1

Introduction

Coordinating Lead Authors:
Ulrich Cubasch (Germany), Donald Wuebbles (USA)

Lead Authors:
Deliang Chen (Sweden), Maria Cristina Facchini (Italy), David Frame (UK/New Zealand), Natalie Mahowald (USA), Jan-Gunnar Winther (Norway)

Contributing Authors:
Achim Brauer (Germany), Lydia Gates (Germany), Emily Janssen (USA), Frank Kaspar (Germany), Janina Körper (Germany), Valérie Masson-Delmotte (France), Malte Meinshausen (Australia/Germany), Matthew Menne (USA), Carolin Richter (Switzerland), Michael Schulz (Germany), Uwe Schulzweida (Germany), Bjorn Stevens (Germany/USA), Rowan Sutton (UK), Kevin Trenberth (USA), Murat Türkeş (Turkey), Daniel S. Ward (USA)

Review Editors:
Yihui Ding (China), Linda Mearns (USA), Peter Wadhams (UK)

This chapter should be cited as:
Cubasch, U., D. Wuebbles, D. Chen, M.C. Facchini, D. Frame, N. Mahowald, and J.-G. Winther, 2013: Introduction. In: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Table of Contents

Frequently Asked Questions

Executive Summary

Human Effects on Climate

Human activities are continuing to affect the Earth's energy budget by changing the emissions and resulting atmospheric concentrations of radiatively important gases and aerosols and by changing land surface properties. Previous assessments have already shown through multiple lines of evidence that the climate is changing across our planet, largely as a result of human activities. The most compelling evidence of climate change derives from observations of the atmosphere, land, oceans and cryosphere. Unequivocal evidence from *in situ* observations and ice core records shows that the atmospheric concentrations of important greenhouse gases such as carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) have increased over the last few centuries. {1.2.2, 1.2.3}

The processes affecting climate can exhibit considerable natural variability. Even in the absence of external forcing, periodic and chaotic variations on a vast range of spatial and temporal scales are observed. Much of this variability can be represented by simple (e.g., unimodal or power law) distributions, but many components of the climate system also exhibit multiple states—for instance, the glacial–interglacial cycles and certain modes of internal variability such as El Niño-Southern Oscillation (ENSO). Movement between states can occur as a result of natural variability, or in response to external forcing. The relationship among variability, forcing and response reveals the complexity of the dynamics of the climate system: the relationship between forcing and response for some parts of the system seems reasonably linear; in other cases this relationship is much more complex. {1.2.2}

Multiple Lines of Evidence for Climate Change

Global mean surface air temperatures over land and oceans have increased over the last 100 years. Temperature measurements in the oceans show a continuing increase in the heat content of the oceans. Analyses based on measurements of the Earth's radiative budget suggest a small positive energy imbalance that serves to increase the global heat content of the Earth system. Observations from satellites and *in situ* measurements show a trend of significant reductions in the mass balance of most land ice masses and in Arctic sea ice. The oceans' uptake of CO_2 is having a significant effect on the chemistry of sea water. Paleoclimatic reconstructions have helped place ongoing climate change in the perspective of natural climate variability. {1.2.3; Figure 1.3}

Observations of CO_2 concentrations, globally averaged temperature and sea level rise are generally well within the range of the extent of the earlier IPCC projections. The recently observed increases in CH_4 and N_2O concentrations are smaller than those assumed in the scenarios in the previous assessments. Each IPCC assessment has used new projections of future climate change that have become more detailed as the models have become more advanced. Similarly, the scenarios used in the IPCC assessments have themselves changed over time to reflect the state of knowledge. The range of climate projections from model results provided and assessed in the first IPCC assessment in 1990 to those in the 2007 AR4 provides an opportunity to compare the projections with the actually observed changes, thereby examining the deviations of the projections from the observations over time. {1.3.1, 1.3.2, 1.3.4; Figures 1.4, 1.5, 1.6, 1.7, 1.10}

Climate change, whether driven by natural or human forcing, can lead to changes in the likelihood of the occurrence or strength of extreme weather and climate events or both. Since the AR4, the observational basis has increased substantially, so that some extremes are now examined over most land areas. Furthermore, more models with higher resolution and a greater number of regional models have been used in the simulations and projections of extremes. {1.3.3; Figure 1.9}

Treatment of Uncertainties

For AR5, the three IPCC Working Groups use two metrics to communicate the degree of certainty in key findings: (1) Confidence is a qualitative measure of the validity of a finding, based on the type, amount, quality and consistency of evidence (e.g., data, mechanistic understanding, theory, models, expert judgment) and the degree of agreement[1]; and (2) Likelihood provides a quantified measure of uncertainty in a finding expressed probabilistically (e.g., based on statistical analysis of observations or model results, or both, and expert judgement)[2]. {1.4; Figure 1.11}

Advances in Measurement and Modelling Capabilities

Over the last few decades, new observational systems, especially satellite-based systems, have increased the number of observations of the Earth's climate by orders of magnitude. Tools to analyse and process these data have been developed or enhanced to cope with this large increase in information, and more climate proxy data have been acquired to improve our knowledge of past changes in climate. Because the Earth's climate system is characterized on multiple spatial and temporal scales, new observations may reduce the uncertainties surrounding the understanding of short timescale

---

[1] In this Report, the following summary terms are used to describe the available evidence: limited, medium, or robust; and for the degree of agreement: low, medium, or high. A level of confidence is expressed using five qualifiers: very low, low, medium, high, and very high, and typeset in italics, e.g., *medium confidence*. For a given evidence and agreement statement, different confidence levels can be assigned, but increasing levels of evidence and degrees of agreement are correlated with increasing confidence (see Section 1.4 and Box TS.1 for more details).

[2] In this Report, the following terms have been used to indicate the assessed likelihood of an outcome or a result: Virtually certain 99–100% probability, Very likely 90–100%, Likely 66–100%, About as likely as not 33–66%, Unlikely 0–33%, Very unlikely 0–10%, Exceptionally unlikely 0–1%. Additional terms (Extremely likely: 95–100%, More likely than not >50–100%, and Extremely unlikely 0–5%) may also be used when appropriate. Assessed likelihood is typeset in italics, e.g., *very likely* (see Section 1.4 and Box TS.1 for more details).

processes quite rapidly. However, processes that occur over longer timescales may require very long observational baselines before much progress can be made. {1.5.1; Figure 1.12}

Increases in computing speed and memory have led to the development of more sophisticated models that describe physical, chemical and biological processes in greater detail. Modelling strategies have been extended to provide better estimates of the uncertainty in climate change projections. The model comparisons with observations have pushed the analysis and development of the models. The inclusion of 'long-term' simulations has allowed incorporation of information from paleoclimate data to inform projections. Within uncertainties associated with reconstructions of past climate variables from proxy record and forcings, paleoclimate information from the Mid Holocene, Last Glacial Maximum, and Last Millennium have been used to test the ability of models to simulate realistically the magnitude and large-scale patterns of past changes. {1.5.2; Figures 1.13, 1.14}

As part of the process of getting model analyses for a range of alternative images of how the future may unfold, four new scenarios for future emissions of important gases and aerosols have been developed for the AR5, referred to as Representative Concentration Pathways (RCPs). {Box 1.1}

1.1 Chapter Preview

This introductory chapter serves as a lead-in to the science presented in the Working Group I (WGI) contribution to the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (AR5). Chapter 1 in the IPCC Fourth Assessment Report (AR4) (Le Treut et al., 2007) provided a historical perspective on the understanding of climate science and the evidence regarding human influence on the Earth's climate system. Since the last assessment, the scientific knowledge gained through observations, theoretical analyses, and modelling studies has continued to increase and to strengthen further the evidence linking human activities to the ongoing climate change. In AR5, Chapter 1 focuses on the concepts and definitions applied in the discussions of new findings in the other chapters. It also examines several of the key indicators for a changing climate and shows how the current knowledge of those indicators compares with the projections made in previous assessments. The new scenarios for projected human-related emissions used in this assessment are also introduced. Finally, the chapter discusses the directions and capabilities of current climate science, while the detailed discussion of new findings is covered in the remainder of the WGI contribution to the AR5.

1.2 Rationale and Key Concepts of the WGI Contribution

1.2.1 Setting the Stage for the Assessment

The IPCC was set up in 1988 by the World Meteorological Organization and the United Nations Environment Programme to provide governments with a clear view of the current state of knowledge about the science of climate change, potential impacts, and options for adaptation and mitigation through regular assessments of the most recent information published in the scientific, technical and socio-economic literature worldwide. The WGI contribution to the IPCC AR5 assesses the current state of the physical sciences with respect to climate change. This report presents an assessment of the current state of research results and is not a discussion of all relevant papers as would be included in a review. It thus seeks to make sure that the range of scientific views, as represented in the peer-reviewed literature, is considered and evaluated in the assessment, and that the state of the science is concisely and accurately presented. A transparent review process ensures that disparate views are included (IPCC, 2012a).

As an overview, Table 1.1 shows a selection of key findings from earlier IPCC assessments. This table provides a non-comprehensive selection of key assessment statements from previous assessment reports—IPCC First Assessment Report (FAR, IPCC, 1990), IPCC Second Assessment Report (SAR, IPCC, 1996), IPCC Third Assessment Report (TAR, IPCC, 2001) and IPCC Fourth Assessment Report (AR4, IPCC, 2007)—with a focus on policy-relevant quantities that have been evaluated in each of the IPCC assessments.

Scientific hypotheses are contingent and always open to revision in light of new evidence and theory. In this sense the distinguishing features of scientific enquiry are the search for truth and the willingness to subject itself to critical re-examination. Modern research science conducts this critical revision through processes such as the peer review. At conferences and in the procedures that surround publication in peer-reviewed journals, scientific claims about environmental processes are analysed and held up to scrutiny. Even after publication, findings are further analysed and evaluated. That is the self-correcting nature of the scientific process (more details are given in AR4 Chapter 1 and Le Treut et al., 2007).

Science strives for objectivity but inevitably also involves choices and judgements. Scientists make choices regarding data and models, which processes to include and which to leave out. Usually these choices are uncontroversial and play only a minor role in the production of research. Sometimes, however, the choices scientists make are sources of disagreement and uncertainty. These are usually resolved by further scientific enquiry into the sources of disagreement. In some cases, experts cannot reach a consensus view. Examples in climate science include how best to evaluate climate models relative to observations, how best to evaluate potential sea level rise and how to evaluate probabilistic projections of climate change. In many cases there may be no definitive solution to these questions. The IPCC process is aimed at assessing the literature as it stands and attempts to reflect the level of reasonable scientific consensus as well as disagreement.

To assess areas of scientific controversy, the peer-reviewed literature is considered and evaluated. Not all papers on a controversial point can be discussed individually in an assessment, but every effort has been made here to ensure that all views represented in the peer-reviewed literature are considered in the assessment process. A list of topical issues is given in Table 1.3.

The Earth sciences study the multitude of processes that shape our environment. Some of these processes can be understood through idealized laboratory experiments, by altering a single element and then tracing through the effects of that controlled change. However, as in other natural and the social sciences, the openness of environmental systems, in terms of our lack of control of the boundaries of the system, their spatially and temporally multi-scale character and the complexity of interactions, often hamper scientists' ability to definitively isolate causal links. This in turn places important limits on the understanding of many of the inferences in the Earth sciences (e.g., Oreskes et al., 1994). There are many cases where scientists are able to make inferences using statistical tools with considerable evidential support and with high degrees of confidence, and conceptual and numerical modelling can assist in forming understanding and intuition about the interaction of dynamic processes.

1.2.2 Key Concepts in Climate Science

Here, some of the key concepts in climate science are briefly described; many of these were summarized more comprehensively in earlier IPCC assessments (Baede et al., 2001). We focus only on a certain number of them to facilitate discussions in this assessment.

First, it is important to distinguish the meaning of weather from climate. Weather describes the conditions of the atmosphere at a certain place and time with reference to temperature, pressure, humidity, wind, and other key parameters (meteorological elements); the

Table 1.1 | Historical overview of major conclusions of previous IPCC assessment reports. The table provides a non-comprehensive selection of key statements from previous assessment reports—IPCC First Assessment Report (FAR; IPCC, 1990), IPCC Second Assessment Report (SAR; IPCC, 1996), IPCC Third Assessment Report (TAR; IPCC, 2001) and IPCC Fourth Assessment Report (AR4; IPCC, 2007)—with a focus on global mean surface air temperature and sea level change as two policy relevant quantities that have been covered in IPCC since the first assessment report.

Topic		FAR SPM Statement	SAR SPM Statement	TAR SPM Statement	AR4 SPM Statement
Human and Natural Drivers of Climate Change		There is a natural greenhouse effect which already keeps the Earth warmer than it would otherwise be. Emissions resulting from human activities are substantially increasing the atmospheric concentrations of the greenhouse gases carbon dioxide, methane, chlorofluorocarbons and nitrous oxide. These increases will enhance the greenhouse effect, resulting on average in an additional warming of the Earth's surface. Continued emissions of these gases at present rates would commit us to increased concentrations for centuries ahead.	Greenhouse gas concentrations have continued to increase. These trends can be attributed largely to human activities, mostly fossil fuel use, land use change and agriculture. Anthropogenic aerosols are short-lived and tend to produce negative radiative forcing.	Emissions of greenhouse gases and aerosols due to human activities continue to alter the atmosphere in ways that are expected to affect the climate. The atmospheric concentration of CO_2 has increased by 31% since 1750 and that of methane by 151%. Anthropogenic aerosols are short-lived and mostly produce negative radiative forcing by their direct effect. There is more evidence for their indirect effect, which is negative, although of very uncertain magnitude. Natural factors have made small contributions to radiative forcing over the past century.	Global atmospheric concentrations of carbon dioxide, methane and nitrous oxide have increased markedly as a result of human activities since 1750 and now far exceed pre-industrial values determined from ice cores spanning many thousands of years. The global increases in carbon dioxide concentration are due primarily to fossil fuel use and land use change, while those of methane and nitrous oxide are primarily due to agriculture. *Very high confidence* that the global average net effect of human activities since 1750 has been one of warming, with a radiative forcing of +1.6 [+0.6 to +2.4] W m^{-2}.
Direct Observations of Recent Climate Change	**Temperature**	Global mean surface air temperature has increased by 0.3°C to 0.6°C over the last 100 years, with the five global-average warmest years being in the 1980s.	Climate has changed over the past century. Global mean surface temperature has increased by between about 0.3 and 0.6°C since the late 19th century. Recent years have been among the warmest since 1860, despite the cooling effect of the 1991 Mt. Pinatubo volcanic eruption.	An increasing body of observations gives a collective picture of a warming world and other changes in the climate system. The global average temperature has increased since 1861. Over the 20th century the increase has been 0.6°C. Some important aspects of climate appear not to have changed.	Warming of the climate system is unequivocal, as is now evident from observations of increases in global average air and ocean temperatures, widespread melting of snow and ice, and rising global average sea level. Eleven of the last twelve years (1995–2006) rank among the 12 warmest years in the instrumental record of global surface temperature (since 1850). The updated 100-year linear trend (1906 to 2005) of 0.74°C [0.56°C to 0.92°C] is therefore larger than the corresponding trend for 1901 to 2000 given in the TAR of 0.6°C [0.4°C to 0.8°C]. Some aspects of climate have not been observed to change.
	Sea Level	Over the same period global sea level has increased by 10 to 20 cm These increases have not been smooth with time, nor uniform over the globe.	Global sea level has risen by between 10 and 25 cm over the past 100 years and much of the rise may be related to the increase in global mean temperature.	Tide gauge data show that global average sea level rose between 0.1 and 0.2 m during the 20th century.	Global average sea level rose at an average rate of 1.8 [1.3 to 2.3] mm per year over 1961 to 2003. The rate was faster over 1993 to 2003: about 3.1 [2.4 to 3.8] mm per year. The total 20th century rise is estimated to be 0.17 [0.12 to 0.22] m.
A Palaeoclimatic Perspective		Climate varies naturally on all timescales from hundreds of millions of years down to the year-to-year. Prominent in the Earth's history have been the 100,000 year glacial–interglacial cycles when climate was mostly cooler than at present. Global surface temperatures have typically varied by 5°C to 7°C through these cycles, with large changes in ice volume and sea level, and temperature changes as great as 10°C to 15°C in some middle and high latitude regions of the Northern Hemisphere. Since the end of the last ice age, about 10,000 years ago, global surface temperatures have probably fluctuated by little more than 1°C. Some fluctuations have lasted several centuries, including the Little Ice Age which ended in the nineteenth century and which appears to have been global in extent.	The limited available evidence from proxy climate indicators suggests that the 20th century global mean temperature is at least as warm as any other century since at least 1400 AD. Data prior to 1400 are too sparse to allow the reliable estimation of global mean temperature.	New analyses of proxy data for the Northern Hemisphere indicate that the increase in temperature in the 20th century is *likely* to have been the largest of any century during the past 1,000 years. It is also *likely* that, in the Northern Hemisphere, the 1990s was the warmest decade and 1998 the warmest year. Because less data are available, less is known about annual averages prior to 1,000 years before present and for conditions prevailing in most of the Southern Hemisphere prior to 1861.	Palaeoclimatic information supports the interpretation that the warmth of the last half century is unusual in at least the previous 1,300 years. The last time the polar regions were significantly warmer than present for an extended period (about 125,000 years ago), reductions in polar ice volume led to 4 to 6 m of sea level rise.

