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Climate uncertainty and policymaking

A policy maker's view

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Summary

Our current understanding of climate science, with all its uncertainties, makes it clear that dangerous climate change is occurring and that an urgent response is required.

To deal with this, in 1995 the United Nations Framework Convention [UNFCCC] entered into force with the objective of achieving safe and stable future greenhouse gas concentration. In 2009 a maximum global temperature target of staying within two degrees centigrade increase above pre-industrial levels was agreed at the Fifteenth Conference of the Parties [COP-15] to the UNFCCC in Copenhagen. However, we are still far from having an effective international mitigation strategy that is compliant with this decision.

Uncertainty in the science and in the methods and tools of the scientists has led to confusion in the policymaking process which itself has been complicated by time-consuming debates about justice and how to apply the UNFCCC's principle of equity.

These notes examine the risks and uncertainties associated with the science, the scientists' tools and methods and the policymaking process and consider how they might be integrated and communicated to policy makers

Climate uncertainty is a characteristic of the climate system. As our knowledge of climate science increases, perceptions of the types and levels of uncertainty may increase or decrease. Assessment of risk and uncertainty in climate change therefore involves a large degree of subjective judgement, erring on the side of the UNFCCC principle of precaution.

Future emissions are a product of complex dynamic systems, determined by driving forces such as demographic and socio-economic development and technological change. However, in order to achieve and maintain safe levels of greenhouse gas [ghg] concentration and temperature, there are two things we can do: reduce ghg emissions and protect the land and ocean sinks. To guide this we need to estimate future global emissions contraction that is consistent with the two degree limit and agree terms for how this is to be shared.

The IPCC emissions scenarios developed for climate modelling are simply approximations of future emissions and the various models that process them usually arrive at different conclusions for a given scenario. A new generation of scenarios for the Fifth Assessment Report offers some improvement. The climate models that process them are in a continuing state of development, but policy makers are obliged to make decisions in time and cannot wait for perfection.

The principle of precaution should have profound influence on matters in this context of complexity and uncertainty. Article 3.3 of the Convention makes specific reference to this: "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".

We must openly recognise uncertainty in all its forms and respond to it rationally and in a precautionary manner. Knowledge of the science and its uncertainties must be distilled to support the quantification of limits on temperature, concentrations and emissions as a first step in defining a global mitigation strategy. GCI's Contraction and Convergence model is proposed in this light.

1. Introduction

The International Panel on Climate Change (IPCC) published its First Assessment Report in 1990.

In May 1992 the UNFCCC international treaty was opened for signature. It committed signatory nations to achieve a safe and stable level of greenhouse gas concentrations in the atmosphere, according to the principles of equity and precaution. It entered into force in March 1994.

By December 2010, about 140 nations had signed the Copenhagen Accord which sets a target for global temperature increase to be kept within two degrees centigrade above pre-industrial levels. The Accord acknowledges that staying below 2 degrees may not be sufficient and includes a review in 2015 of the potential need to aim for staying below 1.5 degrees Celsius, or an atmospheric CO_2 concentration of 350 ppm.

The 2-degree goal had previously been agreed by G8 leaders in Italy in July 2009. At the same time they had also agreed that they should collectively cut emissions by 80% by 2050, and that the world should cut its emissions by 50% by the same date.

After sixteen years and three more IPCC Assessment Reports, the parties to the UN Convention have set a target for its core objective. There is still a very long way to go before a UNFCCC-compliant mitigation agreement is opened for signature.

The policymaking process has been bogged down in the politics of justice and equity whilst ghg concentrations have been rising at a dangerous rate and climate science has become more uncertain in some respects. Uncertainty in the science and in the methods and tools used by climate scientists has led to confusion in the policymaking process.

Climate risk is a measure of our perception of climate damages arising from climate change. UNFCCC signatories have committed to reduce that risk by reducing global ghg emissions to safe levels and protecting the sinks, according to the principle of precaution. In order to define and achieve the required level of stability, we must understand climate uncertainty and provide for it in the policymaking process that must lead to agreed quantified global and national targets for emissions reduction.

These notes attempt to analyse the risks and uncertainties and consider how they might be effectively communicated to policy makers when deciding on action in mitigation of dangerous climate change.

2. Climate uncertainty

2.1 Climate forcing and climate system responses

The following extract from the Royal Society's recent summary of the science of climate change (Ref. 18, The Royal Society, September 2010) encapsulates the fundamentals of the science most succinctly:

"Climate change on a global scale, whether natural or due to human activity, can be initiated by processes that modify either the amount of energy absorbed from the Sun, or the amount of infrared energy emitted to space.

Climate change can therefore be initiated by changes in the energy received from the Sun, changes in the amounts or characteristics of greenhouse gases, particles and clouds, or changes in the reflectivity of the Earth's surface. The imbalance between the absorbed and emitted radiation that results from these changes is referred to here as "climate forcing" (sometimes known as "radiative forcing") and given in units of W/m^2. A positive climate forcing will tend to cause a warming, and a negative forcing a cooling. Climate changes act to restore the balance between the energy absorbed from the Sun and the infrared energy emitted into space.

In principle, changes in climate on a wide range of timescales can also arise from variations within the climate system due to, for example, interactions between the oceans and the atmosphere; this is referred to as "internal climate variability". Such internal variability can occur because the climate is an example of a chaotic system: one that can exhibit complex unpredictable internal variations even in the absence of climate forcings ".

If we agree with the Society's view that climate is a chaotic system then uncertainty must be a characteristic of climate. Further, as our knowledge of climate science increases, perceptions of the types and levels of uncertainty may increase or decrease.

Uncertainties of climate projections for policymaking can be considered in three groups:

- Uncertainties about future climate forcings,
- Uncertainties about how the climate system will respond to past and future forcings,
- Limitations of climate scientists' models and methods for developing climate projections.

The World Meteorological Organisation (WMO) has calculated that total radiative forcing of all ghg's increased by 1% in 2009 and rose by 27.5% between 1990 to 2009.

The overall effect of changes resulting from climate forcing is called "climate sensitivity". This is the amount of climate change, as measured by the equilibrium change in the average global temperature, caused by a given amount of climate forcing. Equilibrium may be reached some considerable time after the forcing. Climate sensitivity is usually expressed as the temperature change that eventually results from a hypothetical doubling of CO_2 concentrations since pre-industrial times. It is often given as a forcing of approximately 3.6 W/m^2. This is reckoned to equate to a temperature change in the range 2.0 - 4.5^oC, with a most likely value of 3^oC.

Future climate forcing depends largely on the choices that current and future society makes regarding energy production and use and land use. These have not yet been fully integrated into climate forcing scenarios and evaluated across a range of models. Sections 3 and 4 of these notes outline the wider limitations of emissions scenarios and climate models.

Climate forcings and system responses by level of certainty

Aspects with Wide agreement	Aspects with Consensus & ongoing debate	Aspects Not well understood
Climate forcing by ghg's	Solar radiation variations	Albedo effect
CO_2 concentration increase	Particles effect	Clouds and particle impact
Other ghg increases	Water vapour effect	Carbon cycle feedbacks
Current CO_2 uptake by sinks	Climate sensitivity	Future CO_2 uptake by sinks
Surface temperature warming	Anthropogenic forcings	Ice cap melt rates
Atmosphere temperature (troposphere) warming	Volcanic eruption short term forcing	Sea level change due to ice melt
Ocean temperature warming (upper 700m)	Temperature projections	Meridianal overturning circulation (MOC) in oceans
Sea level increase		North Atlantic Oscillation (NAO) change
Glacial melting		Regional climate variants
Sea ice coverage reduction		Abrupt climate changes and tipping points
		Extreme events
		Ecosystem process changes

Sources: US National Research Council 05/2010 and The Royal Society 09/2010 (Section 7 Refs. 14 & 18)..

Brief notes on the above forcings and responses can be found in Appendix A. The IPCC also provides a classification of climate uncertainties in the Technical Summary TS.6 Robust Findings and Key Uncertainties of the IPCC AR4 WGI report (see Ref. 4).

Policy maker perceptions of climate risk and uncertainty are largely dependent on information provided by the International Panel on Climate Change (IPCC). This scientific intergovernmental body does not carry out its own original research but bases its assessments mainly on peer reviewed published scientific literature. It has two separate but related functions:

- reviewing and assessing the most recent scientific, technical and socio-economic information relevant to the understanding of climate change,

- publishing special reports on climate change topics relevant to the implementation of the UNFCCC.

The special reports for policy makers and the underlying detailed reports are the paramount sources of information available to policy makers and their advisers worldwide. These notes refer to the various reports of Working Groups I and III as being representative of the information available to policy makers.

The scope of the Working Group I Summary for Policy Makers (SPM) covers:

- changes in human and natural drivers of climate, such as ghg emissions,
- climate change in the atmosphere, cryosphere, oceans, including sea-level rise,
- attribution of climate change,
- projection of climate changes over the rest of the century.

The scope of the Working Group III SPM covers:

- trends in anthropogenic greenhouse emissions,
- projected emissions to the year 2100 under various scenarios,
- reductions in emissions in the short, medium and longer term,
- the technical feasibility and cost of reducing ghg-emissions for various sectors,
- estimates of the economy-wide costs of achieving stabilisation targets.

Climate uncertainty is a prominent theme in the reports of both Working Groups. These notes focus on their treatment of:

WGI: climate forcings and system responses

WGIII: greenhouse gas emission trends, projections and selected stabilisation levels.

2.2 Accounting for climate risk and uncertainty

In 2005, IPCC published guidance notes for its Working Group lead authors on addressing uncertainties. The notes instructed authors on how to treat issues of uncertainty and confidence in the Fourth Assessment Report. They attempted to provide a consistent language for assessing the current level of understanding on key issues. Lead authors were instructed to precede statements on confidence or uncertainty with a general summary of the corresponding state of knowledge. (Ref. 3. 'Guidance notes for Lead Authors of the Fourth Assessment Report on Addressing Uncertainties', IPCC 2005).

Authors were told to "communicate carefully using calibrated language". Three forms of language were given in tabular form as shown below to describe different aspects of confidence and uncertainty and to provide consistency across the AR4;

- Quantitively calibrated levels of confidence
- Likelihood scale, which supported a probabilistic assessment of well defined outcomes,
- Qualitative definition of uncertainty.

Each Working Group was left to decide which of these it would use. WGI, responsible for the Physical Science Basis, chose to use Levels of confidence and the Likelihood scale. WGIII chose Qualitative definition of uncertainty; the other approaches of 'likelihood' and 'confidence' were not used by WGIII as "human choices are considered and none of the other approaches used provides sufficient characterisation of the uncertainties involved in mitigation".

.WGI: Quantitively calibrated levels of confidence

Confidence Terminology	Degree of confidence in being correct
Very high confidence	At least 9 out of 10 chance
High confidence	About 8 out of 10 chance
Medium confidence	About 5 out of 10 chance
Low confidence	About 2 out of 10 chance
Very low confidence	Less than 1 out of 10 chance

Source: IPCCAR4 WGI, 'The Physical Science Basis', Chapter 1.6 Assessments of climate change and uncertainties.

WGI: 'Likelihood Scale'

Likelihood Terminology	Likelihood of the occurrence/ outcome
Virtually certain	> 99% probability
Extremely likely	> 95% probability
Very likely	> 90% probability
Likely	> 66% probability
More likely than not	> 50% probability
About as likely as not	33 to 66% probability
Unlikely	< 33% probability
Very unlikely	< 10% probability
Extremely unlikely	< 5% probability
Exceptionally unlikely	< 1% probability

Source: IPCCAR4 WGI, 'The Physical Science Basis', Chapter 1.6 Assessments of climate change and Uncertainties.

WGI, The Physical Science Basis, Chapter 1.6 Assessments of Climate Change and Uncertainties (Ref. 4), recognised two primary types of uncertainty:

"Uncertainties can be classified in several different ways according to their origin. Two primary types are ‘value uncertainties’ and ‘structural uncertainties’:

Value uncertainties arise from the incomplete determination of particular values or results, for example, when data are inaccurate or not fully representative of the phenomenon of interest.

Structural uncertainties arise from an incomplete understanding of the processes that control particular values or results, for example, when the conceptual framework or model used for analysis does not include all the relevant processes or relationships.

Value uncertainties are generally estimated using statistical techniques and expressed probabilistically. Structural uncertainties are generally described by giving the authors’ collective judgment of their confidence in the correctness of a result. In both cases, estimating uncertainties is intrinsically about describing the limits to knowledge and for this reason involves expert judgment about the state of that knowledge. A different type of uncertainty arises in systems that are either chaotic or not fully deterministic in nature and this also limits our ability to project all aspects of climate change".

It is not clear what statistical techniques and probability estimates are used in the assessment of climate change uncertainties that follows this IPCC statement. As can be seen from Chapter 2.9.1, Uncertainties in Radiative Forcing (see Appendix B below), there is a high degree of subjective judgement involved. 2.9.1 discusses the uncertainty assessment of forcing agents. Evidence for a forcing is given a grade (A to C), with A implying strong evidence and C insufficient evidence. The degree of consensus among forcing estimates is given a 1, 2 or 3 grade, where grade 1 implies a good deal of consensus and grade 3 implies an insufficient consensus. From these two factors, a level of scientific understanding is determined.

The report states that only 'well established' RF's are quantified, where well established implies that there is qualitatively sufficient evidence and sufficient consensus from published results to estimate a central RF estimate and a range. The quantified RF assessments that follow in the report are not accompanied by identification of source or statements of uncertainty.

WGIII: Qualitative definition of uncertainty

Box 2.1 Risk and uncertainty vocabulary used in this report

Uncertainty cannot always be quantified, and thus the vocabulary displayed in Table 2.2 is used to qualitatively describe the degree of scientific understanding behind a finding or about an issue. See text for discussion of Table 2.2's dimensions, the amount of evidence and the level of agreement.

Tabel 2.2: *Qualitative definition of uncertainty*

Level of agreement (on a particular finding)			
	High agreement, limited evidence	High agreement, medium evidence	High agreement, much evidence
	Medium agreement, limited evidence	Medium agreement, medium evidence	Medium agreement, much evidence
	Low agreement, limited evidence	Low agreement, medium evidence	Low agreement, much evidence

Amount of evidence (number and quality of independent sources)

Source: IPCC Guidance Notes on risk and uncertainty (2005).

Source: IPCC AR4 WGIII 'Mitigation of Climate Change', Chapter 2, Guidance notes on risk and uncertainty.

WGIII 'Mitigation of Climate Change', Chapter 2 gives the following guidance on risk and uncertainty:

"The fundamental distinction between 'risk' and 'uncertainty' is as introduced by economist Frank Knight (1921), that risk refers to cases for which the probability of outcomes can be ascertained through well-established theories with reliable complete data, while uncertainty refers to situations in which the appropriate data might be fragmentary or unavailable."

AR4 WGIII 'Summary for Policymakers' (see Appendix D), when presenting stabilisation scenarios for mitigation in the longer term, issues the following caveat:

"Feedbacks between the carbon cycle and climate change affect the required mitigation for a particular stabilization level of atmospheric carbon dioxide concentration. These feedbacks are expected to increase the fraction of anthropogenic emissions that remains in the atmosphere as the climate system warms. Therefore, the emission reductions to meet a particular stabilization level reported in the mitigation studies assessed here might be underestimated".

Similar caveats for uncertainty about feedbacks are repeated throughout the reports of WGI and WGIII. The WGI SPM states that water vapour changes represent the largest feedback affecting climate sensitivity and that cloud feedbacks remain the largest source of uncertainty with climate sensitivity. The WGI Technical Summary (TS6 Robust Findings and Key Uncertainties) lists as a key uncertainty the considerable difference between models in their estimates of different feedbacks in the climate system. The possibility of non-linear abrupt climate change is not addressed.

There was no identifiable common methodology used by the two groups. None of the above language tables were used by both Working Groups, perhaps defeating the objective of consistency.

Across IPCC AR4 in general, the mainstream science embodied in the reports sometimes discusses possible outcomes in terms of fairly precise probability distributions, yet describes its assessments in terms of ‘uncertainties’. The decision framework is rarely made explicit, and sometimes is not clear. The climate models on which the assessments are based are themselves diverse. They provide numerous observations on possibilities out of their diversity; in addition, each generates numerous results from repeated experiments. There are many points at which judgment rather than experience informs the model relationships. (Ref. 10, The Garnaut Review, 1.2 Risk and uncertainty, 2008).

In 2010, the InterAcademy Council (IAC) was asked by the UN and IPCC to assemble a committee to review the processes and procedures of the IPCC and make recommendations for change that would enhance the authoritative nature of the IPCC reports. The Committee made the following recommendations concerning the IPCC's treatment of uncertainty:

1) All Working Groups should use the Qualitative Definition of Uncertainty Scale in their Summary for Policy Makers and Technical Summary, as suggested in IPCC’s uncertainty guidance for the Fourth Assessment Report. This scale may be supplemented by a quantitative probability scale, if appropriate.

2) Lead Authors should provide a traceable account of how they arrived at their ratings for level of scientific understanding and likelihood that an outcome will occur.

3) Quantitative probabilities (as in the Likelihood Scale) should be used to describe the probability of well-defined outcomes only when there is sufficient evidence Authors should indicate the basis for assigning a probability to an outcome or event (e.g., based on measurement, expert judgment, and/or model runs).

4) The Confidence Scale should not be used to assign subjective probabilities to ill-defined outcomes.

5) The Likelihood Scale should be stated in terms of probabilities (numbers) in addition to words to improve understanding of uncertainty.

6) Where practical, formal expert elicitation procedures should be used to obtain subjective probabilities for key results.

(Ref. 17, 'Climate Change Assessments - Review of the processes and procedures of the IPCC', InterAcademy Council, August 2010).

None of the above will change the underlying uncertainties but they might better inform policy makers' perception of risk.

Climate scientists often rely on the successful simulation of past climate change for evidence of their models' suitability for projection of future climate. However, there is a lack of transparency in the decisions and choices made by the scientists and the way in which their models perform. IPCC authors do not compensate for this in their reports; it is possible that they exacerbate the problem by misusing subjective methods, as noted by the IAC. Policy makers are given inadequate information on uncertainties and the subjective judgements made by scientists.

2.3 Impact on policymaking

The IPCC view of risk and uncertainty is key to the policymaking challenge. WGI, responsible for physical science, makes the following distinction:

- Risk refers to cases for which the quantified probability of outcomes and their consequences can be ascertained through well-established theories with reliable, complete data.

- Uncertainty refers to situations in which the appropriate data may be fragmentary or unavailable.

Climate change, the greatest threat to mankind, is resistant to reliable methodological quantification. In many cases it is not possible to "ascertain the probability of outcomes and their consequences through well-established theories with reliable and complete data". Both the risk and uncertainty of climate change require a very large degree of subjective judgement, erring on the side of precaution.

In particular, policy makers and their advisers find themselves with insufficient information on climate forcing and the extent of climate system responses and impacts from that. It is not clear what information will guide them in making decisions on UNFCCC-compliant concentrations and emissions targets. Failure to provide this has led to a wide range of guesses in the UNFCCC debate so far. Proposed limits to CO_2 concentration levels in the atmosphere have ranged from 350ppm to 550ppm and beyond.

In 2009 the Copenhagen Accord set a limit on temperature increase of 2^o Centigrade above pre-industrial levels. This target requires a commensurate concentration level to be agreed; the ways and means of achieving this are still far from clear.

The two degree limit is the target temperature at equilibrium. Achieving it will require reliable calculation or judgement of positive and negative climate forcings and consequent climate system responses over many decades. In view of the many unquantifiable uncertainties scientists and policy makers face, the UNFCCC guiding principle of precaution assumes very great significance.

Beyond this immediate challenge, continuing climate uncertainty will require a decision-making process that allows for re-evaluation of targets and progress in the light of that uncertainty and unpredicted change.

3. *Future emissions uncertainty*

3.1 IPCC SRES Scenarios

IPCC published the 'Special Report on Emissions Scenarios' in 2000. These scenarios were intended to assist in climate change analysis, including climate modelling and the assessment of impacts, adaptation, and mitigation. They have been used extensively since then, particularly in the development of the IPCC Assessment Reports. IPCC warned at the outset that there was considerable uncertainty about the emissions profiles represented by the scenarios:

"Future greenhouse gas (GHG) emissions are the product of very complex dynamic systems, determined by driving forces such as demographic development, socio-economic development, and technological change. Their future evolution is highly uncertain. Scenarios are alternative images of how the future might unfold and are an appropriate tool with which to analyse how driving forces may influence future emission outcomes and to assess the associated uncertainties. The possibility that any single emissions path will occur as described in scenarios is highly uncertain".

Any scenario necessarily includes subjective elements and is open to various interpretations. Preferences for the scenarios presented here vary among users. No judgment is offered in this Report as to the preference for any of the scenarios and they are not assigned probabilities of occurrence, neither must they be interpreted as policy recommendations". (Ref. 1, IPCC 2000).

Four different narrative storylines were developed by the IPCC (see Appendix C). Each storyline represents different demographic, social, economic, technological, and environmental developments. Scenarios were developed to cover a wide range of driving forces of GHG and sulphur emissions and are representative of the published literature. Each scenario represents a specific quantitative interpretation of one of the four storylines. All the scenarios based on the same storyline constitute a scenario “family”.

Six models were used to develop several different scenarios for each storyline in order to examine the range of outcomes arising from a range of models that use similar assumptions about driving forces. One advantage of a multi-model approach is that the resultant forty SRES scenarios together encompass the current range of uncertainties of future GHG emissions arising from different characteristics of these models. This is in addition to the uncertainties that arise from scenario driving forces such as demographic, social and economic, and broad technological developments that drive the models.

No scenarios were included that explicitly assume implementation of the United Nations Framework Convention on Climate Change (UNFCCC) or the emissions targets of the Kyoto Protocol.

IPCC recommended that a range of SRES scenarios with a variety of assumptions regarding driving forces was used in any analysis. Thus more than one family should be used in most analyses. The important uncertainties ranging from driving forces to emissions may be different in different applications. For mitigation analysis, variation in both emissions and socio-economic characteristics may be necessary.

IPCC said that there is no single most likely, “central”, or “best-guess” scenario. Probabilities or likelihood are not assigned to individual SRES scenarios. None of the SRES scenarios represents an estimate of a central tendency for all driving forces or emissions, such as the mean or median, and none should be interpreted as such. Emissions from another scenario, or the population from one and economic development path from another, should not be combined.

IPCC also cautioned that further development was required to account for feedbacks and made the following recommendation:

"Integration into models emissions of particulate, hydrogen, or nitrate aerosol precursors, and processes, such as feedback of climate change on emissions, that may significantly influence scenario results and analyses".

It should also be noted that the IPCC scenarios cover very long time periods (1990-2100) so as to capture the large inertia involved in the climate system and that uncertainties obviously play a major role over such a long period.

3.2 European Commission ENSEMBLES Project Scenarios

The ENSEMBLES Project was completed in November 2009. It was intended to help inform researchers, decision makers, businesses and the public by providing them with climate information obtained through the use of the latest climate modelling and analysis tools. The value of the project was in running multiple climate models (‘ensembles’); a method known to improve the accuracy and reliability of forecasts. The project output is a range of future predictions assessed to decide which of the outcomes are more likely (probable) than the others. This probabilistic information is intended to assist policy makers in determining future strategies to address climate change. The project’s principal objective was to allow the uncertainty in climate projections to be measured.

Early on in the project a critique of the SRES Scenarios was carried out to determine whether they were suitable for use by ENSEMBLES (Ref. 2, 'Critical assessment of the IPCC SRES scenarios', 2005). The report found that there were inconsistencies between the SRES scenarios and more recent scenarios and data, particularly with respect to population, GDP values and rates of economic convergence. However the report concluded that:

"although the IPCC SRES emissions scenarios leave much to be desired, they constitute the standard scenarios, and their quality is not worse, and often better than alternative emissions scenarios. Moreover, much of the critique is directed at the demographic and economic details of the scenarios. This may have lead to a small upward bias of emissions projection. The range of future greenhouse gas emissions is undisputed, however. It is therefore appropriate that the ENSEMBLES GCM's (General Circulation Models) run the SRES scenarios".

The final ENSEMBLES report in November 2009 made it clear that significant advances had been made by the project beyond the SRES standard:

"These (SRES) scenarios, however, do not include climate policy. Recently, attention has focused on scenarios that aim to reach radiative forcing targets below 3W/m2 in 2100 (vanVuuren et al., 2007). Such scenarios would be able to keep global mean temperature increase below 2℃ with a probability higher than 50% . A stated aim of the EC is to keep anthropogenic warming below 2℃ by 2100, and the ENS EMBLES project included the development of a stabilisation scenario to help investigate this area of climate research.

"For the ENSEMBLES project, a scenario based on the SRES A1B scenario but aiming for 2.9 W/m2 in 2100 was developed, called E1 (Lowe et al., 2009). The E1 scenario has an emissions peak around 2010 and eventually stabilises at 450 ppm CO_2-equivalent in the 22nd century. Low stabilisation targets are mostly reached via so-called overshoot emission profiles – based on cost considerations (den Elzen and vanVuuren, 2007). The E1 scenario was developed using the IMAGE 2.4 Integrated Assessment Model, which simulates in detail the energy system, land use and carbon cycle (MNP, 2006; van Vuuren et al., 2007). ….This is the same as the methodology currently being developed by the IPCC for its Fifth Assessment Report, and the work done in ENSEMBLES should help inform the work of the IPCC. (Ref. 11, 'ENSEMBLES: Climate change and its impacts - summary of research and results', European Commission, November 2009)".

3.3 Scenarios for IPCC Fifth Assessment Report

Extensive uncertainties will continue to exist about future forcings of and responses to climate change. Future scenarios will be used to explore the potential consequences of different response options. A new process for creating plausible scenarios has been described in "The next generation of scenarios for climate change research and assessment", Nature, Vol. 463, February 2010, (see Ref. 13).

Since SRES was published, there is nearly a decade of new economic data, information about emerging technologies, and observations of environmental factors such as land use and land cover change that should be reflected in the new scenarios.

End users, including policy makers, have new information needs that require changes in scenario focus. For example, there is a high level of interest in climate scenarios that explore different approaches to mitigation in addition to the traditional ‘no climate policy’ scenarios. As a result, an increasing number of scenarios are being developed to explore conditions consistent with managed long-run climate outcomes, including a 2^{o}C maximum global average surface temperature increase over pre-industrial levels, as well as ‘overshoot’ scenarios in which radiative forcing peaks and then declines to a target level. In addition, increasing attention to the impacts of climate change and the need for adaptation has spawned an interest in climate scenarios that focus on the next two to three decades with higher spatial and temporal resolution and improved representation of extreme events.

Climate models require data on the time-evolving emissions or concentrations of radiatively active constituents. The research community identified emission scenarios from the peer reviewed literature as a plausible pathway to reaching target radiative forcing trajectories. These were called representative concentration pathways (RCP's).

Table 1 | The four RCPs

Name	Radiative forcing	Concentration (p.p.m.)	Pathway	Model providing RCP*	Reference
RCP8.5	>8.5 W m^{-2} in 2100	>1,370 CO_2-equiv. in 2100	Rising	MESSAGE	[55,56]
RCP6.0	~6 W m^{-2} at stabilization after 2100	~850 CO_2-equiv. (at stabilization after 2100)	Stabilization without overshoot	AIM	[57,58]
RCP4.5	~4.5 W m^{-2} at stabilization after 2100	~650 CO_2-equiv. (at stabilization after 2100)	Stabilization without overshoot	GCAM	[48,59]
RCP2.6	Peak at ~3 W m^{-2} before 2100 and then declines	Peak at ~490 CO_2-equiv. before 2100 and then declines	Peak and decline	IMAGE	[60,61]

* MESSAGE, Model for Energy Supply Strategy Alternatives and their General Environmental Impact, International Institute for Applied Systems Analysis, Austria; AIM, Asia-Pacific Integrated Model, National Institute for Environmental Studies, Japan; GCAM, Global Change Assessment Model, Pacific Northwest National Laboratory, USA (previously referred to as MiniCAM); IMAGE, Integrated Model to Assess the Global Environment, Netherlands Environmental Assessment Agency, The Netherlands.

Representative Concentration Pathways (RCP's)

The IPCC as a potential user of the RCP's, requested the development of new scenarios compatible with the literature on reference and mitigation scenarios. The criteria established by the research community included:

- compatibility 'with the full range of stabilisation, mitigation, and reference emissions scenarios available in the current scientific literature';
- a manageable and even number of scenarios (to avoid the inclination with an odd number of cases to select the central case as the 'best estimate');
- an adequate separation of the radiative forcing pathways in the long term in order to provide distinguishable forcing pathways for the climate models; and
- the availability of model outputs for all relevant forcing agents and land use.

The scientific community used these criteria to identify four radiative forcing pathways. A new Integrated Assessment Modelling Consortium (IAMC) then assembled a list of candidate scenarios for each radiative forcing level from the peer-reviewed literature. An individual scenario was then selected for each RCP (Table 1 above).

The RCP's provide a starting point for new research. However, it is important to recognise their uses and limits. They are neither forecasts nor policy recommendations, but were chosen to map a broad range of climate outcomes. The RCP's cannot be treated as a set with consistent internal logic, according to the authors.

Two sets of climate projections will be developed using the RCP's, one focusing on the near term (to 2035) and the other extending to 2100 and beyond. These extended pathways will be used for comparative analysis of the long-term climate and environmental implications of different mitigation scenarios or pathways. The Coupled Model Intercomparison Project, Phase 5 (CMIP5) was used to coordinate this experimental design for climate modelling leading to the Fifth Assessment Report.

These new climate-policy intervention scenarios are intended to provide insights on reducing or stabilising concentrations of greenhouse gases. For example, it is anticipated that scenarios will consider land-use and land-cover choices that include bioenergy production in a world that is also adapting to climate change. Much work is expected to focus on low stabilisation levels and overshoot scenarios in response to growing policy interest.

Realising the potential benefits of the new scenarios will depend on a number of scientific advances. Improvement in the representation of the terrestrial carbon cycle in climate and integrated assessment models is necessary to reconcile how human use of land resources interacts with potential climate change impacts on, for instance, vegetation and carbon cycling; carbon cycle uncertainties are considered to be among the major unknowns affecting scenario development. If decadal prediction is to become effective, progress in understanding the physical climate system is needed. Communicating these decadal predictions in a way that is useful to policy makers and others is also a great challenge.

Managing the uncertainties spanning different types of scenarios and improving characterisation of uncertainties and probabilities for ranges of future forcing and climate change is necessary to make scenarios more useful. Although scenarios do not offer a crystal ball for the future, the new coordinated approach for developing and applying them in climate change research could yield useful insights into the interaction of natural and human-induced climate processes, and the potential costs and benefits of different mixes of adaptation and mitigation policy.

3.4 Impact on mitigation policymaking

Statements of probability or likelihood are not assigned to individual scenarios. None of the scenarios represents an estimate of a central tendency for all driving forces or emissions, such as the mean or median, and none should be interpreted as such.

IPCC climate scientists expect that the new generation of RCP scenarios will improve society's understanding of plausible climate and socio-economic futures. How this understanding can best be communicated to policy makers and in what timeframe is not yet clear. The lack of a "most likely", “central”, or “best-guess” scenario will probably remain and policy makers will be faced with similarly difficult choices

The advance beyond BAU emissions scenarios to concentrations-based mitigation scenarios (RCP's) is an important development. In effect it puts the ghg concentrations horse before the BAU emissions cart. However, the uncertainties of climate and the need for multi-model assessments to address modelling uncertainty will remain.

IPCC Fifth Assessment Report is intended to make use of the new RCP based scenarios, although it will not be completed until late 2013. A UNFCCC-compliant mitigation framework treaty is needed before then. It remains to be seen how much progress can be made in developing reliable input to policymaking in the short term. The new approach may well help to increase scientific understanding, but on a longer timescale.

4. Climate modelling limitations

4.1 Physical climate models

There is a wide variety of physical climate models. The most complex are Atmosphere – Ocean General Circulation Models (AOGCM's) that include components to simulate interactions of the atmosphere, ocean, land and sea ice.

Earth system models (ESM's) are based on physical climate models and include additional ecological and chemical processes, such as land and ocean climate cycle, vegetation and atmospheric chemistry, which respond to changes in climate simulated by the model.

Earth system models of intermediate complexity represent many of the key systems processes but with simplified equations and reduced spatial resolution. These models are used for sensitivity experiments and questions involving very long timescales.

Simple climate models (SCM's) incorporate fewer detailed processes in the atmosphere-ocean system and at coarser spatial scales. They are useful for exploring key uncertainties and have been incorporated into integrated assessment models (see 4.2 below).

The US Climate Change Science Program addressed the following questions:

- how uncertain are climate model results

- in what ways has uncertainty in model-based simulation and prediction changed with increased knowledge about the climate system?

Their findings are extensively reported in 'Climate Models: An Assessment of Strengths and Limitations', Synthesis and Assessment Product 3.1, 2008 (see Ref. 7). Models participating in the WCRP Coupled Model Intercomparison Project (CMIP3) were evaluated.

The study compared climate model results with observations of the mean climate in a number of ways. The ability of models to simulate observed climate changes, particularly those of the past century, were examined extensively. A summary of the main conclusions follows:

- No current model is superior to others in all respects, but rather different models have differing strengths and weaknesses.

- Climate models show many consistent features in their simulations and projections for the future. Accurate simulation of present-day climatology for near-surface temperature and precipitation is necessary for most practical applications of climate modelling. The seasonal cycle and large scale geographical variations of near-surface temperature are indeed well simulated in recent models, with typical correlations between models and observations of 95% or better.

- Climate model simulation of precipitation has improved over time but is still problematic. Correlation between models and observations is 50 to 60% for seasonal means on scales of a few hundred kilometers. Comparing simulated and observed latitude-longitude precipitation maps reveals similarity of magnitudes and patterns in most regions of the globe, with the most striking disagreements occurring in the tropics

- Models forced by the observed well-mixed greenhouse gas concentrations, volcanic aerosols, estimates of variations in solar energy incidence, and anthropogenic aerosol concentrations are able to simulate the recorded 20th Century global mean temperature in a plausible way. Solar variations, observed through direct satellite measurements for the last few decades, do not contribute

- significantly to warming during that period. Solar variations early in the 20th Century are much less certain but are thought to be a potential contributor to warming in that period.

- Uncertainties in the climatic effects of manmade aerosols (liquid and solid particles suspended in the atmosphere) constitute a major stumbling block in quantitative attribution studies and in attempts to use the observational record to constrain climate sensitivity. We do not know how much warming due to greenhouse gases has been cancelled by cooling due to aerosols.

- Uncertainties related to clouds increase the difficulty in simulating the climatic effects of aerosols, since these aerosols are known to interact with clouds and potentially can change cloud radiative properties and cloud cover.

- The possibility that natural variability has been a significant contributor to the detailed time evolution seen in the global temperature record is plausible but still difficult to address with models, given the large differences in characteristics of the natural decadal variability between models.

- Observations of ocean heat uptake are beginning to provide a direct test of aspects of the ocean circulation directly relevant to climate change simulations. Coupled models provide reasonable simulations of observed heat uptake in the oceans but underestimate the observed sea-level rise over the past decades.

- Model simulations of trends in extreme weather typically produce global increases in extreme precipitation and severe drought, with decreases in extreme minimum temperatures and frost days, in general agreement with observations.

- Simulations from different state-of-the-science models have not fully converged since different groups approach uncertain model aspects in distinctive ways. This absence of convergence is one useful measure of the state of climate simulation.

CMIP5 is planned to present a standard set of model simulations for IPCC AR5 in 2013/14 in order to:

- Evaluate how realistic models are in simulating the recent past,

- Provide projections of future climate change on two timescales, near term (out to about 2035) and long term (out to 2100 and beyond),

- Understand some of the factors responsible for differences in model projections including quantifying some feedbacks such as those involving clouds and the carbon cycle.

4.2 Integrated Assessment Models

Integrated Assessment Models (IAM's) represent key features of human systems such as demography, energy use, technology, the economy, agriculture, forestry and land use.

They also incorporate simplified representations of the climate system, ecosystems and climate impacts. They are used to develop emissions scenarios, estimate the potential economic impacts of climate change and the costs and benefits of mitigation, simulate feedbacks and evaluate uncertainties.

By providing quantitative information about future economic, social and environmental indicators in different scenarios, these models can be useful for understanding the consequences of decision-makers' actions. They can provide useful insights for policy makers on the most cost effective and equitable measures to tackle global warming.

Users have pointed out that different models tend to describe specific sets of variables and they recommend that results from a number of IAM's are compared for policy makers to gain the most reliable insights. No model can capture the whole complexity of reality and a multimodel comparison is often necessary to provide a wide and exhaustive overview of the best policies for global warming. Policy makers and analysts are also advised to treat results with caution and place them in the wider context of climate change science and economics (Overseas Development Institute, 2009).

There are three principal areas in which the standard economic approach underlying IAM's is unreliable:

- the discounted utility framework, which attaches less weight to future outcomes,
- the characterisation and monetisation of the benefits of mitigation,
- the projection of mitigation costs, which rests on assumptions about the pace and nature of technical change.

IAM's often suggest that the "optimal" policy is to go slowly and to do relatively little in the near term to reduce greenhouse gas emissions. They typically discount future impacts of climate change at relatively high rates. They estimate costs as an annual percentage loss in GDP. The IPCC's *Fourth Assessment Report* summarised the range of cost estimates for a stabilisation target of 445-535 ppm-CO2 equivalent and found that for all available studies, costs did not exceed 3% of global GDP in the medium term (i.e. 2030). For higher stabilisation targets, estimates ranged from 2–2.5% of GDP.

IAM's assign monetary values to the benefits of climate mitigation on the basis of incomplete information and sometimes speculative judgments concerning the monetary worth of human lives and ecosystems, while downplaying scientific uncertainty about the extent of expected damages.

Policy decisions should be based on a judgment concerning the maximum tolerable increase in temperature and/or ghg levels given the state of scientific understanding. The appropriate role for economists would then be to determine the least-cost global strategy to achieve that target. While this remains a demanding and complex challenge, it is far more manageable than the cost-benefit comparisons attempted by most IAM's.

Economists face a double problem with climate change; the benefits of mitigation are intrinsically unpredictable and unpriceable. Climate change outcomes are to some extent unpredictable and likely to be non-marginal displacements that put us outside the realm of historical human experience. We know that the Earth's climate is a strongly nonlinear system that may be characterised by threshold effects and chaotic dynamics. Under such conditions, forecasts are necessarily indeterminate; within a broad range of possible outcomes, anything can happen.

There is good reason to believe that IAM's overestimate the costs of achieving stabilisation targets. Estimating mitigation costs in monetary terms is more straightforward, in principle, than measuring mitigation benefits.

Uncertainty about climate sensitivity, the key parameter in assessing the probability for ranges of potential equilibrium global temperature changes, is resistant to improvements in scientific understanding of particular climate processes. The combination of unknown probability distributions and potentially disastrous outcomes provides a strong motivation for precautionary policy, as insurance against those disasters.

A science-led policy debate about catastrophic possibilities and consequences would lead to the selection of maximum level safe targets, expressed in terms of allowable increases in temperature and subsequently to calculation of maximum CO_2 concentration levels. The first part of this, temperature, was the most significant outcome from COP15 at Copenhagen. It remains to be seen whether a safe level of concentrations with appropriate emissions reduction trajectories will follow.

Economists do have useful insights for climate policy. While economics itself is insufficient to determine the urgency for precautionary action in the face of low-probability climate catastrophes, or make judgments about intergenerational and intragenerational justice, it does point the way towards achieving climate stabilisation in a cost-effective manner.

Once safe targets have been established, there remain the extremely complex and intellectually challenging tasks of determining the least-cost global strategy for achieving those targets, designing policies that effectively meet the targets, and sharing responsibility for the costs and implementation of that strategy.

Policy makers and scientists should be wary of efforts by economists to specify optimal policy paths using the current generation of IAM's. These models do not embody the state of the art in the economic theory of uncertainty. Many suffer from technical deficiencies that are widely recognised within the economics community (Ref. 8, 'Limitations of Integrated Assessment Models of Climate Change' 2008).

Over time, knowledge of climate uncertainty has increased and models have been improved. However there has been limited convergence between model projections. The extent of the differences between them influences confidence in these models and their projections

4.3 Impact on mitigation policymaking

Climate models have been in a state of development since their inception about fifty years ago or more. This will remain the case for the foreseeable future. They exist to serve the dual purpose of advancing scientific understanding of climate and informing policy makers determining and implementing climate policy. There are many different models developed and run by climate scientists and others around the world. These models often produce different results for given input scenarios, due to variation in focus and function.

The Coupled Model Intercomparison Project (CMIP) was established in 1995 with the purpose of providing climate scientists with a database of coupled GCM simulations under standardised boundary conditions. CMIP investigators use the model output to attempt to discover why different models give different output in response to the same input, or to identify aspects of the simulations in which "consensus" in model predictions or common problematic features exist. It has created an archive of a wide range of model results for this purpose. The Coupled Carbon Cycle Climate Model Intercomparison Project (C4MIP) was designed to compare and analyse the feedbacks between the carbon cycle and climate in the presence of external climate forcing for use by IPCC in development of Assessment Report AR4.

The IPCC assembles and summarises information on original modelling activity carried out elsewhere; it does not carry out original work itself, although it may request others to meet its specific needs from time to time. IPCC AR5 is due to be published in 2013, after the expiry of the Kyoto Protocol and after a future COP18. A UNFCCC-compliant agreement is required before then.

Modelling issues for IPCC and policy makers are:

- How should variances in modelling results for given input scenarios be considered when determining policy? The spread of results from these models gives significant information on the degree of confidence in the reliability of projections of climate change (Ref. 18, The Royal Society, 2010).

- Should experimental model results be included as part of a process that is used to inform policy makers and society of the changes to come? If the merits of a given technique have not yet been thoroughly established through exhaustive testing and the peer-reviewed literature, is it appropriate to employ it under the banner of the IPCC? (Ref. 12, Trenberth, 2010).

On the other hand, there is no case for delaying the UNFCCC agreement process until fully proven modelling results are available. It is already clear that the threat of climate change must be treated at least as a low probability catastrophy requiring urgent action, using the best information available at the time.

5. Policymaking

5.1 Policy decisions

The UNFCCC requires policy makers to reach an agreement on a safe and stable level of ghg's in the atmosphere according to the principles of equity and precaution. At COP 15 in Copenhagen, member states agreed that:

"To achieve the ultimate objective of the Convention to stabilise greenhouse gas concentration in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system, we shall, recognizing the scientific view that the increase in global temperature should be below 2 degrees Celsius, on the basis of equity and in the context of sustainable development, enhance our long-term cooperative action to combat climate change".

The Copenhagen Accord implies that a consensus has been reached among climate scientists, although how this has been measured is not known. There is no mention of the UNFCCC principle of precaution. The words "above pre-industrial levels" are not included. The Accord uses the name Celsius instead of the scale name Centigrade.

Any UNFCCC-compliant policy framework will require policy makers to agree trajectories for global emissions reduction to meet the agreed temperature limit. This requires decisions to be made on the concentration level of ghg's to be targeted and the rate and time period of global emissions reductions to achieve the two degree limit. Each of these three choices, temperature, concentrations and emissions, bears considerable risk and uncertainty:

Decision 1: $<2^{o}$C increase will make us safe.

Policy makers must determine a global course of action that secures a $<2^{o}$C outcome. There is considerable uncertainty about the level of damages that will be experienced at this temperature level.

Decision 2: Concentrations of X ppm will secure $<2^{o}$C increase.

The proxy for temperature must be the concentration level of ghg's (CO_2e). A maximum level of concentrations has to be set that gives an acceptable level of risk for achieving the $<2^{o}$C limit. There is much uncertainty about climate sensitivity and equilibrium temperature outcome at any targeted concentration level. The range is of the order of 1.5 - 4.5 ^{o}C.

Decision 3: N% reduction of ghg emissions over M years will secure X ppm concentrations.

Policy makers must select a reference scenario and then determine a start date, rate of reduction and elapsed time for global emissions reduction that stabilise concentrations within the agreed temperature maximum.

Now that a temperature limit of $<2^{o}$C has been set (without an accompanying assessment of risk of climate damages) the commensurate target level for concentrations, expressed as a finite level of greenhouse gases or their equivalent, must be set based on a rigorous and transparent scientific method.

IPCC Working Group III, in their 'Summary for Policy Makers', offer six stabilisation scenarios based on levels of radiative forcing (see Appendix D). Each forcing scenario shows expected CO_2 and CO_2e concentrations, global mean temperature at equilibrium and CO_2 emissions change by 2050. None of these meet a limit in the rise of temperature to $<2^{o}$C. Some mention is made of associated risk and uncertainty and ranges of values for the above outcomes are given but are unsourced.

IPCC describes the policy makers decision process as follows:

"Decision-making about the appropriate level of global mitigation over time involves an iterative risk management process that includes mitigation and adaptation, taking into account actual and avoided climate change damages, co-benefits, sustainability, equity, and attitudes to risk. Choices about the scale and timing of GHG mitigation involve balancing the economic costs of more rapid emission reductions now against the corresponding medium-term and long-term climate risks of delay."

There is no evidence that this approach was taken when the UNFCCC signatories set the two degree limit. Nor is there evidence that the IPCC authors and scientists attempted this approach when developing the six example scenarios. It is left to policy makers to negotiate the recommended approach and arrive at a concise statement of outcomes for $<2^{o}$C. This predicament highlights a large gap between the IPCC advice (the science), and UNFCCC policy makers (the policy). The boundary between the two needs careful reconsideration.

Just as a "science-based consensus " temperature limit has been set, so it should be for concentrations and absolute emissions reductions; then policy makers can address the rest of the IPCC recommended decision-making approach. Step One should be about "choosing the scale and timing of ghg mitigation" and the principle of precaution should be observed. Step Two should be the rest, and again the principle of precaution should be applied.

5.2 Policy maker requirements

Climate scientists and modellers should more directly serve the needs of policy makers and their policy models. They should participate more closely in setting science-based global targets for temperature, concentrations and emissions. This is essential to achieving the right balance between a sufficient and effective global emissions reduction path and an acceptable political and economic outcome. For the emissions reduction path to be sufficient and effective, risk and uncertainty must be fully and transparently addressed in order that the right levels of precaution can be set.

Policy makers are considering a number of proposed policy models. GCI's Contraction & Convergence policy framework is one that supports this approach (see Ref.19. Global Commons Institute). C&C has been recommended by many policy makers and their advisers as the UNFCCC-compliant model. As a tool for policy analysis leading towards compliance, C&C is 'sequential':

- First, against future projections of the varying future strength of the 'sink-function', it is used to assess the overall 'carbon-weight' of the full-term global emissions-contraction-event [carbon budget] that is needed for future 'safe and stable' levels of ghg concentrations [UNFCCC-compliance].

- Second, within each and any of these budgets, all rates of international convergence on the global per capita average of emissions arising are calculated leading to national quotas that are proportional to national population, with or without the option of a 'population base-year' being used on a date chosen by the user.

In other words, in the cause of securing UNFCCC-compliance, this integrated C&C procedure seeks to keep close-coupling between the scientific, political and economic debates arising in the climate change negotiations (see www.gci.org.uk).

6. Conclusions

The Royal Society has described climate as an example of a chaotic system; others have said it is chaotic in parts. In whatever degree, the presence of chaos brings great uncertainty. In addressing the threat of dangerous climate change, we must openly recognise this uncertainty in all its forms and respond to it rationally. The experience of the last twenty years shows that we still have much to learn.

Over this period there have been great advances in the knowledge and understanding of climate. At the same time, many known uncertainties have remained and new ones have been revealed. This progression is unlikely to change.

The reduction of anthropogenic emissions and conservation of the sinks are the imperative requirements of climate mitigation policy. In order to achieve this, knowledge of the science with all its uncertainties must be distilled to support the quantification of limits on temperature, concentrations and emissions as a first step.

The main sources of information for policy makers on the science are the IPCC Assessments. These have been referred to here as representative of current climate science and policy thinking. The dual role of the IPCC in serving both science and UNFCCC policy gives rise to difficulty. The original science reviewed by the IPCC for its reports is not necessarily constrained to serve policy in a UNFCCC context and timeframe, whereas the IPCC is. This can result in assessments of risk and uncertainty needed by policy makers, whether objective or subjective, being unclear and misunderstood.

In addition, there is a gap between IPCC's published information and the UNFCCC process. IPCC's brief summaries for policy makers are based on very large amounts of information in the main reports with many qualitative and quantitative assessments that cannot be fully reflected in the SPM's. The attempt to provide accuracy and consistency in language and in qualitative assessment categories in the SPM's has proved difficult and conversion of subjective judgements to quantitative assessments is in many cases misleading.

This report suggests that there are layers of uncertainty that must be recognised in the climate science, the emissions scenarios and the models that create and process them and in policymaking itself. The combination of these uncertainties makes policy decision-making a formidable challenge, particularly if the IPCC WGIII description of it is to apply:

"Decision-making about the appropriate level of global mitigation over time involves an iterative risk management process that includes mitigation and adaptation, taking into account actual and avoided climate change damages, co-benefits, sustainability, equity, and attitudes to risk. Choices about the scale and timing of GHG mitigation involve balancing the economic costs of more rapid emission reductions now against the corresponding medium-term and long-term climate risks of delay [high agreement, much evidence]".

The UNFCCC principle of precaution should have profound influence on matters in this context of complexity and uncertainty (some have called it chaos). Article 3.3 of the Convention makes specific reference to uncertainty:

"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".

The issue of precaution, as required by the UNFCCC, does not fit easily within the science remit. Climate scientists strive to present accurate and reliable information on their findings to the best of their ability at the time; theirs is work in progress. When dealing with climate projections, their presentation may take the form of well- informed estimates, with or without error bars or probability statements, for particular phenomena. Precaution is a further step beyond this that requires provision for unlikely and unforeseen events in combination. It can only be satisfied by scientific and political consensus.

Compounding the various perceived risks and uncertainties has not been attempted and probably never will be. A "science based consensus " for temperature limit, concentrations and absolute emissions reductions should be agreed, on condition that it is rational and transparent. Then scientists and policy makers can attempt to comply with the rest of the IPCC recommended decision-making approach, still within the context of continuing change and uncertainty attending the UNFCCC process..

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APPENDIX A

Glossary of Terms

(Source: see Ref. 4, IPCC WGI, Annex I)

Abrupt climate change The nonlinearity of the climate system may lead to abrupt climate change, sometimes called rapid climate change, abrupt event. The term abrupt often refers to time scales faster than the typical time scale of the responsible forcing. Some possible abrupt events that have been proposed include rapid deglaciation and massive melting of permafrost or increases in soil respiration leading to fast changes in the carbon cycle.

Aerosols A collection of airborne solid or liquid particles, with a typical size between 0.01 and 10 μm that reside in the atmosphere for at least several hours. Aerosols may be of either natural or anthropogenic origin. Aerosols may influence climate in several ways: directly through scattering and absorbing radiation, and indirectly by acting as cloud condensation nuclei or modifying the optical properties and lifetime of clouds (see Indirect aerosol effect). (see Particles)

Albedo The fraction of solar radiation reflected by a surface or object, often expressed as a percentage. Snow-covered surfaces have a high albedo, the surface albedo of soils ranges from high to low, and vegetation-covered surfaces and oceans have a low albedo. The Earth's planetary albedo varies mainly through varying cloudiness, snow, ice, leaf area and land cover changes.

Anthropogenic Resulting from or produced by human beings.

Carbon cycle The term used to describe the flow of carbon (in various forms, e.g., as carbon dioxide) through the atmosphere, ocean, terrestrial biosphere and lithosphere.

Chaos A dynamic system such as the climate system, governed by nonlinear deterministic equations may exhibit erratic or chaotic behaviour in the sense that very small changes in the initial state of the system in time lead to large and apparently unpredictable changes in its temporal evolution. Such chaotic behaviour may limit the predictability of nonlinear dynamic systems.

Climate feedback **An interaction mechanism between processes in the climate system is called a climate feedback when the result of an initial process triggers changes in a second process that in turn influences the initial one. A positive feedback intensifies the original process, and a negative feedback reduces it.**

Climate forcing **(Radiative forcing)** Radiative forcing is the change in the net, downward minus upward, irradiance (expressed in W m^{-2}) at the tropopause due to a change in an external driver of climate change, for example, a change in the concentration of carbon dioxide or the output of the Sun. Radiative forcing is computed with all tropospheric properties held fixed at their unperturbed values, and after allowing for stratospheric temperatures, if perturbed, to readjust to radiative-dynamical equilibrium. Radiative forcing is not to be confused with cloud radiative forcing, a similar terminology for describing an unrelated measure of the impact of clouds on the irradiance at the top of the atmosphere.

Climate sensitivity The amount of climate change, as measured by the equilibrium change in the average global temperature, caused by a given amount of climate forcing. Equilibrium may be reached some considerable time after the forcing. Climate sensitivity is usually expressed as the temperature change that eventually results from a hypothetical doubling of CO_2 concentrations since pre-industrial times

Cloud feedback A climate feedback involving changes in any of the properties of clouds as a response to other atmospheric changes. Understanding cloud feedbacks and determining their magnitude and sign require an understanding of how a change in climate may affect the spectrum of cloud types, the cloud fraction and height, and the radiative properties of clouds, and an estimate of the impact of these changes on the Earth's radiation budget. At present, cloud feedbacks remain the largest source of uncertainty in climate sensitivity estimates. See also Cloud radiative forcing; Radiative forcing.

Cloud radiative forcing Cloud radiative forcing is the difference between the all-sky Earth's radiation budget and the clear-sky Earth's radiation budget (units: W m^{-2}).

Ecosystem A system of living organisms interacting with each other and their physical environment. The boundaries of what could be called an ecosystem are somewhat arbitrary, depending on the focus of interest or study. Thus, the extent of an ecosystem may range from very small spatial scales to, ultimately, the entire Earth.

Extreme weather event An extreme weather event is an event that is rare at a particular place and time of year. Definitions of rare vary, but an extreme weather event would normally be as rare as or rarer than the 10th or 90th percentile of the observed probability density function. By definition, the characteristics of what is called extreme weather may vary from place to place in an absolute sense. When a pattern of extreme weather persists for some time, such as a season, it may be classed as an extreme climate event, especially if it yields an average or total that is itself extreme (e.g., drought or heavy rainfall over a season).

Feedback See Climate Feedback.

Glacier A mass of land ice that flows downhill under gravity (through internal deformation and/or sliding at the base) and is constrained by internal stress and friction at the base and sides. A glacier is maintained by accumulation of snow at high altitudes, balanced by melting at low altitudes or discharge into the sea.

Greenhouse gas (GHG) Greenhouse gases are those gaseous constituents of the atmosphere, both natural and anthropogenic, that absorb and emit radiation at specific wavelengths within the spectrum of thermal infrared radiation emitted by the Earth's surface, the atmosphere itself, and by clouds. This property causes the greenhouse effect. Water vapour (H_2O), carbon dioxide (CO_2), nitrous oxide (N_2O), methane (CH_4) and ozone (O_3) are the primary greenhouse gases in the Earth's atmosphere. Moreover, there are a number of entirely human-made greenhouse gases in the atmosphere, such as the halocarbons and other chlorine- and bromine-containing substances, dealt with under the Montreal Protocol. Beside CO_2, N_2O and CH_4, the Kyoto Protocol deals with the greenhouse gases sulphur hexafluoride (SF6), hydrofluorocarbons (HFCs) and perfluorocarbons (PFCs).

Greenhouse gas concentration An increase in the concentration of greenhouse gases leads to an increased infrared opacity of the atmosphere, and therefore to an effective radiation into space from a higher altitude at a lower temperature. This causes a radiative forcing that leads to an enhancement of the greenhouse effect, the so-called enhanced greenhouse effect.

Ice cap A dome shaped ice mass, usually covering a highland area, which is considerably smaller in extent than an ice sheet.

Ice sheet A mass of land ice that is sufficiently deep to cover most of the underlying bedrock topography, so that its shape is mainly determined by its dynamics (the flow of the ice as it deforms internally and/or slides at its base). An ice sheet flows outward from a high central ice plateau with a small average surface slope. There are only three large ice sheets in the modern world, one on Greenland and two on Antarctica, the East and West Antarctic Ice Sheets, divided by the Transantarctic Mountains.

Ice shelf A floating slab of ice of considerable thickness extending from the coast (usually of great horizontal extent with a level or gently sloping surface), often filling embayments in the coastline of the ice sheets. Nearly all ice shelves are in Antarctica, where most of the ice discharged seaward flows into ice shelves.

Meridional Overturning Circulation (MOC) Meridional (north-south) overturning circulation in the ocean quantified by zonal (east-west) sums of mass transports in depth or density layers. In the North Atlantic, away from the subpolar regions, the MOC (which is in principle an observable quantity) is often identified with the Thermohaline Circulation (THC), which is a conceptual interpretation.

North Atlantic Oscillation (NAO) The North Atlantic Oscillation consists of opposing variations of barometric pressure near Iceland and near the Azores. It therefore corresponds to fluctuations in the strength of the main westerly winds across the Atlantic into Europe, and thus to fluctuations in the embedded cyclones with their associated frontal systems.

Particles A collection of airborne solid or liquid particles, with a typical size between 0.01 and 10 μm that reside in the atmosphere for at least several hours. Aerosols may be of either natural or anthropogenic origin.

Aerosols may influence climate in several ways: directly through scattering and absorbing radiation, and indirectly by acting as cloud condensation nuclei or modifying the optical properties and lifetime of clouds (see Aerosols)

Projection A projection is a potential future evolution of a quantity or set of quantities, often computed with the aid of a model. Projections are distinguished from predictions in order to emphasize that projections involve assumptions concerning, for example, future socioeconomic and technological developments that may or may not be realised, and are therefore subject to substantial uncertainty.

Regional climate A region is a territory characterised by specific geographical and climatological features. The climate of a region is affected by regional and local scale forcings like topography, land use characteristics, lakes, etc., as well as remote influences from other regions.

Sea ice Any form of ice found at sea that has originated from the freezing of seawater. Sea ice may be discontinuous pieces (ice floes) moved on the ocean surface by wind and currents (pack ice), or a motionless sheet attached to the coast (land-fast ice). Sea ice less than one year old is called first-year ice. Multi-year ice is sea ice that has survived at least one summer melt season.

Sink Any process, activity or mechanism that removes a greenhouse gas, an aerosol or a precursor of a greenhouse gas or aerosol from the atmosphere. Ocean and land sinks are commonly referred to.

Solar radiation Electromagnetic radiation emitted by the Sun. It is also referred to as shortwave radiation. Solar radiation has a distinctive range of wavelengths (spectrum) determined by the temperature of the Sun, peaking in visible wavelengths.

Thermal infrared radiation Radiation emitted by the Earth's surface, the atmosphere and the clouds. It is also known as terrestrial or longwave radiation, and is to be distinguished from the near-infrared radiation that is part of the solar spectrum. Infrared radiation, in general, has a distinctive range of wavelengths (spectrum) longer than the wavelength of the red colour in the visible part of the spectrum. The spectrum of thermal infrared radiation is practically distinct from that of shortwave or solar radiation because of the difference in temperature between the Sun and the Earth-atmosphere system.

Tipping point A climate tipping point is a point when global climate changes from one stable state to another stable state. After the tipping point has been passed, a transition to a new state occurs. The tipping event may be irreversible. Some scientists maintain the term is too vague for a non-linear system such as the Earth's climate, in which there may be transitions between several equilibrium states.

Uncertainty An expression of the degree to which a value (e.g., the future state of the climate system) is unknown. Uncertainty can result from lack of information or from disagreement about what is known or even knowable. It may have many types of sources, from quantifiable errors in the data to ambiguously defined concepts or terminology, or uncertain projections of human behaviour. Uncertainty can therefore be represented by quantitative measures, for example, a range of values calculated by various models, or by qualitative statements, for example, reflecting the judgement of a team of experts

Volcanic forcing Volcanic eruptions are examples of a natural climate forcing mechanism. An individual volcanic eruption has its largest effects on the climate for only a few years after the eruption; these effects are dependent on the location, size and type of the eruption.

Water vapour In addition to clouds, the two gases making the largest contribution to the greenhouse effect are water vapour followed by carbon dioxide (CO_2). The amount of water vapour is expected to increase in response to a warming. Increases in water vapour alone, in response to warming, are estimated to approximately double the climate sensitivity from its value in the absence of amplifying processes. There nevertheless remain uncertainties in how much water vapour amounts will change, and how these changes will be distributed in the atmosphere.

APPENDIX B Climate Change 2007, WGI, The Physical Science Basis

Extracts from: Chapter 2: Changes in Atmospheric Constituents and in Radiative Forcing

2.9.1 Uncertainties in Radiative Forcing

The TAR assessed uncertainties in global mean RF by attaching an error bar to each RF term that was 'guided by the range of published values and physical understanding'. It also quoted a level of scientific understanding (LOSU) for each RF, which was a subjective judgment of the estimate's reliability.

The concept of LOSU has been slightly modified based on the IPCC Fourth Assessment Report (AR4) uncertainty guidelines. Error bars now represent the 5 to 95% (90%) confidence range (see Box TS.1). Only 'well-established' RF's are quantified. 'Well established' implies that there is qualitatively both sufficient evidence and sufficient consensus from published results to estimate a central RF estimate and a range. 'Evidence' is assessed by an A to C grade, with an A grade implying strong evidence and C insufficient evidence. Strong evidence implies that observations have verified aspects of the RF mechanism and that there is a sound physical model to explain the RF. 'Consensus' is assessed by assigning a number between 1 and 3, where 1 implies a good deal of consensus and 3 insufficient consensus. This ranks the number of studies, how well studies agree on quantifying the RF and especially how well observation-based studies agree with models. The product of 'Evidence' and 'Consensus' factors give the LOSU rank. These ranks are high, medium, medium-low, low or very low. Ranks of very low are not evaluated. The quoted 90% confidence range of RF quantifies the value uncertainty, as derived from the expert assessment of published values and their ranges. For most RF's, many studies have now been published, which generally makes the sampling of parameter space more complete and the value uncertainty more realistic, compared to the TAR. This is particularly true for both the direct and cloud albedo aerosol RF (see Section 2.4).Table 2.11 summarises the key certainties and uncertainties and indicates the basis for the 90% confidence range estimate. Note that the aerosol terms will have added uncertainties due to the uncertain semi-direct and cloud lifetime effects. These uncertainties in the response to the RF (efficacy) are discussed in Section 2.8.5

Table 2.11indicates that there is now stronger evidence for most of the RF's discussed in this chapter. Some effects are not quantified, either because they do not have enough evidence or because their quantification lacks consensus. These include certain mechanisms associated with land use, stratospheric water vapour and cosmic rays. Cloud lifetime and the semi-direct effects are also excluded from this analysis as they are deemed to be part of the climate response (see Section 7.5). The RF's from the LLGHG's have both a high degree of consensus and a very large amount of evidence and, thereby, place understanding of these effects at a considerably higher level than any other effect. Uncertainty assessment of forcing agents discussed in this chapter. Evidence for the forcing is given a grade (A to C), with A implying strong evidence and C insufficient evidence. The degree of consensus among forcing estimates is given a 1, 2 or 3 grade, where grade 1 implies a good deal of consensus and grade 3 implies an insufficient consensus. From these two factors, a level of scientific understanding is determined (LOSU). Uncertainties are in approximate order of importance with first-order uncertainties listed first.

Table 2.11

Table 2.11. *Uncertainty assessment of forcing agents discussed in this chapter. Evidence for the forcing is given a grade (A to C), with A implying strong evidence and C insufficient evidence. The degree of consensus among forcing estimates is given a 1, 2 or 3 grade, where grade 1 implies a good deal of consensus and grade 3 implies an insufficient consensus. From these two factors, a level of scientific understanding is determined (LOSU). Uncertainties are in approximate order of importance with first-order uncertainties listed first.*

	Evidence	Consensus	LOSU	Certainties	Uncertainties	Basis of RF range
LLGHGs	A	1	High	Past and present concentrations; spectroscopy	Pre-industrial concentrations of some species; vertical profile in stratosphere; spectroscopic strength of minor gases	Uncertainty assessment of measured trends from different observed data sets and differences between radiative transfer models
Stratospheric ozone	A	2	Medium	Measured trends and its vertical profile since 1980; cooling of stratosphere; spectroscopy	Changes prior to 1970; trends near tropopause; effect of recent trends	Range of model results weighted to calculations employing trustworthy observed ozone trend data
Tropospheric ozone	A	2	Medium	Present-day concentration at surface and some knowledge of vertical and spatial structure of concentrations and emissions; spectroscopy	Pre-industrial values and role of changes in lightning; vertical structure of trends near tropopause; aspects of emissions and chemistry	Range of published model results, upper bound increased to account for anthropogenic trend in lightning
Stratospheric water vapour from CH_4	A	3	Low	Global trends since 1990; CH_4 contribution to trend; spectroscopy	Global trends prior to 1990; radiative transfer in climate models; CTM models of CH_4 oxidation	Range based on uncertainties in CH_4 contribution to trend and published RF estimates
Direct aerosol	A	2 to 3	Medium to Low	Ground-based and satellite observations; some source regions and modelling	Emission sources and their history vertical structure of aerosol, optical properties, mixing and separation from natural background aerosol	Range of published model results with allowances made for comparisons with satellite data
Cloud albedo effect (all aerosols)	B	3	Low	Observed in case studies – e.g., ship tracks; GCMs model an effect	Lack of direct observational evidence of a global forcing	Range of published model results and published results where models have been constrained by satellite data
Surface albedo (land use)	A	2 to 3	Medium to Low	Some quantification of deforestation and desertification	Separation of anthropogenic changes from natural	Based on range of published estimates and published uncertainty analyses
Surface albedo (BC aerosol on snow)	B	3	Low	Estimates of BC aerosol on snow; some model studies suggest link	Separation of anthropogenic changes from natural; mixing of snow and BC aerosol; quantification of RF	Estimates based on a few published model studies
Persistent linear Contrails	A	3	Low	Cirrus radiative and microphysical properties; aviation emissions; contrail coverage in certain regions	Global contrail coverage and optical properties	Best estimate based on recent work and range from published model results

	Evidence	Consensus	LOSU	Certainties	Uncertainties	Basis of RF range
Solar irradiance	B	3	Low	Measurements over last 25 years; proxy indicators of solar activity	Relationship between proxy data and total solar irradiance; indirect ozone effects	Range from available reconstructions of solar irradiance and their qualitative assessment
Volcanic aerosol	A	3	Low	Observed aerosol changes from Mt. Pinatubo and El Chichón; proxy data for past eruptions; radiative effect of volcanic aerosol	Stratospheric aerosol concentrations from pre-1980 eruptions; atmospheric feedbacks	Past reconstructions/estimates of explosive volcanoes and observations of Mt. Pinatubo aerosol
Stratospheric water vapour from causes other than CH_4 oxidation	C	3	Very Low	Empirical and simple model studies suggest link; spectroscopy	Other causes of water vapour trends poorly understood	Not given
Tropospheric water vapour from irrigation	C	3	Very Low	Process understood; spectroscopy; some regional information	Global injection poorly quantified	Not given
Aviation-induced cirrus	C	3	Very Low	Cirrus radiative and microphysical properties; aviation emissions; contrail coverage in certain regions	Transformation of contrails to cirrus; aviation's effect on cirrus clouds	Not given
Cosmic rays	C	3	Very Low	Some empirical evidence and some observations as well as microphysical models suggest link to clouds	General lack/doubt regarding physical mechanism; dependence on correlation studies	Not given
Other surface effects	C	3	Very Low	Some model studies suggest link and some evidence of relevant processes	Quantification of RF and interpretation of results in forcing feedback context difficult	Not given

Appendix C Emissions Scenarios

Appendix C1

Extracts from: 'Special Report on Emissions Scenarios - Summary for policy makers', Special report of the IPCC Working Group III, 2000.

Box SPM.1: The emission scenarios of the IPCC Special Report on Emission Scenarios (SRES)

A1. The A1 storyline and scenario family describes a future world of very rapid economic growth, global population that peaks in mid-century and declines thereafter, and the rapid introduction of new and more efficient technologies. Major underlying themes are convergence among regions, capacity building and increased cultural and social interactions, with a substantial reduction in regional differences in per capita income. The A1 scenario family develops into three groups that describe alternative directions of technological change in the energy system. The three A1 groups are distinguished by their technological emphasis: fossil intensive (A1FI), non fossil energy sources (A1T), or a balance across all sources (A1B) (where balanced is defined as not relying too heavily on one particular energy source, on the assumption that similar improvement rates apply to all energy supply and end use technologies).

A2. The A2 storyline and scenario family describes a very heterogeneous world. The underlying theme is self reliance and preservation of local identities. Fertility patterns across regions converge very slowly, which results in continuously increasing population. Economic development is primarily regionally oriented and per capita economic growth and technological change more fragmented and slower than other storylines.

B1. The B1 storyline and scenario family describes a convergent world with the same global population, that peaks in mid-century and declines thereafter, as in the A1 storyline, but with rapid change in economic structures toward a service and information economy, with reductions in material intensity and the introduction of clean and resource efficient technologies. The emphasis is on global solutions to economic, social and environmental sustainability, including improved equity, but without additional climate initiatives.

B2. The B2 storyline and scenario family describes a world in which the emphasis is on local solutions to economic, social and environmental sustainability. It is a world with continuously increasing global population, at a rate lower than A2, intermediate levels of economic development, and less rapid and more diverse technological change than in the B1 and A1 storylines. While the scenario is also oriented towards environmental protection and social equity, it focuses on local and regional levels.

An illustrative scenario was chosen for each of the six scenario groups A1B, A1FI, A1T, A2, B1 and B2. All should be considered equally sound. The SRES scenarios do not include additional climate initiatives, which means that no scenarios are included that explicitly assume implementation of the United Nations Framework Convention on Climate Change or the emissions targets of the Kyoto Protocol.

APPENDIX C2

Extracts from: 'Critical assessment of the IPCC SRES scenarios', ENSEMBLES Project D7.1b, 2005.

2. A brief overview of SRES

There are four base scenarios: A1, A2, B1, and B2. The A scenarios place more emphasis on economic growth, the B scenarios on environmental protection; the 1 scenarios assume more globalisation, the 2 scenarios more regionalisation. The A1 scenario has three variants, A1(B), A1FI, and A1T.

Population growth is highest in A2 (15 billion people in 2100), followed by B2 (10 billion) and A1 and B1 (7 billion). Economic growth is most rapid in the A1 scenario, followed by B1, B2 and A2. All four scenarios assume that developing countries grow faster than developed ones; the gap between rich and poor closes most rapidly in the A1 scenario, followed by B1, B2 and A2. Energy intensity falls in all four scenarios, most rapidly in the B1 scenario, followed by A1, B2 and A2. Coal as an energy source is almost phased out in B1, A1B and A1T, roughly constant (as a share in total energy supply) in A1FI and B2, and increasing in A2. Annual carbon dioxide emissions from fossil fuel combustion reach 30 GtC in the A1FI scenario, 29 GtC in A2, 14 GtC in B2, 13 GtC in A1, 5 GtC in B1 and 4 GtC in A1T in 2100. Carbon dioxide emissions from land use range from 0 to –2 GtC in 2100, equalising the differences between A1FI and A2, between A1B and B2, and between A1T and B1. Sulphur emissions fall in all scenarios, fastest in A1T and slowest in A2. Methane and nitrous oxide emissions rise in some scenarios (A1F1, A2, B2) but fall in others (A1B, A1T, B1); A1FI has the highest emissions, B1 (for methane) and A1T (for nitrous oxide) the lowest. Emissions of other greenhouse gas increase in all scenarios, except for B1, where they are roughly constant. Precursors follow the same pattern as methane and nitrous oxide.

3. Scenarios and observations

Regarding the question of whether the SRES scenarios have become outdated or not, there are obviously no hard criteria. With a few exceptions, the study reported here has shown the assumed SRES trends to still be plausible. In addition, there is no evidence that underlying axioms of the storylines have been falsified. As a result, at this point in time there seems to be no need for a large-scale IPCC-led update of the SRES scenarios on the sole basis of their performance in the 1990-2000 period, or on the comparison with more recent projections. At the same time, however, individual modelling groups could decide to update their scenarios, making them fully consistent with current trends, while still preserving the connection with the SRES storylines and harmonisation criteria.

7. Conclusions

The IPCC SRES emissions scenarios leave much to be desired. However, they constitute the standard scenarios, and their quality is not worse, and often better than alternative emissions scenarios. Moreover, much of the critique is directed at the demographic and economic details of the scenarios. This may have lead to a small upward bias of emissions projection. The range of future greenhouse gas emissions is undisputed, however. It is therefore appropriate that the ENSEMBLES GCM's run the SRES scenarios

Appendix D

IPCC AR4 WGIII Summary for Policy Makers 2007

Extracts from: D Mitigation in the long term (after 2030)

18. In order to stabilize the concentration of GHGs in the atmosphere, emissions would need to peak and decline thereafter. The lower the stabilization level, the more quickly this peak and decline would need to occur. Mitigation efforts over the next two to three decades will have a large impact on opportunities to achieve lower stabilization levels (see Table SPM.5, and Figure SPM. 8) (*high agreement, much evidence*).

• Recent studies using multi-gas reduction have explored lower stabilization levels than reported in TAR.

• Assessed studies contain a range of emissions profiles for achieving stabilization of GHG concentrations. Most of these studies used a least cost approach and include both early and delayed emission reductions (Figure SPM.7) [Box SPM.2]. Table SPM.5 summarizes the required emissions levels for different groups of stabilization concentrations and the associated equilibrium global mean temperature increase, using the 'best estimate' of climate sensitivity (see also Figure SPM.8 for the likely range of uncertainty). Stabilization at lower concentration and related equilibrium temperature levels advances the date when emissions need to peak, and requires greater emissions reductions by 2050.

D Mitigation in the long term (after 2030)

Table SPM.5: *Characteristics of post-TAR stabilization scenarios [Table TS 2, 3.10][a)]*

Category	Radiative forcing (W/m²)	CO_2 concentration[c)] (ppm)	CO_2-eq concentration[c)] (ppm)	Global mean temperature increase above pre-industrial at equilibrium, using "best estimate" climate sensitivity[b), c)] (°C)	Peaking year for CO_2 emissions[d)]	Change in global CO_2 emissions in 2050 (% of 2000 emissions)[d)]	No. of assessed scenarios
I	2.5-3.0	350-400	445-490	2.0-2.4	2000-2015	-85 to -50	6
II	3.0-3.5	400-440	490-535	2.4-2.8	2000-2020	-60 to -30	18
III	3.5-4.0	440-485	535-590	2.8-3.2	2010-2030	-30 to +5	21
IV	4.0-5.0	485-570	590-710	3.2-4.0	2020-2060	+10 to +60	118
V	5.0-6.0	570-660	710-855	4.0-4.9	2050-2080	+25 to +85	9
VI	6.0-7.5	660-790	855-1130	4.9-6.1	2060-2090	+90 to +140	5
						Total	177

a) The understanding of the climate system response to radiative forcing as well as feedbacks is assessed in detail in the AR4 WGI Report. Feedbacks between the carbon cycle and climate change affect the required mitigation for a particular stabilization level of atmospheric carbon dioxide concentration. These feedbacks are expected to increase the fraction of anthropogenic emissions that remains in the atmosphere as the climate system warms. Therefore, the emission reductions to meet a particular stabilization level reported in the mitigation studies assessed here might be underestimated.

b) The best estimate of climate sensitivity is 3ºC [WG 1 SPM].

c) Note that global mean temperature at equilibrium is different from expected global mean temperature at the time of stabilization of GHG concentrations due to the inertia of the climate system. For the majority of scenarios assessed, stabilisation of GHG concentrations occurs between 2100 and 2150.

d) Ranges correspond to the 15th to 85th percentile of the post-TAR scenario distribution. CO2 emissions are shown so multi-gas scenarios can be compared with CO2- only scenarios.

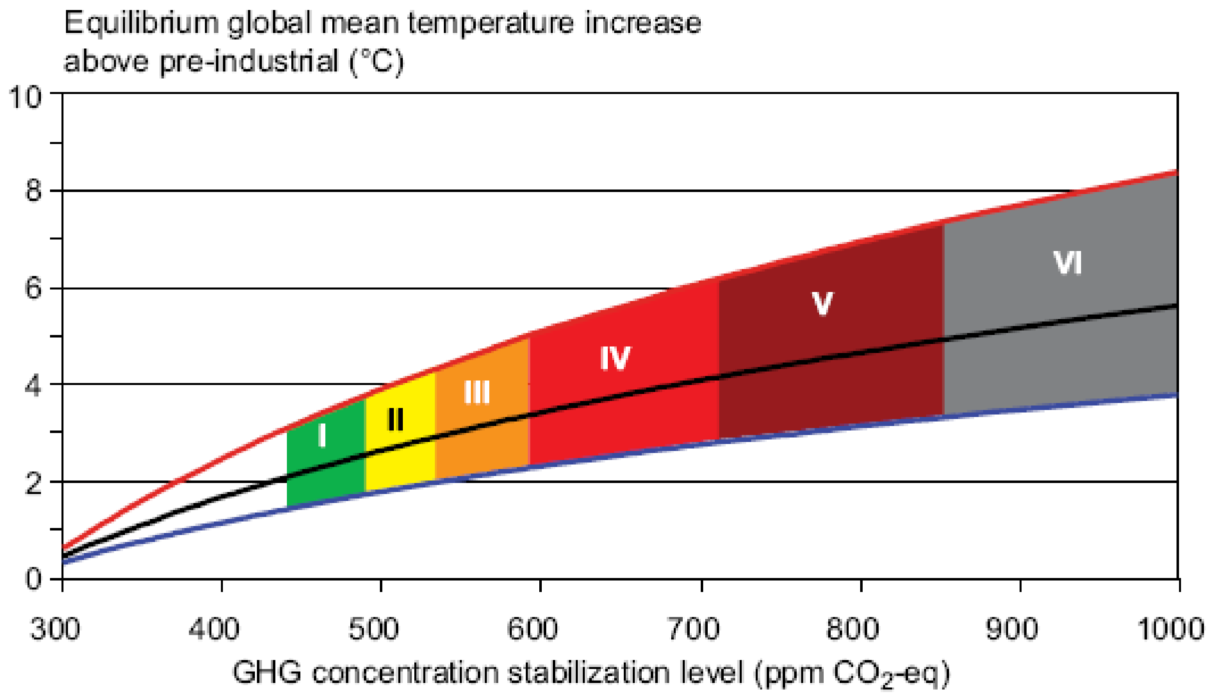

Figure SPM.8: *Stabilization scenario categories as reported in Figure SPM.7 (coloured bands) and their relationship to equilibrium global mean temperature change above pre-industrial, using "best estimate" climate sensitivity of 3℃ (black line in middle of sha ded area), (ii) upper bound of likely range of climate sensitivity of 4.5℃ (red line at top of shaded area) (iii) lower bound of likely range of climate sensitivity of 2℃ (blue line at bottom of shaded area). Coloured shading shows the concentration bands for stabilization of greenhouse gases in the atmosphere corresponding to the stabilization scenario categories I to VI as indicated in Figure SPM.7. The data are drawn from AR4 WGI, Chapter 10.8.*

21. Decision-making about the appropriate level of global mitigation over time involves an iterative risk management process that includes mitigation and adaptation, taking into account actual and avoided climate change damages, co-benefits, sustainability, equity, and attitudes to risk. Choices about the scale and timing of GHG mitigation involve balancing the economic costs of more rapid emission reductions now against the corresponding medium-term and long-term climate risks of delay *[high agreement, much evidence].*

- Limited and early analytical results from integrated analyses of the costs and benefits of mitigation indicate that these are broadly comparable in magnitude, but do not as yet permit an unambiguous determination of an emissions pathway or stabilisation level where benefits exceed costs [3.5].

- Integrated assessment of the economic costs and benefits of different mitigation pathways shows that the economically optimal timing and level of mitigation depends upon the uncertain shape and character of the assumed climate change damage cost curve. To illustrate this dependency:

    - if the climate change damage cost curve grows slowly and regularly, and there is good foresight (which increases the potential for timely adaptation), later and less stringent mitigation is economically justified;

    - alternatively if the damage cost curve increases steeply, or contains non linearities (e.g. vulnerability thresholds or even small probabilities of catastrophic events), earlier and more stringent mitigation is economically justified [3.6].

- Climate sensitivity is a key uncertainty for mitigation scenarios that aim to meet a specific temperature level. Studies show that if climate sensitivity is high then the timing and level of mitigation is earlier and more stringent than when it is low [3.5, 3.6].

- Delayed emission reductions lead to investments that lock in more emission intensive infrastructure and development pathways. This significantly constrains the opportunities to achieve lower stabilisation levels (as shown in Table SPM.5) and increases the risk of more severe climate change impacts [3.4, 3.1, 3.5, 3.6]