional stress, particularly to the many ecological and socio-economic systems already affected by pollution, increasing resource demands and nonsustainable management practices. The most vulnerable systems are those with the greatest sensitivity to climate changes and the least adaptability.

BOX 2. TIME-SCALES OF PROCESSES INFLUENCING THE CLIMATE SYSTEM

- Turnover of the capital stock responsible for emissions of greenhouse gases: Years to decades

  (without premature retirement)

- Stabilization of atmospheric concentrations of long-lived greenhouse gases given a stable level of greenhouse gas emissions: Decades to millennia
- Equilibration of the climate system given a stable level of greenhouse gas concentrations: Decades to centuries
- Equilibration of sea level given a stable climate: Centuries
- Restoration/rehabilitation of damaged or disturbed ecological systems: Decades to centuries

  (some changes, such as species extinction, are irreversible, and it may be impossible to reconstruct and re-establish some disturbed ecosystems)

BOX 3. SENSITIVITY, ADAPTABILITY AND VULNERABILITY

Sensitivity is the degree to which a system will respond to a change in climatic conditions (e.g., the extent of change in ecosystem composition, structure and functioning, including primary productivity, resulting from a given change in temperature or precipitation).

Adaptability refers to the degree to which adjustments are possible in practices, processes or structures of systems to projected or actual changes of climate. Adaptation can be spontaneous or planned, and can be carried out in response to or in anticipation of changes in conditions.

Vulnerability defines the extent to which climate change may damage or harm a system. It depends not only on a system's sensitivity but also on its ability to adapt to new climatic conditions.

Both the magnitude and the rate of climate change are important in determining the sensitivity, adaptability and vulnerability of a system.

Most systems are sensitive to climate change. Natural ecological systems, socio-economic systems and human health are all sensitive to both the magnitude and the rate of climate change.

Impacts are difficult to quantify and existing studies are limited in scope. Although our knowledge has increased significantly during the last decade, and qualitative estimates can be developed, quantitative projections of the impacts of climate change on any particular system at any particular location are difficult because regional-scale climate change predictions are uncertain; our current understanding of many critical processes is limited; and systems are subject to multiple climatic and non-climatic stresses, the interactions of which are not always linear or additive. Most impact studies have assessed how systems would respond to climate change resulting from an arbitrary doubling of equivalent atmospheric carbon dioxide (CO_2) concentrations. Furthermore, very few studies have considered dynamic responses to steadily increasing concentrations of greenhouse gases; fewer still have examined the consequences of increases beyond a doubling of equivalent atmospheric CO_2 concentrations or assessed the implications of multiple stress factors.

Successful adaptation depends upon technological advances, institutional arrangements, availability of financing and information exchange. Technological advances generally have increased adaptation options for managed systems such as agriculture and water supply. However, many regions of the world currently have limited access to these technologies and appropriate information. The efficacy and cost-effective use of adaptation strategies will depend upon the availability of financial resources, technology transfer, and cultural, educational, managerial, institutional, legal and regulatory practices, both domestic and international in scope. Incorporating climate-change concerns into resource-use and development decisions and plans for regularly scheduled investments in infrastructure will facilitate adaptation.

Vulnerability increases as adaptive capacity decreases. The vulnerability of human health and socio-economic systems —and, to a lesser extent, ecological systems — depends upon economic circumstances and institutional infrastructure. This implies that systems typically are more vulnerable in developing countries where economic and institutional circumstances are less favourable. People who live on arid or semi-arid lands, in low-lying coastal areas, in water-limited or flood-prone areas, or on small islands are particularly vulnerable to climate change. Some regions have become more vulnerable to hazards such as storms, floods and droughts as a result of increasing population density in sensitive areas such as river basins and coastal plains. Human activities, which fragment many landscapes, have increased the vulnerability of lightly managed and unmanaged ecosystems. Fragmentation limits natural adaptation potential and the potential effectiveness of measures to assist adaptation in these systems, such as the provision of migration corridors. A changing climate's near-term effects on ecological and socio-economic systems most likely will result from changes in the intensity and seasonal and geographic distribution of common weather hazards such as storms, floods and droughts. In most of these examples, vulnerability can be reduced by strengthening adaptive capacity.

Detection will be difficult and unexpected changes cannot be ruled out. Unambiguous detection of climate-induced changes in most ecological and social systems will prove extremely difficult in the coming decades. This is because of the complexity of these systems, their many non-linear feedbacks, and their sensitivity to a large number of climatic and non-climatic factors, all of which are expected to continue to change simultaneously. The development of a baseline projecting future conditions without climate change is crucial, for it is this baseline against which all projected impacts are measured. As future climate extends beyond the boundaries of empirical knowledge (i.e., the documented impacts of climate variation in the past), it becomes more likely that actual outcomes will include surprises and unanticipated rapid changes.

Further research and monitoring are essential. Enhanced support for research and monitoring, including cooperative efforts from national, international and multi-lateral institutions, is essential in order to improve significantly regional-scale climate projections; understand the responses of human health, ecological and socio-economic systems to changes in climate and other stress factors; and improve our understanding of the efficacy and cost-effectiveness of adaptation strategies.

3.1 Terrestrial and aquatic ecosystems

Ecosystems contain the Earth's entire reservoir of genetic and species diversity and provide many goods and services critical to individuals and societies. These goods and services include: (i) providing food, fibre, medicines and energy; (ii) processing and storing carbon and other nutrients; (iii) assimilating wastes, purifying water, regulating water runoff, and controlling floods, soil degradation and beach erosion; and (iv) providing opportunities for recreation and tourism. These systems and the functions they provide are sensitive to the rate and extent of changes in climate. Figure 1 illustrates that mean annual temperature and mean annual precipitation can be correlated with the distribution of the world's major biomes.

The composition and geographic distribution of many ecosystems will shift as individual species respond to changes in climate; there will likely be reductions in biological diversity and in the goods and services that ecosystems provide society. Some ecological systems may not reach a new equilibrium for several centuries after the climate achieves a new balance.

Forests. Models project that a sustained increase of 1°C in global mean temperature is sufficient to cause changes in regional climates that will affect the growth and regeneration capacity of forests in many regions. In several instances this will alter the function and composition of forests significantly. As a consequence of possible changes in temperature and water availability under doubled equivalent-CO_2 equilibrium conditions, a substantial fraction (a global average of one-third, varying by region from one-seventh to two-thirds) of the existing forested area of the world will undergo major changes in broad vegetation types — with the greatest changes occurring in high latitudes and the least in the tropics.

Climate change is expected to occur at a rapid rate relative to the speed at which forest species grow, reproduce and re-establish themselves. For mid-latitude regions, a global average warming of 1–3.5°C over the next 100 years would be equivalent to a poleward shift of the present isotherms by approximately 150–550 km or an altitude shift of about 150–550 m; in low latitudes, temperatures would generally be increased to higher levels than now exist. This compares to past tree species migration rates that are believed to be on the order of 4–200 km per century. Therefore, the species composition of forests is likely to change; entire forest types may disappear, while new assemblages of species, hence new ecosystems, may be established. Figure 2 depicts potential distribution of biomes under current and a doubled equivalent-CO_2 climate. Although net primary productivity could increase, the standing biomass of forests may not because of more frequent outbreaks and extended ranges of pests and pathogens, and increasing frequency and intensity of fires. Large amounts of carbon could be released into the atmosphere during transitions from one forest type to another because the rate at which carbon can be lost during times of high forest mortality is greater than the rate at which it can be gained through growth to maturity.

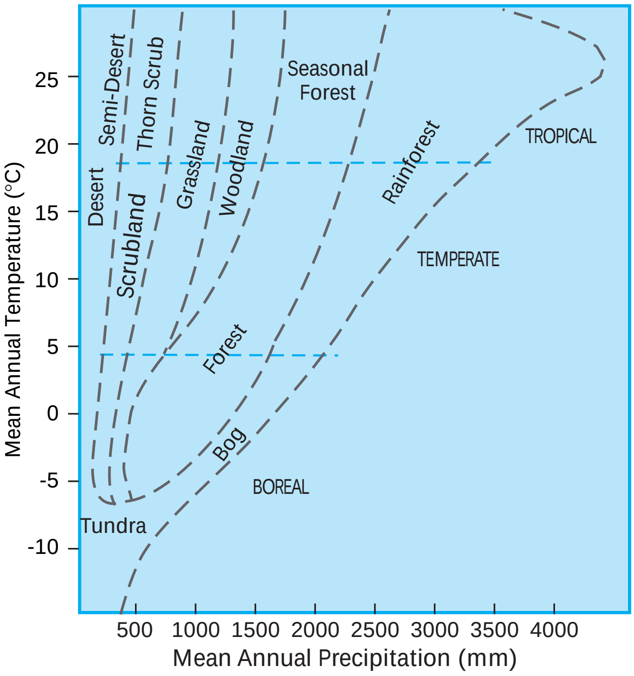


Figure 1. This figure illustrates that mean annual temperature and mean annual precipitation can be correlated with the distribution of the world's major biomes. While the role of these annual means in affecting this distribution is important, it should be noted that the distribution of biomes may also strongly depend on seasonal factors such as the length of the dry season or the lowest absolute minimum temperature, on soil properties such as water-holding capacity, on land-use history such as agriculture or grazing and on disturbance regimes such as the frequency of fire.

Rangelands. In tropical rangelands, mean temperature increases should not lead to major alterations in productivity and species composition, but altered rainfall amount and seasonality and increased evapotranspiration will. Increases in atmospheric CO_2 concentration may raise the carbon-to-nitrogen ratio of forage for herbivores, thus reducing its food value. Shifts in temperature and precipitation in temperate rangelands may result in altered growing seasons and boundary shifts between grasslands, forests and shrublands.

Deserts and desertification. Deserts are likely to become more extreme — in that, with few exceptions, they are projected to become hotter but not significantly wetter. Temperature increases could be a threat to organisms that exist near their heat-tolerance limits. The impacts on water balance, hydrology and vegetation are uncertain. Desertification, as defined by the UN Convention to Combat Desertification, is land degradation in arid, semi-arid and dry sub-humid areas resulting from various factors, including climatic variations and human activities. Desertification is more likely to become irreversible if the environment becomes drier and the soil becomes further degraded through erosion and compaction. Adaptation to drought and desertification may rely on the development of diversified production systems.

Cryosphere. Models project that between one-third and one-half of existing mountain glacier mass could disappear over the next 100 years. The reduced extent of glaciers and depth of snow cover also would affect the seasonal distribution of river flow and water supply for hydroelectric generation and agriculture. Anticipated hydrological changes and reductions in the areal extent and depth of permafrost could lead to large-scale damage to infrastructure, an additional flux of CO_2 into the atmosphere and changes in processes that contribute to the flux of methane (CH_4) into the atmosphere. Reduced sea-ice extent and thickness would increase the seasonal duration of navigation on rivers and in coastal areas that are presently affected by seasonal ice cover and may increase navigability in the Arctic Ocean. Little change in the extent of the Greenland and Antarctic ice sheets is expected over the next 50–100 years.

Mountain regions. The projected decrease in the extent of mountain glaciers, permafrost and snow cover caused by a warmer climate will affect hydrologic systems, soil stability and related socio-economic systems. The altitudinal distribution of vegetation is projected to shift to higher elevation; some species with climatic ranges limited to mountain tops could become extinct because of disappearance of habitat or reduced migration potential. Mountain resources such as food and fuel for indigenous populations may be disrupted in many developing countries. Recreational industries — of increasing economic importance to many regions — also are likely to be disrupted.

Lakes, streams and wetlands. Inland aquatic ecosystems will be influenced by climate change through altered water temperatures, flow regimes and water levels. In lakes and streams, warming would have the greatest biological effects at high latitudes, where biological productivity would increase, and at the low-latitude boundaries of cold- and cool-water species ranges, where extinctions would be

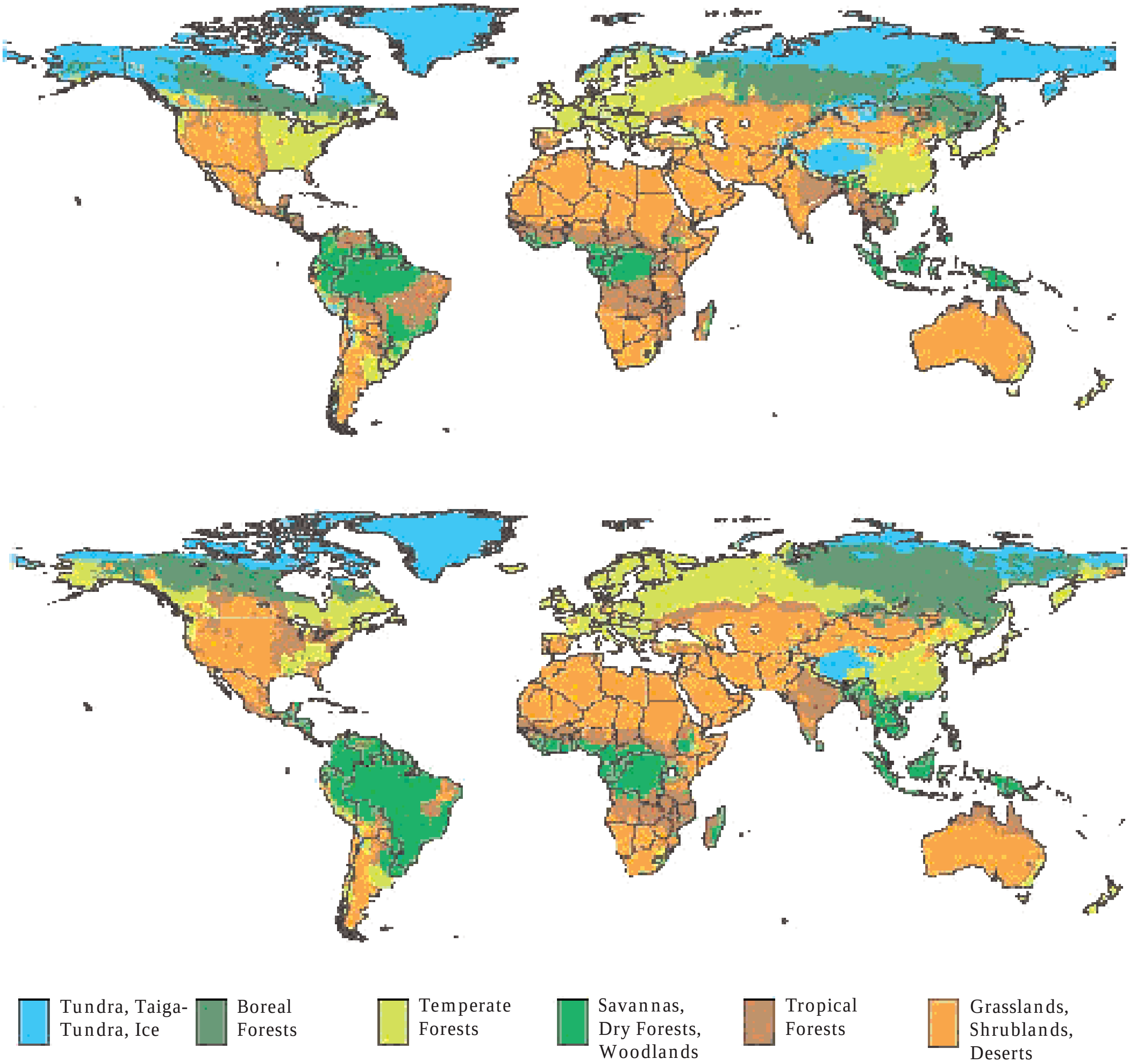


Figure 2. Potential distribution of the major world biomes under current climate conditions, simulated by Mapped Atmosphere-Plant-Soil System (MAPSS) model (top). "Potential distribution" indicates the natural vegetation that can be supported at each site, given monthly inputs of precipitation, temperature, humidity and windspeed. The lower product illustrates the projected distribution of the major world biomes by simulating the effects of 2 × CO_2-equivalent concentrations (GFDL general circulation model), including the direct physiological effects of CO_2 on vegetation. Both products are adapted from: Neilson, R.P. and D. Marks, 1994: A global perspective of regional vegetation and hydrologic sensitivities from climate change. *Journal of Vegetation Science*, 5, 715-730.

greatest. Warming of larger and deeper temperate zone lakes would increase their productivity; although in some shallow lakes and in streams, warming could increase the likelihood of anoxic conditions. Increases in flow variability, particularly the frequency and duration of large floods and droughts, would tend to reduce water quality and biological productivity and habitat in streams. Water-level declines will be most severe in lakes and streams in dry evaporative drainages and in basins with small catchments. The geographical distribution of wetlands is likely to shift with changes in temperature and precipitation. There will be an impact of climate change on greenhouse gas release from non-tidal wetlands, but there is uncertainty regarding the exact effects from site to site.

Coastal systems. Coastal systems are economically and ecologically important and are expected to vary widely in their response to changes in climate and sea level. Climate change and a rise in sea level or changes in storms or storm surges could result in the erosion of shores and associated habitat, increased salinity of estuaries and freshwater aquifers, altered tidal ranges in rivers and bays, changes in sediment and nutrient transport, a change in the pattern of chemical and microbiological contamination in coastal areas, and increased coastal flooding. Some coastal ecosystems are particularly at risk, including saltwater marshes, mangrove ecosystems, coastal wetlands, coral reefs, coral atolls and river deltas. Changes in these ecosystems would have major negative effects on tourism, freshwater supplies, fisheries and biodiversity. Such impacts would add to modifications in the functioning of coastal oceans and inland waters that already have resulted from pollution, physical modification and material inputs due to human activities.

Oceans. Climate change will lead to changes in sea level, increasing it on average, and also could lead to altered ocean circulation, vertical mixing, wave climate and reductions in sea-ice cover. As a result, nutrient availability, biological productivity, the structure and functions of marine ecosystems, and heat and carbon storage capacity may be affected, with important feedbacks to the climate system. These changes would have implications for coastal regions, fisheries, tourism and recreation, transport, off-shore structures and communication. Paleoclimatic data and model experiments suggest that abrupt climatic changes can occur if freshwater influx from the movement and melting of sea ice or ice sheets significantly weakens global thermohaline circulation.

3.2 Hydrology and water resources management

Climate change will lead to an intensification of the global hydrological cycle and can have major impacts on regional water resources. A change in the volume and distribution of water will affect both ground and surface water supply for domestic and industrial uses, irrigation, hydropower generation, navigation, instream ecosystems and water-based recreation.

Changes in the total amount of precipitation and in its frequency and intensity directly affect the magnitude and timing of runoff and the intensity of floods and droughts; however, at present, specific regional effects are uncertain. Relatively small changes in temperature and precipitation, together with the non-linear effects on evapotranspiration and soil moisture, can result in relatively large changes in runoff, especially in arid and semi-arid regions. High-latitude regions may experience increased runoff due to increased precipitation, whereas runoff may decrease at lower latitudes due to the combined effects of increased evapotranspiration and decreased precipitation. More intense rainfall would tend to increase runoff and the risk of flooding, although this would depend not only on the change in rainfall but also on catchment physical and biological characteristics. A warmer climate could decrease the proportion of precipitation falling as snow, leading to reductions in spring runoff and increases in winter runoff.

The quantity and quality of water supplies already are serious problems today in many regions, including some low-lying coastal areas, deltas and small islands, making countries in these regions particularly vulnerable to any additional reduction in indigenous water supplies. Water availability currently falls below 1,000 m^3 per person per year — a common benchmark for water scarcity — in a number of countries (e.g., Kuwait, Jordan, Israel, Rwanda, Somalia, Algeria, Kenya) or is expected to fall below this benchmark in the next two to three decades (e.g., Libya, Egypt, South Africa, Iran, Ethiopia). In addition, a number of countries in conflict-prone areas are highly dependent on water originating outside their borders (e.g., Cambodia, Syria, Sudan, Egypt, Iraq).

The impacts of climate change will depend on the baseline condition of the water supply system and the ability of water resource managers to respond not only to climate change but also to population growth and changes in demands, technology, and economic, social and legislative conditions. In some cases — particularly in wealthier countries with integrated water-management systems — improved management may protect water users from climate change at minimal cost; in many others, however, there could be substantial economic, social and environmental costs, particularly in regions that already are water-limited and where there is considerable competition among users. Experts disagree over whether water supply systems will evolve substantially enough in the future to compensate for the anticipated negative impacts of climate change on water resources and for potential increases in demand.

Options for dealing with the possible impacts of a changed climate and increased uncertainty about future supply and demand for freshwater include more efficient management of existing supplies and infrastructure; institutional arrangements to limit future demands/promote conservation; improved monitoring and forecasting systems for floods/droughts; rehabilitation of watersheds, especially in the tropics; and construction of new reservoir capacity to capture and store excess flows produced by altered patterns of snowmelt and storms.

3.3 Food and fibre

Agriculture. Crop yields and changes in productivity due to climate change will vary considerably across regions and among localities, thus changing the patterns of production. Productivity is projected to increase in some areas and decrease in others, especially the tropics and subtropics (Table 2). However, existing studies show that on the whole global agricultural production could be maintained relative to baseline production in the face of climate change modeled by general circulation models (GCMs) at doubled equivalent-CO_2 equilibrium conditions, but that regional effects would vary widely. This conclusion takes into account the beneficial effects of CO_2 fertilization, but does not allow for changes in agricultural pests and the possible effects of changing climatic variability.

Focusing on global agricultural production does not address the potentially serious consequences of large differences at local and

Table 2. Selected crop study results for 2 × CO_2-equivalent equilibrium GCM scenarios.

Region	*Crop*	*Yield Impact (%)*	*Comments*
Latin America	Maize	–61 to increase	Data are from Argentina, Brazil, Chile and Mexico; range is across GCM scenarios, with and without CO_2 effect.
	Wheat	–50 to –5	Data are from Argentina, Uruguay and Brazil; range is across GCM scenarios, with and without CO_2 effect.
	Soybean	–10 to +40	Data are from Brazil; range is across GCM scenarios, with CO_2 effect.
Former Soviet Union	Wheat	–19 to +41	Range is across GCM scenarios and region, with CO_2 effect.
	Grain	–14 to +13	
Europe	Maize	–30 to increase	Data are from France, Spain and northern Europe; with adaptation and CO_2 effect; assumes longer season, irrigation efficiency loss and northward shift.
	Wheat	increase or decrease	Data are from France, UK and northern Europe; with adaptation and CO_2 effect; assumes longer season, northward shift, increased pest damage and lower risk of crop failure.
	Vegetables	increase	Data are from UK and northern Europe; assumes increased pest damage and lower risk of crop failure.
North America	Maize	–55 to +62	Data are from USA and Canada; range is across GCM scenarios and sites, with/without adaptation and with/without CO_2 effect.
	Wheat	–100 to +234	
	Soybean	–96 to +58	Data are from USA; less severe or increase with CO_2 and adaptation.
Africa	Maize	–65 to +6	Data are from Egypt, Kenya, South Africa and Zimbabwe; range is over studies and climate scenarios, with CO_2 effect.
	Millet	–79 to –63	Data are from Senegal; carrying capacity fell 11–38%.
	Biomass	Decrease	Data are from South Africa; agrozone shifts.
South Asia	Rice	–22 to +28	Data are from Bangladesh, India, Philippines, Thailand, Indonesia, Malaysia and Myanmar; range is over GCM scenarios, with CO_2 effect; some studies also consider adaptation.
	Maize	–65 to –10	
	Wheat	–61 to +67	
China	Rice	–78 to +28	Includes rainfed and irrigated rice; range is across sites and GCM scenarios; genetic variation provides scope for adaptation.
Other Asia and Pacific Rim	Rice	–45 to +30	Data are from Japan and South Korea; range is across GCM scenarios; generally positive in north Japan and negative in south.
	Pasture	–1 to +35	Data are from Australia and New Zealand; regional variation.
	Wheat	–41 to +65	Data are from Australia and Japan; wide variation, depending on cultivar.

Note: For most regions, studies have focused on one or two principal grains. These studies strongly demonstrate the variability in estimated yield impacts among countries, scenarios, methods of analysis and crops, making it difficult to generalize results across areas or for different climate scenarios.

regional scales, even at mid-latitudes. There may be increased risk of hunger and famine in some locations; many of the world's poorest people — particularly those living in subtropical and tropical areas and dependent on isolated agricultural systems in semi-arid and arid regions — are most at risk of increased hunger. Many of these at-risk populations are found in sub-Saharan Africa; south, east and southeast Asia; and tropical areas of Latin America, as well as some Pacific island nations.

Adaptation — such as changes in crops and crop varieties, improved water-management and irrigation systems, and changes in planting schedules and tillage practices — will be important in limiting negative effects and taking advantage of beneficial changes in climate. The extent of adaptation depends on the affordability of such measures, particularly in developing countries; access to know-how and technology; the rate of climate change; and biophysical constraints such as water availability, soil characteristics and crop genetics. The incremental costs of adaptation strategies could create a serious burden for developing countries; some adaptation strategies may result in cost savings for some countries. There are significant uncertainties about the capacity of different regions to adapt successfully to projected climate change.

Livestock production may be affected by changes in grain prices and rangeland and pasture productivity. In general, analyses indicate that intensively managed livestock systems have more potential for adaptation than crop systems. This may not be the case in pastoral systems, where the rate of technology adoption is slow and changes in technology are viewed as risky.

Forest products. Global wood supplies during the next century may become increasingly inadequate to meet projected consumption due to both climatic and non-climatic factors. Boreal forests are likely to undergo irregular and large-scale losses of living trees because of the impacts of projected climate change. Such losses could initially generate additional wood supply from salvage harvests, but could severely reduce standing stocks and wood-product availability over the long term. The exact timing and extent of this pattern is uncertain. Climate and land-use impacts on the production of temperate forest products are expected to be relatively small. In tropical regions, the availability of forest products is projected to decline by about half for non-climatic reasons related to human activities.

Fisheries. Climate-change effects interact with those of pervasive overfishing, diminishing nursery areas, and extensive inshore and coastal pollution. Globally, marine fisheries production is expected to remain about the same; high-latitude freshwater and aquaculture production are likely to increase, assuming that natural climate variability and the structure and strength of ocean currents remain about the same. The principal impacts will be felt at the national and local levels as species mix and centres of production shift. The positive effects of climate change — such as longer growing seasons, lower natural winter mortality and faster growth rates in higher latitudes — may be offset by negative factors such as changes in established reproductive patterns, migration routes and ecosystem relationships.

3.4 Human infrastructure

Climate change and resulting sea-level rise can have a number of negative impacts on energy, industry and transportation infrastructure; human settlements; the property insurance industry; tourism; and cultural systems and values.

In general, the sensitivity of the energy, industry and transportation sectors is relatively low compared to that of agricultural or natural ecosystems, and the capacity for adaptation through management and normal replacement of capital is expected to be high. However, infrastructure and activities in these sectors would be susceptible to sudden changes, surprises and increased frequency or intensity of extreme events. The subsectors and activities most sensitive to climate change include agroindustry, energy demand, production of renewable energy such as hydroelectricity and biomass, construction, some transportation activities, existing flood mitigation structures, and transportation infrastructure located in many areas, including vulnerable coastal zones and permafrost regions.

Climate change clearly will increase the vulnerability of some coastal populations to flooding and erosional land loss. Estimates put about 46 million people per year currently at risk of flooding due to storm surges. This estimate results from multiplying the total number of people currently living in areas potentially affected by ocean flooding by the probability of flooding at these locations in any year, given the present protection levels and population density. In the absence of adaptation measures, a 50-cm sea-level rise would increase this number to about 92 million; a 1-m sea-level rise would raise it to 118 million. If one incorporates anticipated population growth, the estimates increase substantially. Some small island nations and other countries will confront greater vulnerability because their existing sea and coastal defense systems are less well-established. Countries with higher population densities would be more vulnerable. For these countries, sea-level rise could force internal or international migration of populations.

A number of studies have evaluated sensitivity to a 1-m sea-level rise. This increase is at the top of the range of IPCC Working Group I estimates for 2100; it should be noted, however, that sea level is actually projected to continue to rise beyond 2100. Studies using this 1-m projection show a particular risk for small islands and deltas. Estimated land losses range from 0.05% for Uruguay, 1% for Egypt, 6% for the Netherlands and 17.5% for Bangladesh to about 80% for the Majuro Atoll in the Marshall Islands, given the present state of protection systems. Large numbers of people also are affected — for example, about 70 million each in China and Bangladesh. Many nations face lost capital value in excess of 10% of their gross domestic product (GDP). Although annual protection costs for many nations are relatively modest (about 0.1% of GDP), the average annual costs to many small island states total several per cent of GDP. For some island nations, the high cost of providing storm-surge protection would make it essentially infeasible, especially given the limited availability of capital for investment.

The most vulnerable human settlements are located in damage-prone areas of the developing world that do not have the resources to cope with impacts. Effective coastal-zone management and land-use regulation can help direct population shifts away from vulnerable locations such as flood plains, steep hillsides and low-lying coastlines. One of the potentially unique and destructive effects on human settlements is forced internal or international migration of populations. Programmes of disaster assistance can offset some of the more serious negative consequences of climate change and reduce the number of ecological refugees.

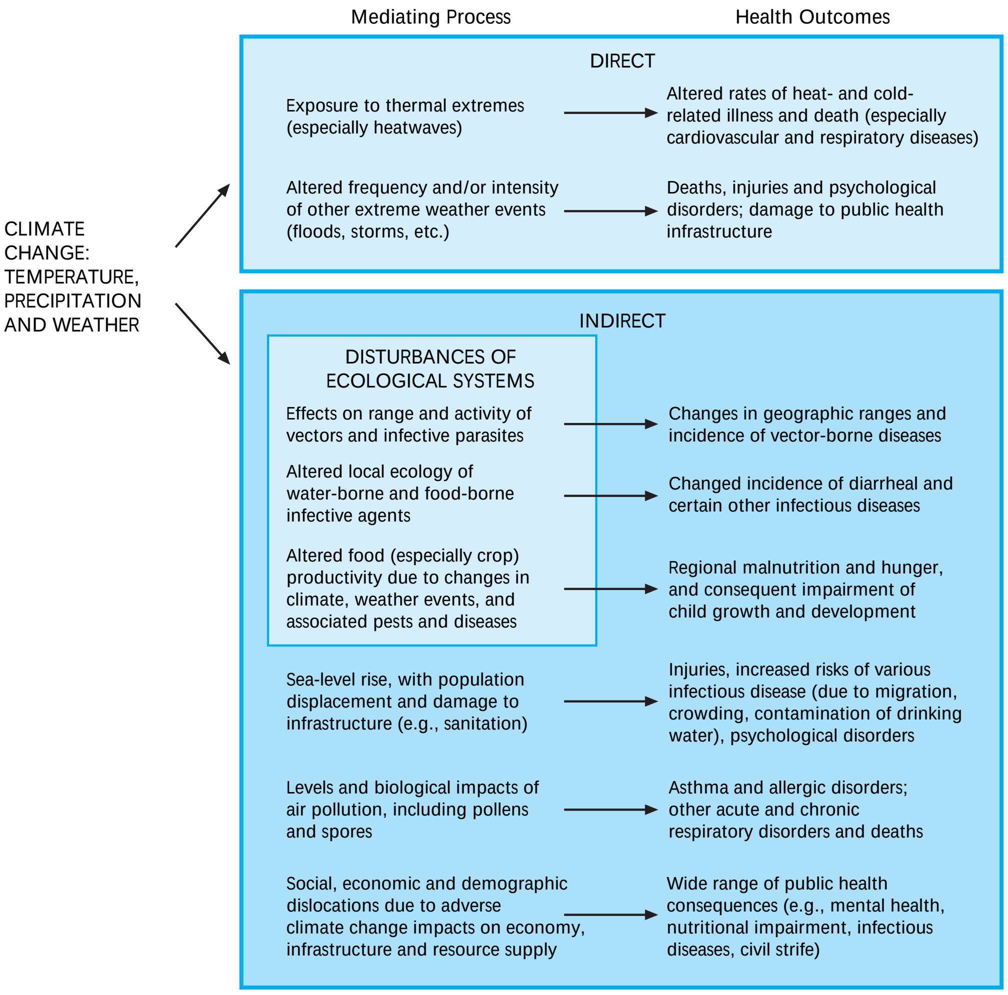
Property insurance is vulnerable to extreme climate events. A higher risk of extreme events due to climate change could lead to higher insurance premiums or the withdrawal of coverage for property in some vulnerable areas. Changes in climate variability and the risk for extreme events may be difficult to detect or predict, thus making it difficult for insurance companies to adjust premiums appropriately. If such difficulty leads to insolvency, companies may not be able to honour insurance contracts, which could economically weaken other sectors, such as banking. The insurance industry currently is under stress from a series of "billion dollar" storms since 1987, resulting in dramatic increases in losses, reduced availability of insurance and higher costs. Some in the insurance industry perceive a current trend toward increased frequency and severity of extreme climate events. Examination of the meteorological data fails to support this perception in the context of a long-term change, although a shift within the limits of natural variability may have occurred. Higher losses strongly reflect increases in infrastructure and economic worth in vulnerable areas as well as a possible shift in the intensity and frequency of extreme weather events.

3.5 Human health

Climate change is likely to have wide-ranging and mostly adverse impacts on human health, with significant loss of life. These impacts would arise by both direct and indirect pathways (Figure 3) and it is likely that the indirect impacts would, in the longer term, predominate.

Direct health effects include increases in (predominantly cardio-respiratory) mortality and illness due to an anticipated increase in the intensity and duration of heat waves. Temperature increases in colder regions should result in fewer cold-related deaths. An increase in extreme weather would cause a higher incidence of death, injury, psychological disorders and exposure to contaminated water supplies.

Indirect effects of climate change include increases in the potential transmission of vector-borne infectious diseases (e.g., malaria, dengue, yellow fever and some viral encephalitis) resulting from



Note: Populations with different levels of natural, technical and social resources would differ in their vulnerability to climate-induced health impacts.

Figure 3. Ways in which climate change can affect human health.

extensions of the geographical range and season for vector organisms. Projections by models (that entail necessary simplifying assumptions) indicate that the geographical zone of potential malaria transmission in response to world temperature increases at the upper part of the IPCC-projected range (3–5°C by 2100) would increase from approximately 45% of the world population to approximately 60% by the latter half of the next century. This could lead to potential increases in malaria incidence (on the order of 50–80 million additional annual cases, relative to an assumed global background total of 500 million cases), primarily in tropical, subtropical and less well-protected temperate-zone populations. Some increases in non-vector-borne infectious diseases — such as salmonellosis, cholera and giardiasis — also could occur as a result of elevated temperatures and increased flooding.

Additional indirect effects include respiratory and allergic disorders due to climate-enhanced increases in some air pollutants, pollens and mold spores. Exposure to air pollution and stressful weather events combine to increase the likelihood of morbidity and mortality. Some regions could experience a decline in nutritional status as a result of adverse impacts on food and fisheries productivity. Limitations on freshwater supplies also will have human health consequences.

Quantifying the projected impacts is difficult because the extent of climate-induced health disorders depends on numerous coexistent and interacting factors that characterize the vulnerability of the particular population, including environmental and socio-economic circumstances, nutritional and immune status, population density and access to quality health care services. Adaptive options to reduce health impacts include protective technology (e.g., housing, air conditioning, water purification and vaccination), disaster preparedness and appropriate health care.

4. OPTIONS TO REDUCE EMISSIONS AND ENHANCE SINKS OF GREENHOUSE GASES

Human activities are directly increasing the atmospheric concentrations of several greenhouse gases, especially CO_2, CH_4, halocarbons, sulfur hexafluoride (SF_6) and nitrous oxide (N_2O). CO_2 is the most important of these gases, followed by CH_4. Human activities also indirectly affect concentrations of water vapour and ozone. Significant reductions in net greenhouse gas emissions are technically possible and can be economically feasible. These reductions can be achieved by utilizing an extensive array of technologies and policy measures that accelerate technology development, diffusion and transfer in all sectors including the energy, industry, transportation, residential/commercial and agricultural/forestry sectors. By the year 2100, the world's commercial energy system in effect will be replaced at least twice, offering opportunities to change the energy system without premature retirement of capital stock; significant amounts of capital stock in the industrial, commercial, residential and agricultural/forestry sectors will also be replaced. These cycles of capital replacement provide opportunities to use new, better performing technologies. It should be noted that the analyses of Working Group II do not attempt to quantify potential macroeconomic consequences that may be associated with mitigation measures. Discussion of macroeconomic analyses is found in the IPCC Working Group III contribution to the Second Assessment Report. The degree to which technical potential and cost-effectiveness are realized is dependent on initiatives to counter lack of information and overcome cultural, institutional, legal, financial and economic barriers that can hinder diffusion of technology or behavioral changes. The pursuit of mitigation options can be carried out within the limits of sustainable development criteria. Social and environmental criteria not related to greenhouse gas emissions abatement could, however, restrict the ultimate potential of each of the options.

4.1 Energy, industrial process and human settlement emissions

Global energy demand has grown at an average annual rate of approximately 2% for almost two centuries, although energy demand growth varies considerably over time and between different regions. In the published literature, different methods and conventions are used to characterize energy consumption. These conventions differ, for example, according to their definition of sectors and their treatment of energy forms. Based on aggregated national energy balances, 385 EJ of primary energy was consumed in the world in 1990, resulting in the release of 6 GtC as CO_2. Of this, 279 EJ was delivered to end users, accounting for 3.7 GtC emissions as CO_2 at the point of consumption. The remaining 106 EJ was used in energy conversion and distribution, accounting for 2.3 GtC emissions as CO_2. In 1990, the three largest sectors of energy consumption were industry (45% of total CO_2 releases), residential/commercial sector (29%) and transport (21%). Of these, transport sector energy use and related CO_2 emissions have been the most rapidly growing over the past two decades. For the detailed sectoral mitigation option assessment in this report, 1990 energy consumption estimates are based on a range of literature sources; a variety of conventions are used to define these sectors and their energy use, which is estimated to amount to a total of 259–282 EJ.

Figure 4 depicts total energy-related emissions by major world region. Organization for Economic Cooperation and Development (OECD) nations have been and remain major energy users and fossil-fuel CO_2 emitters, although their share of global fossil fuel carbon emissions has been declining. Developing nations, taken as a group, still account for a smaller portion of total global CO_2 emissions than industrialized nations — OECD and former Soviet Union/Eastern Europe (FSU/EE) — but most projections indicate that with forecast rates of economic and population growth, the future share of developing countries will increase. Future energy demand is anticipated to continue to grow, at least through the first half of the next century. The IPCC (1992, 1994) projects that without policy intervention, there could be significant growth in emissions from the industrial, transportation and commercial/ residential buildings sectors.

4.1.1 *Energy demand*

Numerous studies have indicated that 10–30% energy-efficiency gains above present levels are feasible at little or no net cost in many

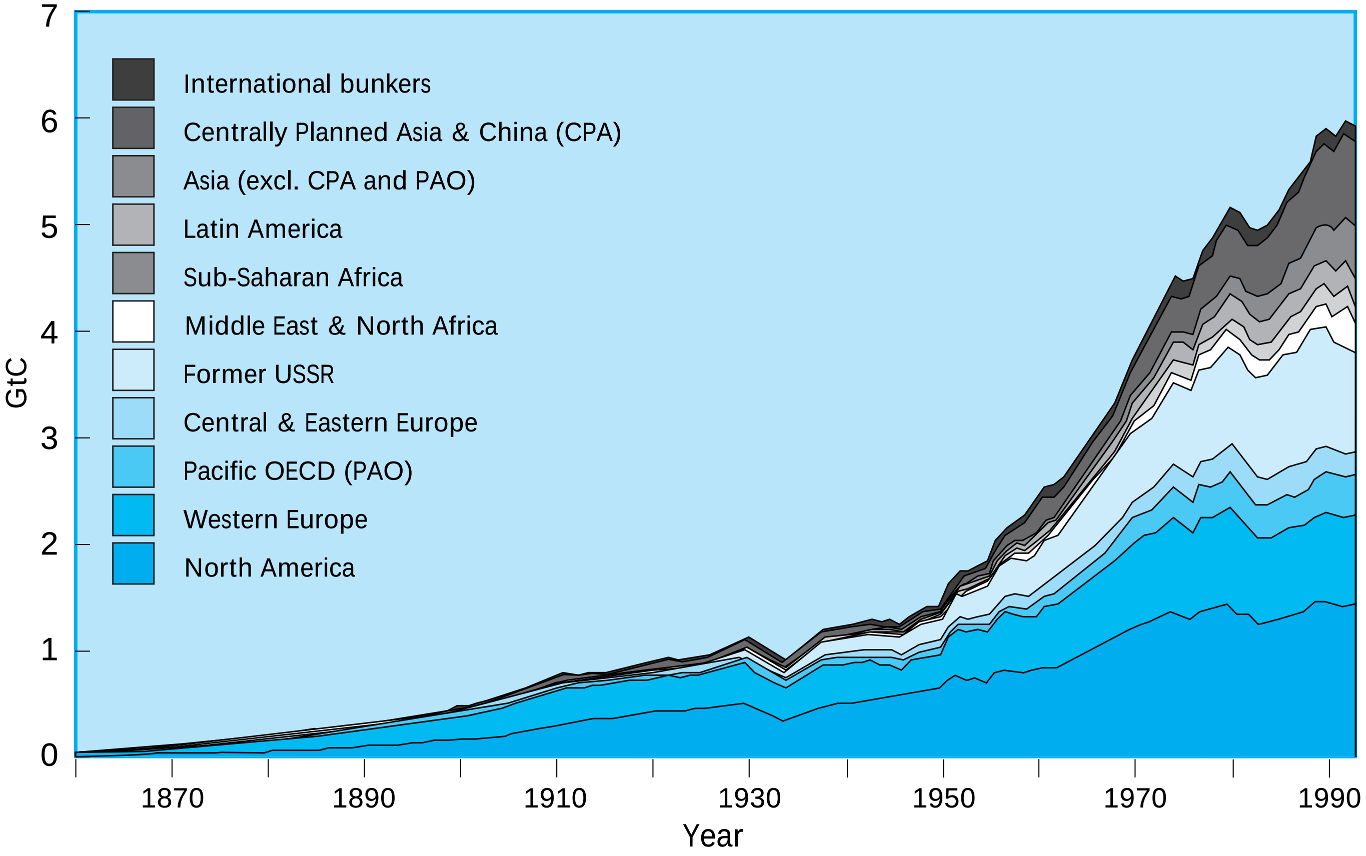


Figure 4. Global energy-related CO_2 emissions by major world region in GtC/yr. Sources: Keeling, 1994; Marland *et al.*, 1994; Grübler and Nakicenovic, 1992; Etemad and Luciani, 1991; Fujii, 1990; UN, 1952 (see the Energy Primer for reference information).

parts of the world through technical conservation measures and improved management practices over the next two to three decades. Using technologies that presently yield the highest output of energy services for a given input of energy, efficiency gains of 50–60% would be technically feasible in many countries over the same time period. Achieving these potentials will depend on future cost reductions, financing and technology transfer, as well as measures to overcome a variety of non-technical barriers. The potential for greenhouse gas emission reductions exceeds the potential for energy use efficiency because of the possibility of switching fuels and energy sources. Because energy use is growing worldwide, even replacing current technology with more efficient technology could still lead to an absolute increase in CO_2 emissions in the future.

In 1992, the IPCC produced six scenarios (IS92a-f) of future energy use and associated greenhouse gas emissions (IPCC, 1992, 1995). These scenarios provide a wide range of possible future greenhouse gas emission levels, without mitigation measures.

In the Second Assessment Report, future energy use has been re-examined on a more detailed sectoral basis, both with and without new mitigation measures, based on existing studies. Despite different assessment approaches, the resulting ranges of energy consumption increases to 2025 without new measures are broadly consistent with those of IS92. If past trends continue, greenhouse gas emissions will grow more slowly than energy use, except in the transport sector.

The following paragraphs summarize energy-efficiency improvement potentials estimated in the IPCC Second Assessment Report. Strong policy measures would be required to achieve these potentials. Energy-related greenhouse gas emission reductions depend on the source of the energy, but reductions in energy use will in general lead to reduced greenhouse gas emissions.

Industry. Energy use in 1990 was estimated to be 98–117 EJ and is projected to grow to 140–242 EJ in 2025 without new measures. Countries differ widely in their current industrial energy use and energy-related greenhouse gas emission trends. Industrial sector energy-related greenhouse gas emissions in most industrialized countries are expected to be stable or decreasing as a result of industrial restructuring and technological innovation, whereas industrial emissions in developing countries are projected to increase mainly as a result of industrial growth. The short-term potential for energy-efficiency improvements in the manufacturing sector of major industrial countries is estimated to be 25%. The potential for greenhouse gas emission reductions is larger. Technologies and measures for reducing energy-related emissions from this sector include improving efficiency (e.g., energy and materials savings, co-generation, energy cascading, steam recovery, and use of more efficient motors and other electrical devices); recycling materials and switching to those with lower greenhouse gas emissions; and developing processes that use less energy and materials.

Transportation. Energy use in 1990 was estimated to be 61–65 EJ and is projected to grow to 90–140 EJ in 2025 without new measures. Projected energy use in 2025 could be reduced by about a third to 60–100 EJ through vehicles using very efficient drive-trains, lightweight construction and low air-resistance design, without compromising comfort and performance. Further energy-use reductions are possible through the use of smaller vehicles; altered land-use patterns, transport systems, mobility patterns and lifestyles; and shifting to less energy-intensive transport modes. Greenhouse gas emissions per unit of energy used could be reduced through the use of alternative fuels and electricity from renewable sources. These measures, taken together, provide the opportunity for reducing global transport energy-related greenhouse gas emissions by as much as 40% of projected emissions by 2025. Actions to reduce energy-related greenhouse gas emissions from transport can simultaneously address other problems such as local air pollution.

Commercial/Residential Sector. Energy use in 1990 was estimated to be about 100 EJ and is projected to grow to 165–205 EJ in 2025 without new measures. Projected energy use could be reduced by about a quarter to 126–170 EJ by 2025 without diminishing services through the use of energy efficient technology. The potential for greenhouse gas emission reductions is larger. Technical changes might include reduced heat transfers through building structures and more efficient space-conditioning and water supply systems, lighting and appliances. Ambient temperatures in urban areas can be reduced through increased vegetation and greater reflectivity of building surfaces, reducing the energy required for space conditioning. Energy-related greenhouse gas emission reductions beyond those obtained through reduced energy use could be achieved through changes in energy sources.

4.1.2 *Mitigating industrial process and human settlement emissions*

Process-related greenhouse gases including CO_2, CH_4, N_2O, halocarbons and SF6 are released during manufacturing and industrial processes, such as the production of iron, steel, aluminum, ammonia, cement and other materials. Large reductions are possible in some cases. Measures include modifying production processes, eliminating solvents, replacing feedstocks, materials substitution, increased recycling and reduced consumption of greenhouse gas-intensive materials. Capturing and utilizing CH_4 from landfills and sewage treatment facilities and lowering the leakage rate of halocarbon refrigerants from mobile and stationary sources also can lead to significant greenhouse gas emission reductions.

4.1.3 *Energy supply*

This assessment focuses on new technologies for capital investment and not on potential retrofitting of existing capital stock to use less carbon-intensive forms of primary energy. It is technically possible to realize deep emissions reductions in the energy supply sector in step with the normal timing of investments to replace infrastructure and equipment as it wears out or becomes obsolete. Many options for achieving these deep reductions will also decrease the emissions of sulfur dioxide, nitrogen oxides and volatile organic compounds. Promising approaches, not ordered according to priority, are described below.

4.1.3.1 *Greenhouse gas reductions in the use of fossil fuels*

More efficient conversion of fossil fuels. New technology offers considerably increased conversion efficiencies. For example, the efficiency of power production can be increased from the present world average of about 30% to more than 60% in the longer term. Also, the use of combined heat and power production replacing separate production of power and heat —whether for process heat or space heating — offers a significant rise in fuel conversion efficiency.

Switching to low-carbon fossil fuels and suppressing emissions. Switching from coal to oil or natural gas, and from oil to natural gas, can reduce emissions. Natural gas has the lowest CO_2 emissions per unit of energy of all fossil fuels at about 14 kg C/GJ, compared to oil with about 20 kg C/GJ and coal with about 25 kg C/GJ. The lower carbon-containing fuels can, in general, be converted with higher efficiency than coal. Large resources of natural gas exist in many areas. New, low capital cost, highly efficient combined-cycle technology has reduced electricity costs considerably in some areas. Natural gas could potentially replace oil in the transportation sector. Approaches exist to reduce emissions of CH_4 from natural gas pipelines and emissions of CH_4 and/or CO_2 from oil and gas wells and coal mines.

Decarbonization of flue gases and fuels and CO_2 storage. The removal and storage of CO_2 from fossil fuel power-station stack gases is feasible, but reduces the conversion efficiency and significantly increases the production cost of electricity. Another approach to decarbonization uses fossil fuel feedstocks to make hydrogen-rich fuels. Both approaches generate a byproduct stream of CO_2 that could be stored, for example, in depleted natural gas fields. The future availability of conversion technologies such as fuel cells that can efficiently use hydrogen would increase the relative attractiveness of the latter approach. For some longer term CO_2 storage options, the costs, environmental effects and efficacy of such options remain largely unknown.

4.1.3.2 *Switching to non-fossil fuel sources of energy*

Switching to nuclear energy. Nuclear energy could replace baseload fossil fuel electricity generation in many parts of the world if generally acceptable responses can be found to concerns such as reactor safety, radioactive-waste transport and disposal, and nuclear proliferation.

Switching to renewable sources of energy. Solar, biomass, wind, hydro and geothermal technologies already are widely used. In 1990, renewable sources of energy contributed about 20% of the world's primary energy consumption, most of it fuelwood and hydropower. Technological advances offer new opportunities and declining costs for energy from these sources. In the longer term, renewable sources of energy could meet a major part of the world's demand for energy. Power systems can easily accommodate limited fractions of intermittent generation, and with the addition of fast-responding backup and storage units, also higher fractions. Where biomass is sustainably regrown and used to displace fossil fuels in energy production, net carbon emissions are avoided as the CO_2 released in converting the biomass to energy is again fixed in biomass through photosynthesis. If the development of biomass energy can be carried out in ways that effectively address concerns about other environmental issues and competition with other land uses, biomass could make major contributions in both the electricity and fuels markets, as well as offering prospects of increasing rural employment and income.

4.1.4 *Integration of energy system mitigation options*

To assess the potential impact of combinations of individual measures at the energy system level, in contrast to the level of individual technologies, variants of a Low CO_2-Emitting Energy Supply System (LESS) are described. The LESS constructions are "thought experiments" exploring possible global energy systems.

The following assumptions were made: World population grows from 5.3 billion in 1990 to 9.5 billion by 2050 and 10.5 billion by 2100. GDP grows 7-fold by 2050 (5-fold and 14-fold in industrialized and developing countries, respectively) and 25-fold by 2100 (13-fold and 70-fold in industrialized and developing countries, respectively), relative to 1990. Because of emphasis on energy efficiency, primary energy consumption rises much more slowly than GDP. The energy supply constructions were made to meet energy demand in: (i) projections developed for the IPCC's First Assessment Report (1990) in a low energy demand variant, where global primary commercial energy use approximately doubles, with no net change for industrialized countries but a 4.4-fold increase for developing countries from 1990 to 2100; and (ii) a higher energy demand variant, developed in the IPCC IS92a scenario where energy demand quadruples from 1990 to 2100. The energy demand levels of the LESS constructions are consistent with the energy demand mitigation chapters of this Second Assessment Report.

Figure 5 shows combinations of different energy sources to meet changing levels of demand over the next century. The analysis of these variants leads to the following conclusions:

- Deep reductions of CO_2 emissions from energy supply systems are technically possible within 50 to 100 years, using alternative strategies.
- Many combinations of the options identified in this assessment could reduce global CO_2 emissions from fossil fuels from about 6 GtC in 1990 to about 4 GtC/yr by 2050 and to about 2 GtC/yr by 2100 (see Figure 6). Cumulative CO_2 emissions, from 1990 to 2100, would range from about 450 to about 470 GtC in the alternative LESS constructions.
- Higher energy efficiency is underscored for achieving deep reductions in CO_2 emissions, for increasing the flexibility of supply side combinations, and for reducing overall energy system costs.
- Interregional trade in energy grows in the LESS constructions compared to today's levels, expanding sustainable development options for Africa, Latin America and the Middle East during the next century.

Costs for energy services in each LESS variant relative to costs for conventional energy depend on relative future energy prices, which are uncertain within a wide range, and on the performance and cost characteristics assumed for alternative technologies. However, within the wide range of future energy prices, one or more of the variants would plausibly be capable of providing the demanded energy services at estimated costs that are approximately the same as estimated future costs for current conventional energy. It is not possible to identify a least-cost future energy system for the longer term, as the relative costs of options depend on resource constraints and technological opportunities that are imperfectly known, and on actions by governments and the private sector.

The literature provides strong support for the feasibility of achieving the performance and cost characteristics assumed for energy technologies in the LESS constructions, within the next two decades, though it is impossible to be certain until the research and development is complete and the technologies have been tested in the market. Moreover, these performance and cost characteristics cannot be achieved without a strong and sustained investment in research, development and demonstration (RD&D). Many of the technologies being developed would need initial support to enter the market, and to reach sufficient volume to lower costs to become competitive.

Market penetration and continued acceptability of different energy technologies ultimately depends on their relative cost, performance (including environmental performance), institutional arrangements, and regulations and policies. Because costs vary by location and application, the wide variety of circumstances creates initial opportunities for new technologies to enter the market. Deeper understanding of the opportunities for emissions reductions would require more detailed analysis of options, taking into account local conditions.

Because of the large number of options, there is flexibility as to how the energy supply system could evolve, and paths of energy system development could be influenced by considerations other than climate change, including political, environmental (especially indoor and urban air pollution, acidification and land restoration) and socio-economic circumstances.

4.2 Agriculture, rangelands and forestry

Beyond the use of biomass fuels to displace fossil fuels, the management of forests, agricultural lands and rangelands can play an important role in reducing current emissions of CO_2, CH_4 and N_2O and in enhancing carbon sinks. A number of measures could conserve and sequester substantial amounts of carbon (approximately 60–90 GtC in the forestry sector alone) over the next 50 years. In the forestry sector, costs for conserving and sequestering carbon in biomass and soil are estimated to range widely but can be competitive with other mitigation options. Factors affecting costs include opportunity costs of land; initial costs of planting and establishment; costs of nurseries; the cost of annual maintenance and monitoring; and transaction costs. Direct and indirect benefits will vary with national circumstances and could offset the costs. Other practices in the agriculture sector could reduce emissions of other greenhouse gases such as CH_4 and N_2O. Land-use and management measures include:

- Sustaining existing forest cover
- Slowing deforestation
- Regenerating natural forests
- Establishing tree plantations
- Promoting agroforestry
- Altering management of agricultural soils and rangelands
- Improving efficiency of fertilizer use
- Restoring degraded agricultural lands and rangelands
- Recovering CH_4 from stored manure
- Improving the diet quality of ruminants.

The net amount of carbon per unit area conserved or sequestered in living biomass under a particular forest management practice and present climate is relatively well understood. The most important uncertainties associated with estimating a global value are: (i) the amount of land suitable and available for forestation, regeneration and/or restoration programmes; (ii) the rate at which tropical deforestation can actually be reduced; (iii) the long-term use (security) of

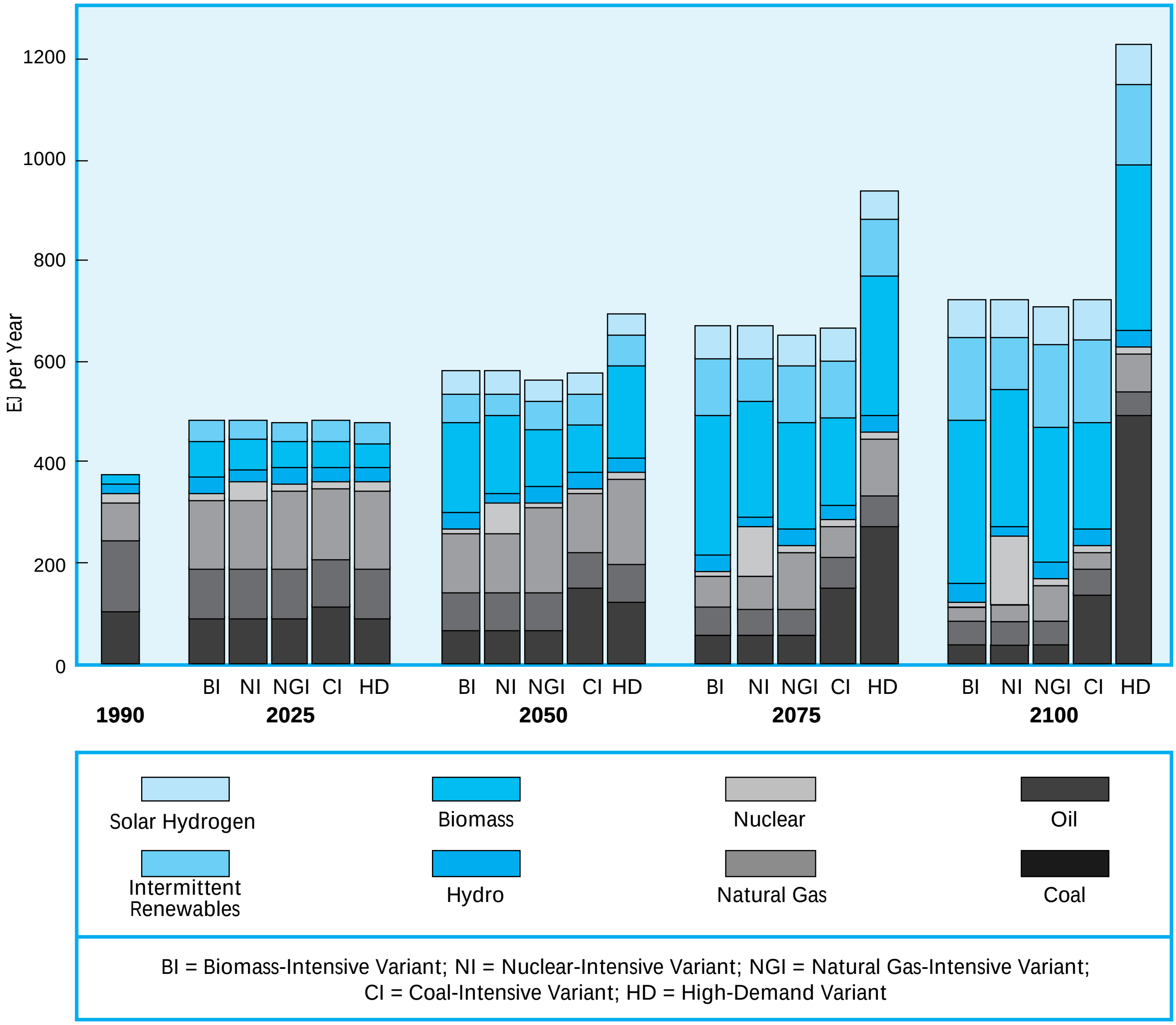


Figure 5. Global primary energy use for alternative Low CO_2-Emitting Energy Supply System (LESS) constructions: Alternatives for meeting different energy demand levels over time, using various fuel mixes.

these lands; and (iv) the continued suitability of some practices for particular locations given the possibility of changes in temperature, water availability and so forth under climate change.

4.3 Cross-sectoral issues

Cross-sectoral assessment of different combinations of mitigation options focuses on the interactions of the full range of technologies and practices that are potentially capable of reducing emissions of greenhouse gases or sequestering carbon. Current analysis suggests the following:

- **Competing uses of land, water and other natural resources.** A growing population and expanding economy will increase the demand for land and other natural resources needed to provide, *inter alia*, food, fibre, forest products and recreation services. Climate change will interact with the resulting intensified patterns of resource use. Land and other resources could also be required for mitigation of greenhouse gas emissions. Agricultural productivity improvements throughout the world and especially in developing countries would increase availability of land for production of biomass energy.
- **Geoengineering options.** Some geoengineering approaches to counterbalance greenhouse gas-induced climate change have been suggested (e.g., putting solar radiation reflectors in space or injecting sulfate aerosols into the atmosphere to mimic the cooling influence of volcanic eruptions). Such approaches generally are likely to be ineffective, expensive to sustain and/or to have serious environmental and other effects that are in many cases poorly understood.

4.4 Policy instruments

Mitigation depends on reducing barriers to the diffusion and transfer of technology, mobilizing financial resources, supporting capacity building in developing countries, and other approaches to assist in the implementation of behavioral changes and technological opportunities in all regions of the globe. The optimum mix of policies will vary from country to country, depending upon political structure and societal receptiveness. The leadership of national governments in applying these policies will contribute to responding to adverse

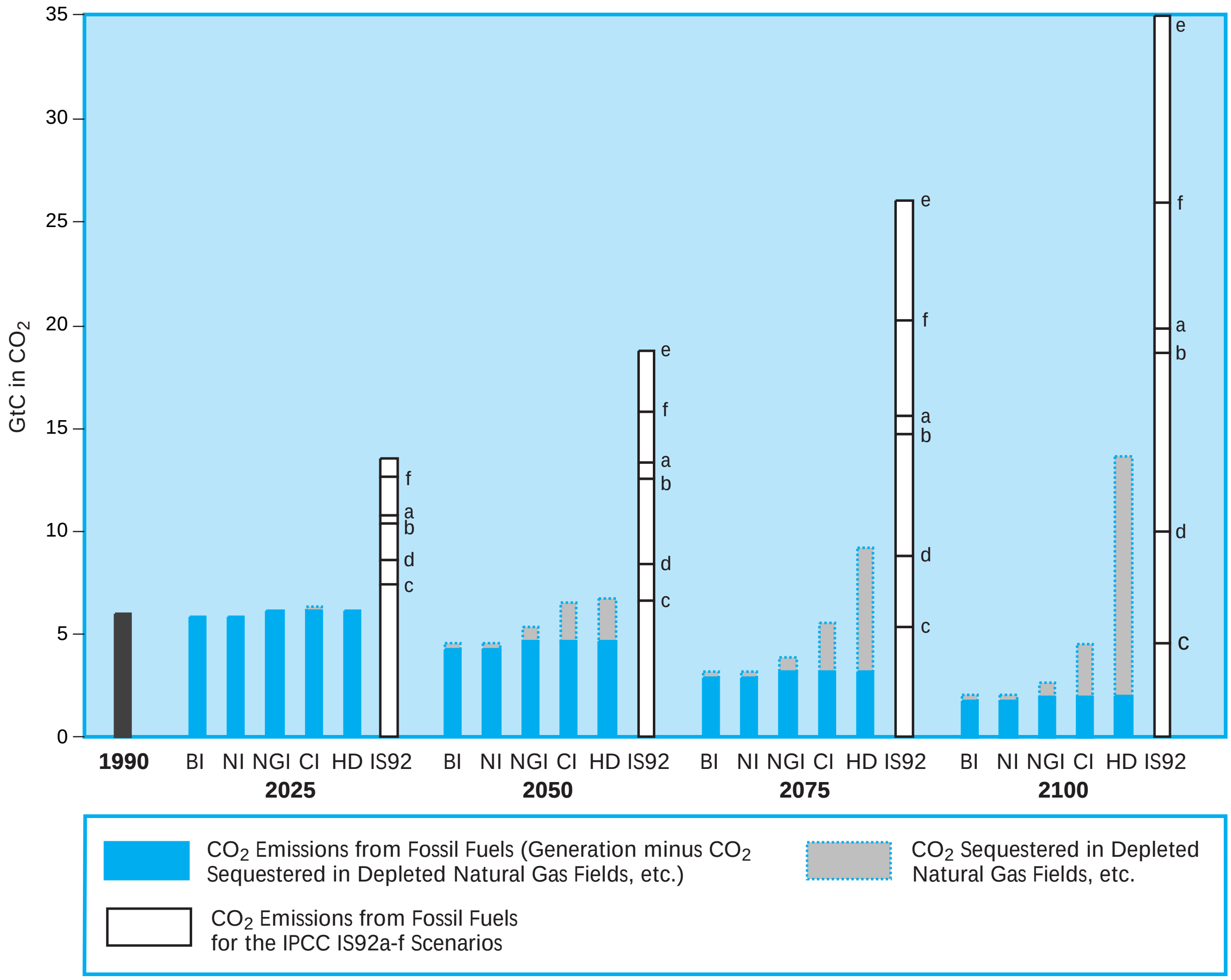


Figure 6. Annual CO_2 emissions from fossil fuels for alternative LESS constructions, with comparison to the IPCC IS92a-f scenarios (see Figure 5 for acronym definitions).

consequences of climate change. Governments can choose policies that facilitate the penetration of less greenhouse gas-intensive technologies and modified consumption patterns. Indeed, many countries have extensive experience with a variety of policies that can accelerate the adoption of such technologies. This experience comes from efforts over the past 20 to 30 years to achieve improved energy efficiency, reduce the environmental impacts of agricultural policies, and meet conservation and environmental goals unrelated to climate change. Policies to reduce net greenhouse gas emissions appear more easily implemented when they are designed to address other concerns that impede sustainable development (e.g., air pollution and soil erosion). A number of policies, some of which may need regional or international agreement, can facilitate the penetration of less greenhouse gas-intensive technologies and modified consumption patterns, including:

- Putting in place appropriate institutional and structural frameworks
- Energy pricing strategies (e.g., carbon or energy taxes and reduced energy subsidies)
- Reducing or removing other subsidies (e.g., agricultural and transport subsidies) that increase greenhouse gas emissions
- Tradable emissions permits
- Voluntary programmes and negotiated agreements with industry
- Utility demand-side management programmes
- Regulatory programmes, including minimum energy efficiency standards (e.g., for appliances and fuel economy)
- Stimulating RD&D to make new technologies available
- Market pull and demonstration programmes that stimulate the development and application of advanced technologies
- Renewable energy incentives during market build-up
- Incentives such as provisions for accelerated depreciation and reduced costs for consumers
- Education and training; information and advisory measures
- Options that also support other economic and environmental goals.

Accelerated development of technologies that will reduce greenhouse gas emissions and enhance greenhouse gas sinks — as well as understanding the barriers that inhibit their diffusion into the marketplace — requires intensified research and development by governments and the private sector.

SUMMARY FOR POLICYMAKERS:

THE ECONOMIC AND SOCIAL DIMENSIONS OF CLIMATE CHANGE

IPCC WORKING GROUP III

SUMMARY FOR POLICYMAKERS: THE ECONOMIC AND SOCIAL DIMENSIONS OF CLIMATE CHANGE

1. INTRODUCTION

Working Group III of the Intergovernmental Panel on Climate Change (IPCC) was restructured in November 1992 and charged with conducting "technical assessments of the socio-economics of impacts, adaptation and mitigation of climate change over both the short and long term and at the regional and global levels". Working Group III responded to this charge by further stipulating in its work plan that it would place the socio-economic perspectives in the context of sustainable development and, in accordance with the UN Framework Convention on Climate Change (UNFCCC), provide comprehensive treatment of both mitigation and adaptation options while covering all economic sectors and all relevant sources of greenhouse gases and sinks.

This report assesses a large part of the existing literature on the socio-economics of climate change and identifies areas in which a consensus has emerged on key issues and areas where differences exist[1]. The chapters have been arranged so that they cover several key issues. First, frameworks for socio-economic assessment of costs and benefits of action and inaction are described. Particular attention is given to the applicability of cost-benefit analysis, the incorporation of equity and social considerations, and consideration of intergenerational equity issues. Second, the economic and social benefits of limiting greenhouse gas emissions and enhancing sinks are reviewed. Third, the economic, social and environmental costs of mitigating greenhouse gas emissions are assessed. Next, generic mitigation and adaptation response options are reviewed, methods for assessing the costs and effectiveness of different response options are summarized, and integrated assessment techniques are discussed. Finally, the report provides an economic assessment of policy instruments to combat climate change.

In accordance with the approved work plan, this assessment of the socio-economic literature related to climate change focuses on economic studies; material from other social sciences is found mostly in the chapter on equity and social considerations. The report is an assessment of the state of knowledge — what we know and do not know — and not a prescription for policy implementation. Countries can use the information in this report to help take decisions they believe are most appropriate for their specific circumstances.

2. SCOPE OF THE ASSESSMENT

Climate change presents the decision maker with a set of formidable complications: a considerable number of remaining uncertainties (which are inherent in the complexity of the problem), the potential for irreversible damages or costs, a very long planning horizon, long time lags between emissions and effects, wide regional variation in causes and effects, the irreducibly global scope of the problem, and the need to consider multiple greenhouse gases and aerosols. Yet another complication arises from the fact that effective protection of the climate system requires global cooperation.

Still, a number of insights that may be useful to policymakers can be drawn from the literature:

- Analyses indicate that a prudent way to deal with climate change is through a portfolio of actions aimed at mitigation, adaptation and improvement of knowledge. The appropriate portfolio will differ for each country. The challenge is not to find the best policy today for the next 100 years, but to select a prudent strategy and to adjust it over time in the light of new information.
- Earlier mitigation action may increase flexibility in moving toward stabilization of atmospheric concentrations of greenhouse gases (UN Framework Convention on Climate Change, Article 2). The choice of abatement paths involves balancing the economic risks of rapid abatement now (that premature capital stock retirement will later be proved unnecessary) against the corresponding risk of delay (that more rapid reduction will then be required, necessitating premature retirement of future capital stock).
- The literature indicates that significant "no-regrets"[2] opportunities are available in most countries and that the risk of aggregate net damage due to climate change, consideration of risk aversion, and application of the precautionary principle provide rationales for action beyond no regrets.
- The value of better information about climate change processes and impacts and society's responses to them is likely to be great. In particular, the literature accords high value to information about climate sensitivity to greenhouse gases and aerosols, climate change damage functions, and variables such as determinants of economic growth and rates of energy efficiency improvements. Better information about the costs and benefits of mitigation and

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[1] The UN Framework Convention on Climate Change defines "climate change" as a change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods. The question as to whether such changes are potential or can already be identified is analyzed in the volume on the science of climate change of the IPCC Second Assessment Report (SAR).

[2] "No regrets" measures are those whose benefits, such as reduced energy costs and reduced emissions of local/regional pollutants equal or exceed their cost to society, *excluding* the benefits of climate change mitigation. They are sometimes known as "measures worth doing anyway".

adaptation measures and how they might change in coming decades also has a high value.

- Analysis of economic and social issues related to climate change, especially in developing countries where little work of this nature has been carried out, is a high priority for research. More generally, research is needed on integrated assessment and analysis of decision-making related to climate change. Further, research advancing the economic understanding of non-linearities and new theories of economic growth is also needed. Research and development related to energy efficiency technologies and non-fossil energy options also offer high potential value. In addition, there is also a need for research on the development of sustainable consumption patterns.

A portfolio of possible actions that policymakers could consider, in accordance with applicable international agreements, to implement low-cost and/or cost-effective measures to reduce emissions of greenhouse gases and adapt to climate change can include:

- Implementing energy efficiency measures, including the removal of institutional barriers to energy efficiency improvements;
- Phasing out existing distortionary policies and practices that increase greenhouse gas emissions, such as some subsidies and regulations, non-internalization of environmental costs and distortions in transport pricing;
- Implementing cost-effective fuel switching measures from more to less carbon-intensive fuels and to carbon-free fuels such as renewables;
- Implementing measures to enhance sinks or reservoirs of greenhouse gases, such as improving forest management and land use practices;
- Implementing measures and developing new techniques for reducing methane, nitrous oxide and other greenhouse gas emissions;
- Encouraging forms of international cooperation to limit greenhouse gas emissions, such as implementing coordinated carbon/energy taxes, activities implemented jointly and tradable quotas;
- Promoting the development and implementation of national and international energy efficiency standards;
- Promoting voluntary actions to reduce greenhouse gas emissions;
- Promoting education and training, implementing information and advisory measures for sustainable development and consumption patterns that will facilitate climate change mitigation and adaptation;
- Planning and implementing measures to adapt to the consequences of climate change;
- Undertaking research aimed at better understanding of the causes and impacts of climate change and facilitating more effective adaptation to it;
- Conducting technological research aimed at minimizing emissions of greenhouse gases from continued use of fossil fuels and developing commercial non-fossil energy sources;
- Developing improved institutional mechanisms, such as improved insurance arrangements, to share the risks of damages due to climate change.

Contribution of economics

- Estimates of the costs and benefits of stabilizing greenhouse gas *concentrations* are sensitive, *inter alia*, to the ultimate target concentration, the emissions path toward this level, the discount rate, and assumptions concerning the costs and availability of technologies and practices.
- Despite its widespread use in economic policy evaluation, Gross Domestic Product is widely recognized to be an imperfect measure of society's well-being, largely because it fails to account for degradation of the environment and natural systems. Other methodologies exist that try to take these nonmarket values and social and ecological sustainability into account. Such methodologies would provide a more complete indication of how climate change might affect society's well-being.
- Given the interrelated nature of the global economic system, attempts to mitigate climate change through actions in one region or sector may have offsetting economic effects that risk increasing the emissions of other regions and sectors (so-called leakages). These emission leakages can be lessened through coordinated actions of groups of countries.
- The literature suggests that flexible, cost-effective policies relying on economic incentives and instruments, as well as coordinated instruments, can considerably reduce mitigation or adaptation costs or increase the cost-effectiveness of emission reduction measures.

Equity considerations

In considering equity principles and issues related to greenhouse gas emissions, it is important for policy consideration to take into account in particular Articles 3, 4.2a and 11.2 of the UN Framework Convention on Climate Change, Principle 2 of the Rio Declaration and general principles of international law.

Scientific analyses cannot prescribe how equity should be applied in implementing the UN Framework Convention on Climate Change, but analysis can clarify the implications of alternative choices and their ethical basis.

- Developing countries require support for institutional and endogenous capacity building, so that they may effectively participate in climate change decision-making.
- It is important that both efficiency and equity concerns be considered during the analysis of mitigation and adaptation measures. For the purposes of analysis, it is possible to separate efficiency from equity. This analytical separation pre-supposes that (and is valid, for policy purposes, only if) effective institutions exist or can be created for appropriate redistribution of climate change costs. It may be worthwhile to conduct analyses of the equity implications of particular measures for achieving efficiency, including their social considerations and impacts.

3. DECISION-MAKING FRAMEWORKS FOR ADDRESSING CLIMATE CHANGE

Since climate change is a global issue, comprehensive analyses of mitigation, adaptation and research measures are needed to identify the most efficient and appropriate strategy to address climate change. International decision-making related to climate change, as established by the UNFCCC, is a collective process in which a variety of concerns such as equity, ecological protection, economics, ethics and poverty-related issues, are of special significance for present and future generations. Treatments of decision-making under uncertainty, risk aversion, technology development and diffusion processes, and distributional considerations are at present relatively poorly developed in international environmental economics, and especially in the climate change literature.

Decision-making related to climate change must take into account the unique characteristics of the "problem": large uncertainties (scientific and economic), possible non-linearities and irreversibilities, asymmetric distribution of impacts geographically and temporally, the very long time horizon, and the global nature of climate change with the associated potential for free riding. Beyond scientific uncertainties (discussed in the volume on the science of climate change of the IPCC Second Assessment Report (SAR)) and impact uncertainties (the volume on the scientific-technical analyses of impacts, adaptations and mitigation of climate change of the IPCC Second Assessment Report (SAR)), *socio-economic uncertainties* relate to estimates of how these changes will affect human society (including direct economic and broader welfare impacts) and to the socio-economic implications of emission abatement.

The other dimension that magnifies uncertainties and complicates decision-making is *geographical:* climate change is a global problem encompassing an incredibly diverse mix of human societies, with differing histories, circumstances and capabilities. Many developing countries are in relatively hot climates, depend more heavily on agriculture, and have less well developed infrastructure and social structures; thus, they may suffer more than average, perhaps much more. In developed countries, there may also be large climate change impacts.

The literature also emphasizes that delaying responses is itself a decision involving costs. Some studies suggest that the cost of delay is small; others emphasize that the costs could include imposition of risks on all parties (particularly the most vulnerable), greater utilization of limited atmospheric capacity and potential deferral of desirable technical development. No consensus is reflected in the literature.

The global nature of the problem — necessitating collective action by sovereign states — and the large differences in the circumstances of different parties raise consequential as well as procedural issues. Consequential issues relate to outcomes while procedural issues relate to how decisions are made. In relation to climate change, the existence of an agreed legal framework involves a collective process within a negotiated framework (the UNFCCC). Accordingly, decision-making can be considered within three different categories of frameworks, each with different implications and with distinct foci: global optimization (trying to find the globally optimal result), procedural decision-making (establishing and refining rules of procedure) and collective decision-making (dealing with distributional issues and processes involving the interaction of numerous independent decision makers).

Application of the literature on decision-making to climate change provides elements that can be used in building collective and/or market-oriented strategies for sharing risks and realizing mutual benefits. It suggests that actions be sequential (temporally distributed), that countries implement a portfolio of mitigation, adaptation and research measures, and that they adjust this portfolio continuously in response to new knowledge. The potential for transfers of financial resources and technology to developing countries may be considered as a part of any comprehensive analytical framework.

Elements of a market-related strategy concern *insurance and markets for risk*. Pooling risk does not change the risk, but it can improve economic efficiency and welfare. Although insurance capable of sharing climate change risks on a global basis currently does not exist, one of the important potential gains from cooperating in a collective framework, such as the UN Framework Convention on Climate Change, is that of risk sharing. Creating an insurance system to cover the risks of climate change is difficult[3] and the international community has not yet established such sophisticated instruments. This, however, does not preclude future international action to establish insurance markets sufficient for some international needs.

4. EQUITY AND SOCIAL CONSIDERATIONS

Equity considerations are an important aspect of climate change policy and of the Convention. In common language equity means "the quality of being impartial" or "something that is fair and just". The UNFCCC, including the references to equity and equitable in Articles 3.1, 4.2.a and 11.2, provides the context for efforts to apply equity in meeting the purposes and the objective of the Convention. International law, including relevant decisions of the International Court of Justice, may also provide guidance.

A variety of ethical principles, including the importance of meeting people's basic needs, may be relevant to addressing climate change, but the application to relations among states of principles originally developed to guide individual behaviour is complex and not straightforward. Climate change policies should not aggravate existing disparities between one region and another nor attempt to redress all equity issues.

Equity involves procedural as well as consequential issues. Procedural issues relate to how decisions are made while consequential issues relate to outcomes. To be effective and to promote cooperation, agreements must be regarded as legitimate, and equity is an important element in gaining legitimacy.

Procedural equity encompasses process and participation issues. It requires that all parties be able to participate effectively in international negotiations related to climate change. Appropriate measures

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[3] Without knowing the extent of potential impacts, the ability of private markets to insure against losses associated with climate change is unknown.

to enable developing country parties to participate effectively in negotiations increase the prospects for achieving effective, lasting and equitable agreements on how best to address the threat of climate change. Concern about equity and social impacts points to the need to build endogenous capabilities and strengthen institutional capacities, particularly in developing countries, to make and implement collective decisions in a legitimate and equitable manner.

Consequential equity has two components: the distribution of the costs of damages or adaptation and of measures to mitigate climate change. Because countries differ substantially in vulnerability, wealth, capacity, resource endowments and other factors listed below, the costs of the damages, adaptation and mitigation may be borne inequitably, unless the distribution of these costs is addressed explicitly.

Climate change is likely to impose costs on future generations and on regions where damages occur, including regions with low greenhouse gas emissions. Climate change impacts will be distributed unevenly.

The Convention recognizes in Article 3.1 the principle of common but differentiated responsibilities and respective capabilities. Actions beyond “no-regrets” measures impose costs on the present generation. Mitigation policies unavoidably raise issues about how to share the costs. The initial emission limitation intentions of Annex I parties represent an agreed collective first step of those parties in addressing climate change.

Equity arguments can support a variety of proposals to distribute mitigation costs. Most of them seem to cluster around two main approaches: equal per capita emission allocations and allocations based on incremental departures from national baseline emissions (current or projected). Some proposals combine these approaches in an effort to incorporate equity concerns not addressed by relying exclusively on one or the other approach. The IPCC can clarify scientifically the implications of different approaches and proposals, but the choice of particular proposals is a policy judgment.

There are substantial variations both among developed and developing countries that are relevant to the application of equity principles to mitigation. These include variations in historical and cumulative emissions, current total and per capita emissions, emission intensities and economic output, and factors such as wealth, energy structures and resource endowments. The literature is weak on the equity implications of these variations both among developed and developing countries.

In addition, the implications of climate change for developing countries are different from those for developed countries. The former often have different urgent priorities, weaker institutions, and are generally more vulnerable to climate change. However, it is likely that developing countries’ share of emissions will grow further to meet their social and developmental needs. Greenhouse gas emissions are likely to become increasingly global, even whilst substantial per capita disparities are likely to remain.

It is important that both efficiency and equity concerns should be considered during the analysis of mitigation and adaptation measures. It may be worthwhile to conduct analyses of the equity implications of particular measures for achieving efficiency, including their social considerations and impacts.

5. INTERTEMPORAL EQUITY AND DISCOUNTING

Climate policy, like many other policy issues, raises particular questions of equity among generations, because future generations are not able to influence directly the policies being chosen today that could affect their well-being and because it might not be possible to compensate future generations for consequent reductions in their well-being.

Sustainable development is one approach to intergenerational equity. Sustainable development meets “the needs of the present without compromising the ability of future generations to meet their own needs”.[4] A consensus exists among economists that this does not imply that future generations should inherit a world with at least as much of every resource. Nevertheless, sustainable development would require that use of exhaustible natural resources and environmental degradation are appropriately offset — for example, by an increase in productive assets sufficient to enable future generations to obtain at least the same standard of living as those alive today. There are different views in the literature on the extent to which infrastructure and knowledge, on the one hand, and natural resources, such as a healthy environment, on the other hand, are substitutes. This is crucial to applying these concepts. Some analysts stress that there are exhaustible resources that are unique and cannot be substituted for. Others believe that current generations can compensate future generations for decreases in the quality or quantity of environmental resources by increases in other resources.

Discounting is the principal analytical tool economists use to compare economic effects that occur at different points in time. The choice of discount rate is of crucial technical importance for analyses of climate change policy, because the time horizon is extremely long, and mitigation costs tend to come much earlier than the benefits of avoided damages. The higher the discount rate, the less future benefits and the more current costs matter in the analysis.

Selection of a social discount rate is also a question of values since it inherently relates the costs of present measures, to possible damages suffered by future generations if no action is taken.[5] How best to choose a discount rate is, and will likely remain, an unresolved question in economics. Partly as a consequence, different

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[4] A related (somewhat stronger) concept is that each generation is entitled to inherit a planet and cultural resource base at least as good as that of previous generations.

[5] A social discount rate is a discount rate appropriate for use by governments in the evaluation of public policy.

discount rates are used in different countries. Analysts typically conduct sensitivity studies using various discount rates. It should also be recognized that the social discount rate pre-supposes that all effects are transformed to their equivalent in consumption. This makes it difficult to apply to those nonmarket impacts of climate change which for ethical reasons might not be, or for practical reasons cannot be, converted into consumption units.

The literature on the appropriate social discount rate for climate change analysis can be grouped into two broad categories. One approach discounts consumption by different generations using the "social rate of time preference," which is the sum of the rate of "pure time preference" (impatience) and the rate of increase of welfare derived from higher per capita incomes in the future. Depending upon the values taken for the different parameters, the discount rate tends to fall between 0.5% and 3.0% per year on a global basis — using this approach. However, wide variations in regional discount rates exist, but these may still be consistent with a particular global average.

The second approach to the discount rate considers market returns to investment, which range between 3% and 6% in real terms for long-term, risk-free public investments. Conceptually, funds could be invested in projects that earn such returns, with the proceeds being used to increase the consumption for future generations.

The choice of the social discount rate for public investment projects is a matter of policy preference but has a major impact on the economic evaluation of climate change actions.[6] For example, in today's dollars, $1,000 of damage 100 years from now would be valued at $370 using a 1% discount rate (near the low end of the range for the first approach) but would be valued at $7.60 using a 5% discount rate (near the upper end of the range for the second approach). However, in cost-effectiveness analyses of policies over short time horizons, the impact of using different discount rates is much smaller. In all areas analysts should specify the discount rate(s) they use to facilitate comparison and aggregation of results.

6. APPLICABILITY OF COST AND BENEFIT ASSESSMENTS

Many factors need to be taken into account in the evaluation of projects and public policy issues related to climate change, including the analysis of possible costs and benefits. Although costs and benefits cannot all be measured in monetary terms, various techniques exist which offer a useful framework for organizing information about the consequences of alternative actions for addressing climate change.

The family of analytical techniques for examining economic environmental policies and decisions includes traditional project level cost-benefit analysis, cost-effectiveness analysis, multicriteria analysis and decision analysis. Traditional cost-benefit analysis attempts to compare all costs and benefits expressed in terms of a common monetary unit. Cost-effectiveness analysis seeks to find the lowest-cost option to achieve an objective specified using other criteria. Multicriteria analysis is designed to deal with problems where some benefits and/or costs are measured in nonmonetary units. Decision analysis focuses specifically on making decisions under uncertainty.

In principle, this group of techniques can contribute to improving public policy decisions concerning the desirable extent of actions to mitigate global climate change, the timing of such actions and the methods to be employed.

Traditional cost-benefit analysis is based on the concept that the level of emission control at each point in time is determined such that marginal costs equal marginal benefits. However, both costs and benefits may be hard, sometimes impossible, to assess. This may be due to large uncertainties, possible catastrophes with very small probabilities, or simply because there is no available consistent methodology for monetizing the effects. In some of these cases, it may be possible to apply multicriteria analysis. This provides policymakers with a broader set of information, including evaluation of relevant costs and benefits, estimated within a common framework.

Practical application of traditional cost-benefit analysis to the problem of climate change is therefore difficult because of the global, regional and intergenerational nature of the problem. Estimates of the costs of mitigation options also vary widely. Furthermore, estimates of potential physical damages due to climate change also vary widely. In addition, confidence in monetary estimates for important consequences (especially nonmarket consequences) is low. These uncertainties, and the resolution of uncertainty over time, may be decisive for the choice of strategies to combat climate change. The objective of decision analysis is to deal with such problems. Furthermore, for some categories of ecological, cultural and human health impacts, widely accepted economic concepts of value are not available. To the extent that some impacts and measures cannot be valued in monetary terms, economists augment the traditional cost-benefit analysis approach with such techniques as multicriteria analysis, permitting some quantitative expression of the trade-offs to be made. These techniques do not resolve questions involving equity — for example, determining who should bear the costs. However, they provide important information on the incidence of damage, mitigation, and adaptation costs and on where cost-effective action might be taken.

Despite their many imperfections, these techniques provide a valuable framework for identifying essential questions that policymakers must face when dealing with climate change, namely:

- By how much should emissions of greenhouse gases be reduced?
- When should emissions be reduced?
- How should emissions be reduced?

These analytical techniques assist decision makers in comparing the consequences of alternative actions, including that of no action, on a quantitative basis — and can certainly make a contribution to resolution of these questions.

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[6] Despite the differences in the value of the discount rate, policies developed on the basis of the two approaches may lead to similar results.

7. THE SOCIAL COSTS OF ANTHROPOGENIC CLIMATE CHANGE: DAMAGES OF INCREASED GREENHOUSE GAS EMISSIONS

The literature on the subject in this section is controversial and mainly based on research done on developed countries, often extrapolated to developing countries. There is no consensus about how to value statistical lives or how to aggregate statistical lives across countries.[7] Monetary valuation should not obscure the human consequences of anthropogenic climate change damages, because the value of life has meaning beyond monetary valuation. It should be noted that the Rio Declaration and Agenda 21 call for human beings to remain at the centre of sustainable development. The approach taken to this valuation might affect the scale of damage reduction strategies. It may be noted that, in virtually all of the literature discussed in this section, the developing country statistical lives have not been equally valued at the developed country value, nor are other damages in developing countries equally valued at the developed country value. Because national circumstances, including opportunity costs, differ, economists sometimes evaluate certain kinds of impacts differently amongst countries.

The benefits of limiting greenhouse gas emissions and enhancing sinks are: (a) the climate change damages avoided; and (b) the secondary benefits associated with the relevant policies. Secondary benefits include reductions in other pollutants jointly produced with greenhouse gases and the conservation of biological diversity. Net climate change damages include both market and nonmarket impacts as far as they can be quantified at present and, in some cases, adaptation costs. Damages are expressed in net terms to account for the fact that there are some beneficial impacts of global warming as well, which are, however, dominated by the damage costs. Nonmarket impacts, such as human health, risk of human mortality and damage to ecosystems, form an important component of available estimates of the social costs of climate change. The literature on monetary valuation of such nonmarket effects reflects a number of divergent views and approaches. The estimates of nonmarket damages, however, are highly speculative and not comprehensive.

Nonmarket damage estimates are a source of major uncertainty in assessing the implications of global climate change for human welfare. While some regard monetary valuation of such impacts as essential to sound decision-making, others reject monetary valuation of some impacts, such as risk of human mortality, on ethical grounds. Additionally, there is a danger that entire unique cultures may be obliterated. This is not something that can be considered in monetary terms, but becomes a question of loss of human diversity, for which we have no indicators to measure economic value.

The assessed literature contains only a few estimates of the monetized damages associated with doubled CO_2 equivalent concentration scenarios. These estimates are aggregated to a global scale and illustrate the potential impacts of climate change under selected scenarios. Aggregating individual monetized damages to obtain total social welfare impacts implies difficult decisions about equity amongst countries. Global estimates are based upon an aggregation of monetary damages across countries (damages which are themselves implicit aggregations across individuals) that reflects intercountry differences in wealth and income — this fundamentally influences the monetary valuation of damages. Taking income differences as given implies that an equivalent impact in two countries (such as an equal increase in human mortality) would receive very different weights in the calculations of global damages.

To enable choices between different ways of promoting human welfare to be made on a consistent basis, economists have for many years sought to express a wide range of human and environmental impacts in terms of monetary equivalents, using various techniques. The most commonly used of those techniques is an approach based on the observed willingness to pay for various nonmarket benefits.[8] This is the approach that has been taken in most of the assessed literature.

Human life is an element outside the market and societies may want to preserve it in an equal way. An approach that includes equal valuation of impacts on human life wherever they occur may yield different global aggregate estimates than those reported below. For example, equalizing the value of a statistical life at a global average could leave total global damage unchanged but would increase markedly the share of these damages borne by the developing world. Equalizing the value at the level typical in developed countries would increase monetized damages several times, and would further increase the share of the developing countries in the total damage estimate.

Other aggregation methods can be used to adjust for differences in the wealth or incomes of countries in calculations of monetary damages. Because estimates of monetary damage tend to be a higher percentage of national GDP for low-income countries than for high-income countries, aggregation schemes that adjust for wealth or income effects are expected to yield higher estimates of global damages than those presented in this report.

The assessed literature quantifying total damages from 2-3°C warming provides a wide range of point estimates for damages, given the presumed change in atmospheric greenhouse gas concentrations. The aggregate estimates tend to be a few per cent of world GDP, with, in general, considerably higher estimates of damage to developing countries as a share of their GDP. The aggregate estimates are subject to considerable uncertainty, but the range of uncertainty cannot be

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[7] The value of a statistical life is defined as the value people assign to a change in the risk of death among the population.

[8] The concept of willingness to pay is indicative, based on expressed desires, available resources and information of a human being's preferences at a certain moment in time. The values may change over time. Also, other concepts (such as willingness to accept compensation for damage) have been advanced, but not yet widely applied, in the literature, and the interpretation and application of willingness to pay and other concepts to the climate problem may evolve.

gauged from the literature. The range of estimates cannot be interpreted as a confidence interval, given the widely differing assumptions and methodologies in the studies. As noted above, aggregation is likely to mask even greater uncertainties about damage components.

Regional or sectoral approaches to estimating the consequences of climate change include a much wider range of estimates of the net economic effects. For some areas, damages are estimated to be significantly greater and could negatively affect economic development. For others, climate change is estimated to increase economic production and present opportunities for economic development. For countries generally having a diversified, industrial economy and an educated and flexible labour force, the limited set of published estimates of damages are of the order one to a few per cent of GDP. For countries generally having a specialized and natural resource-based economy (e.g., heavily emphasizing agriculture or forestry), and a poorly developed and land-tied labour force, estimates of damages from the few studies available are several times larger. Small islands and low-lying coastal areas are particularly vulnerable. Damages from possible large-scale catastrophes, such as major changes in ocean circulation, are not reflected in these estimates. There is little agreement across studies about the exact magnitude of each category of damages or relative ranking of the damage categories.[9] Climate changes of this magnitude are not expected to be realized for several decades, and damages in the interim could be smaller. Damages over a longer period of time might be greater.[10]

IPCC does not endorse any particular range of values for the marginal damage of CO_2 emissions, but published estimates range between $5 and $125 (1990 U.S.) per tonne of carbon emitted now. This range of estimates does not represent the full range of uncertainty. The estimates are also based on models that remain simplistic and are limited representations of the actual climate processes in being and are based on earlier IPCC scientific reports. The wide range of damage estimates reflects variations in model scenarios, discount rates and other assumptions. It must be emphasized that the social cost estimates have a wide range of uncertainty because of limited knowledge of impacts, uncertain future technological and socio-economic developments, and the possibility of catastrophic events or surprises.

8. GENERIC ASSESSMENT OF RESPONSE STRATEGIES

A wide range of technologies and practices is available for mitigating emissions of carbon dioxide, methane, nitrous oxide and other greenhouse gases. There are also many adaptation measures available for responding to the impacts of climate change. All these technologies, practices and measures have financial and environmental costs as well as benefits. This section surveys the range of options currently available or discussed in the literature. The optimal mix of response options will vary by country and over time as local conditions and costs change.

A review of CO_2 mitigation options suggests that:

- A large potential for cost-effective **energy conservation and efficiency improvements** in energy supply and energy use exists in many sectors. These options offer economic and environmental benefits in addition to reducing emissions of greenhouse gases. Various of these options can be deployed rapidly due to small unit size, modular design characteristics and low lifetime costs.

  The options for **CO_2 mitigation in energy use** include alternative methods and efficiency improvements, among others in the construction, residential, commercial, agriculture and industry sectors. Not all cost-effective strategies are based on new technology; some may rely on improved information dissemination and public education, managerial strategies, pricing policies and institutional reforms.
- Estimates of the technical potential for **switching to less carbon-intensive** fuels vary regionally and with the type of measure and the economic availability of reserves of fossil and alternative fuels. These estimates also have to take account of potential methane emissions from leakage of natural gas during production and distribution.
- **Renewable energy technologies** (e.g., solar, hydroelectric, wind, traditional and modern biomass, and ocean thermal energy conversion) have achieved different levels of technical development, economic maturity and commercial readiness. The potential of these energy sources is not fully realized. Cost estimates for these technologies are sensitive to site-specific characteristics, resource variability and the form of final energy delivered. These cost estimates vary widely.
- **Nuclear energy**[11] is a technology that has been deployed for several decades in many countries. However, a number of factors have slowed the expansion of nuclear power, including: (a) wary public perceptions resulting from nuclear accidents, (b) not yet fully resolved issues concerning reactor safety, proliferation of fissile material, power-plant decommissioning and long-term disposal of nuclear waste, as well as, in some instances, lower-than-anticipated levels of demand for electricity. Regulatory and siting difficulties have increased construction lead times, leading to higher capital costs for this option in some countries. If these issues, including *inter alia* the social, political and environmental aspects mentioned above, can be resolved, nuclear energy has the potential to increase its present share in worldwide energy production.
- **CO_2 capture and disposal** may be ultimately limited for technical and environmental reasons, because not all forms of disposal ensure prevention of carbon re-entering the atmosphere.

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[9] Due to time lags between findings in the natural sciences, their use in determination of potential physical and biological impacts, and subsequent incorporation into economic analyses of climate change, the estimates of climate change damage are based mainly on the scientific results from the 1990 and 1992 IPCC reports.

[10] See the volume on the science of climate change and the volume on the scientific-technical analyses of impacts, adaptations and mitigation of climate change of the IPCC Second Assessment Report (SAR).

[11] For more information on the technical aspects of nuclear power, see the volume on the scientific-technical analyses of impacts, adaptations and mitigation of climate change of the IPCC Second Assessment Report (SAR).

- **Forestry** options, in some circumstances, offer large potential, modest costs, low risk and other benefits. Further, the potential modern use of biomass as a source of fuels and electricity could become attractive. Halting or slowing deforestation and increasing reforestation through increased silvicultural productivity and sustainable management programmes that increase agricultural productivity, the expansion of forest reserves and promotion of ecotourism are among the cost-effective options for slowing the atmospheric build-up of CO_2. Forestry programmes raise important equity considerations.[12]

There is also a wide range of available technologies and practices for reducing emissions of **methane** from such sources as natural gas systems, coal mines, waste dumps and farms. However, the issue of reduction of emissions related to food supply may imply trade-offs with rates of food production. These trade-offs must be carefully assessed, as they may affect the provision of basic needs in some countries, particularly in developing countries.

Most **nitrous oxide** emissions come from diffuse sources related to agriculture and forestry. These emissions are difficult to reduce rapidly. Industrial emissions of **nitrous oxide and halogenated compounds** tend to be concentrated in a few key sectors and tend to be easier to control. Measures to limit such emissions may be attractive for many countries.

The slow implementation of many of the technologically attractive and cost-effective options listed above has many possible explanations, with both actual and perceived costs being a major factor. Among other factors, capital availability, information gaps, institutional obstacles and market imperfections affect the rate of diffusion for these technologies. Identifying the reasons specific to a particular country is a precondition to devising sound and efficient policies to encourage their broader adoption.

Education and training as well as information and advisory measures are important aspects of various response options.

Many of the emission-reducing technologies and practices described above also provide other benefits to society. These additional benefits include improved air quality, better protection of surface and underground waters, enhanced animal productivity, reduced risk of explosions and fire, and improved use of energy resources.

Many options are also available for adapting to the impacts of climate change and thus reducing the damages to national economies and natural ecosystems. Adaptive options are available in many sectors, ranging from agriculture and energy to health, coastal zone management, offshore fisheries and recreation. Some of these provide enhanced ability to cope with the current impacts of climate variability. However, possible trade-offs between implementation of mitigation and adaptation measures are important to consider in future research. A summary of sectoral options for adaptation is presented in the volume on the scientific-technical analyses of impacts, adaptations and mitigation of climate change of the IPCC Second Assessment Report (SAR).

The optimal response strategy for each country will depend on the special circumstances and conditions which that country must face. Nonetheless, many recent studies and empirical observations suggest that some of the most cost-effective options can be most successfully implemented on a joint or cooperative basis among nations.

9. COSTS OF RESPONSE OPTIONS

It must be emphasized that the text in this section is an assessment of the technical literature and does not make recommendations on policy matters. The available literature is primarily from developed countries.

Cost concepts

From the perspective of this section on assessing mitigation or adaptation costs, what matters is the net cost (total cost less secondary benefits and costs). These net costs exclude the social costs of climate change, which are discussed in Section 7 above. The assessed literature yields a very wide range of estimates of the costs of response options. The wide range largely reflects significant differences in assumptions about the efficiency of energy and other markets, and about the ability of government institutions to address perceived market failures or imperfections.

Measures to reduce greenhouse gas emissions may yield additional economic impacts (for example, through technological externalities associated with fostering research and development programmes) and/or environmental impacts (such as reduced emissions of acid rain and urban smog precursors). Studies suggest that the secondary environmental benefits may be substantial but are likely to differ from country to country.

Specific results

Estimates of the cost of greenhouse gas emission reduction depend critically upon assumptions about the levels of energy efficiency improvements in the baseline scenario (that is, in the absence of climate policy) and upon a wide range of factors such as consumption patterns, resource and technology availability, the desired level and timing of abatement, and the choice of policy instruments. Policymakers should not place too much confidence in the specific numerical results from any one analysis. For example, mitigation cost analyses reveal the costs of mitigation relative to a given baseline, but neither the baseline nor the intervention scenarios should be interpreted as representing likely future conditions. The focus should be on the general insights regarding the underlying determinants of costs.

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[12] These are addressed in Section 4 above and in the volume on economic and social dimensions of climate change of the IPCC Second Assessment Report (SAR).

The costs of stabilizing atmospheric concentrations of greenhouse gases at levels and within a time-frame that will prevent dangerous anthropogenic interference with the climate system (the ultimate objective of the UNFCCC) will be critically dependent on the choice of emission timepath. The cost of the abatement programme will be influenced by the rate of capital replacement, the discount rate, and the effect of research and development.

Failure to adopt policies as early as possible to encourage efficient replacement investments at the end of the economic life of a plant and equipment (i.e., at the point of capital stock turnover) imposes an economic cost to society. Implementing emission reductions at rates that can be absorbed in the course of normal stock turnover is likely to be cheaper than enforcing premature retirement now.

The choice of abatement paths thus involves balancing the economic risks of rapid abatement now (that premature capital stock retirement will later be proved unnecessary) against the corresponding risk of delay (that more rapid reduction will then be required, necessitating premature retirement of future capital stock).

Appropriate long-run signals are required to allow producers and consumers to adapt cost-effectively to constraints on greenhouse gas emissions and to encourage research and development. Benefits associated with the implementation of any “no-regret” policies will offset, at least in part, the costs of a full portfolio of mitigation measures. This will also increase the time available to learn about climate risks and to bring new technologies into the marketplace.

Despite significant differences in views, there is agreement that energy efficiency gains of perhaps 10-30% above baseline trends over the next two to three decades can be realized at negative to zero net cost. (Negative net cost means an economic benefit.) With longer time horizons, which allow a more complete turnover of capital stocks, and which give research and development and market transformation policies a chance to impact multiple replacement cycles, this potential is much higher. The magnitude of such “no-regret” potentials depends upon the existence of substantial market or institutional imperfections that prevent cost-effective emission reduction measures from occurring. The key question is then the extent to which such imperfections and barriers can be removed cost-effectively by policy initiatives such as efficiency standards, incentives, removal of subsidies, information programmes and funding of technology transfer.

Progress has been made in a number of countries in cost-effectively reducing imperfections and institutional barriers in markets through policy instruments based on voluntary agreements, energy efficiency incentives, product efficiency standards and energy efficiency procurement programmes involving manufacturers, as well as utility regulatory reforms. Where empirical evaluations have been made, many have found the benefit-cost ratio of increasing energy efficiency to be favourable, suggesting the practical feasibility of realizing “no-regret” potentials at negative net cost. More information is needed on similar and improved programmes in a wider range of countries.

Infrastructure decisions are critical in determining long-term emissions and abatement costs because they can enhance or restrict the number and type of future options. Infrastructure decisions determine development patterns in transportation, urban settlement and land-use, and influence energy system development and deforestation patterns. This issue is of particular importance to developing countries and many economies in transition where major infrastructure decisions will be made in the near term.

If a carbon or carbon-energy tax is used as a policy instrument for reducing emissions, the taxes could raise substantial revenues, and how the revenues are distributed could dramatically affect the cost of mitigation. If the revenues are distributed by reducing distortionary taxes in the existing system, they will help reduce the excess burden of the existing tax system, potentially yielding an additional economic benefit (double dividend). For example, those European studies which are more optimistic regarding the potential for tax recycling show lower and, in some instances, slightly negative costs. Conversely, inefficient recycling of the tax revenues could increase costs. For example, if the tax revenues are used to finance government programmes that yield a lower return than the private sector investments foregone because of the tax, then overall costs will increase.

There are large differences in the costs of reducing greenhouse gas emissions among countries because of their state of economic development, infrastructure choices and natural resource base. This indicates that international cooperation could significantly reduce the global cost of reducing emissions. Research suggests that, in principle, substantial savings would be possible if emissions are reduced where it is cheapest to do so. In practice, this requires international mechanisms ensuring appropriate capital flows and technology transfers between countries. Conversely, a failure to achieve international cooperation could compromise unilateral attempts by a country or a group of countries to limit greenhouse gas emissions. However, estimates of so called leakage effects vary so widely that they provide little guidance to policymakers.

There has been more analysis to date of emission reduction potentials and costs for developed countries than for other parts of the world. Moreover, many existing models are not well-suited to study economies in transition or economies of developing countries. Much work is needed to develop and apply models for use outside developed countries (for example, to represent more explicitly market imperfections, institutional barriers, and traditional and informal economic sectors). In addition, the discussion below and the bulk of the underlying report deal with costs of response options at the national or regional level in terms of effect on GDP. Further analysis is required concerning effects of response options on employment, inflation, trade competitiveness and other public issues.

A large number of studies using both top-down and bottom-up approaches (see Box 1 for definitions) were reviewed. Estimates of the costs of limiting fossil fuel carbon dioxide emissions (expressed as carbon) vary widely and depend upon choice of methodologies, underlying assumptions, emission scenarios, policy instruments,

BOX 1. TOP-DOWN AND BOTTOM-UP MODELS

Top-down models are aggregate models of the entire macroeconomy that draw on analysis of historical trends and relationships to predict the large-scale interactions between the sectors of the economy, especially the interactions between the energy sector and the rest of the economy. Top-down models typically incorporate relatively little detail on energy consumption and technological change, compared with bottom-up models.

In contrast, bottom-up models incorporate detailed studies of the engineering costs of a wide range of available and forecast technologies, and describe energy consumption in great detail. However, compared with top-down models, they typically incorporate relatively little detail on nonenergy consumer behaviour and interactions with other sectors of the economy.

This simple characterization of top-down and bottom-up models is increasingly misleading as more recent versions of each approach have tended to provide greater detail in the aspects that were less developed in the past. As a result of this convergence in model structure, model results are tending to converge, and the remaining differences reflect differences in assumptions about how rapidly and effectively market institutions adopt cost-effective new technologies or can be induced to adopt them by policy interventions.

Many existing models are not well suited to study economies in transition or those of developing countries. More work is needed to develop the appropriate methodologies, data and models and to build the local institutional capacity to undertake analyses.

reporting year and other criteria. For specific results of individual studies, see the volume on economic and social dimenstions of climate change of the IPCC Second Assessment Report (SAR).

OECD countries. Although it is difficult to generalize, top-down analyses suggest that the costs of substantial reductions below 1990 levels could be as high as several per cent of GDP. In the specific case of stabilizing emissions at 1990 levels, most studies estimate that annual costs in the range of –0.5% of GDP (equivalent to a gain of about $60 billion in total for OECD countries at today’s GDP levels) to 2% of GDP (equivalent to a loss of about $240 billion) could be reached over the next several decades. However, studies also show that appropriate timing of abatement measures and the availability of low-cost alternatives may substantially reduce the size of the overall bill.

Bottom-up studies are more optimistic about the potential for low or negative cost emission reductions, and the capacity to implement that potential. Such studies show that the costs of reducing emissions by 20% in developed countries within two to three decades are negligible to negative. Other bottom-up studies suggest that there exists a potential for absolute reductions in excess of 50% in the longer term, without increasing, and perhaps even reducing, total energy system costs.

The results of top-down and bottom-up analyses differ because of such factors as higher estimates of no-regrets potential and technological progress, and earlier saturation in energy services per unit GDP. In the most favourable assessments, savings of 10-20% in the total cost of energy services can be achieved.

Economies in transition. The potential for cost-effective reductions in energy use is apt to be considerable, but the realizable potential will depend upon what economic and technological development path is chosen, as well as the availability of capital to pursue different paths. A critical issue is the future of structural changes in these countries that are apt to change dramatically the level of baseline emissions and the emission reduction costs.

Developing countries. Analyses suggest that there may be substantial low-cost fossil fuel carbon dioxide emission reduction opportunities for developing countries. Development pathways that increase energy efficiency, promote alternative energy technologies, reduce deforestation, and enhance agricultural productivity and biomass energy production can be economically beneficial. To embark upon this pathway may require significant international cooperation and financial and technology transfers. However, these are likely to be insufficient to offset rapidly increasing emissions baselines, associated with increased economic growth and overall welfare. Stabilization of carbon dioxide emissions is likely to be costly.

It should be noted that analyses of costs to economies in transition and developing countries typically neglect the general equilibrium effects of unilateral actions taken by developed countries. These effects may be either positive or negative and their magnitude is difficult to quantify.

It should also be noted that estimates of costs or benefits of the order of a few per cent of GDP may represent small differences in GDP growth rates, but are nevertheless substantial in absolute terms.

Preservation and augmentation of carbon sinks offer a substantial and often cost-effective component of a greenhouse gas mitigation strategy. Studies suggest that as much as 15-30% of 1990 global energy-related emissions could be offset by carbon sequestration in forests for a period of 50-100 years. The costs of carbon sequestration, which are competitive with source control options, may differ among regions of the world.

Control of emissions of other greenhouse gases, especially methane and nitrous oxide, can provide significant cost-effective opportunities in some countries. About 10% of anthropogenic methane emissions could be reduced at negative or low cost using available mitigation options for such methane sources as natural gas systems, waste management and agriculture.

10. INTEGRATED ASSESSMENT

Integrated assessment models combine knowledge from a wide range of disciplines to provide insights that would not be observed through traditional disciplinary research. They are used to explore possible states of human and natural systems, analyze key questions related to policy formulation and help set research priorities. Integration helps coordinate assumptions from different disciplines and allows feedbacks and interactions absent from individual disciplines to be analyzed. However, the results of such analyses are no better than the information drawn from the underlying economic, atmospheric and biological sciences. Integrated assessment models are limited both by the underlying knowledge base upon which they draw and by the relatively limited experiential base.

Most current integrated assessment models do not reflect the specific social and economic dynamics of the developing and transition economies well; for example, none of the existing models addresses most market imperfections, institutional barriers, or the operation of the informal sector in these countries. This can lead to biases in global assessments when mitigation options and impacts on developing or transition economies are valued as if their economies operated like those in the developed countries.

While relatively new, integrated assessment models of climate change have evolved rapidly. Integrated assessment models tend to fall into two categories: *policy evaluation* and *policy optimization* models. Policy evaluation models are rich in physical detail and have been used to analyze the potential for deforestation as a consequence of interactions between demographics, agricultural productivity and economic growth, and the relationship between climate change and the extent of potentially malarial regions. Policy optimization models optimize over key variables (e.g., emission rates, carbon taxes) to achieve formulated policy goals (e.g., cost minimization or welfare optimization).

Key uncertainties in current integrated assessments include the sensitivity of the climate system to changes in greenhouse gas concentrations, the specification and valuation of impacts where there are no markets, changes in national and regional demographics, the choice of discount rates, and assumptions regarding the cost, availability and diffusion of technologies.

11. AN ECONOMIC ASSESSMENT OF POLICY INSTRUMENTS TO COMBAT CLIMATE CHANGE

Governments may have different sets of criteria for assessing international as well as domestic greenhouse policy instruments. Among these criteria are efficiency and cost-effectiveness, effectiveness in achieving stated environmental targets, distributional (including intergenerational) equity, flexibility in the face of new knowledge, understandability to the general public, and consistency with national priorities, policies, institutions and traditions. The choice of instruments may also partly reflect a desire on the part of governments to achieve other objectives, such as sustainable economic development, meeting social development goals and fiscal targets, or influencing pollution levels that are indirectly related to greenhouse gas emissions. A further concern of governments may lie with the effect of policies on competitiveness.

The world economy and indeed some individual national economies suffer from a number of price distortions which increase greenhouse gas emissions, such as some agricultural and fuel subsidies and distortions in transport pricing. A number of studies of this issue indicate that global emission reductions of 4-18%, together with increases in real incomes, are possible from phasing out fuel subsidies. For the most part, reducing such distortions could lower emissions and increase economic efficiency. However, subsidies are often introduced and price distortions maintained for social and distributional reasons, and they may be difficult to remove.

Policy instruments may be identified at two different levels: those that might be used by a group of countries and those that might be used by individual nations unilaterally or to achieve compliance with a multilateral agreement.

A group[13] of countries may choose from policy measures and instruments including encouragement of voluntary actions and further research, tradable quotas, joint implementation (specifically activities implemented jointly under the pilot phase[14]), harmonized domestic carbon taxes, international carbon taxes, nontradable quotas and various international standards. If the group did not include all major greenhouse gas emitters, then there might be a tendency for fossil fuel use to increase in countries not participating in this group. This outcome might reduce the international competitiveness of some industries in participating countries as well as the environmental effectiveness of the countries' efforts.

At both the international and national levels, the economic literature indicates that instruments that provide economic incentives, such as taxes and tradable quotas/permits, are likely to be more cost-effective than other approaches. Uniform standards among groups of countries participating in an international agreement are likely to be difficult to achieve. However, for one group of countries there has been agreement on the application of some uniform standards.

At the international level, all of the potentially efficient market-based instruments could be examined during the course of future negotiations. A tradable quota system has the disadvantage of making the marginal cost of emissions uncertain, while a carbon tax (and related instruments) has the disadvantage of leaving the effect on the level at which emissions are controlled uncertain. The weight given to the importance of reducing these different types of uncertainty would be one crucial factor in further evaluating these alternative instruments. Because of the lack of appropriate scientific knowledge, there would remain a high degree of uncertainty about the results of limiting emissions at specific levels. The adoption of

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[13] The group could contain only a few, quite a number, or even all countries.

[14] See decision 5/CP.1 of the first Conference of the Parties (COP1) to the UNFCCC.

either a tradable quota scheme or international taxes would have implications for the international distribution of wealth. The distributional consequences would be the subject of negotiation. To insure the practicability of such instruments, there is a need for additional studies on the possible design of tradable quotas and harmonized taxes and on the institutional framework in which they might operate.

Individual countries that seek to implement mitigation policies can choose from among a large set of potential policies and instruments, including carbon taxes, tradable permits, deposit refund systems (and related instruments) and subsidies, as well as technology standards, performance standards, product bans, direct government investment and voluntary agreements. Public education on the sustainable use of resources could play an important part in modifying consumption patterns and other human behaviour. The choice of measures at the domestic level may reflect objectives other than cost-effectiveness, such as meeting fiscal targets. Revenue from carbon taxes or auctioned tradable permits could be used to replace existing distortionary taxes. The choice of instruments may also reflect other environmental objectives, such as reducing non-greenhouse pollution emissions, or increasing forest cover, or other concerns such as specific impacts on particular regions or communities.

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