(continued on next page)

(Table 1.1 continued)

Topic		FAR SPM Statement	SAR SPM Statement	TAR SPM Statement	AR4 SPM Statement
Understanding and Attributing Climate Change		The size of this warming is broadly consistent with predictions of climate models, but it is also of the same magnitude as natural climate variability. Thus the observed increase could be largely due to this natural variability; alternatively this variability and other human factors could have offset a still larger human-induced greenhouse warming. The unequivocal detection of the enhanced greenhouse effect from observations is not likely for a decade or more.	The balance of evidence suggests a discernible human influence on global climate. Simulations with coupled atmosphere–ocean models have provided important information about decade to century timescale natural internal climate variability.	There is new and stronger evidence that most of the warming observed over the last 50 years is attributable to human activities. There is a longer and more scrutinized temperature record and new model estimates of variability. Reconstructions of climate data for the past 1,000 years indicate this warming was unusual and is *unlikely* to be entirely natural in origin.	Most of the observed increase in global average temperatures since the mid-20th century is *very likely* due to the observed increase in anthropogenic greenhouse gas concentrations. Discernible human influences now extend to other aspects of climate, including ocean warming, continental-average temperatures, temperature extremes and wind patterns.
Projections of Future Changes in Climate	**Temperature**	Under the IPCC Business-as-Usual-emissions of greenhouse gases, a rate of increase of global mean temperature during the next century of about 0.3°C per decade (with an uncertainty range of 0.2°C to 0.5°C per decade); this is greater than that seen over the past 10,000 years.	Climate is expected to continue to change in the future. For the mid-range IPCC emission scenario, IS92a, assuming the 'best estimate' value of climate sensitivity and including the effects of future increases in aerosols, models project an increase in global mean surface air temperature relative to 1990 of about 2°C by 2100.	Global average temperature and sea level are projected to rise under all IPCC SRES scenarios. The globally averaged surface temperature is projected to increase by 1.4°C to 5.8°C over the period 1990 to 2100. Confidence in the ability of models to project future climate has increased. Anthropogenic climate change will persist for many centuries.	For the next two decades, a warming of about 0.2°C per decade is projected for a range of SRES emission scenarios. Even if the concentrations of all greenhouse gases and aerosols had been kept constant at year 2000 levels, a further warming of about 0.1°C per decade would be expected. There is now higher confidence in projected patterns of warming and other regional-scale features, including changes in wind patterns, precipitation and some aspects of extremes and of ice. Anthropogenic warming and sea level rise would continue for centuries, even if greenhouse gas concentrations were to be stabilised.
	Sea Level	An average rate of global mean sea level rise of about 6 cm per decade over the next century (with an uncertainty range of 3 to 10 cm per decade) is projected.	Models project a sea level rise of 50 cm from the present to 2100.	Global mean sea level is projected to rise by 0.09 to 0.88 m between 1990 and 2100.	Global sea level rise for the range of scenarios is projected as 0.18 to 0.59 m by the end of the 21st century.

presence of clouds, precipitation; and the occurrence of special phenomena, such as thunderstorms, dust storms, tornados and others. Climate in a narrow sense is usually defined as the average weather, or more rigorously, as the statistical description in terms of the mean and variability of relevant quantities over a period of time ranging from months to thousands or millions of years. The relevant quantities are most often surface variables such as temperature, precipitation and wind. Classically the period for averaging these variables is 30 years, as defined by the World Meteorological Organization. Climate in a wider sense also includes not just the mean conditions, but also the associated statistics (frequency, magnitude, persistence, trends, etc.), often combining parameters to describe phenomena such as droughts. Climate change refers to a change in the state of the climate that can be identified (e.g., by using statistical tests) by changes in the mean and/or the variability of its properties, and that persists for an extended period, typically decades or longer.

The Earth's climate system is powered by solar radiation (Figure 1.1). Approximately half of the energy from the Sun is supplied in the visible part of the electromagnetic spectrum. As the Earth's temperature has been relatively constant over many centuries, the incoming solar energy must be nearly in balance with outgoing radiation. Of the incoming solar shortwave radiation (SWR), about half is absorbed by the Earth's surface. The fraction of SWR reflected back to space by gases and aerosols, clouds and by the Earth's surface (albedo) is approximately 30%, and about 20% is absorbed in the atmosphere. Based on the temperature of the Earth's surface the majority of the outgoing energy flux from the Earth is in the infrared part of the spectrum. The longwave radiation (LWR, also referred to as infrared radiation) emitted from the Earth's surface is largely absorbed by certain atmospheric constituents—water vapour, carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and other greenhouse gases (GHGs); see Annex III for Glossary—and clouds, which themselves emit LWR into all directions. The downward directed component of this LWR adds heat to the lower layers of the atmosphere and to the Earth's surface (greenhouse effect). The dominant energy loss of the infrared radiation from the Earth is from higher layers of the troposphere. The Sun provides its energy to the Earth primarily in the tropics and the subtropics; this energy is then partially redistributed to middle and high latitudes by atmospheric and oceanic transport processes.

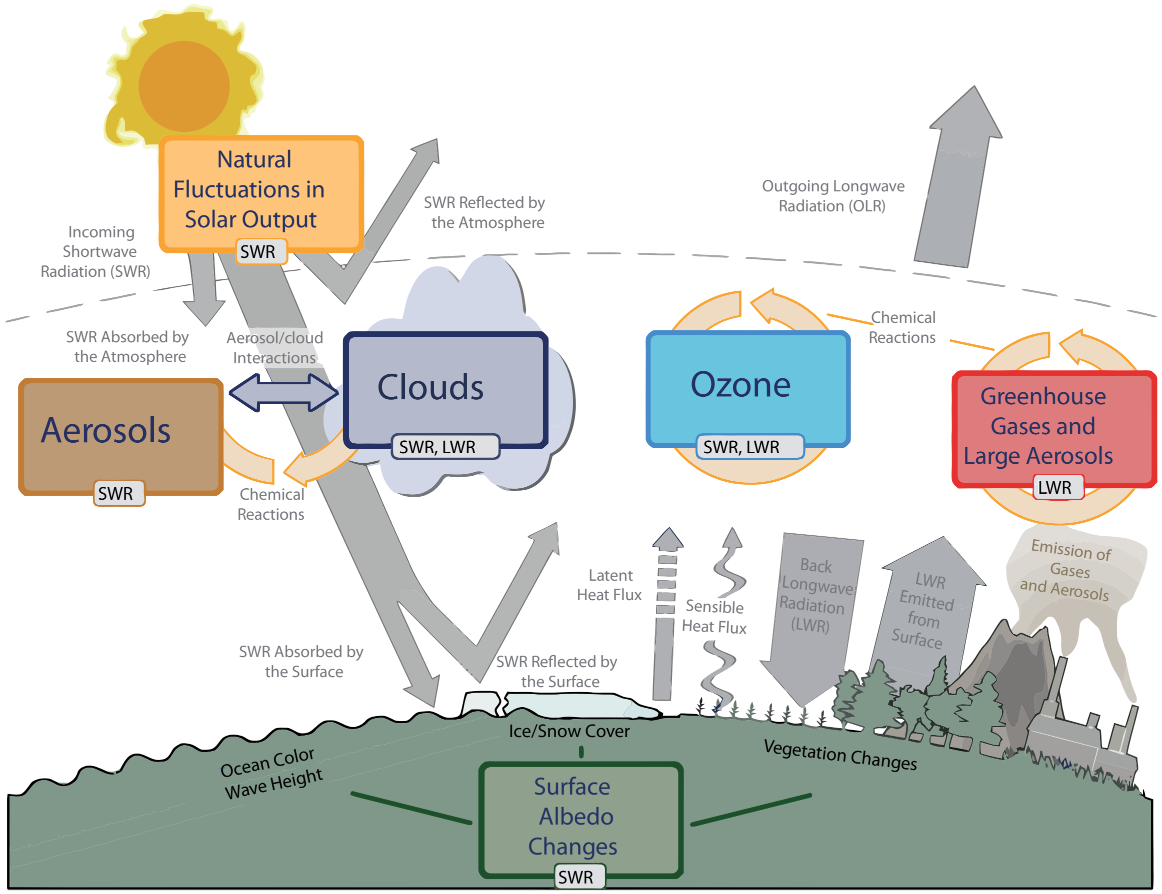


Figure 1.1 | Main drivers of climate change. The radiative balance between incoming solar shortwave radiation (SWR) and outgoing longwave radiation (OLR) is influenced by global climate 'drivers'. Natural fluctuations in solar output (solar cycles) can cause changes in the energy balance (through fluctuations in the amount of incoming SWR) (Section 2.3). Human activity changes the emissions of gases and aerosols, which are involved in atmospheric chemical reactions, resulting in modified O_3 and aerosol amounts (Section 2.2). O_3 and aerosol particles absorb, scatter and reflect SWR, changing the energy balance. Some aerosols act as cloud condensation nuclei modifying the properties of cloud droplets and possibly affecting precipitation (Section 7.4). Because cloud interactions with SWR and LWR are large, small changes in the properties of clouds have important implications for the radiative budget (Section 7.4). Anthropogenic changes in GHGs (e.g., CO_2, CH_4, N_2O, O_3, CFCs) and large aerosols (>2.5 μm in size) modify the amount of outgoing LWR by absorbing outgoing LWR and re-emitting less energy at a lower temperature (Section 2.2). Surface albedo is changed by changes in vegetation or land surface properties, snow or ice cover and ocean colour (Section 2.3). These changes are driven by natural seasonal and diurnal changes (e.g., snow cover), as well as human influence (e.g., changes in vegetation types) (Forster et al., 2007).

Changes in the global energy budget derive from either changes in the net incoming solar radiation or changes in the outgoing longwave radiation (OLR). Changes in the net incoming solar radiation derive from changes in the Sun's output of energy or changes in the Earth's albedo. Reliable measurements of total solar irradiance (TSI) can be made only from space, and the precise record extends back only to 1978. The generally accepted mean value of the TSI is about 1361 W m^{-2} (Kopp and Lean, 2011; see Chapter 8 for a detailed discussion on the TSI); this is lower than the previous value of 1365 W m^{-2} used in the earlier assessments. Short-term variations of a few tenths of a percent are common during the approximately 11-year sunspot solar cycle (see Sections 5.2 and 8.4 for further details). Changes in the outgoing LWR can result from changes in the temperature of the Earth's surface or atmosphere or changes in the emissivity (measure of emission efficiency) of LWR from either the atmosphere or the Earth's surface. For the atmosphere, these changes in emissivity are due predominantly to changes in cloud cover and cloud properties, in GHGs and in aerosol concentrations. The radiative energy budget of the Earth is almost in balance (Figure 1.1), but ocean heat content and satellite measurements indicate a small positive imbalance (Murphy et al., 2009; Trenberth et al., 2009; Hansen et al., 2011) that is consistent with the rapid changes in the atmospheric composition.

In addition, some aerosols increase atmospheric reflectivity, whereas others (e.g., particulate black carbon) are strong absorbers and also modify SWR (see Section 7.2 for a detailed assessment). Indirectly, aerosols also affect cloud albedo, because many aerosols serve as cloud condensation nuclei or ice nuclei. This means that changes in aerosol types and distribution can result in small but important changes in cloud albedo and lifetime (Section 7.4). Clouds play a critical role in climate because they not only can increase albedo, thereby cooling the planet, but also because of their warming effects through infrared radiative transfer. Whether the net radiative effect of a cloud is one of cooling or of warming depends on its physical properties (level of occurrence, vertical extent, water path and effective cloud particle size) as well as on the nature of the cloud condensation nuclei population (Section 7.3). Humans enhance the greenhouse effect directly by emitting GHGs such as CO_2, CH_4, N_2O and chlorofluorocarbons (CFCs) (Figure 1.1). In addition, pollutants such as carbon monoxide (CO), volatile organic compounds (VOC), nitrogen oxides (NO_x) and sulphur dioxide (SO_2), which by themselves are negligible GHGs, have an indirect effect on the greenhouse effect by altering, through atmospheric chemical reactions, the abundance of important gases to the amount of outgoing LWR such as CH_4 and ozone (O_3), and/or by acting as precursors of secondary aerosols. Because anthropogenic emission sources simultaneously can emit some chemicals that affect climate and others that affect air pollution, including some that affect both, atmospheric chemistry and climate science are intrinsically linked.

In addition to changing the atmospheric concentrations of gases and aerosols, humans are affecting both the energy and water budget of the planet by changing the land surface, including redistributing the balance between latent and sensible heat fluxes (Sections 2.5, 7.2, 7.6 and 8.2). Land use changes, such as the conversion of forests to cultivated land, change the characteristics of vegetation, including its colour, seasonal growth and carbon content (Houghton, 2003; Foley et al., 2005). For example, clearing and burning a forest to prepare agricultural land reduces carbon storage in the vegetation, adds CO_2 to the atmosphere, and changes the reflectivity of the land (surface albedo), rates of evapotranspiration and longwave emissions (Figure 1.1).

Changes in the atmosphere, land, ocean, biosphere and cryosphere—both natural and anthropogenic—can perturb the Earth's radiation budget, producing a radiative forcing (RF) that affects climate. RF is a measure of the net change in the energy balance in response to an external perturbation. The drivers of changes in climate can include, for example, changes in the solar irradiance and changes in atmospheric trace gas and aerosol concentrations (Figure 1.1). The concept of RF cannot capture the interactions of anthropogenic aerosols and clouds, for example, and thus in addition to the RF as used in previous assessments, Sections 7.4 and 8.1 introduce a new concept, effective radiative forcing (ERF), that accounts for rapid response in the climate system. ERF is defined as the change in net downward flux at the top of the atmosphere after allowing for atmospheric temperatures, water vapour, clouds and land albedo to adjust, but with either sea surface temperatures (SSTs) and sea ice cover unchanged or with global mean surface temperature unchanged.

Once a forcing is applied, complex internal feedbacks determine the eventual response of the climate system, and will in general cause this response to differ from a simple linear one (IPCC, 2001, 2007). There are many feedback mechanisms in the climate system that can either amplify ('positive feedback') or diminish ('negative feedback') the effects of a change in climate forcing (Le Treut et al., 2007) (see Figure 1.2 for a representation of some of the key feedbacks). An example of a positive feedback is the water vapour feedback whereby an increase in surface temperature enhances the amount of water vapour present in the atmosphere. Water vapour is a powerful GHG: increasing its atmospheric concentration enhances the greenhouse effect and leads to further surface warming. Another example is the ice albedo feedback, in which the albedo decreases as highly reflective ice and snow surfaces melt, exposing the darker and more absorbing surfaces below. The dominant negative feedback is the increased emission of energy through LWR as surface temperature increases (sometimes also referred to as blackbody radiation feedback). Some feedbacks operate quickly (hours), while others develop over decades to centuries; in order to understand the full impact of a feedback mechanism, its timescale needs to be considered. Melting of land ice sheets can take days to millennia.

A spectrum of models is used to project quantitatively the climate response to forcings. The simplest energy balance models use one box to represent the Earth system and solve the global energy balance to deduce globally averaged surface air temperature. At the other extreme, full complexity three-dimensional climate models include the explicit solution of energy, momentum and mass conservation equations at millions of points on the Earth in the atmosphere, land, ocean and cryosphere. More recently, capabilities for the explicit simulation of the biosphere, the carbon cycle and atmospheric chemistry have been added to the full complexity models, and these models are called Earth System Models (ESMs). Earth System Models of Intermediate Complexity include the same processes as ESMs, but at reduced resolution, and thus can be simulated for longer periods (see Annex III for Glossary and Section 9.1).

An equilibrium climate experiment is an experiment in which a climate model is allowed to adjust fully to a specified change in RF. Such experiments provide information on the difference between the initial and final states of the model simulated climate, but not on the time-dependent response. The equilibrium response in global mean surface air temperature to a doubling of atmospheric concentration of CO_2 above pre-industrial levels (e.g., Arrhenius, 1896; see Le Treut et al., 2007 for a comprehensive list) has often been used as the basis for the concept of equilibrium climate sensitivity (e.g., Hansen et al., 1981; see Meehl et al., 2007 for a comprehensive list). For more realistic simulations of climate, changes in RF are applied gradually over time, for example, using historical reconstructions of the CO_2, and these simulations are called transient simulations. The temperature response in these transient simulations is different than in an equilibrium simulation. The transient climate response is defined as the change in global surface temperature at the time of atmospheric CO_2 doubling in a global coupled ocean–atmosphere climate model simulation where concentrations of CO_2 were increased by 1% yr^{-1}. The transient climate response is a measure of the strength and rapidity of the surface temperature response to GHG forcing. It can be more meaningful for some problems as well as easier to derive from observations (see Figure 10.20; Section 10.8; Chapter 12; Knutti et al., 2005; Frame et al., 2006; Forest et al., 2008), but such experiments are not intended to replace the more realistic scenario evaluations.

Climate change commitment is defined as the future change to which the climate system is committed by virtue of past or current forcings. The components of the climate system respond on a large range of timescales, from the essentially rapid responses that characterise some radiative feedbacks to millennial scale responses such as those associated with the behaviour of the carbon cycle (Section 6.1) and ice sheets (see Figure 1.2 and Box 5.1). Even if anthropogenic emissions were immediately ceased (Matthews and Weaver, 2010) or if climate forcings were fixed at current values (Wigley, 2005), the climate system would continue to change until it came into equilibrium with those forcings (Section 12.5). Because of the slow response time of some components

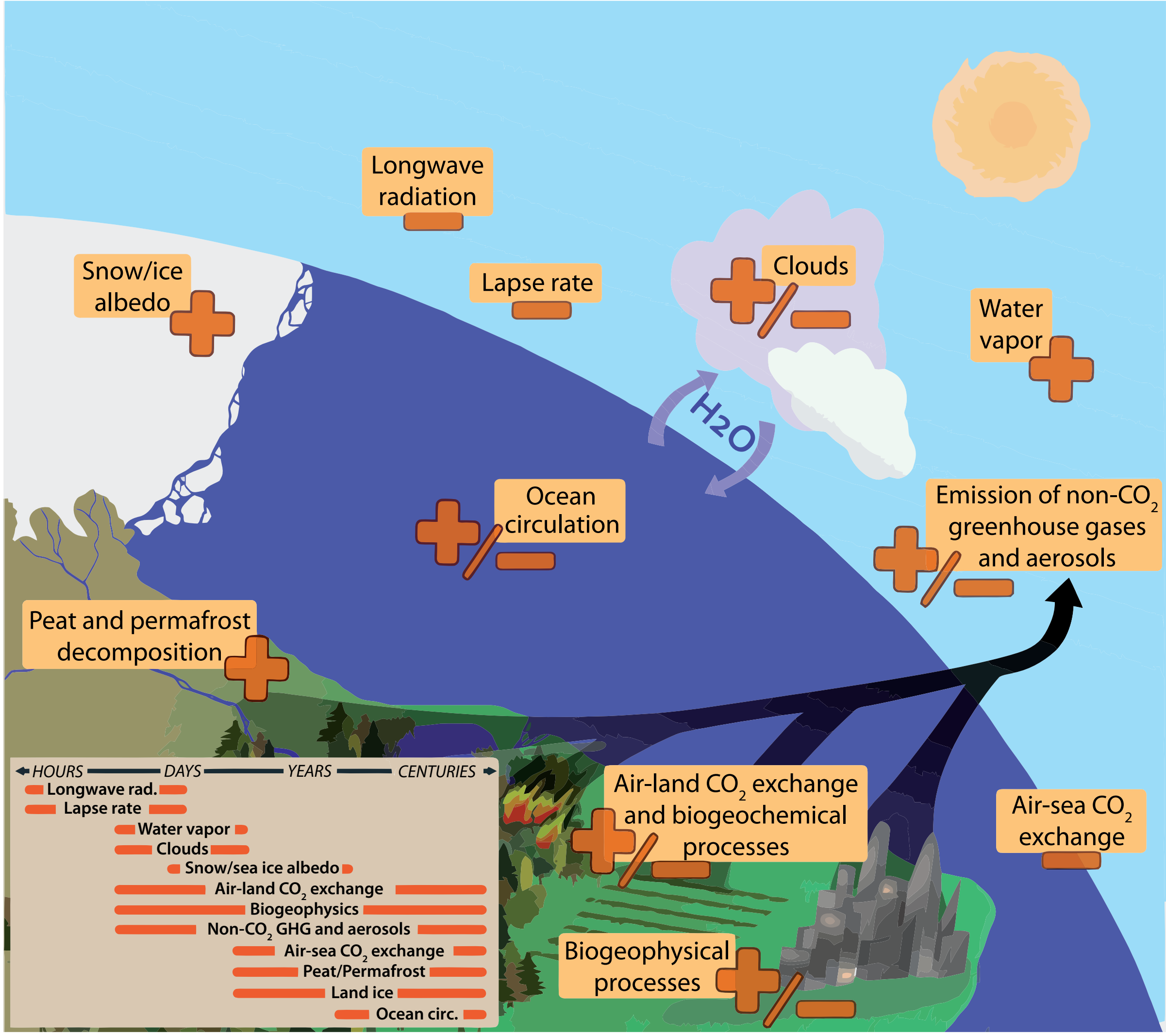


Figure 1.2 | Climate feedbacks and timescales. The climate feedbacks related to increasing CO_2 and rising temperature include negative feedbacks (–) such as LWR, lapse rate (see Glossary in Annex III), and air–sea carbon exchange and positive feedbacks (+) such as water vapour and snow/ice albedo feedbacks. Some feedbacks may be positive or negative (±): clouds, ocean circulation changes, air–land CO_2 exchange, and emissions of non-GHGs and aerosols from natural systems. In the smaller box, the large difference in timescales for the various feedbacks is highlighted.

of the climate system, equilibrium conditions will not be reached for many centuries. Slow processes can sometimes be constrained only by data collected over long periods, giving a particular salience to paleoclimate data for understanding equilibrium processes. Climate change commitment is indicative of aspects of inertia in the climate system because it captures the ongoing nature of some aspects of change.

A summary of perturbations to the forcing of the climate system from changes in solar radiation, GHGs, surface albedo and aerosols is presented in Box 13.1. The energy fluxes from these perturbations are balanced by increased radiation to space from a warming Earth, reflection of solar radiation and storage of energy in the Earth system, principally the oceans (Box 3.1, Box 13.1).

The processes affecting climate can exhibit considerable natural variability. Even in the absence of external forcing, periodic and chaotic variations on a vast range of spatial and temporal scales are observed. Much of this variability can be represented by simple (e.g., unimodal or power law) distributions, but many components of the climate system also exhibit multiple states—for instance, the glacial-interglacial cycles and certain modes of internal variability such as El Niño-Southern Oscillation (ENSO) (see Box 2.5 for details on patterns and indices of climate variability). Movement between states can occur as a result of natural variability, or in response to external forcing. The relationship between variability, forcing and response reveals the complexity of the dynamics of the climate system: the relationship between forcing and response for some parts of the system seems reasonably linear; in other cases this relationship is much more complex, characterised by hysteresis (the dependence on past states) and a non-additive combination of feedbacks.

Related to multiple climate states, and hysteresis, is the concept of irreversibility in the climate system. In some cases where multiple states and irreversibility combine, bifurcations or 'tipping points' can been reached (see Section 12.5). In these situations, it is difficult if not impossible for the climate system to revert to its previous state, and the change is termed irreversible over some timescale and forcing range. A small number of studies using simplified models find evidence for global-scale 'tipping points' (e.g., Lenton et al., 2008); however, there is no evidence for global-scale tipping points in any of the most comprehensive models evaluated to date in studies of climate evolution in the 21st century. There is evidence for threshold behaviour in certain aspects of the climate system, such as ocean circulation (see Section 12.5) and ice sheets (see Box 5.1), on multi-centennial-to-millennial timescales. There are also arguments for the existence of regional tipping points, most notably in the Arctic (e.g., Lenton et al., 2008; Duarte et al., 2012; Wadhams, 2012), although aspects of this are contested (Armour et al., 2011; Tietsche et al., 2011).

1.2.3 Multiple Lines of Evidence for Climate Change

While the first IPCC assessment depended primarily on observed changes in surface temperature and climate model analyses, more recent assessments include multiple lines of evidence for climate change. The first line of evidence in assessing climate change is based on careful analysis of observational records of the atmosphere, land, ocean and cryosphere systems (Figure 1.3). There is incontrovertible evidence from *in situ* observations and ice core records that the atmospheric concentrations of GHGs such as CO_2, CH_4, and N_2O have increased substantially over the last 200 years (Sections 6.3 and 8.3). In addition, instrumental observations show that land and sea surface temperatures have increased over the last 100 years (Chapter 2). Satellites allow a much broader spatial distribution of measurements, especially over the last 30 years. For the upper ocean temperature the observations indicate that the temperature has increased since at least 1950 (Willis et al., 2010; Section 3.2). Observations from satellites and *in situ* measurements suggest reductions in glaciers, Arctic sea ice and ice sheets (Sections 4.2, 4.3 and 4.4). In addition, analyses based on measurements of the radiative budget and ocean heat content suggest a small imbalance (Section 2.3). These observations, all published in peer-reviewed journals, made by diverse measurement groups in multiple countries using different technologies, investigating various climate-relevant types of data, uncertainties and processes, offer a wide range of evidence on the broad extent of the changing climate throughout our planet.

Conceptual and numerical models of the Earth's climate system offer another line of evidence on climate change (discussions in Chapters 5 and 9 provide relevant analyses of this evidence from paleoclimatic to recent periods). These use our basic understanding of the climate system to provide self-consistent methodologies for calculating impacts of processes and changes. Numerical models include the current knowledge about the laws of physics, chemistry and biology, as well as hypotheses about how complicated processes such as cloud formation can occur. Because these models can represent only the existing state of knowledge and technology, they are not perfect; they are, however, important tools for analysing uncertainties or unknowns, for testing different hypotheses for causation relative to observations, and for making projections of possible future changes.

One of the most powerful methods for assessing changes occurring in climate involves the use of statistical tools to test the analyses from models relative to observations. This methodology is generally called detection and attribution in the climate change community (Section 10.2). For example, climate models indicate that the temperature response to GHG increases is expected to be different than the effects from aerosols or from solar variability. Radiosonde measurements and satellite retrievals of atmospheric temperature show increases in tropospheric temperature and decreases in stratospheric temperatures, consistent with the increases in GHG effects found in climate model simulations (e.g., increases in CO_2, changes in O_3), but if the Sun was the main driver of current climate change, stratospheric and tropospheric temperatures would respond with the same sign (Hegerl et al., 2007).

Resources available prior to the instrumental period—historical sources, natural archives, and proxies for key climate variables (e.g., tree rings, marine sediment cores, ice cores)—can provide quantitative information on past regional to global climate and atmospheric composition variability and these data contribute another line of evidence. Reconstructions of key climate variables based on these data sets have provided important information on the responses of the Earth system to a variety of external forcings and its internal variability over a wide range of timescales (Hansen et al., 2006; Mann et al., 2008). Paleoclimatic reconstructions thus offer a means for placing the current changes in climate in the perspective of natural climate variability (Section 5.1). AR5 includes new information on external RFs caused by variations in volcanic and solar activity (e.g., Steinhilber et al., 2009; see Section 8.4). Extended data sets on past changes in atmospheric concentrations and distributions of atmospheric GHG concentrations (e.g., Lüthi et al., 2008; Beerling and Royer, 2011) and mineral aerosols (Lambert et al., 2008) have also been used to attribute reconstructed paleoclimate temperatures to past variations in external forcings (Section 5.2).

1.3 Indicators of Climate Change

There are many indicators of climate change. These include physical responses such as changes in the following: surface temperature, atmospheric water vapour, precipitation, severe events, glaciers, ocean and land ice, and sea level. Some key examples of such changes in important climate parameters are discussed in this section and all are assessed in much more detail in other chapters.

As was done to a more limited extent in AR4 (Le Treut et al., 2007), this section provides a test of the planetary-scale hypotheses of climate change against observations. In other words, how well do the projections used in the past assessments compare with observations to date? Seven additional years of observations are now available to evaluate earlier model projections. The projected range that was given in each assessment is compared to observations. The largest possible range of scenarios available for a specific variable for each of the previous assessment reports is shown in the figures.

Based on the assessment of AR4, a number of the key climate and associated environmental parameters are presented in Figure 1.3, which updates the similar figure in the Technical Summary (TS) of IPCC (2001). This section discusses the recent changes in several indicators, while more thorough assessments for each of these indicators are

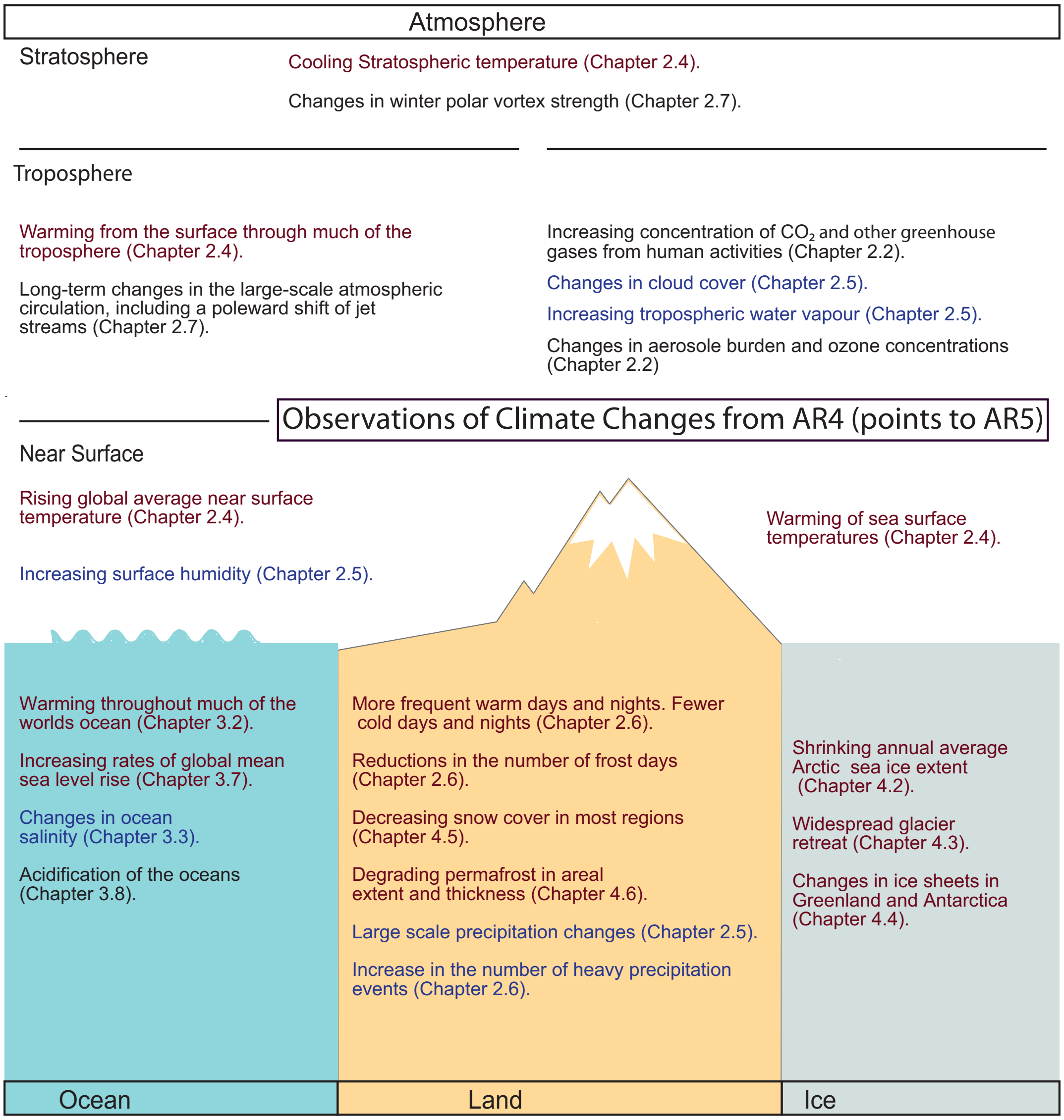


Figure 1.3 | Overview of observed climate change indicators as listed in AR4. Chapter numbers indicate where detailed discussions for these indicators are found in AR5 (temperature: red; hydrological: blue; others: black).

provided in other chapters. Also shown in parentheses in Figure 1.3 are the chapter and section where those indicators of change are assessed in AR5.

Note that projections presented in the IPCC assessments are not predictions (see the Glossary in Annex III); the analyses in the discussion below only examine the short-term plausibility of the projections up to AR4, including the scenarios for future emissions and the models used to simulate these scenarios in the earlier assessments. Model results from the Coupled Model Intercomparison Project Phase 5 (CMIP5) (Taylor et al., 2012) used in AR5 are therefore not included in this section; Chapters 11 and 12 describe the projections from the new modelling studies. Note that none of the scenarios examined in the IPCC assessments were ever intended to be short-term predictors of change.

1.3.1 Global and Regional Surface Temperatures

Observed changes in global mean surface air temperature since 1950 (from three major databases, as anomalies relative to 1961–1990) are shown in Figure 1.4. As in the prior assessments, global climate models generally simulate global temperatures that compare well with observations over climate timescales (Section 9.4). Even though the projections from the models were never intended to be predictions over such a short timescale, the observations through 2012 generally fall within the projections made in all past assessments. The 1990–2012 data have been shown to be consistent with the FAR projections (IPCC, 1990), and not consistent with zero trend from 1990, even in the presence of substantial natural variability (Frame and Stone, 2013).

The scenarios were designed to span a broad range of plausible futures, but are not aimed at predicting the most likely outcome. The scenarios considered for the projections from the earlier reports (FAR, SAR) had a much simpler basis than those of the Special Report on Emission Scenarios (SRES) (IPCC, 2000) used in the later assessments. For example, the FAR scenarios did not specify future aerosol distributions. AR4 presented a multiple set of projections that were simulated using comprehensive ocean–atmosphere models provided by CMIP3 and these projections are continuations of transient simulations of the 20th century climate. These projections of temperature provide in addition a measure of the natural variability that could not be obtained

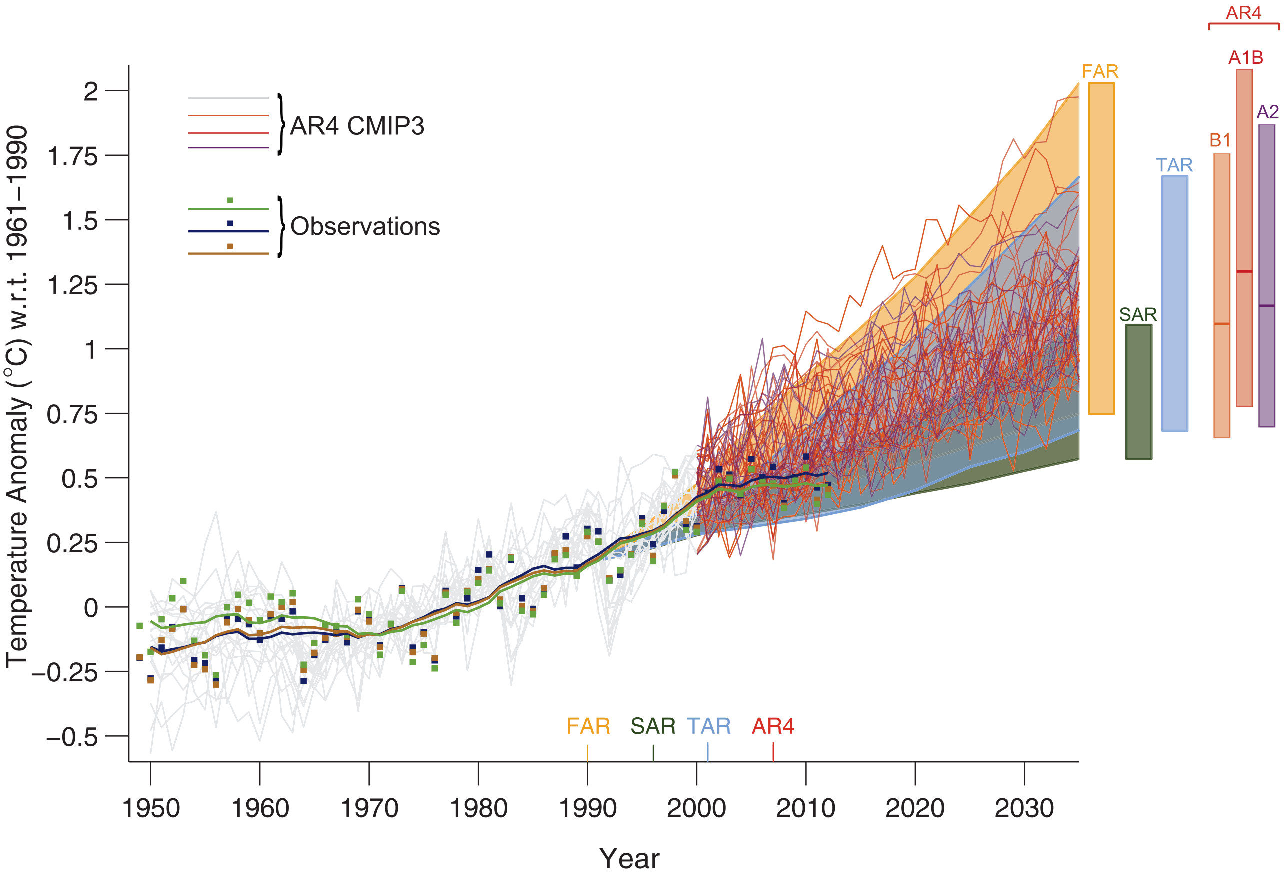


Figure 1.4 | Estimated changes in the observed globally and annually averaged surface temperature anomaly relative to 1961–1990 (in °C) since 1950 compared with the range of projections from the previous IPCC assessments. Values are harmonized to start from the same value in 1990. Observed global annual mean surface air temperature anomaly, relative to 1961–1990, is shown as squares and smoothed time series as solid lines (NASA (dark blue), NOAA (warm mustard), and the UK Hadley Centre (bright green) reanalyses). The coloured shading shows the projected range of global annual mean surface air temperature change from 1990 to 2035 for models used in FAR (Figure 6.11 in Bretherton et al., 1990), SAR (Figure 19 in the TS of IPCC, 1996), TAR (full range of TAR Figure 9.13(b) in Cubasch et al., 2001). TAR results are based on the simple climate model analyses presented and not on the individual full three-dimensional climate model simulations. For the AR4 results are presented as single model runs of the CMIP3 ensemble for the historical period from 1950 to 2000 (light grey lines) and for three scenarios (A2, A1B and B1) from 2001 to 2035. The bars at the right-hand side of the graph show the full range given for 2035 for each assessment report. For the three SRES scenarios the bars show the CMIP3 ensemble mean and the *likely* range given by –40% to +60% of the mean as assessed in Meehl et al. (2007). The publication years of the assessment reports are shown. See Appendix 1.A for details on the data and calculations used to create this figure.

from the earlier projections based on models of intermediate complexity (Cubasch et al., 2001).

Note that before TAR the climate models did not include natural forcing (such as volcanic activity and solar variability). Even in AR4 not all models included natural forcing and some also did not include aerosols. Those models that allowed for aerosol effects presented in the AR4 simulated, for example, the cooling effects of the 1991 Mt Pinatubo eruption and agree better with the observed temperatures than the previous assessments that did not include those effects.

The bars on the side for FAR, SAR and TAR represent the range of results for the scenarios at the end of the time period and are not error bars. In contrast to the previous reports, the AR4 gave an assessment of the individual scenarios with a mean estimate (cross bar; ensemble mean of the CMIP3 simulations) and a *likely* range (full bar; –40% to +60% of the mean estimate) (Meehl et al., 2007).

In summary, the trend in globally averaged surface temperatures falls within the range of the previous IPCC projections. During the last decade the trend in the observations is smaller than the mean of the projections of AR4 (see Section 9.4.1, Box 9.2 for a detailed assessment of the hiatus in global mean surface warming in the last 15 years). As shown by Hawkins and Sutton (2009), trends in the observations during short-timescale periods (decades) can be dominated by natural variability in the Earth's climate system. Similar episodes are also seen in climate model experiments (Easterling and Wehner, 2009). Due to their experimental design these episodes cannot be duplicated with the same timing as the observed episodes in most of the model simulations; this affects the interpretation of recent trends in the scenario evaluations (Section 11.2). Notwithstanding these points, there is evidence that early forecasts that carried formal estimates of uncertainty have proved highly consistent with subsequent observations (Allen et al., 2013). If the contributions of solar variability, volcanic activity and ENSO are removed from the observations the remaining trend of surface air temperature agree better with the modelling studies (Rahmstorf et al., 2012).

1.3.2 Greenhouse Gas Concentrations

Key indicators of global climate change also include the changing concentrations of the radiatively important GHGs that are significant drivers for this change (e.g., Denman et al., 2007; Forster et al., 2007). Figures 1.5 through 1.7 show the recent globally and annually averaged observed concentrations for the gases of most concern, CO_2, CH_4, and N_2O (see Sections 2.2, 6.3 and 8.3 for more detailed discussion of these and other key gases). As discussed in the later chapters, accurate measurements of these long-lived gases come from a number of monitoring stations throughout the world. The observations in these figures are compared with the projections from the previous IPCC assessments.

The model simulations begin with historical emissions up to 1990. The further evolution of these gases was described by scenario projections.

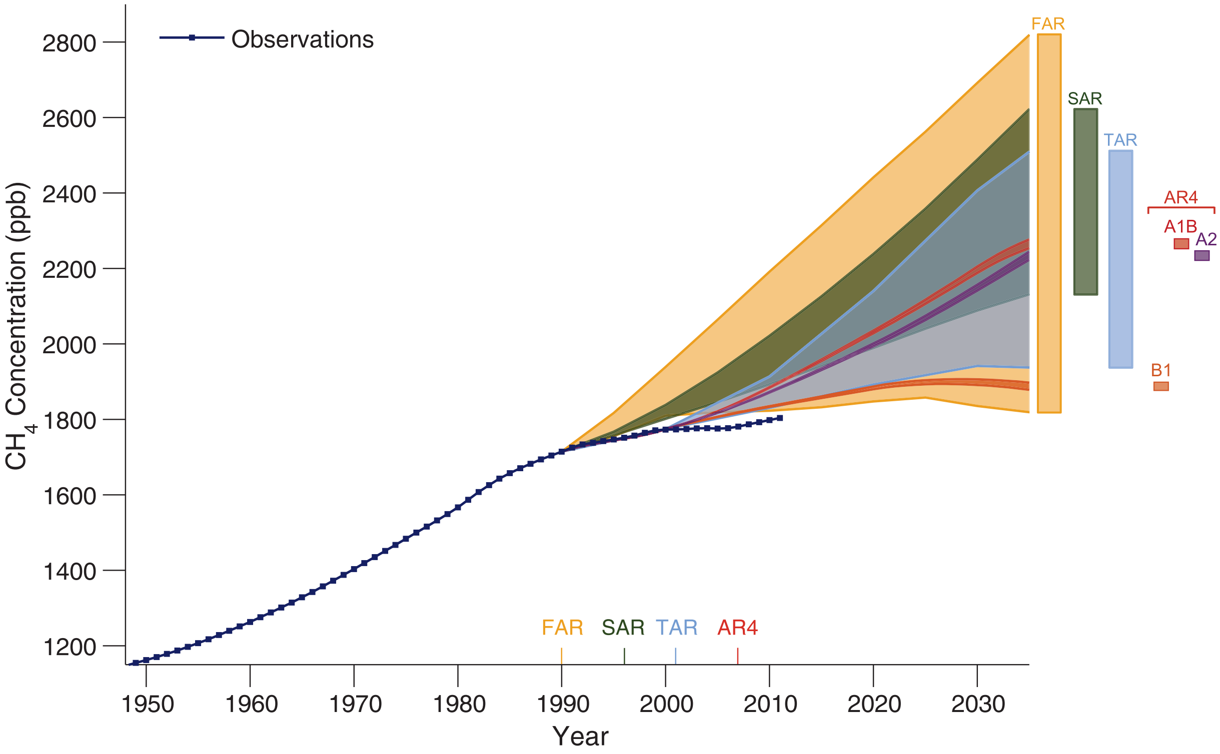


Figure 1.6 | Observed globally and annually averaged CH_4 concentrations in parts per billion (ppb) since 1950 compared with projections from the previous IPCC assessments. Estimated observed global annual CH_4 concentrations are shown in dark blue. The shading shows the largest model projected range of global annual CH_4 concentrations from 1950 to 2035 from FAR (Figure A.3 of the Annex of IPCC, 1990); SAR (Table 2.5a in Schimel et al., 1996); TAR (Appendix II of IPCC, 2001); and from the A2, A1B and B1 scenarios presented in the AR4 (Figure 10.26 in Meehl et al., 2007). The bars at the right-hand side of the graph show the full range given for 2035 for each assessment report. The publication years of the assessment reports are shown. See Appendix 1.A for details on the data and calculations used to create this figure.

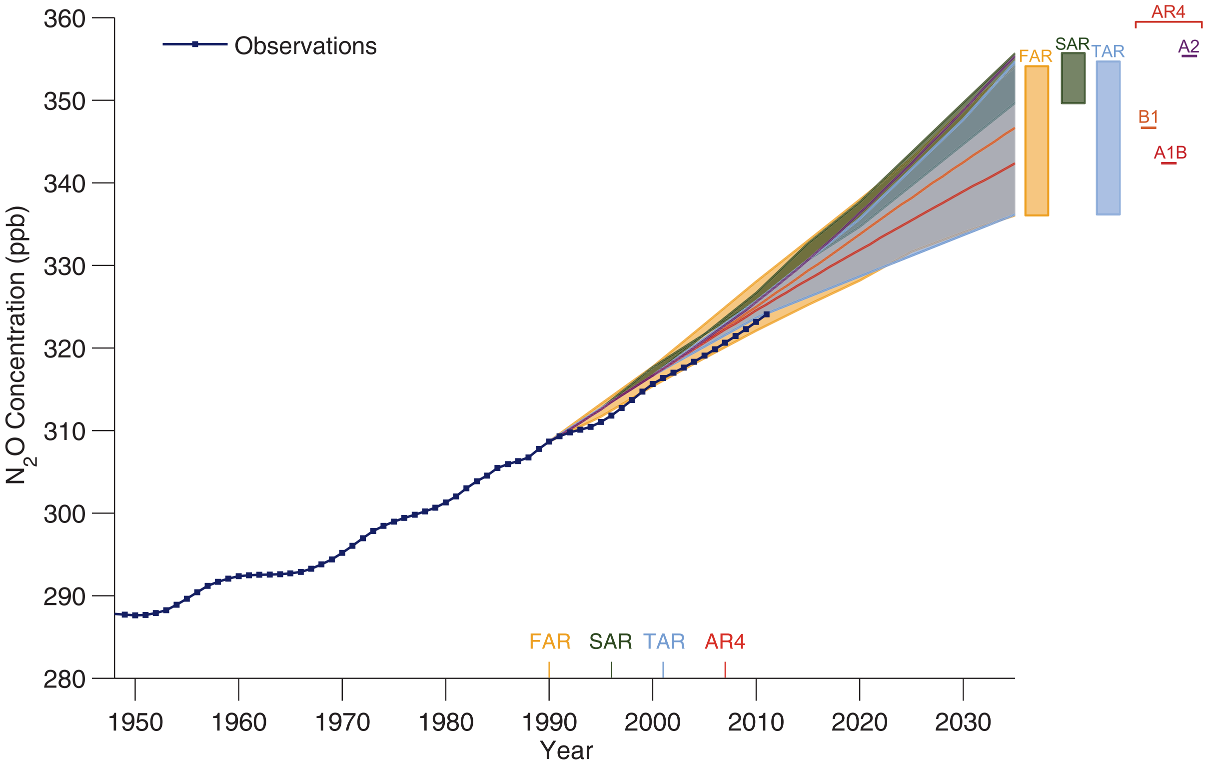


Figure 1.7 | Observed globally and annually averaged N_2O concentrations in parts per billion (ppb) since 1950 compared with projections from the previous IPCC assessments. Observed global annual N_2O concentrations are shown in dark blue. The shading shows the largest model projected range of global annual N_2O concentrations from 1950 to 2035 from FAR (Figure A3 in the Annex of IPCC, 1990), SAR (Table 2.5b in Schimel et al., 1996), TAR (Appendix II of IPCC, 2001), and from the A2, A1B and B1 scenarios presented in the AR4 (Figure 10.26 in Meehl et al., 2007). The bars at the right hand side of the graph show the full range given for 2035 for each assessment report. The publication years of the assessment reports are shown. See Appendix 1.A for details on the data and calculations used to create this figure.

scenarios but those model results may also account for historical emissions analyses. The recent observed trends in CO_2 concentrations tend to be in the middle of the scenarios used for the projections (Figure 1.5).

As discussed in Dlugokencky et al. (2009), trends in CH_4 showed a stabilization from 1999 to 2006, but CH_4 concentrations have been increasing again starting in 2007 (see Sections 2.2 and 6.3 for more discussion on the budget and changing concentration trends for CH_4). Because at the time the scenarios were developed (e.g., the SRES scenarios were developed in 2000), it was thought that past trends would continue, the scenarios used and the resulting model projections assumed in FAR through AR4 all show larger increases than those observed (Figure 1.6).

Concentrations of N_2O have continued to increase at a nearly constant rate (Elkins and Dutton, 2010) since about 1970 as shown in Figure 1.7. The observed trends tend to be in the lower part of the projections for the previous assessments.

1.3.3 Extreme Events

Climate change, whether driven by natural or human forcings, can lead to changes in the likelihood of the occurrence or strength of extreme weather and climate events such as extreme precipitation events or warm spells (see Chapter 3 of the IPCC Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation (SREX); Seneviratne et al., 2012). An extreme weather event is one that is rare at a particular place and/or 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 a probability density function estimated from observations (see also Glossary in Annex III and FAQ 2.2). By definition, the characteristics of what is called extreme weather may vary from place to place in an absolute sense. At present, single extreme events cannot generally be directly attributed to anthropogenic influence, although the change in likelihood for the event to occur has been determined for some events by accounting for observed changes in climate (see Section 10.6). When a pattern of extreme weather persists for some time, such as a season, it may be classified 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). For some climate extremes such as drought, floods and heat waves, several factors such as duration and intensity need to be combined to produce an extreme event (Seneviratne et al., 2012).

The probability of occurrence of values of a climate or weather variable can be described by a probability density function (PDF) that for some variables (e.g., temperature) is shaped similar to a Gaussian curve. A PDF is a function that indicates the relative chances of occurrence of different outcomes of a variable. Simple statistical reasoning indicates that substantial changes in the frequency of extreme events (e.g., the maximum possible 24-hour rainfall at a specific location) can result from a relatively small shift in the distribution of a weather or climate variable. Figure 1.8a shows a schematic of such a PDF and illustrates the effect of a small shift in the mean of a variable on the frequency of extremes at either end of the distribution. An increase in the frequency of one extreme (e.g., the number of hot days) can be accompanied by

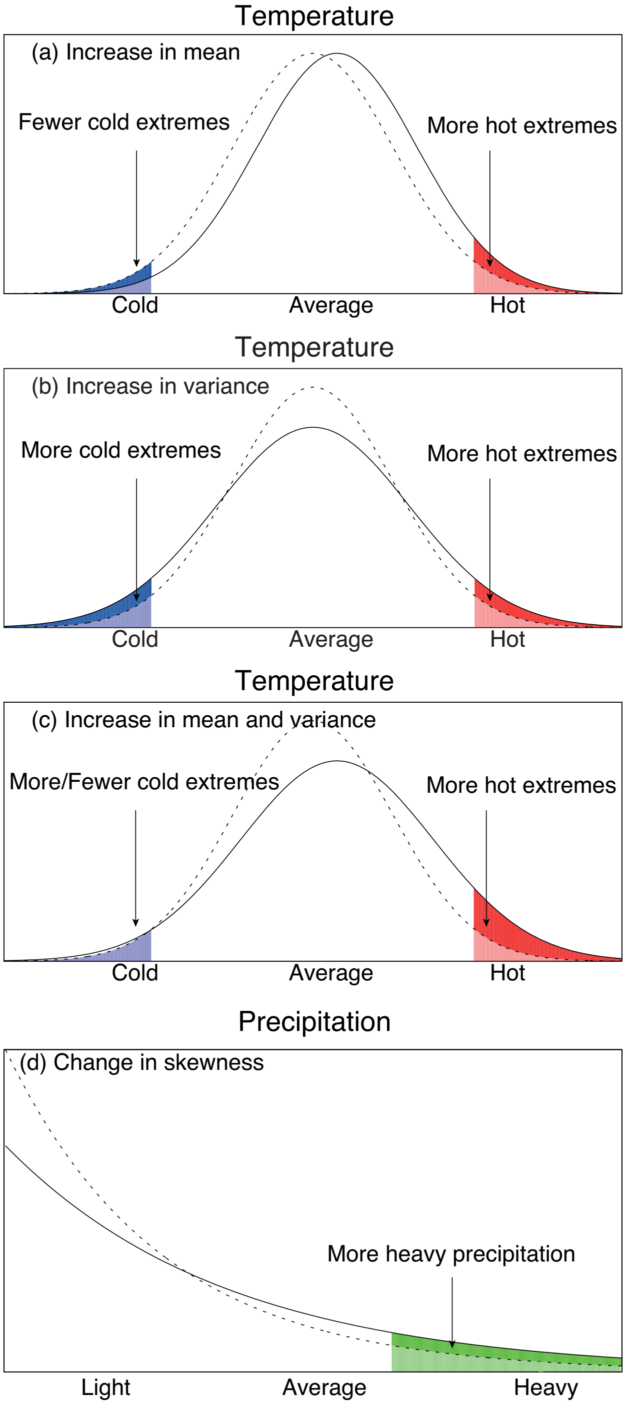
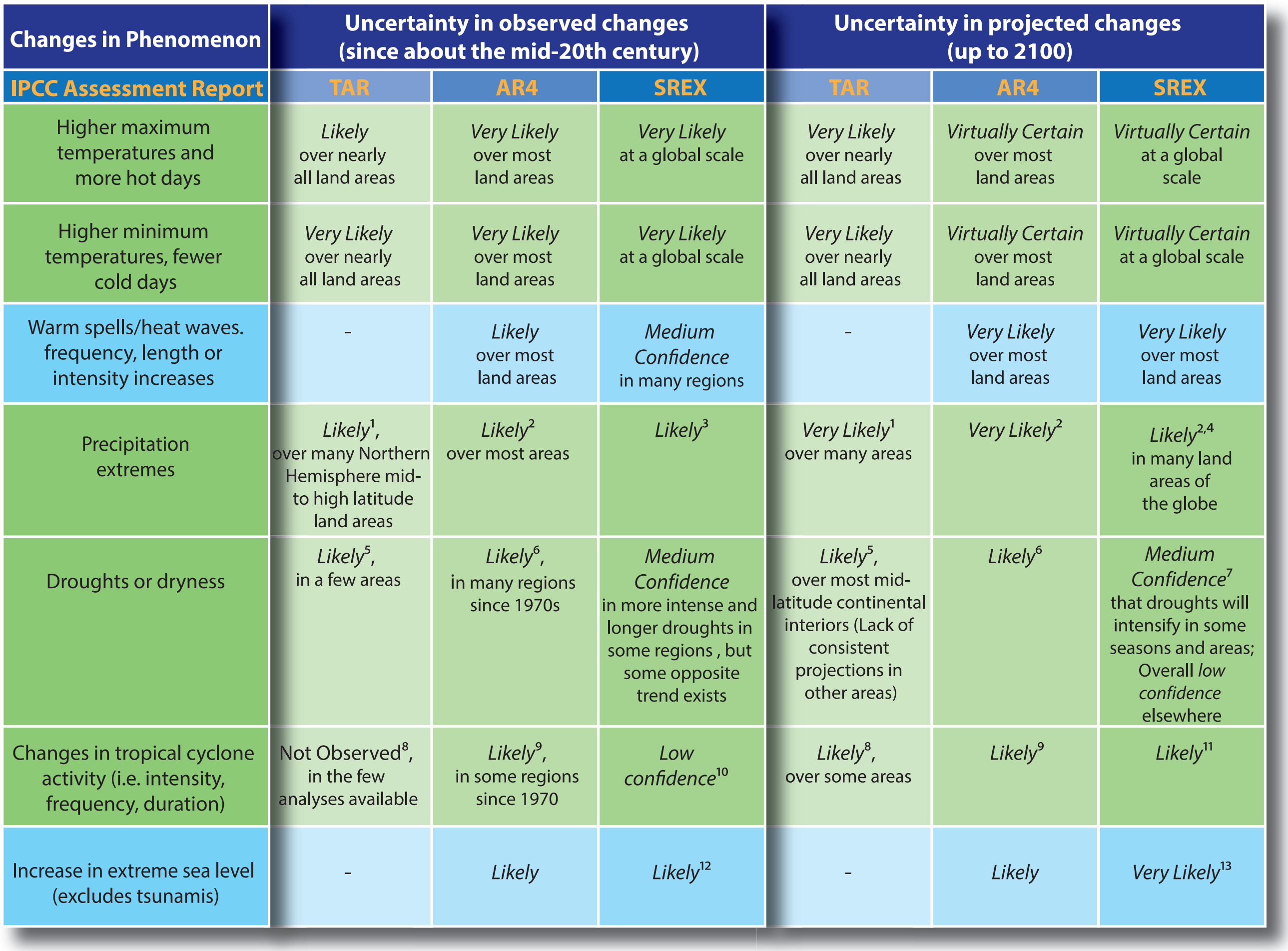


Figure 1.8 | Schematic representations of the probability density function of daily temperature, which tends to be approximately Gaussian, and daily precipitation, which has a skewed distribution. Dashed lines represent a previous distribution and solid lines a changed distribution. The probability of occurrence, or frequency, of extremes is denoted by the shaded areas. In the case of temperature, changes in the frequencies of extremes are affected by changes (a) in the mean, (b) in the variance or shape, and (c) in both the mean and the variance. (d) In a skewed distribution such as that of precipitation, a change in the mean of the distribution generally affects its variability or spread, and thus an increase in mean precipitation would also imply an increase in heavy precipitation extremes, and vice-versa. In addition, the shape of the right-hand tail could also change, affecting extremes. Furthermore, climate change may alter the frequency of precipitation and the duration of dry spells between precipitation events. (Parts a–c modified from Folland et al., 2001, and d modified from Peterson et al., 2008, as in Zhang and Zwiers, 2012.)

a decline in the opposite extreme (in this case the number of cold days such as frost days). Changes in the variability, skewness or the shape of the distribution can complicate this simple picture (Figure 1.8b, c and d).

While the SAR found that data and analyses of extremes related to climate change were sparse, improved monitoring and data for changes in extremes were available for the TAR, and climate models were being analysed to provide projections of extremes. In AR4, the observational basis of analyses of extremes had increased substantially, so that some extremes were now examined over most land areas (e.g., rainfall extremes). More models with higher resolution, and a larger number of regional models have been used in the simulation and projection of extremes, and ensemble integrations now provide information about PDFs and extremes.

Since the TAR, climate change studies have especially focused on changes in the global statistics of extremes, and observed and projected changes in extremes have been compiled in the so-called 'Extremes'-Table (Figure 1.9). This table has modified further to account for the SREX assessment. For some extremes ('higher maximum temperature', 'higher minimum temperature', 'precipitation extremes', 'droughts or dryness'), all of these assessments found an increasing trend in the observations and in the projections. In the observations for



Changes in Phenomenon	Uncertainty in observed changes (since about the mid-20th century)			Uncertainty in projected changes (up to 2100)		
IPCC Assessment Report	**TAR**	**AR4**	**SREX**	**TAR**	**AR4**	**SREX**
Higher maximum temperatures and more hot days	*Likely* over nearly all land areas	*Very Likely* over most land areas	*Very Likely* at a global scale	*Very Likely* over nearly all land areas	*Virtually Certain* over most land areas	*Virtually Certain* at a global scale
Higher minimum temperatures, fewer cold days	*Very Likely* over nearly all land areas	*Very Likely* over most land areas	*Very Likely* at a global scale	*Very Likely* over nearly all land areas	*Virtually Certain* over most land areas	*Virtually Certain* at a global scale
Warm spells/heat waves. frequency, length or intensity increases	-	*Likely* over most land areas	*Medium Confidence* in many regions	-	*Very Likely* over most land areas	*Very Likely* over most land areas
Precipitation extremes	*Likely*[1], over many Northern Hemisphere mid- to high latitude land areas	*Likely*[2] over most areas	*Likely*[3]	*Very Likely*[1] over many areas	*Very Likely*[2]	*Likely*[2,4] in many land areas of the globe
Droughts or dryness	*Likely*[5], in a few areas	*Likely*[6], in many regions since 1970s	*Medium Confidence* in more intense and longer droughts in some regions , but some opposite trend exists	*Likely*[5], over most mid-latitude continental interiors (Lack of consistent projections in other areas)	*Likely*[6]	*Medium Confidence*[7] that droughts will intensify in some seasons and areas; Overall *low confidence* elsewhere
Changes in tropical cyclone activity (i.e. intensity, frequency, duration)	Not Observed[8], in the few analyses available	*Likely*[9], in some regions since 1970	*Low confidence*[10]	*Likely*[8], over some areas	*Likely*[9]	*Likely*[11]
Increase in extreme sea level (excludes tsunamis)	-	*Likely*	*Likely*[12]	-	*Likely*	*Very Likely*[13]

[1] More intense precipitation events

[2] Heavy precipitation events. Frequency (or proportion of total rainfall from heavy falls) increases

[3] Statistically significant trends in the number of heavy precipitation events in some regions. It is *likely* that more of these regions have experienced increases than decreases.

[4] See SREX Table 3-3 for details on precipitation extremes for the different regions.

[5] Increased summer continental drying and associated risk of drought

[6] Area affected by droughts increases

[7] Some areas include southern Europe and the Mediterranean region, central Europe, central North America and Mexico, northeast Brazil and southern Africa

[8] Increase in tropical cyclone peak wind intensities

[9] Increase in intense tropical cyclone activity

[10] In any observed long-term (i.e., 40 years or more) after accounting for past changes in observing capabilities (see SREX, section 3.4.4)

[11] Increase in average tropical cyclone maximum wind speed is, although not in all ocean basins; either decrease or no change in the global frequency of tropical cyclones

[12] Increase in extreme coastal high water worldwide related to increases in mean sea level in the late 20th century

[13] Mean sea level rise will contribute to upward trends in extreme coastal high water levels

Figure 1.9 | Change in the confidence levels for extreme events based on prior IPCC assessments: TAR, AR4 and SREX. Types of extreme events discussed in all three reports are highlighted in green. Confidence levels are defined in Section 1.4. Similar analyses for AR5 are discussed in later chapters. Please note that the nomenclature for confidence level changed from AR4 to SREX and AR5.

the 'higher maximum temperature' the likelihood level was raised from *likely* in the TAR to *very likely* in SREX. While the diurnal temperature range was assessed in the Extremes-Table of the TAR, it was no longer included in the Extremes-Table of AR4, since it is not considered a climate extreme in a narrow sense. Diurnal temperature range was, however, reported to decrease for 21st century projections in AR4 (Meehl et al., 2007). In projections for precipitation extremes, the spatial relevance has been improved from *very likely* 'over many Northern Hemisphere mid-latitudes to high latitudes land areas' from the TAR to *very likely* for all regions in AR4 (these 'uncertainty labels' are discussed in Section 1.4). However, likelihood in trends in projected precipitation extremes was downscaled to *likely* in the SREX as a result of a perception of biases and a fairly large spread in the precipitation projections in some regions. SREX also had less confidence than TAR and AR4 in the trends for droughts and dryness, 'due to lack of direct observations, some geographical inconsistencies in the trends, and some dependencies of inferred trends on the index choice' (IPCC, 2012b).

For some extremes (e.g., 'changes in tropical cyclone activity') the definition changed between the TAR and the AR4. Whereas the TAR only made a statement about the peak wind speed of tropical cyclones, the AR4 also stressed the overall increase in intense tropical cyclone activity. The '*low confidence*' for any long term trend (>40 years) in the observed changes of the tropical cyclone activities is due to uncertainties in past observational capabilities (IPCC, 2012b). The 'increase in extreme sea level' has been added in the AR4. Such an increase is *likely* according to the AR4 and the SREX for observed trends, and *very likely* for the climate projections reported in the SREX.

The assessed likelihood of anthropogenic contributions to trends is lower for variables where the assessment is based on indirect evidence. Especially for extremes that are the result of a combination of factors such as droughts, linking a particular extreme event to specific causal relationships is difficult to determine (e.g., difficult to establish the clear role of climate change in the event) (see Section 10.6 and Peterson et al., 2012). In some cases (e.g., precipitation extremes), however, it may be possible to estimate the human-related contribution to such changes in the probability of occurrence of extremes (Pall et al., 2011; Seneviratne et al., 2012).

1.3.4 Climate Change Indicators

Climate change can lead to other effects on the Earth's physical system that are also indicators of climate change. Such integrative indicators include changes in sea level (ocean warming + land ice melt), in ocean acidification (ocean uptake of CO_2) and in the amount of ice on ocean and land (temperature and hydrological changes). See Chapters 3, 4 and 13 for detailed assessment.

1.3.4.1 Sea Level

Global mean sea level is an important indicator of climate change (Section 3.7 and Chapter 13). The previous assessments have all shown that observations indicate that the globally averaged sea level is rising. Direct observations of sea level change have been made for more than 150 years with tide gauges, and for more than 20 years with satellite radar altimeters. Although there is regional variability from non-uniform density change, circulation changes, and deformation of ocean basins, the evidence indicates that the global mean sea level is rising, and that this is *likely* (according to AR4 and SREX) resulting from global climate change (ocean warming plus land ice melt; see Chapter 13 for AR5 findings). The historical tide gauge record shows that the average rate of global mean sea level rise over the 20th century was 1.7 ± 0.2 mm yr^{-1} (e.g., Church and White, 2011). This rate increased to 3.2 ± 0.4 mm yr^{-1} since 1990, mostly because of increased thermal expansion and land ice contributions (Church and White, 2011; IPCC, 2012b). Although the long-term sea level record shows decadal and multi-decadal oscillations, there is evidence that the rate of global mean sea level rise during the 20th century was greater than during the 19th century.

All of the previous IPCC assessments have projected that global sea level will continue to rise throughout this century for the scenarios examined. Figure 1.10 compares the observed sea level rise since 1950 with the projections from the prior IPCC assessments. Earlier models had greater uncertainties in modelling the contributions, because of limited observational evidence and deficiencies in theoretical understanding of relevant processes. Also, projections for sea level change in the prior assessments are scenarios for the response to anthropogenic forcing only; they do not include unforced or natural interannual variability. Nonetheless, the results show that the actual change is in the middle of projected changes from the prior assessments, and towards the higher end of the studies from TAR and AR4.

1.3.4.2 Ocean Acidification

The observed decrease in ocean pH resulting from increasing concentrations of CO_2 is another indicator of global change. As discussed in AR4, the ocean's uptake of CO_2 is having a significant impact on the chemistry of sea water. The average pH of ocean surface waters has fallen by about 0.1 units, from about 8.2 to 8.1 (total scale) since 1765 (Section 3.8). Long time series from several ocean sites show ongoing declines in pH, consistent with results from repeated pH measurements on ship transects spanning much of the globe (Sections 3.8 and 6.4; Byrne et al., 2010; Midorikawa et al., 2010). Ocean time-series in the North Atlantic and North Pacific record a decrease in pH ranging between –0.0015 and –0.0024 per year (Section 3.8). Due to the increased storage of carbon by the ocean, ocean acidification will increase in the future (Chapter 6). In addition to other impacts of global climate change, ocean acidification poses potentially serious threats to the health of the world's oceans ecosystems (see AR5 WGII assessment).

1.3.4.3 Ice

Rapid sea ice loss is one of the most prominent indicators of Arctic climate change (Section 4.2). There has been a trend of decreasing Northern Hemisphere sea ice extent since 1978, with the summer of 2012 being the lowest in recorded history (see Section 4.2 for details). The 2012 minimum sea ice extent was 49% below the 1979 to 2000 average and 18% below the previous record from 2007. The amount of multi-year sea ice has been reduced, i.e., the sea ice has been thinning and thus the ice volume is reduced (Haas et al., 2008; Kwok et al., 2009). These changes make the sea ice less resistant to wind forcing.

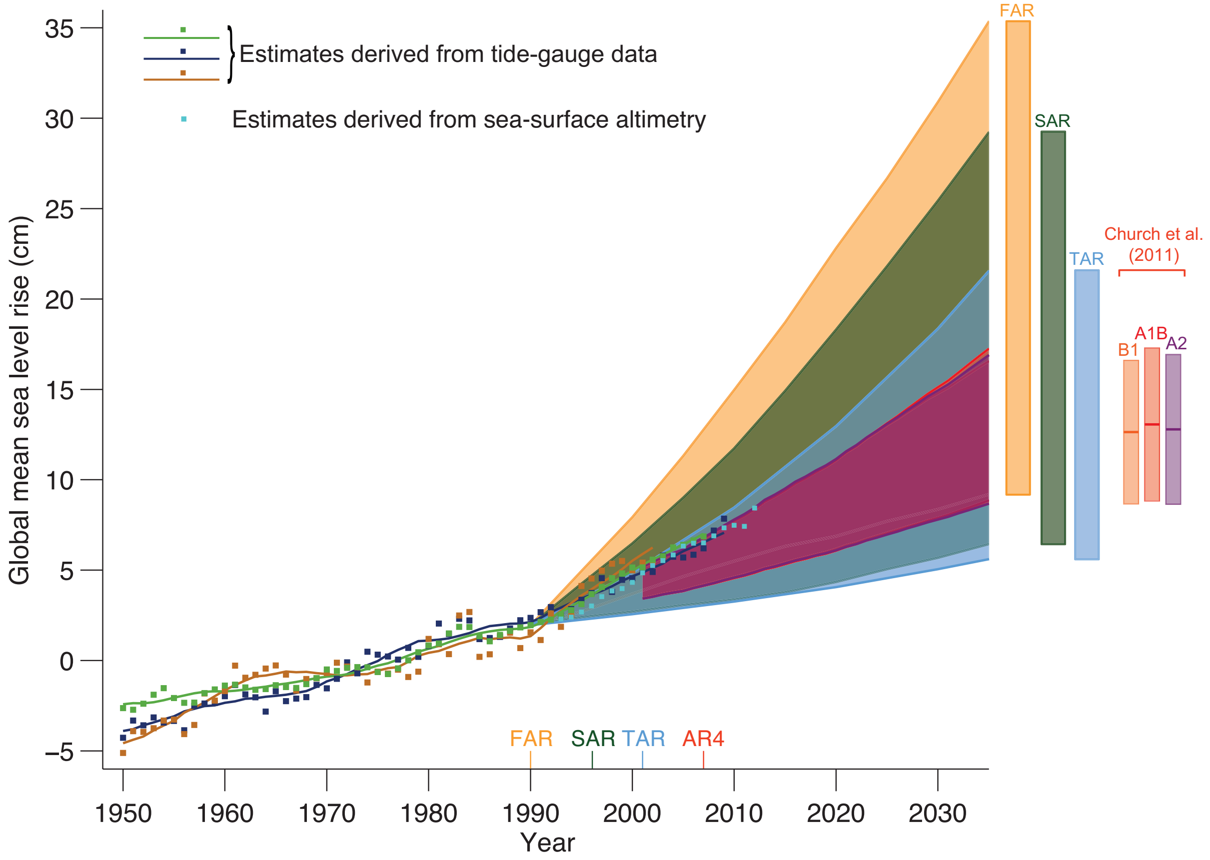


Figure 1.10 | Estimated changes in the observed global annual mean sea level (GMSL) since 1950 relative to 1961–1990. Estimated changes in global annual sea level anomalies are presented based on tide gauge data (warm mustard: Jevrejeva et al., 2008; dark blue: Church and White, 2011; dark green: Ray and Douglas, 2011) and based on sea surface altimetry (light blue). The altimetry data start in 1993 and are harmonized to start from the mean 1993 value of the tide gauge data. Squares indicate annual mean values and solid lines smoothed values. The shading shows the largest model projected range of global annual sea level rise from 1950 to 2035 for FAR (Figures 9.6 and 9.7 in Warrick and Oerlemans, 1990), SAR (Figure 21 in TS of IPCC, 1996), TAR (Appendix II of IPCC, 2001) and for Church et al. (2011) based on the Coupled Model Intercomparison Project Phase 3 (CMIP3) model results not assessed at the time of AR4 using the SRES B1, A1B and A2 scenarios. Note that in the AR4 no full range was given for the sea level projections for this period. Therefore, the figure shows results that have been published subsequent to the AR4. The bars at the right-hand side of the graph show the full range given for 2035 for each assessment report. For Church et al. (2011) the mean sea level rise is indicated in addition to the full range. See Appendix 1.A for details on the data and calculations used to create this figure.

Sea ice extent has been diminishing significantly faster than projected by most of the AR4 climate models (SWIPA, 2011). While AR4 found no consistent trends in Antarctica sea ice, more recent studies indicate a small increase (Section 4.2). Various studies since AR4 suggest that this has resulted in a deepening of the low-pressure systems in West Antarctica that in turn caused stronger winds and enhanced ice production in the Ross Sea (Goosse et al., 2009; Turner and Overland, 2009).

AR4 concluded that taken together, the ice sheets in Greenland and Antarctica have *very likely* been contributing to sea level rise. The Greenland Ice Sheet has lost mass since the early 1990s and the rate of loss has increased (see Section 4.4). The interior, high-altitude areas are thickening due to increased snow accumulation, but this is more than counterbalanced by the ice loss due to melt and ice discharge (AMAP, 2009; Ettema et al., 2009). Since 1979, the area experiencing surface melting has increased significantly (Tedesco, 2007; Mernild et al., 2009), with 2010 breaking the record for surface melt area, runoff, and mass loss, and the unprecedented areal extent of surface melt of the Greenland Ice Sheet in 2012 (Nghiem et al., 2012). Overall, the Antarctic continent now experiences a net loss of ice (Section 4.4). Significant mass loss has been occurring in the Amundsen Sea sector of West Antarctica and the northern Antarctic Peninsula. The ice sheet on the rest of the continent is relatively stable or thickening slightly (Lemke et al., 2007; Scott et al., 2009; Turner et al., 2009). Since AR4, there have been improvements in techniques of measurement, such as gravity, altimetry and mass balance, and understanding of the change (Section 4.4).

As discussed in the earlier assessments, most glaciers around the globe have been shrinking since the end of the Little Ice Age, with increasing rates of ice loss since the early 1980s (Section 4.3). The vertical profiles of temperature measured through the entire thickness of mountain glaciers, or through ice sheets, provide clear evidence of a warming climate over recent decades (e.g., Lüthi and Funk, 2001; Hoelzle et al., 2011). As noted in AR4, the greatest mass losses per unit area in the last four decades have been observed in Patagonia, Alaska, northwest USA, southwest Canada, the European Alps, and the Arctic. Alaska and the Arctic are especially important regions as contributors to sea level rise (Zemp et al., 2008, 2009).

1.4 Treatment of Uncertainties

1.4.1 Uncertainty in Environmental Science

Science always involves uncertainties. These arise at each step of the scientific method: in the development of models or hypotheses, in measurements and in analyses and interpretation of scientific assumptions. Climate science is not different in this regard from other areas of science. The complexity of the climate system and the large range of processes involved bring particular challenges because, for example, gaps in direct measurements of the past can be filled only by reconstructions using proxy data.

Because the Earth's climate system is characterized by multiple spatial and temporal scales, uncertainties do not usually reduce at a single, predictable rate: for example, new observations may reduce the uncertainties surrounding short-timescale processes quite rapidly, while longer timescale processes may require very long observational baselines before much progress can be made. Characterization of the interaction between processes, as quantified by models, can be improved by model development, or can shed light on new areas in which uncertainty is greater than previously thought. The fact that there is only a single realization of the climate, rather than a range of different climates from which to draw, can matter significantly for certain lines of enquiry, most notably for the detection and attribution of causes of climate change and for the evaluation of projections of future states.

1.4.2 Characterizing Uncertainty

'Uncertainty' is a complex and multifaceted property, sometimes originating in a lack of information, and at other times from quite fundamental disagreements about what is known or even knowable (Moss and Schneider, 2000). Furthermore, scientists often disagree about the best or most appropriate way to characterize these uncertainties: some can be quantified easily while others cannot. Moreover, appropriate characterization is dependent on the intended use of the information and the particular needs of that user community.

Scientific uncertainty can be partitioned in various ways, in which the details of the partitioning usually depend on the context. For instance, the process and classifications used for evaluating observational uncertainty in climate science is not the same as that employed to evaluate projections of future change. Uncertainty in measured quantities can arise from a range of sources, such as statistical variation, variability, inherent randomness, inhomogeneity, approximation, subjective judgement, and linguistic imprecision (Morgan et al., 1990), or from calibration methodologies, instrumental bias or instrumental limitations (JCGM, 2008).

In the modelling studies that underpin projections of future climate change, it is common to partition uncertainty into four main categories: scenario uncertainty, due to uncertainty of future emissions of GHGs and other forcing agents; 'model uncertainty' associated with climate models; internal variability and initial condition uncertainty; and forcing and boundary condition uncertainty for the assessment of historical and paleoclimate simulations (e.g., Collins and Allen, 2002; Yip et al., 2011).

Model uncertainty is an important contributor to uncertainty in climate predictions and projections. It includes, but is not restricted to, the uncertainties introduced by errors in the model's representation of dynamical and physical and bio-geochemical aspects of the climate system as well as in the model's response to external forcing. The phrase 'model uncertainty' is a common term in the climate change literature, but different studies use the phrase in different senses: some use it to represent the range of behaviours observed in ensembles of climate model (model spread), while others use it in more comprehensive senses (see Sections 9.2, 11.2 and 12.2). Model spread is often used as a measure of climate response uncertainty, but such a measure is crude as it takes no account of factors such as model quality (Chapter 9) or model independence (e.g., Masson and Knutti, 2011; Pennell and Reichler, 2011), and not all variables of interest are adequately simulated by global climate models.

To maintain a degree of terminological clarity this report distinguishes between 'model spread' for this narrower representation of climate model responses and 'model uncertainty' which describes uncertainty about the extent to which any particular climate model provides an accurate representation of the real climate system. This uncertainty arises from approximations required in the development of models. Such approximations affect the representation of all aspects of the climate including the response to external forcings.

Model uncertainty is sometimes decomposed further into parametric and structural uncertainty, comprising, respectively, uncertainty in the values of model parameters and uncertainty in the underlying model structure (see Section 12.2). Some scientific research areas, such as detection and attribution and observationally-constrained model projections of future climate, incorporate significant elements of both observational and model-based science, and in these instances both sets of relevant uncertainties need to be incorporated.

Scenario uncertainty refers to the uncertainties that arise due to limitations in our understanding of future emissions, concentration or forcing trajectories. Scenarios help in the assessment of future developments in complex systems that are either inherently unpredictable, or that have high scientific uncertainties (IPCC, 2000). The societal choices defining future climate drivers are surrounded by considerable uncertainty, and these are explored by examining the climate response to a wide range of possible futures. In past reports, emissions scenarios from the SRES (IPCC, 2000) were used as the main way of exploring uncertainty in future anthropogenic climate drivers. Recent research has made use of Representative Concentration Pathways (RCP) (van Vuuren et al., 2011a, 2011b).

Internal or natural variability, the natural fluctuations in climate, occur in the absence of any RF of the Earth's climate (Hawkins and Sutton, 2009). Climate varies naturally on nearly all time and space scales, and quantifying precisely the nature of this variability is challenging, and is characterized by considerable uncertainty. The analysis of internal and forced contributions to recent climate is discussed in Chapter 10. The fractional contribution of internal variability compared with other forms of uncertainty varies in time and in space, but usually diminishes with time as other sources of uncertainty become more significant (Hawkins and Sutton, 2009; see also Chapter 11 and FAQ 1.1).

In the WGI contribution to the AR5, uncertainty is quantified using 90% uncertainty intervals unless otherwise stated. The 90% uncertainty interval, reported in square brackets, is expected to have a 90% likelihood of covering the value that is being estimated. The value that is being estimated has a 5% likelihood of exceeding the upper endpoint of the uncertainty interval, and the value has a 5% likelihood of being less than that the lower endpoint of the uncertainty interval. A best estimate of that value is also given where available. Uncertainty intervals are not necessarily symmetric about the corresponding best estimate.

In a subject as complex and diverse as climate change, the information available as well as the way it is expressed, and often the interpretation of that material, varies considerably with the scientific context. In some cases, two studies examining similar material may take different approaches even to the quantification of uncertainty. The interpretation of similar numerical ranges for similar variables can differ from study to study. Readers are advised to pay close attention to the caveats and conditions that surround the results presented in peer-reviewed studies, as well as those presented in this assessment. To help readers in this complex and subtle task, the IPCC draws on specific, calibrated language scales to express uncertainty (Mastrandrea et al., 2010), as well as specific procedures for the expression of uncertainty (see Table 1.2). The aim of these structures is to provide tools through which chapter teams might consistently express uncertainty in key results.

1.4.3 Treatment of Uncertainty in IPCC

In the course of the IPCC assessment procedure, chapter teams review the published research literature, document the findings (including uncertainties), assess the scientific merit of this information, identify the key findings, and attempt to express an appropriate measure of the uncertainty that accompanies these findings using a shared guidance procedure. This process has changed over time. The early Assessment Reports (FAR and SAR) were largely qualitative. As the field has grown and matured, uncertainty is being treated more explicitly, with a greater emphasis on the expression, where possible and appropriate, of quantified measures of uncertainty.

Although IPCC's treatment of uncertainty has become more sophisticated since the early reports, the rapid growth and considerable diversity of climate research literature presents ongoing challenges. In the wake of the TAR the IPCC formed a Cross-Working Group team charged with identifying the issues and compiling a set of Uncertainty Guidance Notes that could provide a structure for consistent treatment of uncertainty across the IPCC's remit (Manning et al., 2004). These expanded on the procedural elements of Moss and Schneider (2000) and introduced calibrated language scales designed to enable chapter teams to use the appropriate level of precision to describe findings. These notes were revised between the TAR and AR4 and again between AR4 and AR5 (Mastrandrea et al., 2010).

Recently, increased engagement of social scientists (e.g., Patt and Schrag, 2003; Kandlikar et al., 2005; Risbey and Kandlikar, 2007; Broomell and Budescu, 2009; Budescu et al., 2009; CCSP, 2009) and expert advisory panels (CCSP, 2009; InterAcademy Council, 2010) in the area of uncertainty and climate change has helped clarify issues and procedures to improve presentation of uncertainty. Many of the recommendations of these groups are addressed in the revised Guidance Notes. One key revision relates to clarification of the relationship between the 'confidence' and 'likelihood' language, and pertains to demarcation between qualitative descriptions of 'confidence' and the numerical representations of uncertainty that are expressed by the likelihood scale. In addition, a finding that includes a probabilistic measure of uncertainty does not require explicit mention of the level of confidence associated with that finding if the level of *confidence* is *high* or *very high*. This is a concession to stylistic clarity and readability: if something is described as having a high likelihood, then in the absence of additional qualifiers it should be inferred that it also has *high* or *very high confidence*.

1.4.4 Uncertainty Treatment in This Assessment

All three IPCC Working Groups in the AR5 have agreed to use two metrics for communicating the degree of certainty in key findings (Mastrandrea et al., 2010):

- Confidence in the validity of a finding, based on the type, amount, quality, and consistency of evidence (e.g., data, mechanistic understanding, theory, models, expert judgment) and the degree of agreement. Confidence is expressed qualitatively.

- Quantified measures of uncertainty in a finding expressed probabilistically (based on statistical analysis of observations or model results, or expert judgement).

A level of confidence synthesizes the Chapter teams' judgements about the validity of findings as determined through evaluation of the available evidence and the degree of scientific agreement. The evidence and agreement scale underpins the assessment, as it is on the basis of evidence and agreement that statements can be made with scientific confidence (in this sense, the evidence and agreement scale replaces the 'level of scientific understanding' scale used in previous WGI assessments). There is flexibility in this relationship; for a given evidence and agreement statement, different confidence levels could be assigned, but increasing levels of evidence and degrees of agreement are correlated with increasing confidence. Confidence cannot necessarily be assigned for all combinations of evidence and agreement, but where key variables are highly uncertain, the available evidence and scientific agreement regarding that variable are presented and discussed. Confidence should not be interpreted probabilistically, and it is distinct from 'statistical confidence'.

The confidence level is based on the evidence (robust, medium and limited) and the agreement (high, medium and low). A combination of different methods, e.g., observations and modelling, is important for evaluating the confidence level. Figure 1.11 shows how the combined evidence and agreement results in five levels for the confidence level used in this assessment.

The qualifier 'likelihood' provides calibrated language for describing quantified uncertainty. It can be used to express a probabilistic estimate of the occurrence of a single event or of an outcome, for example, a climate parameter, observed trend, or projected change

Frequently Asked Questions

FAQ 1.1 | If Understanding of the Climate System Has Increased, Why Hasn't the Range of Temperature Projections Been Reduced?

The models used to calculate the IPCC's temperature projections agree on the direction of future global change, but the projected size of those changes cannot be precisely predicted. Future greenhouse gas (GHG) emission rates could take any one of many possible trajectories, and some underlying physical processes are not yet completely understood, making them difficult to model. Those uncertainties, combined with natural year-to-year climate variability, produce an 'uncertainty range' in temperature projections.

The uncertainty range around projected GHG and aerosol precursor emissions (which depend on projections of future social and economic conditions) cannot be materially reduced. Nevertheless, improved understanding and climate models—along with observational constraints—may reduce the uncertainty range around some factors that influence the climate's response to those emission changes. The complexity of the climate system, however, makes this a slow process. (FAQ1.1, Figure 1)

Climate science has made many important advances since the last IPCC assessment report, thanks to improvements in measurements and data analysis in the cryosphere, atmosphere, land, biosphere and ocean systems. Scientists also have better understanding and tools to model the role of clouds, sea ice, aerosols, small-scale ocean mixing, the carbon cycle and other processes. More observations mean that models can now be evaluated more thoroughly, and projections can be better constrained. For example, as models and observational analysis have improved, projections of sea level rise have become more accurate, balancing the current sea level rise budget.

Despite these advances, there is still a range in plausible projections for future global and regional climate—what scientists call an 'uncertainty range'. These uncertainty ranges are specific to the variable being considered (precipitation vs. temperature, for instance) and the spatial and temporal extent (such as regional vs. global averages). Uncertainties in climate projections arise from natural variability and uncertainty around the rate of future emissions and the climate's response to them. They can also occur because representations of some known processes are as yet unrefined, and because some processes are not included in the models.

There are fundamental limits to just how precisely annual temperatures can be projected, because of the chaotic nature of the climate system. Furthermore, decadal-scale projections are sensitive to prevailing conditions—such as the temperature of the deep ocean—that are less well known. Some natural variability over decades arises from interactions between the ocean, atmosphere, land, biosphere and cryosphere, and is also linked to phenomena such as the El Niño-Southern Oscillation (ENSO) and the North Atlantic Oscillation (see Box 2.5 for details on patterns and indices of climate variability).

Volcanic eruptions and variations in the sun's output also contribute to natural variability, although they are externally forced and explainable. This natural variability can be viewed as part of the 'noise' in the climate record, which provides the backdrop against which the 'signal' of anthropogenic climate change is detected.

Natural variability has a greater influence on uncertainty at regional and local scales than it does over continental or global scales. It is inherent in the Earth system, and more knowledge will not eliminate the uncertainties it brings. However, some progress is possible—particularly for projections up to a few years ahead—which exploit advances in knowledge of, for instance, the cryosphere or ocean state and processes. This is an area of active research. When climate variables are averaged over decadal timescales or longer, the relative importance of internal variability diminishes, making the long-term signals more evident (FAQ1.1, Figure 1). This long-term perspective is consistent with a common definition of climate as an average over 30 years.

A second source of uncertainty stems from the many possible trajectories that future emission rates of GHGs and aerosol precursors might take, and from future trends in land use. Nevertheless, climate projections rely on input from these variables. So to obtain these estimates, scientists consider a number of alternative scenarios for future human society, in terms of population, economic and technological change, and political choices. They then estimate the likely emissions under each scenario. The IPCC informs policymaking, therefore climate projections for different emissions scenarios can be useful as they show the possible climatic consequences of different policy choices. These scenarios are intended to be compatible with the full range of emissions scenarios described in the current scientific literature, with or without climate policy. As such, they are designed to sample uncertainty in future scenarios. *(continued on next page)*

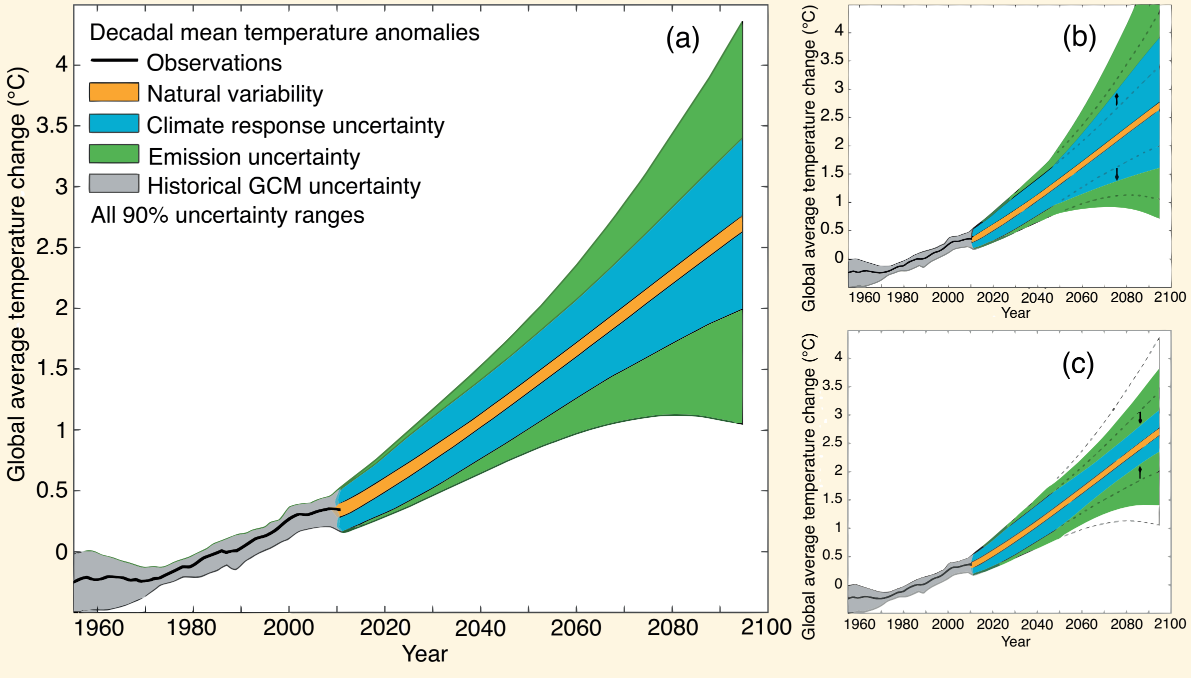
FAQ 1.1 (continued)

Projections for the next few years and decades are sensitive to emissions of short-lived compounds such as aerosols and methane. More distant projections, however, are more sensitive to alternative scenarios around long-lived GHG emissions. These scenario-dependent uncertainties will not be reduced by improvements in climate science, and will become the dominant uncertainty in projections over longer timescales (e.g., 2100) (FAQ 1.1, Figure 1).

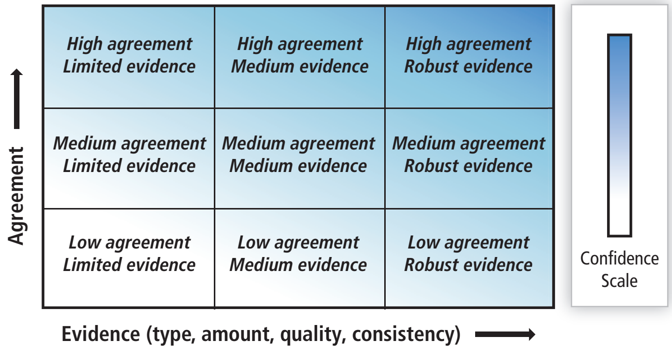
The final contribution to the uncertainty range comes from our imperfect knowledge of how the climate will respond to future anthropogenic emissions and land use change. Scientists principally use computer-based global climate models to estimate this response. A few dozen global climate models have been developed by different groups of scientists around the world. All models are built on the same physical principles, but some approximations are needed because the climate system is so complex. Different groups choose slightly different approximations to represent specific processes in the atmosphere, such as clouds. These choices produce differences in climate projections from different models. This contribution to the uncertainty range is described as 'response uncertainty' or 'model uncertainty'.

The complexity of the Earth system means that future climate could follow many different scenarios, yet still be consistent with current understanding and models. As observational records lengthen and models improve, researchers should be able, within the limitations of the range of natural variability, to narrow that range in probable temperature in the next few decades (FAQ 1.1, Figure 1). It is also possible to use information about the current state of the oceans and cryosphere to produce better projections up to a few years ahead.

As science improves, new geophysical processes can be added to climate models, and representations of those already included can be improved. These developments can appear to increase model-derived estimates of climate response uncertainty, but such increases merely reflect the quantification of previously unmeasured sources of uncertainty (FAQ1.1, Figure 1). As more and more important processes are added, the influence of unquantified processes lessens, and there can be more confidence in the projections.



FAQ 1.1, Figure 1 | Schematic diagram showing the relative importance of different uncertainties, and their evolution in time. (a) Decadal mean surface temperature change (°C) from the historical record (black line), with climate model estimates of uncertainty for historical period (grey), along with future climate projections and uncertainty. Values are normalised by means from 1961 to 1980. Natural variability (orange) derives from model interannual variability, and is assumed constant with time. Emission uncertainty (green) is estimated as the model mean difference in projections from different scenarios. Climate response uncertainty (blue-solid) is based on climate model spread, along with added uncertainties from the carbon cycle, as well as rough estimates of additional uncertainty from poorly modelled processes. Based on Hawkins and Sutton (2011) and Huntingford et al. (2009). (b) Climate response uncertainty can appear to increase when a new process is discovered to be relevant, but such increases reflect a quantification of previously unmeasured uncertainty, or (c) can decrease with additional model improvements and observational constraints. The given uncertainty range of 90% means that the temperature is estimated to be in that range, with a probability of 90%.



High agreement Limited evidence	*High agreement Medium evidence*	*High agreement Robust evidence*
Medium agreement Limited evidence	*Medium agreement Medium evidence*	*Medium agreement Robust evidence*
Low agreement Limited evidence	*Low agreement Medium evidence*	*Low agreement Robust evidence*

Figure 1.11 | The basis for the confidence level is given as a combination of evidence (limited, medium, robust) and agreement (low, medium and high) (Mastrandrea et al., 2010).

lying in a given range. Statements made using the likelihood scale may be based on statistical or modelling analyses, elicitation of expert views, or other quantitative analyses. Where sufficient information is available it is preferable to eschew the likelihood qualifier in favour of the full probability distribution or the appropriate probability range. See Table 1.2 for the list of 'likelihood' qualifiers to be used in AR5.

Many social sciences studies have found that the interpretation of uncertainty is contingent on the presentation of information, the context within which statements are placed and the interpreter's own lexical preferences. Readers often adjust their interpretation of probabilistic language according to the magnitude of perceived potential consequences (Patt and Schrag, 2003; Patt and Dessai, 2005). Furthermore, the framing of a probabilistic statement impinges on how it is interpreted (Kahneman and Tversky, 1979): for example, a 10% chance of dying is interpreted more negatively than a 90% chance of surviving.

In addition, work examining expert judgement and decision making shows that people—including scientific experts—are prone to a range of heuristics and biases that affect their judgement (e.g., Kahneman et al., 1982). For example, in the case of expert judgements there is a tendency towards overconfidence both at the individual level (Morgan et al., 1990) and at the group level as people converge on a view and draw confidence in its reliability from each other. However, in an assessment of the state of scientific knowledge across a field such as climate change—characterized by complexity of process and heterogeneity of data constraints—some degree of expert judgement is inevitable (Mastrandrea et al., 2010).

Table 1.2 | Likelihood terms associated with outcomes used in the AR5.

Term	Likelihood of the Outcome
Virtually certain	99–100% probability
Very likely	90–100% probability
Likely	66–100% probability
About as likely as not	33–66% probability
Unlikely	0–33% probability
Very unlikely	0–10% probability
Exceptionally unlikely	0–1% probability

Notes:
Additional terms that were used in limited circumstances in the AR4 (*extremely likely* = 95–100% probability, *more likely than not* = >50–100% probability, and *extremely unlikely* = 0–5% probability) may also be used in the AR5 when appropriate.

These issues were brought to the attention of chapter teams so that contributors to the AR5 might be sensitized to the ways presentation, framing, context and potential biases might affect their own assessments and might contribute to readers' understanding of the information presented in this assessment. There will always be room for debate about how to summarize such a large and growing literature. The uncertainty guidance is aimed at providing a consistent, calibrated set of words through which to communicate the uncertainty, confidence and degree of consensus prevailing in the scientific literature. In this sense the guidance notes and practices adopted by IPCC for the presentation of uncertainties should be regarded as an interdisciplinary work in progress, rather than as a finalized, comprehensive approach. Moreover, one precaution that should be considered is that translation of this assessment from English to other languages may lead to a loss of precision.

1.5 Advances in Measurement and Modelling Capabilities

Since AR4, measurement capabilities have continued to advance. The models have been improved following the progress in the understanding of physical processes within the climate system. This section illustrates some of those developments.

1.5.1 Capabilities of Observations

Improved understanding and systematic monitoring of Earth's climate requires observations of various atmospheric, oceanic and terrestrial parameters and therefore has to rely on various technologies (ranging from ground-based instruments to ships, buoys, ocean profilers, balloons, aircraft, satellite-borne sensors, etc.). The Global Climate Observing System (GCOS, 2009) defined a list of so-called Essential Climate Variables, that are technically and economically feasible to observe, but some of the associated observing systems are not yet operated in a systematic manner. However, during recent years, new observational systems have increased the number of observations by orders of magnitude and observations have been made at places where there have been no data before (see Chapters 2, 3 and 4 for an assessment of changes in observations). Parallel to this, tools to analyse and process the data have been developed and enhanced to cope with the increase of information and to provide a more comprehensive picture of the Earth's climate. At the same time, it should be kept in mind that there has been some limited progress in developing countries in filling gaps in their *in situ* observing networks, but developed countries have made little progress in ensuring long-term continuity for several important observing systems (GCOS, 2009). In addition, more proxy (non-instrumental) data have been acquired to provide a more comprehensive picture of climate changes in the past (see Chapter 5). Efforts are also occurring to digitize historic observations, mainly of ground-station data from periods prior to the second half of the 20th century (Brunet and Jones, 2011).

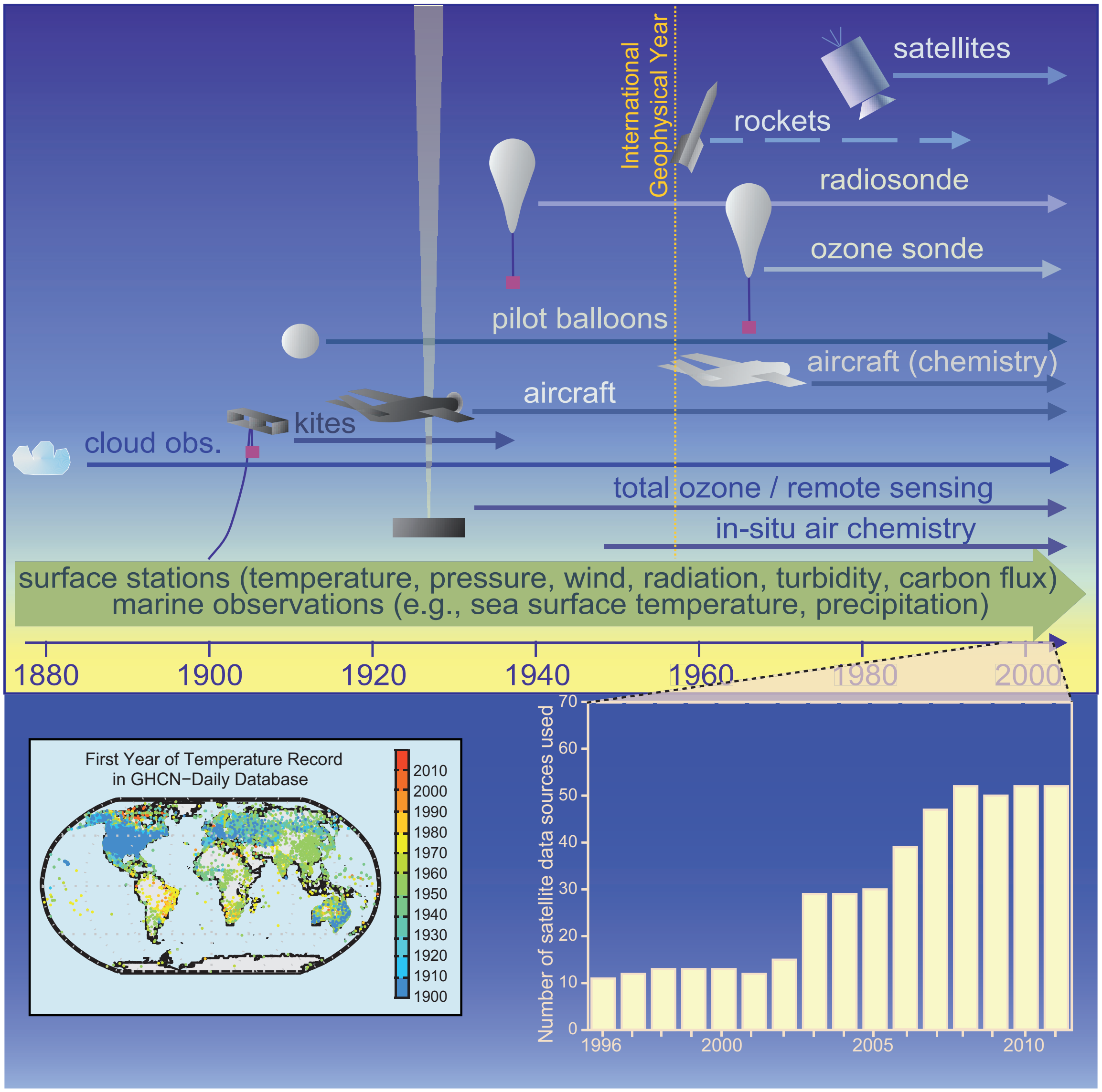


Figure 1.12 | Development of capabilities of observations. Top: Changes in the mix and increasing diversity of observations over time create challenges for a consistent climate record (adapted from Brönnimann et al., 2008). Bottom left: First year of temperature data in Global Historical Climatology Network (GHCN) daily database (available at http://www.ncdc.noaa.gov/oa/climate/ghcn-daily/; Menne et al., 2012). Bottom right: Number of satellite instruments from which data have been assimilated in the European Centre for Medium-Range Weather Forecasts production streams for each year from 1996 to 2010. This figure is used as an example to demonstrate the fivefold increase in the usage of satellite data over this time period.

Reanalysis is a systematic approach to produce gridded dynamically consistent data sets for climate monitoring and research by assimilating all available observations with help of a climate model (Box 2.3). Model-based reanalysis products play an important role in obtaining a consistent picture of the climate system. However, their usefulness in detecting long-term climate trends is currently limited by changes over time in observational coverage and biases, linked to the presence of biases in the assimilating model (see also Box 2.3 in Chapter 2). Because AR4 both the quantity and quality of the observations that are assimilated through reanalysis have increased (GCOS, 2009). As an example, there has been some overall increase in mostly atmospheric observations assimilated in European Centre for Medium-Range Weather Forecasts Interim Reanalysis since 2007 (Dee et al., 2011). The overwhelming majority of the data, and most of the increase over recent years, come from satellites (Figure 1.12) (GCOS, 2011). For example, information from Global Positioning System radio occultation measurements has increased significantly since 2007. The increases in data from fixed stations are often associated with an increased frequency of reporting, rather than an increase in the number of stations. Increases in data quality come from improved instrument design or from more accurate correction in the ground-station processing that is applied before the data are transmitted to users and data centres. As an example for *in situ* data, temperature biases of radiosonde measurements from radiation effects have been reduced over recent years. The new generation of satellite sensors such as the high spectral resolution infrared sounders (such as the Atmospheric Infrared Sounder and the Infrared Atmospheric Sounding Interferometer) are instrumental to achieving a better temporal stability for recalibrating sensors such as the High-Resolution Infrared Radiation Sounder. Few instruments (e.g., the Advanced Very High Resolution Radiometer) have now been in orbit for about three decades, but these were not originally designed for climate applications and therefore require careful re-calibration.

A major achievement in ocean observation is due to the implementation of the Argo global array of profiling floats system (GCOS, 2009). Deployment of Argo floats began in 2000, but it took until 2007 for numbers to reach the design target of 3000 floats. Since 2000 the ice-free upper 2000 m of the ocean have been observed systematically for temperature and salinity for the first time in history, because both the Argo profiling float and surface drifting buoy arrays have reached global coverage at their target numbers (in January 2009, there were 3291 floats operating). Biases in historical ocean data have been identified and reduced, and new analytical approaches have been applied (e.g., Willis et al., 2009). One major consequence has been the reduction of an artificial decadal variation in upper ocean temperature and heat content that was apparent in the observational assessment for AR4 (see Section 3.2). The spatial and temporal coverage of biogeochemical measurements in the ocean has also expanded. Satellite observations for sea level (Sections 3.7 and 13.2), sea surface salinity (Section 3.3), sea ice (Section 4.2) and ocean colour have also been further developed over the past few years.

Progress has also been made with regard to observation of terrestrial Essential Climate Variables. Major advances have been achieved in remote sensing of soil moisture due to the launch of the Soil Moisture and Oceanic Salinity mission in 2009 but also due to new retrieval techniques that have been applied to data from earlier and ongoing missions (see Seneviratne et al., 2010 for a detailed review). However, these measurements have limitations. For example, the methods fail under dense vegetation and they are restricted to the surface soil. Updated Advanced Very High Resolution Radiometer-based Normalized Differenced Vegetation Index data provide new information on the change in vegetation. During the International Polar Year 2007–2009 the number of borehole sites was significantly increased and therefore allows a better monitoring of the large-scale permafrost features (see Section 4.7).

1.5.2 Capabilities in Global Climate Modelling

Several developments have especially pushed the capabilities in modelling forward over recent years (see Figure 1.13 and a more detailed discussion in Chapters 6, 7 and 9).

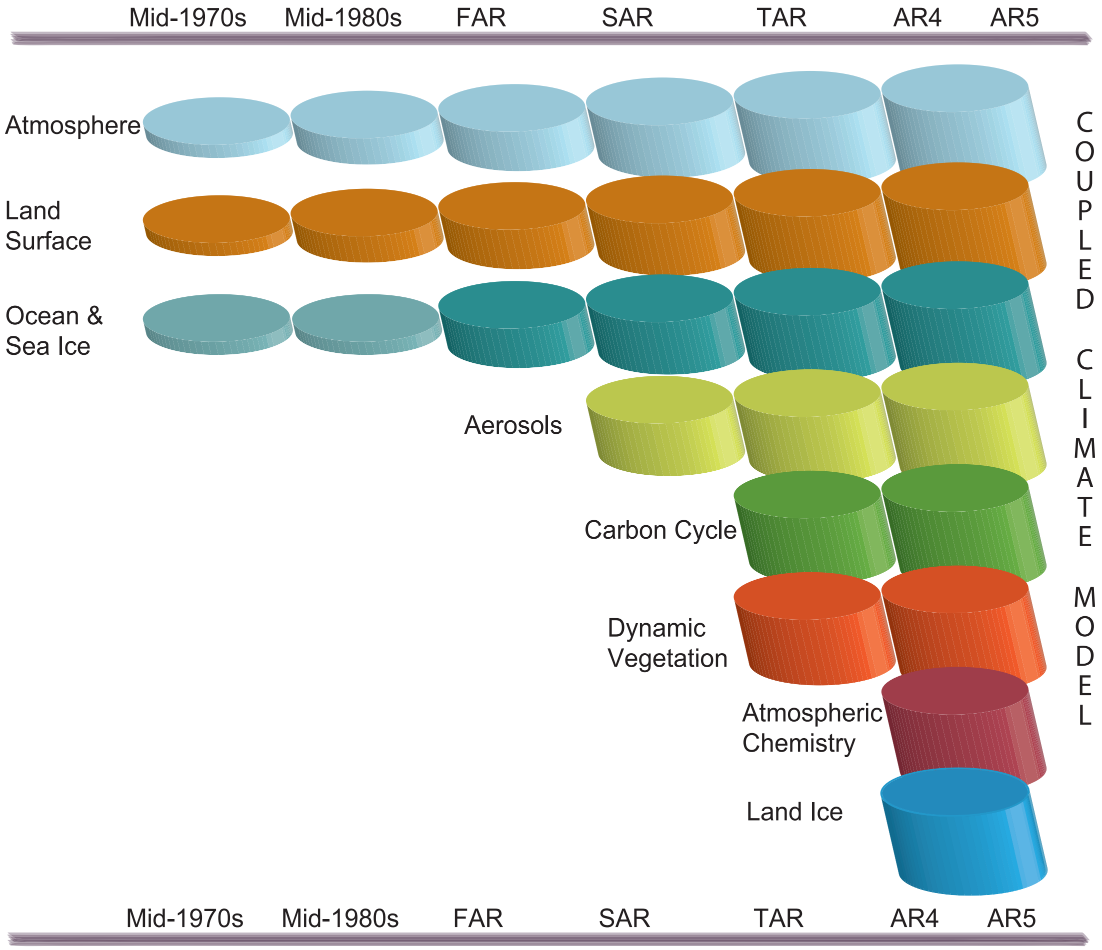


Figure 1.13 | The development of climate models over the last 35 years showing how the different components were coupled into comprehensive climate models over time. In each aspect (e.g., the atmosphere, which comprises a wide range of atmospheric processes) the complexity and range of processes has increased over time (illustrated by growing cylinders). Note that during the same time the horizontal and vertical resolution has increased considerably e.g., for spectral models from T21L9 (roughly 500 km horizontal resolution and 9 vertical levels) in the 1970s to T95L95 (roughly 100 km horizontal resolution and 95 vertical levels) at present, and that now ensembles with at least three independent experiments can be considered as standard.

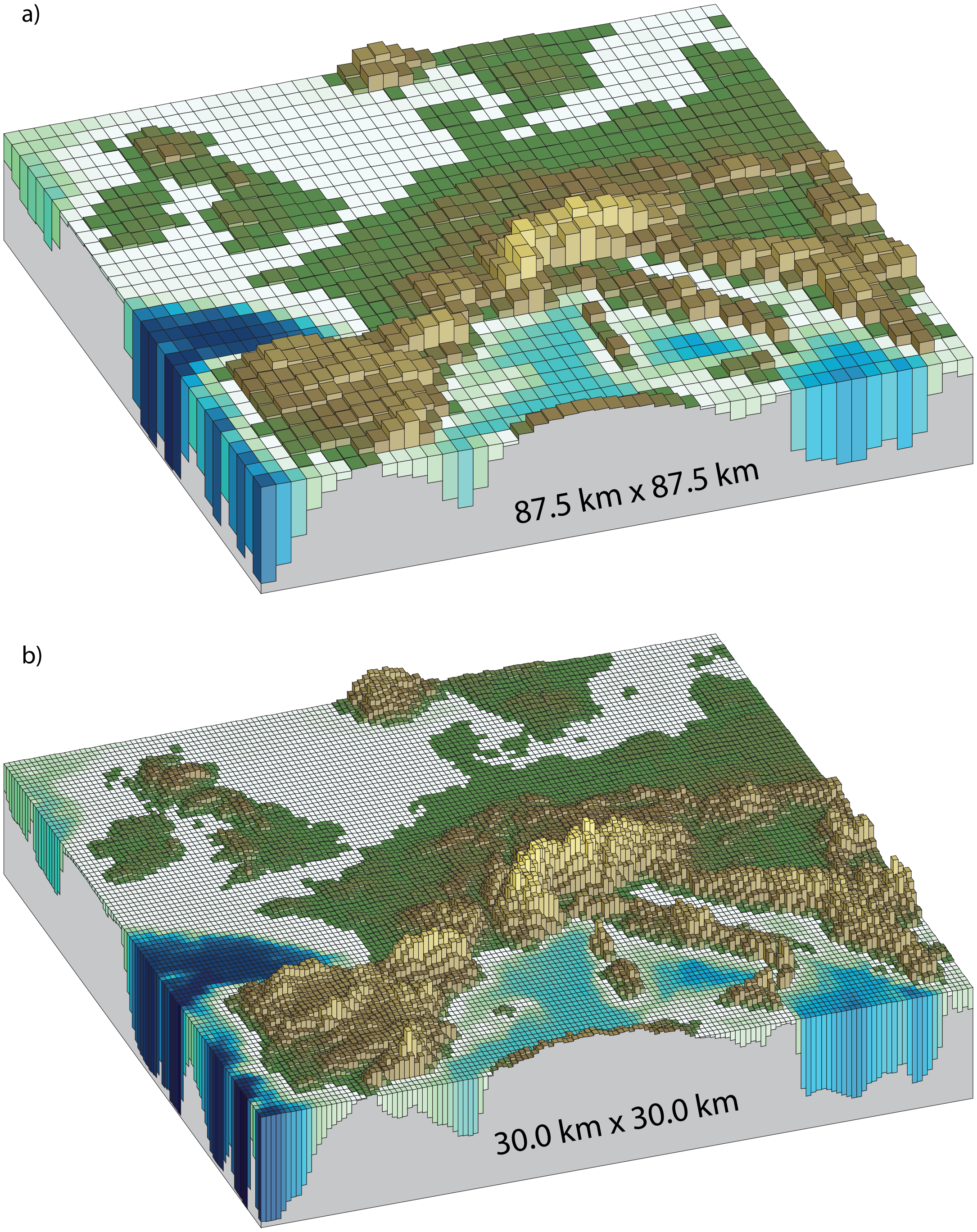


Figure 1.14 | Horizontal resolutions considered in today's higher resolution models and in the very high resolution models now being tested: (a) Illustration of the European topography at a resolution of 87.5 × 87.5 km; (b) same as (a) but for a resolution of 30.0 × 30.0 km.

There has been a continuing increase in horizontal and vertical resolution. This is especially seen in how the ocean grids have been refined, and sophisticated grids are now used in the ocean and atmosphere models making optimal use of parallel computer architectures. More models with higher resolution are available for more regions. