PERSPECTIVES

The next generation of scenarios for climate change research and assessment

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Advances in the science and observation of climate change are providing a clearer understanding of the inherent variability of Earth's climate system and its likely response to human and natural influences. The implications of climate change for the environment and society will depend not only on the response of the Earth system to changes in radiative forcings, but also on how humankind responds through changes in technology, economies, lifestyle and policy. Extensive uncertainties exist in future forcings of and responses to climate change, necessitating the use of scenarios of the future to explore the potential consequences of different response options. To date, such scenarios have not adequately examined crucial possibilities, such as climate change mitigation and adaptation, and have relied on research processes that slowed the exchange of information among physical, biological and social scientists. Here we describe a new process for creating plausible scenarios to investigate some of the most challenging and important questions about climate change confronting the global community.

To improve understanding of the complex interactions of the climate system, ecosystems, and human activities and conditions, the research community develops and uses scenarios. These scenarios provide plausible descriptions of how the future might unfold in several key areas—socioeconomic, technological and environmental conditions, emissions of greenhouse gases and aerosols, and climate. When applied in climate change research, scenarios help to evaluate uncertainty about human contributions to climate change, the response of the Earth system to human activities, the impacts of a range of future climates, and the implications of different approaches to mitigation (measures to reduce net emissions) and adaptation (actions that facilitate response to new climate conditions).

Traditionally, model-based scenarios used in climate change research have been developed using a sequential process focused on a step-by-step and time-consuming delivery of information between separated scientific disciplines. Now, climate change researchers from different disciplines have established a new coordinated parallel process for developing scenarios. This starts with four scenarios of future radiative forcings (the change in the balance between incoming and outgoing radiation to the atmosphere caused by changes in atmospheric constituents, such as carbon dioxide). Using this starting point, the parallel process will encourage research that will characterize a broad range of possible future climate conditions, taking into account recent climate observations and new information about climate system processes. Studies will give more attention to evaluating adaptation needs and strategies, exploring mitigation options, and improving understanding of potentially large feedbacks (that is, impacts of climate change such as melting of permafrost or dieback of forests that cause further changes in climate).

Central to the new parallel process is the concept that the four radiative forcing pathways can be achieved by a diverse range of socioeconomic and technological development scenarios. Among other issues, the parallel process facilitates exploration of the question 'What are the ways in which the world could develop in order to reach a particular radiative forcing pathway?' An immediate consequence of this new approach will be heightened collaboration between impacts, adaptation and vulnerability research, and climate and integrated assessment modelling (Box 1). This will improve the analysis of complex issues, such as the costs, benefits and risks of different policy choices and climate and socioeconomic futures. The parallel process will reduce the time lags between the creation of emissions scenarios, their use in climate modelling, and the application of the resulting climate scenarios in research on impacts, adaptation and vulnerability.

This Perspective provides an overview of how scenarios are used in climate change research, and summarizes the new process initiated with 'representative concentration pathways' (RCPs) that will provide a framework for modelling in the next stages of scenario-based research. Additional information can be found in refs 1–4.

Alternative futures

The use of scenarios originated in military planning and gaming, and in the early 1960s was extended into strategic planning in businesses and other organizations where decision makers wanted to analyse, in a systematic way, the implications of investment and other strategic decisions with long-term consequences[5–8]. The goal of working with scenarios is not to predict the future, but to better understand uncertainties in order to reach decisions that are robust under a wide range of possible futures[9].

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In climate change research, scenarios describe plausible trajectories of climate conditions and other aspects of the future. A variety of techniques have been used, including temporal and spatial analogues of future climates and model-based scenarios, which are the focus of this Perspective[10]. The earliest model-based 'scenarios' were stylized representations of increases in the atmospheric concentrations of carbon dioxide (a greenhouse gas that retains energy radiating from the Earth's surface). Initially a doubling or quadrupling of carbon dioxide was used as an input to 'force' early climate models. These scenarios provided a coherent basis for using climate models to address the question, 'If carbon dioxide concentrations increased by a specified amount or rate, how might the climate system respond?'

Over time, an increasingly broad array of scenarios has been developed to address different components of the issue[11]; we show in Fig. 1 an historical perspective on the development of scenarios, some notable applications, and some context. Today, scenarios represent major driving forces, processes, impacts (physical, ecological and economic) and potential responses important for informing climate change policy (Fig. 2). Within the overall category of scenarios, several types are prominent in climate change research.

Emissions scenarios. Emissions scenarios are descriptions of potential future discharges to the atmosphere of substances that affect the Earth's radiation balance, such as greenhouse gases and aerosols. Along with information on other related conditions such as land use and land cover, emissions scenarios provide inputs to climate models. They are produced with integrated assessment models (Box 1) based on assumptions about driving forces, such as patterns of economic and population growth, technology development, and other factors. Over time, the information provided by integrated assessment models and used in climate models has become increasingly comprehensive, including time-dependent emissions of radiatively significant gases and particles, precursor pollutant compounds, and land cover and use.

In addition to their use as inputs to climate models, emissions scenarios are used to explore alternative energy and technology futures. This allows exploration of what changes in technologies, economic development, policy, or other factors would be required to shift emissions from a baseline to a lower path—for example, keeping greenhouse gas concentrations (or global average surface air temperature increases) below a specified level. They can be used to analyse the need for and the value of technology, and the implications of choices to limit radiative forcing to prescribed limits. Although scenario outputs include emissions and land use/cover, they also include drivers of change, such as patterns and rates of economic growth, demographic change, technology, policy and other factors that are important for the assessment of the impacts of climate change[12].

Emissions scenarios for climate change research are not forecasts or predictions, but reflect expert judgments regarding plausible future emissions based on research into socioeconomic, environmental, and technological trends represented in integrated assessment models. Emissions scenarios for climate change research do not track 'short-term' fluctuations, such as business cycles or oil market price volatility. Instead, they focus on long-term (decades to centuries) trends in energy and land-use patterns. The long-term focus is necessary for evaluating the slow response of the climate system (centuries) to changing concentrations of greenhouse gases. The long-term focus also reflects the long time horizon for retiring and replacing many components of energy and economic infrastructure. Uncertainty in emissions scenarios results from the inherent uncertainty of future socioeconomic and technology conditions, uncertainty in the policy environment, and differences in representations of processes and relationships across integrated assessment models, among other factors. An underlying key issue is whether probabilities can be usefully associated with scenarios or different

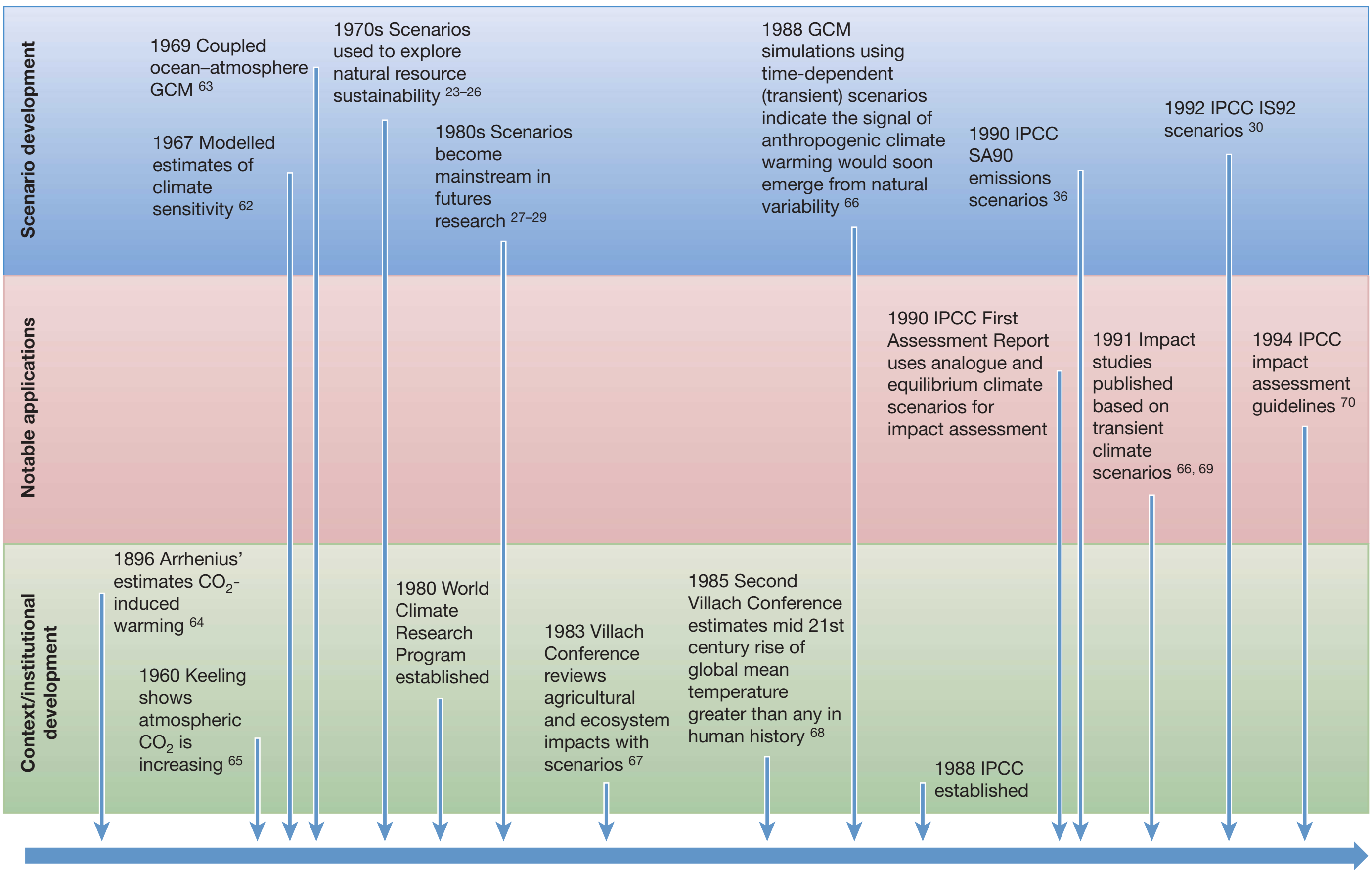


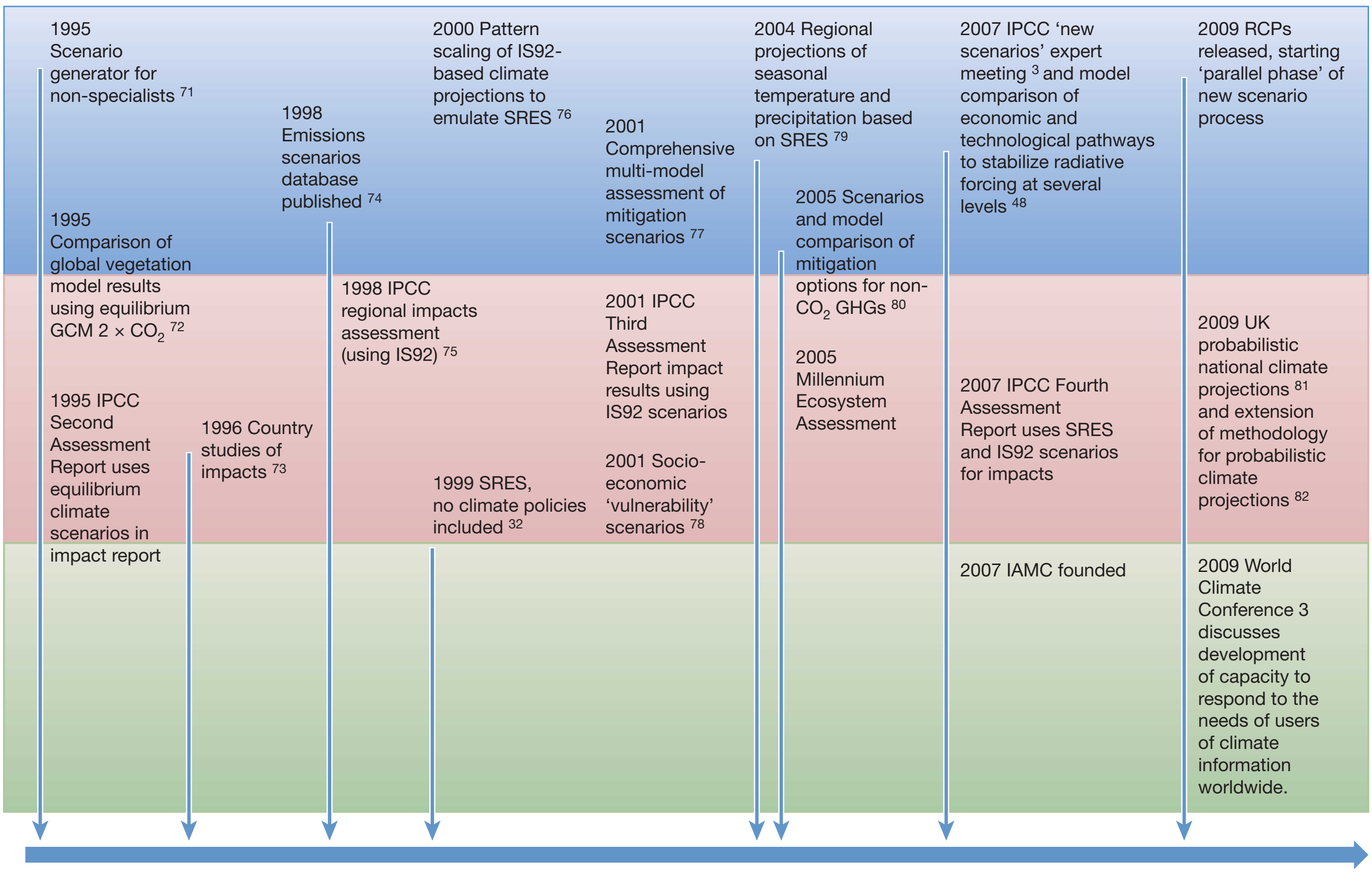
Figure 1 | Timeline highlighting some notable developments in the creation and use of emissions and climate scenarios. The entries are illustrative of the overall course of model-based scenario development (blue) and application (beige) described in this Perspective, and also give some context (green); they do levels of radiative forcing; for example, the probability that concentrations will stabilize above or below a specified level[13–15].

Climate scenarios. Climate scenarios are plausible representations of future climate conditions (temperature, precipitation and other climatological phenomena). They can be produced using a variety of approaches including: incremental techniques where particular climatic (or related) elements are increased by plausible amounts; spatial and temporal analogues in which recorded climate regimes that may resemble the future climate are used as example future conditions; other techniques, such as extrapolation and expert judgment; and techniques that use a variety of physical climate and Earth system models, including regional climate models[10]. All of these techniques continue to play a useful role in development of scenarios, with the appropriate choice of method depending on the intended use of the scenario[16], but most major advances are expected with model-based approaches. There is a notable increase in interest in regional-scale climate scenarios and projection methods, especially for impact and adaptation assessment[17].

Environmental scenarios. Analysis of the potential impact of a particular climate scenario requires environmental scenarios of ecological and physical conditions at greater detail than is included in climate models. These scenarios focus on changes in environmental conditions other than climate that may occur regardless of climate change. Such factors include water availability and quality at basin levels (including human uses), sea level rise incorporating geological and climate factors, characteristics of land cover and use, and local atmospheric and other conditions affecting air quality. Climate change merges with these factors, and in many cases, the potential impact of climate change and effectiveness of adaptation options cannot be understood without examining these interactions[16,18].

Vulnerability scenarios. Finally, scenarios of factors affecting vulnerability, such as demographic, economic, policy, cultural and institutional characteristics are needed for different types of impact modelling and research. This information is crucial for evaluating the potential of humankind to be affected by changes in climate, as well as for examining how different types of economic growth and social change affect vulnerability and the capacity to adapt to potential impacts. Although some of these factors can be modelled and applied at regional or national scales[19], for the most part data at finer spatial resolution are required. An increasing body of literature, including some using integrated assessment models, is exploring alternative methods for the quantitative and qualitative 'downscaling' of these vulnerability factors in a way that is consistent with the socioeconomic assumptions underlying global emissions scenarios[20–22].

Earlier scenario work. Antecedents of contemporary global scenarios were developed in 'futures studies' that explored the long-term sustainability of natural resources[23–26] and the implications of global energy needs for future CO_2 emissions and concentrations[27–29]. The Intergovernmental Panel on Climate Change (IPCC) has used emissions and climate scenarios as a central component of its work of assessing climate change research. It stimulated development of the field by commissioning several sets of emissions scenarios for use in its reports. In earlier emissions scenario exercises, the IPCC convened authors and modellers, provided terms of reference, and approved the scenarios through an intergovernmental process that took several years. The 1990 IPCC scenario A (SA90)[30] set explored four emissions pathways, including a 'business as usual' future and three policy scenarios. They were followed by the 1992 IPCC scenarios (IS92)[31] that played out the implications of uncertainties in economic growth, population and technology in a number of business as usual energy and economic futures. The latest set of scenarios from the IPCC, contained in the Special Report on Emissions Scenarios (SRES)[32], investigated the uncertainty of future greenhouse gas and short-lived pollutant emissions given a wide range of driving forces. Some of the cases explored the implications of economic convergence between developed and developing



not provide a comprehensive account of all major scenarios and significant studies or assessments that have used them. See Supplementary Information for details. GCM, general circulation model; GHG, greenhouse gas; IAMC, Integrated Assessment Modelling Consortium.

countries. Unlike previous emissions scenarios, the quantitative SRES projections were complemented by 'storylines' or narratives of the future, which facilitated the interpretation of the scenarios. Unlike previous scenarios that were developed using only one or two models, the SRES scenarios were produced through an 'open process' involving many different modelling teams. The IS92 and SRES scenarios assumed there were no policy actions to mitigate climate change.

Many other organizations have developed scenarios that include greenhouse gas emissions and their interactions with other socio-economic and environmental systems (for example, the International Energy Agency[33] and the Millennium Ecosystem Assessment[34]) or have played a substantial role in shaping the scenario development process (the Energy Modelling Forum). Overviews of scenario development in climate change research are available[32,35,36] (see also timeline in Fig. 1).

Motivations for new scenarios

Although the previous IPCC scenarios and process have been productive, new scenarios and a new process for selecting and using them are needed. Nearly a decade of new economic data, information about emerging technologies, and observations of environmental factors such as land use and land cover change should be reflected in new scenarios[37,87].

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 °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[38–42]. 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. Analysis of adaptation also requires development of socioeconomic scenarios suitable to support analysis of vulnerability.

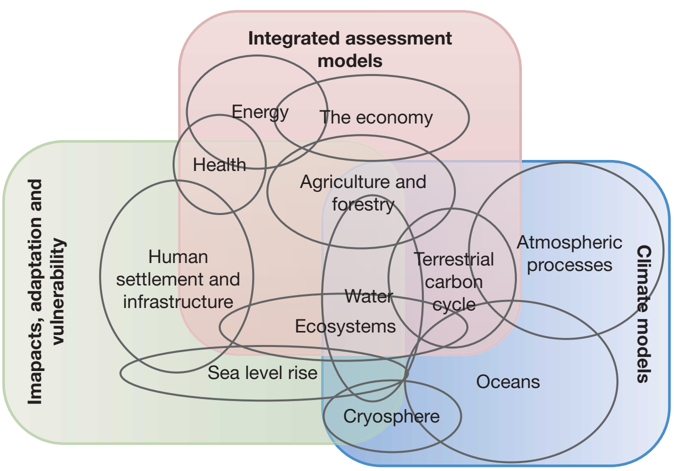
Box 1 | Models and frameworks

Scenarios are generated and used by three broad types of models and analytic frameworks in climate change research: integrated assessment models, climate models, and models and other approaches used to help assess impacts, adaptation and vulnerability.

(1) Integrated assessment models 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 in some cases, climate impacts[12]. These simplified representations are calibrated against more complex climate and impact models. Because of their breadth, these models integrate information needed to study the interactions of human systems (including potential climate policies) and environmental processes that affect climate change and its impacts. Integrated assessment models typically disaggregate the world into a dozen or more regions with time steps of about a decade. Integrated assessment models 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. Because they are increasingly comprehensive and include more detail about air pollutant emissions and land use, these models are increasingly important for research on the interaction of climate change with other policy objectives (such as air-pollution control and biodiversity protection).

(2) Climate models[44,84] are numerical representations of the Earth's natural systems used to study how climate responds to changes in natural and human-induced perturbations. There are a wide variety and complexity of climate models. Atmosphere–ocean general circulation models are the most complex physical climate models, and include components that simulate interactions of the atmosphere, ocean, land and sea ice. They divide the atmosphere and oceans into thousands of grid cells, and include interactive land-surface and biophysical processes. Regional climate models focus on subcontinental scale geographies at finer resolution. Earth system models are based on physical climate models, and include additional ecological and chemical processes, such as the land and ocean carbon 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 and processes, but with simplified equations and reduced spatial resolution. These models are useful for sensitivity experiments, questions involving long timescales (hundreds to thousands of years), or when a large number of simulations are required. Simple climate models 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 many integrated assessment models.

(3) Assessing impacts, adaptation and vulnerability to climate change depends on a wide array of methods and tools that includes both quantitative and qualitative approaches. Prominent approaches include observations, modelling, assessment techniques that engage stakeholders in participatory processes, economic evaluation methods and decision analysis[85]. The models and frameworks span the range from biophysical to economic, and explore the consequences of changes in climate for climate-sensitive resources and activities, such as agriculture, water resources, human health, ecosystems and coastal infrastructure. These frameworks inform decision makers of the potential risks and opportunities presented by climate change, and provide a means of evaluating the impacts associated with different magnitudes of climate change and the comparative effectiveness of various response strategies and management options. When impact models include representations of changes in fluxes of greenhouse gases to the atmosphere from natural and managed systems, they are useful for studying climate system 'feedbacks'; for example, from forest dieback or permafrost melting. The figure depicts the domains of the three sets of models and frameworks[86], and illustrates that the models increasingly are covering overlapping substantive domains, which underscores the importance of coordination and consistency in using scenarios.



Scientific advances also motivate interest in new scenarios within the scientific community. Interest in modelling future climate conditions nearer to a long-term equilibrium across components of the climate system, such as the oceans and the ice sheets, has created a demand for emissions scenarios to extend well beyond the conventional 2100 end-point[2,43]. Simultaneously, climate models are becoming more comprehensive and incorporating the oceanic and terrestrial carbon cycle, aerosols, atmospheric chemistry, ice sheets and dynamic vegetation[44–46]. As more physical processes are simulated, more detailed emissions scenarios are required, along with higher resolution and more consistent land-use and land-cover data and projections. Finally, increasing the overlap in the substantive domains of climate, impact and integrated assessment models (Box 1) creates a demand for harmonization of assumptions and data on some initial conditions, within the limits posed by historical and observational uncertainties.

Apart from responding to new opportunities and information needs, a new process for developing scenarios is needed in part because the IPCC decided at its twenty-fifth session in 2006 not to commission another set of emissions scenarios, leaving new scenario development to the research community. IPCC instead limited its role to catalysing and assessing the large and growing scenario literature. The research community responded by, among other things, creating this new process to provide cross-disciplinary coordination. Finally, a new process that shortens development time and leads to greater coordination will facilitate additional scientific advances, including increased understanding of different types of feedbacks and improved synthesis of research on adaptation, mitigation and damages incurred and avoided by different policy options.

Redesigned scenario process

The earlier sequential approach. Until now, scenarios were developed and applied sequentially in a linear causal chain that extended from the socioeconomic factors that influence greenhouse gas emissions to atmospheric and climate processes to impacts (Fig. 3).

This sequential process involved developing emissions scenarios based on different socioeconomic futures, estimating concentrations and radiative forcing from emissions, projecting the ensuing climate, and then using those scenarios in impact research. The process led to inconsistency because of delays between the development of the emissions scenarios, their use in climate modelling, and the availability of the resulting climate scenarios for impact research and assessment. For example, work on the SRES scenarios[32] started in 1997 and took approximately three years to complete (Fig. 1). The first climate model results using these scenarios as inputs were assessed in the 2001 IPCC Third Assessment Report, but not until 2007, when the IPCC published its Fourth Assessment Report, was a more complete set of SRES-driven climate scenarios available and impact, adaptation and vulnerability research using these scenarios assessed by IPCC. By this time, results from a new generation of climate models were being assessed in the same report, thus creating inconsistencies between the new climate scenarios and the older ones used in the impact studies. This complicated the synthesis of results on issues such as costs and benefits, and created challenges when comparing feedbacks from different models.

The parallel approach. To shorten the time between the development of emissions scenarios and the use of the resulting climate scenarios in impact research, as well as to address the key information needs of users more effectively, the integrated assessment, climate and impact research communities have cooperated to devise an alternative 'parallel' approach for creating and using scenarios (Fig. 4). Rather than starting with detailed socioeconomic storylines to generate emissions and then climate scenarios, the parallel process begins with the identification of important characteristics for scenarios of radiative forcings for climate modelling, the most prominent of which is the level of radiative forcing in the year 2100. These radiative forcing trajectories are not associated with unique socioeconomic or emissions scenarios, and instead can result from different combinations of economic, technological, demographic, policy and institutional futures

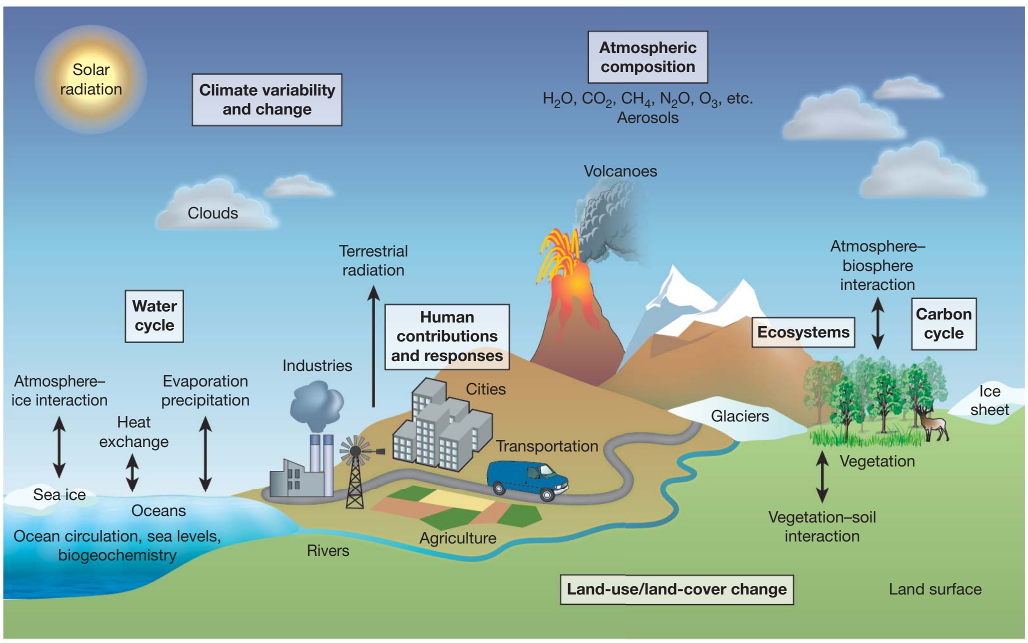


Figure 2 | Major natural and anthropogenic processes and influences on the climate system addressed in scenarios. The climate system consists of five interacting components: the atmosphere, the hydrosphere, the cryosphere, the land surface and the biosphere. Scenarios of emissions and other drivers are used to assess the impact of a range of human activities on these components. Changes in climate described in climate scenarios are major drivers of changes in both natural and human systems. Impacts on ecosystems, natural resources, economic activities and infrastructure, and human well-being, depend not only on climate change, but also on other changes in the environment (depicted in environmental scenarios) and the capacity of societies and economies to buffer and adapt to impacts (addressed in scenarios of vulnerability and adaptive capacity). Closer integration of scenarios is required to address feedback loops and other issues, such as the ecological and economic implications of different sets of adaptation and mitigation policies. Figure from ref. 83.

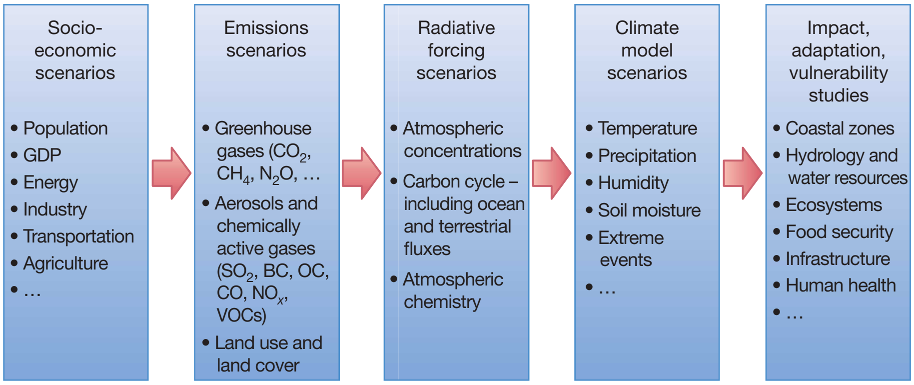


Figure 3 | Sequential approach. This figure depicts the simple linear chain of causes and consequences of anthropogenic climate change. Scenarios were developed on the basis of this sequence, and handed from one research community to the next in a lengthy process that led to inconsistencies. GDP, gross domestic product; BC, black carbon; OC, organic carbon; VOCs, volatile organic compounds. Figure adapted from ref. 11.

(for comparisons of how different emissions scenarios generated with different integrated assessment models stabilize at specified target levels, see refs 47, 48).

Climate models require data on the time-evolving emissions or concentrations of radiatively active constituents, and some have additional requirements for information about the time-evolving paths for land use and land cover. The research community identified a specific emission scenario (including data on land use and land cover) from the peer-reviewed literature as a plausible pathway towards reaching each target radiative forcing trajectory (Table 1; the selection process and criteria are described more fully below). These were given the label 'representative concentration pathways' (RCPs). The word 'representative' signifies that each RCP provides only one of many possible scenarios that would lead to the specific radiative forcing characteristics. The term 'pathway' emphasizes that not only the long-term concentration levels are of interest, but also the trajectory taken over time to reach that outcome. In summary, the new parallel process starts with the selection of four RCPs, each of which corresponds to a specific radiative forcing pathway.

In the 'parallel phase' of the process, climate and integrated assessment modellers will work simultaneously rather than sequentially. The climate modellers will conduct new climate model experiments and produce new climate scenarios using the time series of emissions and concentrations from the four RCPs. The focus on a few, well-spaced RCPs will produce discernible climate change outcomes from one RCP to another, save computational resources, and thus make it possible to conduct additional new types of experiments.

At the same time as the climate modellers are preparing simulations with the RCPs, the integrated assessment modellers will develop an ensemble of new socioeconomic and emissions scenarios. Because this work is done in parallel rather than sequentially, the process is shortened by the time previously devoted to up-front development of emissions scenarios. The new ensemble of integrated assessment model scenarios will constitute an important complement to the RCPs, because they will help to identify the range of different technological, socioeconomic and policy futures that could lead to a particular concentration pathway and magnitude of climate change. This will encourage new research into novel approaches to meet

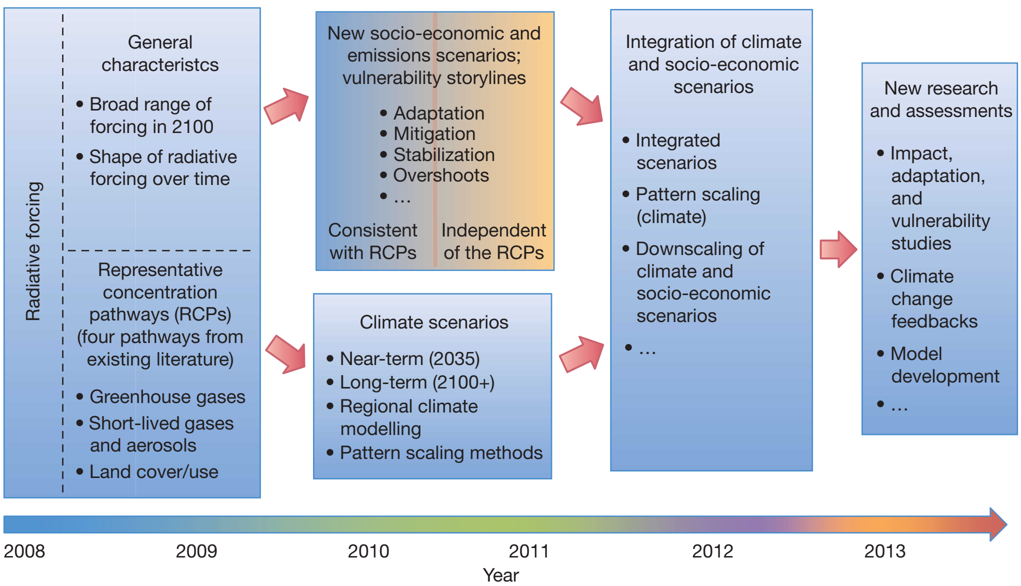


Figure 4 | The parallel process. This figure depicts the process of developing new scenarios that will be used in future climate change research and impacts assessments. The process began with identification of radiative forcing characteristics that support modelling of a wide range of possible future climates. Representative concentration pathways (RCPs) were selected from the published literature to provide needed inputs of emissions, concentrations and land use/cover for climate models. In parallel with development of climate scenarios based on the RCPs, new socio-economic scenarios (some consistent with the radiative forcing characteristics used to identify the RCPs and some developed to explore completely different futures and issues) will be developed to explore important socio-economic uncertainties affecting both adaptation and mitigation. Using a variety of tools and methods, such as pattern scaling, the new socio-economic scenarios will be integrated with the new climate scenarios. New research using the integrated scenarios will explore adaptation, mitigation and other issues such as feedbacks, using consistent assumptions. This research will provide insights into the costs, benefits and risks of different climate futures, policies and socio-economic development pathways.

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.

targets identified by policy makers. In addition, the integrated assessment modellers will develop entirely new scenarios with different radiative forcing pathways to explore additional issues and uncertainties. For example, new reference scenarios will be developed to explore alternative demographic, socioeconomic, land use, and technology scenario backgrounds. Scenarios will be created to explore alternative stabilization levels, including higher overshoot pathways, as well as the technology, institutional, policy and economic conditions associated with these pathways. Other scenarios will be developed to explore uncertainties in processes such as the terrestrial carbon cycle, the ocean carbon cycle and the atmospheric chemistry of aerosols. A variety of new regionally based scenarios will be developed using regional models by research teams in developing and transition-economy countries. The process by which new scenarios will be produced and the nature of coordination across research teams is not specified here and remains to be determined.

The socioeconomic assumptions underlying the new emissions scenarios (along with information about the spatial distribution of these characteristics, when possible) will be used to develop scenarios of factors affecting vulnerability, and will then be paired with climate model results to provide consistent inputs for impact, adaptation and vulnerability research. It is an open research question how wide a range of socioeconomic conditions could be consistent with a given forcing pathway, including its ultimate level, pathway over time and spatial pattern; however, the range of underlying socioeconomic scenarios that are consistent is potentially very wide (carbon cycle uncertainties are among the major unknowns affecting scenario development[46]).

A significant portion of the new research anticipated to result from the RCPs and the subsequent process will be assessed in the IPCC's Fifth Assessment Report, now under way and scheduled for release during 2013 and 2014.

Selection process for the RCPs

A careful selection process was used to identify the RCPs, using criteria that reflected the needs of both climate scenario developers and users[3]. As a user of the RCPs and the ensuing research, the IPCC requested the development of new scenarios compatible with the literature of reference and mitigation scenarios and helped catalyse the selection process. The criteria established by the research community included compatibility 'with the full range of stabilization, mitigation, and reference emissions scenarios available in the current scientific literature'[43]; 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, and a new Integrated Assessment Modelling Consortium (IAMC), comprising 45 participating organizations (http://www.iamconsortium.org), then assembled a list of candidate scenarios for each radiative forcing level from the peer-reviewed literature. The selection process relied on previous assessment of the literature conducted by IPCC Working Group III during development of the Fourth Assessment Report[49]. Of the 324 scenarios considered, 32 met the selection criteria and were able to provide data in the required format. An individual scenario was then selected for each RCP (Table 1). The final RCP selections (RCP2.6, RCP4.5, RCP6.0 and RCP8.5) were made on the basis of discussions at an IPCC expert

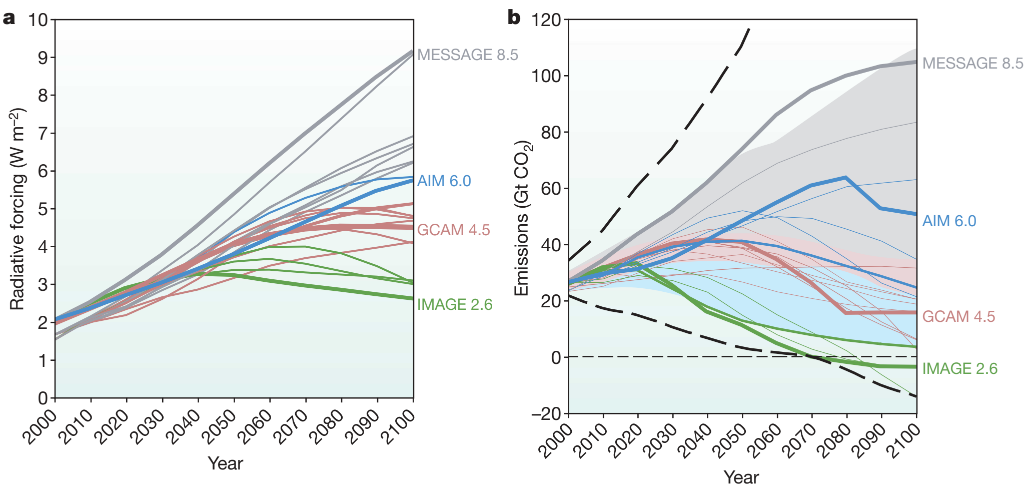


Figure 5 | Representative concentration pathways. **a**, Changes in radiative forcing relative to pre-industrial conditions. Bold coloured lines show the four RCPs; thin lines show individual scenarios from approximately 30 candidate RCP scenarios that provide information on all key factors affecting radiative forcing from ref. 47 and the larger set analysed by IPCC Working Group III during development of the Fourth Assessment Report[49]. **b**, Energy and industry CO_2 emissions for the RCP candidates. The range of emissions in the post-SRES literature is presented for the maximum and minimum (thick dashed curve) and 10th to 90th percentile (shaded area). Blue shaded area corresponds to mitigation scenarios; grey shaded area corresponds to reference scenarios; pink area represents the overlap between reference and mitigation scenarios.

meeting in September 2007, a subsequent open review of proposed selections involving many modelling teams and users, and the recommendation of an ad hoc committee convened to review alternatives for the lowest RCP[50].

The IAMC coordinated preparation of the RCP data in consultation with the climate modelling and impact research communities[4,51]. The regional and spatial RCP data for the climate simulations is publicly available through the IAMC-RCP database (http://www.iiasa.ac.at/web-apps/tnt/RcpDb)

Figure 5 illustrates how the selected RCPs represent the literature in terms of radiative forcing (Fig. 5a) and energy and industry CO_2 emissions (Fig. 5b). The selected set of RCPs spans the range of radiative forcing scenarios in the published literature at September 2007. For energy and industry CO_2 emissions, RCP8.5 represents the 90th percentile of the reference emissions range, while RCP2.6 represents pathways below the 10th percentile of mitigation scenarios. They are also similarly representative of emissions of greenhouse gases and particles other than CO_2 (refs 3, 47, 49 and 51).

The RCPs provide a starting point for new and wide-ranging research. However, it is important to recognize their uses and limits. They are neither forecasts nor policy recommendations, but were chosen to map a broad range of climate outcomes. The RCPs cannot be treated as a set with consistent internal logic. For example, RCP8.5 cannot be used as a no-climate-policy reference scenario for the other RCPs because RCP8.5's socioeconomic, technology and biophysical assumptions differ from those of the other RCPs.

New products and collaborations

Two sets of climate projections will be developed using the RCPs, one focusing on the near term (to 2035) and the other extending to 2100 and beyond (the Coupled Model Intercomparison Project, Phase 5 (CMIP5) was used to coordinate the experimental design for climate modelling leading to the Fifth Assessment Report[43]). The near-term climate projections (mainly comprising 'decadal predictions'[52]) will use the single mid-range RCP4.5, because the radiative forcing in the different RCPs does not diverge appreciably until after this time period (Fig. 5a). Because multiple scenarios do not need to be run to span radiative forcing uncertainties, it is possible to run the models at higher resolution and to prepare larger ensembles (a group of model experiments used to analyse uncertainty) to improve understanding of likely extremes, thereby aiding evaluation of impacts and adaptation needs for the coming decades. Another set of runs will provide long-term climate projections to the year 2100, with some pathways extended to 2300. These extended pathways will be used for comparative analysis of the long-term climate and environmental implications of different mitigation scenarios or pathways. 'Pattern-scaling' methods, which use the outcomes of simple climate models to scale the patterns of climate change produced by complex climate models to correspond to different emissions scenarios, will be further evaluated and developed[53,54].

The new process will increase collaboration among researchers working on impacts, adaptation and vulnerability with climate and integrated assessment modellers. One area of collaboration is preparation of narrative storylines and quantitative vulnerability scenarios that are coordinated with emissions scenarios, thus encouraging more impact research that is coordinated explicitly with emissions and climate scenarios. This will extend the use of socioeconomic scenarios, which previously have been used more to project greenhouse gas emissions than to assess adaptive capacity and vulnerability. The narratives will provide an interpretative tool for relating the scenarios to conditions that affect vulnerability at the local and regional scales at which many impact studies are undertaken. In addition, downscaled socioeconomic data for consistent, comparable research on impacts, adaptation and vulnerability will be developed and evaluated. Results from impact studies using the RCPs will feed back into climate and integrated assessment modelling.

New climate-policy-intervention scenarios will provide insights on reducing or stabilizing 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 stabilization levels and overshoot scenarios in response to growing policy interest (Table 1 and Fig. 5a).

Another anticipated advance is the development of integrated Earth system models that incorporate integrated assessment models, climate models and impact models. Whereas integrated Earth system models will not replace the three existing classes of models, they will bring them closer together than ever before and enable new insights into the challenge of integrating adaptation and mitigation in climate change risk management.

Concluding comments

This new generation of scenarios will improve society's understanding of plausible climate and socio-economic futures. The importance of the new scenarios is matched by the importance of the increased level of communication and collaboration across different groups of researchers.

The new process is only a first step toward the goal of integrating the now separate tasks of developing scenarios, making projections and evaluating the impact of the projections. Next steps for further strengthening the process include establishing mechanisms for ongoing coordination and information exchange, integrating data and information systems, and improving support for users. Institutions for coordination and knowledge management across groups working on impacts, adaptation and vulnerability need to be strengthened. In addition, the scenario process will need to continue to evolve to increase the involvement of researchers and users from developing countries to focus additional attention on crucial interactions among development strategies, adaptation and mitigation. These steps will improve the climate change impact and response knowledge base, contribute to the development of socioeconomic scenarios as a tool for assessing climate change risks and vulnerabilities, and increase the use of climate scenarios as one starting point for impact and response analysis.

Realizing the potential benefits of the new process also depends 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. If decadal prediction is to become skilful, progress in understanding the physical climate system and new approaches for data assimilation and initialization of models are needed. Communicating decadal predictions in a way that is useful to society at large is also a great challenge. Developing new approaches for making socioeconomic scenarios more useful for research on adaptive capacity and vulnerability is essential to improving our ability to compare the consequences of adaptation and mitigation strategies. Managing the cascade of uncertainties that span different types of scenarios and improving characterization of uncertainties and probabilities for ranges of future forcing and climate change is necessary to make scenarios more useful to decision makers.

Although scenarios do not offer a crystal ball for the future, the new coordinated approach for developing and applying them in climate change research will yield valuable 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.

1. Meehl, G. A. & Hibbard, K. A. *A Strategy for Climate Change Stabilization Experiments with AOGCMs and ESMs* (WCRP Informal Report No. 3/2007, ICPO Publication No. 112, IGBP Report No. 57, World Climate Research Programme, Geneva, 2007).
2. Hibbard, K. A., Meehl, G. A., Cox, P. & Friedlingstein, P. A strategy for climate change stabilization experiments. *Eos* 88, 217, 219, 221 (2007).

3. Moss, R. H. *et al. Towards New Scenarios for Analysis of Emissions, Climate Change, Impacts, and Response Strategies* (IPCC Expert Meeting Report, IPCC, Geneva, 2008).
4. van Vuuren, D. P. *et al.* Work plan for data exchange between the integrated assessment and climate modeling community in support of phase-0 of scenario analysis for climate change assessment (representative community pathways). ⟨http://www.aimes.ucar.edu/docs/RCP_handshake.pdf⟩ (6 October 2008).
5. Bradfield, R., Wright, G., Burta, G., Carnish, G. & Van Der Heijden, K. The origins and evolution of scenario techniques in long range business planning. *Futures* **37,** 795–812 (2005).
6. Jefferson, M. in *Beyond Positive Economics?* (ed. Wiseman, J.) 122–159 (Macmillan, 1983).
7. Kahn, H. & Weiner, A. *The Year 2000: A Framework for Speculation on the Next Thirty-three Years* (Macmillan, 1967).
8. World Energy Council. *Energy for Tomorrow's World* (Kogan Page, London, 1993).
9. Schwartz, P. *The Art of the Long View: Planning for the Future in an Uncertain World* (Doubleday, 1996).
10. Mearns, L. O. *et al.* in *Climate Change 2001: The Physical Science Basis* (eds Houghton, J. T., Ding, Y. & Griggs, D. J.) 739–768 (Cambridge Univ. Press, 2001).
11. Parson, E. A. *et al. Global Change Scenarios: Their Development and Use* (Sub-report 2.1B of Synthesis and Assessment Product 2.1, US Climate Change Science Program and the Subcommittee on Global Change Research, Department of Energy, Office of Biological & Environmental Research, Washington DC (2007).
12. Weyant, J. *et al.* in *Climate Change 1995: Economic and Social Dimensions of Climate Change* (eds Bruce, J. P., Lee, H. & Haites, E. F.) 367–398 (Cambridge Univ. Press, 1996).
13. Schneider, S. H. What is ''dangerous'' climate change? *Nature* **411,** 17–19 (2001).
14. Grubler, A. & Nakicenovic, N. Identifying dangers in an uncertain climate. *Nature* **412,** 15 (2001).
15. Pittock, A. B., Jones, R. N. & Mitchell, C. D. Probabilities will help us plan for climate change. *Nature* **413,** 249 (2001).
16. Carter, T. R. *et al. General Guidelines on the Use of Scenario Data for Climate Impact and Adaptation Assessment* (Task Group on Data and Scenario Support for Impact and Climate Assessment (TGICA), IPCC, Geneva, 2007).
17. Christensen, J. H. *et al.* in *Climate Change 2007: The Physical Science Basis* (eds Solomon, S., Qin, D. & Manning, M.) 847–940 (Cambridge Univ. Press, 2007).
18. Carter, T. R. *et al.* in *Climate Change 2001: Impacts, Adaptation and Vulnerability* (eds McCarthy, J. J., Canziani, O. F., Leary, N. A., Dokken, D. J. & White, K. S.) 145–190 (Cambridge Univ. Press, 2001).
19. Malone, E. L. & Brenkert, A. L. in *The Distributional Effects of Climate Change: Social and Economic Implications* (eds Ruth, M. & Ibarraran, M.) 8–45 (Elsevier Science, 2009).
20. Gaffin, S. R., Rosenzweig, C., Xing, X. & Yetman, G. Downscaling and geo-spatial gridding of socio-economic projections from the IPCC Special Report on Emissions Scenarios (SRES). *Glob. Environ. Change* **14,** 105–123 (2004).
21. Grubler, A. *et al.* Regional, national, and spatially explicit scenarios of demographic and economic change based on SRES. *Technol. Forecast. Soc. Change* **74,** 980–1029 (2006).
22. Van Vuuren, D. P., Lucas, P. & Hilderink, H. Downscaling drivers of global environmental change. Enabling use of global SRES scenarios at the national and grid levels. *Glob. Environ. Change* **17,** 114–130 (2007).
23. Meadows, D. *et al. The Limits to Growth* (Universe Books, 1972).
24. Leontief, W. *The Future of the World Economy: A Study on the Impact of Prospective Economic Issues and Policies on the International Development Strategy* (United Nations, New York, 1976).
25. Herrera, A. *et al. Catastrophe or New Society? A Latin American World Model* (IDRC, Ottawa, 1976).
26. Mesarovic, M. & Pestel, E. *Mankind at the Turning Point* (Dutton, 1974).
27. Häfele, W., Anderer, J., McDonald, A. & Nakicenovic, N. *Energy in a Finite World: Paths to a Sustainable Future* (Ballinger, 1981).
28. Robertson, J. *The Sane Alternative – A Choice of Futures* (River Basin, 1983).
29. Svedin, U. & Aniansson, B. *Surprising Futures: Notes From an International Workshop on Long-term World Development* (Swedish Council for Planning and Coordination of Research, Stockholm, 1987).
30. Response Strategies Working Group. in *Climate Change: The IPCC Scientific Assessment* (eds Houghton, J. T., Jenkins, G. J. & Ephraums J. J.) 329–341 (Cambridge Univ. Press, 1990).
31. Leggett, J., Pepper, W. J. & Swart, R. J. in *Climate Change 1992: The Supplementary Report to the IPCC Scientific Assessment* (eds Houghton, J. T., Callander, B. A. & Varney, S. K.) 69–95 (Cambridge Univ. Press, 1992).
32. Nakićenović, N., *et al. Special Report on Emissions Scenarios: A Special Report of Working Group III of the Intergovernmental Panel on Climate Change* (Cambridge Univ. Press, 2000).
33. *World Energy Outlook* (International Energy Agency, Paris, 2009).
34. Millennium Ecosystem Assessment. *Ecosystems and Human Well-being: Scenarios*, Vol. 2 (eds Carpenter, S. R. *et al.*) xix–551 (Island Press, 2005).
35. Alcamo, J. *et al.* in *Climate Change 1994: Radiative Forcing of Climate Change and an Evaluation of the IPCC IS92 Emission Scenarios* (eds Houghton, J. T. *et al.*) 247–304 (Cambridge Univ. Press, 1995).
36. Carter, T. R. *et al.* in *Climate Change 2007: Impacts, Adaptation and Vulnerability* (eds Parry, M. L., Canziani, O. F., Palutikof, J. P., van der Linden, P. J. & Hanson, C. E.) 133–171 (Cambridge Univ. Press, 2007).
37. Hurtt, G. C. *et al.* Harmonization of global land-use scenarios for the period 1500-2100 for IPCC-AR5. *iLEAPS Newsl.* **7,** 6–8 (2009).
38. Clarke, L. & Weyant, J. Introduction to the EMF Special Issue on climate change control scenarios. *Energy Econ.* **31,** S63–S81 (2009).
39. Huntingford, C. & Lowe, J. Overshoot scenarios and climate change. *Science* **316,** 829 (2007).
40. Wigley, T. M. L., Richels, R. & Edmonds, J. in *Human-Induced Climate Change: An Interdisciplinary Perspective* (eds Schlesinger, M. *et al.*) 84–92 (Cambridge Univ. Press, 2007).
41. Calvin, K. *et al.* Limiting climate change to 450 ppm CO_2 equivalent in the 21st century. *Energy Econ.* **31,** S107–S120 (2009).
42. Rao, S. *et al. IMAGE and MESSAGE Scenarios Limiting GHG Concentration to Low Levels* (IIASA Interim Report IR-08-020, International Institute for Applied Systems Analysis, Laxenburg, Austria, 2008).
43. Taylor, K. E., Stouffer, R. J. & Meehl, G. A. A summary of the CMIP5 experimental design. ⟨http://cmip-pcmdi.llnl.gov/cmip5/experiment_design.html?submenuheader=1⟩ (18 December 2009).
44. Randall, D. A. *et al.* in *Climate Change 2007: The Physical Science Basis* (eds Solomon, S., Qin, D. & Manning, M.) 589–662 (Cambridge Univ. Press, 2007).
45. Cox, P. M. *et al.* Acceleration of global warming due to carbon-cycle feedbacks in a coupled climate model. *Nature* **408,** 184–187 (2000).
46. Friedlingstein, P. *et al.* Climate-carbon cycle feedback analysis: results from the (CMIP)-M-4 model intercomparison. *J. Clim.* **19,** 3337–3353 (2006).
47. van Vuuren, D. P. *et al.* Temperature increase of 21st century mitigation scenarios. *Proc. Natl Acad. Sci. USA* **105,** 15258–15262 (2008).
48. Clarke, L. *et al. Scenarios of Greenhouse Gas Emissions and Atmospheric Concentrations* (Sub-report 2.1A of Synthesis and Assessment Product 2.1, US Climate Change Science Program and the Subcommittee on Global Change Research, Department of Energy, Office of Biological & Environmental Research, Washington DC, 2007).
49. Fisher, B. S. *et al.* in *Climate Change 2007: Mitigation* (eds Metz, B., Davidson, O. R., Bosch, P. R., Dave, R. & Meyer, L. A.) 169–250 (Cambridge Univ. Press, 2007).
50. Weyant, J. *et al. Report of 2.6 versus 2.9 Watts/m² RCP evaluation panel* ⟨http://www.ipcc.ch/meetings/session30/inf6.pdf⟩ (31 March 2009).
51. Lamarque, J.-F. *et al.* Gridded emissions in support of IPCC AR5. *IGAC Newsl.* **41,** 12–18 (2009).
52. Meehl, G. A. *et al.* Decadal prediction: can it be skillful? *Bull. Am. Meteorol. Soc.* **90,** 1467–1485 (2009).
53. Mitchell, T. D. Pattern scaling – an examination of the accuracy of the technique for describing future climates. *Clim. Change* **60,** 217–242 (2003).
54. Huntingford, C. & Cox, P. M. An analogue model to derive additional climate change scenarios from existing GCM simulations. *Clim. Dyn.* **16,** 575–586 (2000).
55. Rao, S. & Riahi, K. The role of non-CO_2 greenhouse gases in climate change mitigation: Long-term scenarios for the 21st century. Multigas mitigation and climate policy. *Energy J.* **3** (Special Issue), 177–200 (2006).
56. Riahi, K., Gruebler, A. & Nakicenovic, N. Scenarios of long-term socio-economic and environmental development under climate stabilization. *Technol. Forecast. Soc. Change* **74,** 887–935 (2007).
57. Fujino, J. *et al.* Multigas mitigation analysis on stabilization scenarios using AIM global model. Multigas mitigation and climate policy. *Energy J.* **3** (Special Issue), 343–354 (2006).
58. Hijioka, Y., Matsuoka, Y., Nishimoto, H., Masui, M. & Kainuma, M. Global GHG emissions scenarios under GHG concentration stabilization targets. *J. Glob. Environ. Eng.* **13,** 97–108 (2008).
59. Smith, S. J. & Wigley, T. M. L. Multi-gas forcing stabilization with the MiniCAM. Multigas mitigation and climate policy. *Energy J.* **3** (Special Issue), 373–391 (2006).
60. van Vuuren, D. P., Eickhout, B., Lucas, P. L. & den Elzen, M. G. J. Long-term multi-gas scenarios to stabilise radiative forcing — Exploring costs and benefits within an integrated assessment framework. Multigas mitigation and climate policy. *Energy J.* **3** (Special Issue), 201–234 (2006).
61. van Vuuren, D. P. *et al.* Stabilizing greenhouse gas concentrations at low levels: an assessment of reduction strategies and costs. *Clim. Change* **81,** 119–159 (2007).
62. Manabe, S. & Wetherald, R. T. Thermal equilibrium of the atmosphere with a given distribution of relative humidity. *J. Atmos. Sci.* **24,** 241–259 (1967).
63. Manabe, S. *et al.* A global ocean-atmosphere climate model: Part I. The atmospheric circulation. *J. Phys. Oceanogr.* **5,** 3–29 (1975).
64. Arrhenius, S. On the influence of carbonic acid in the air upon the temperature of the ground. *Lond. Edinb. Dublin Phil. Mag. J. Sci. (5th ser.)* **41,** 237–275 (1896).
65. Keeling, C. D. The concentration and isotopic abundance of carbon dioxide in the atmosphere. *Tellus* **12,** 200–203 (1960).
66. Hansen, J. *et al.* Global climate changes as forecast by Goddard Institute for Space Studies three-dimensional model. *J. Geophys. Res.* **93,** 9341–9364 (1988).
67. WMO/UNEP/ICSU. *Report of the Study Conference on Sensitivity of Ecosystems and Society to Climate Change* (WCP-83, UNESCO, Geneva, 1984).
68. WMO/UNEP/ICSU. *Report of the International Conference on the Assessment of the Role of Carbon Dioxide and of other Greenhouse Gases in Climate Variations and Associated Impacts* (WMO No. 661, UNESCO, Geneva, 1986).
69. Carter, T. R., Parry, M. L. & Porter, J. H. Climatic change and future agroclimatic potential in Europe. *Int. J. Climatol.* **11,** 251–269 (1991).
70. Carter, T. R., Parry, M. L., Harasawa, H. & Nishioka, S. (eds) *IPCC Technical Guidelines for Assessing Climate Change Impacts and Adaptations* (Dept of Geography, University College London, UK, and Center for Global Environmental Research, National Institute for Environmental Studies, Tsukuba, Japan, 1994).

71. Hulme, M., Raper, S. C. B. & Wigley, T. M. L. An integrated framework to address climate change (ESCAPE) and further developments of the global and regional climate modules (MAGICC). *Energy Policy* **23,** 347–355 (1995).
72. Melillo, J. M. *et al.* Vegetation/Ecosystem Modeling and Analysis Project (VEMAP): comparing biogeography and biogeochemistry models in a continental-scale study of terrestrial ecosystem responses to climate change and CO_2 doubling. *Glob. Biogeochem. Cycles* **9,** 407–437 (1995).
73. Smith, J. B., *et al. Vulnerability and Adaptation to Climate Change. Interim Results from the U.S. Country Studies Program* (Kluwer Academic, 1996).
74. Nakićenović, N., Victor, N. & Morita, T. Emissions scenarios database and review of scenarios. *Mitig. Adapt. Strategies Glob. Change* **3,** 95–120 (1998).
75. Watson, R. T., Zinyowera, M. C. & Moss, R. H. (eds) *The Regional Impacts of Climate Change: An Assessment of Vulnerability* (Cambridge Univ. Press, 1998).
76. Carter, T. R. *et al. Climate Change in the 21st Century – Interim Characterizations Based on the New IPCC Emissions Scenarios* (The Finnish Environment 433, Finnish Environment Institute, Helsinki, 2000).
77. Morita, T. *et al.* in *Climate Change 2001: Mitigation* (eds Metz, B., Davidson, O., Swart, R. & Pan J.) 115–166 (Cambridge Univ. Press, 2007).
78. United Kingdom Climate Impacts Programme. *Socio-economic Scenarios for Climate Change Impact Assessment: A Guide to Their Use in the UK Climate Impacts Programme* (United Kingdom Climate Impacts Programme, Oxford, 2001).
79. Ruosteenoja, K., Carter, T. R., Jylhä, K. & Tuomenvirta, H. *Future Climate in World Regions: An Intercomparison of Model-based Projections for the New IPCC Emissions Scenarios* (The Finnish Environment 644, Finnish Environment Institute, Helsinki, 2003).
80. Weyant, J. P., De La Chesnaye, C. F. & Blenford, J. Overview of EMF21: multi-greenhouse gas mitigation and climate policy. *Energy J.* **27** (Special Issue), 1–33 (2006).
81. Murphy, J. M. *et al. UK Climate Projections Science Report: Climate Change Projections* (Met Office Hadley Centre, Exeter, UK, 2009).
82. van der Linden, P. & Mitchell, J. F. B. (eds) *ENSEMBLES: Climate Change and its Impacts: Summary of research and results from the ENSEMBLES project* (Met Office Hadley Centre, Exeter, UK, 2009).
83. U.S. Climate Change Science Program. *Strategic Plan for the Climate Change Science Program, Final Report* (eds Subcommittee on Global Change Research) Figure 2.5 19 (US Climate Change Science Program, Washington DC, 2003).
84. Le Treut, H. *et al.* in *Climate Change 2007: The Physical Science Basis* (eds Solomon, S. *et al.*) 93–127 (Cambridge Univ. Press, 2007).
85. Ahmad, Q. K. *et al.* in *Climate Change 2001: Impacts, Adaptation and Vulnerability* (eds McCarthy, J. J., Canziani, O. F., Leary, N. A., Dokken, D. J. & White, K. S.) 105–143 (Cambridge Univ. Press, 2001).
86. US Department of Energy. *Science Challenges and Future Directions: Climate Change Integrated Assessment Research* (Report of the Workshop on Integrated Assessment, November 2008, US Department of Energy, Office of Science, Washington DC, 2009).
87. van Vuuren, D. P. & Riahi, K. Do recent emission trends imply higher emissions forever? *Clim. Change* **91,** 237–248 (2008).

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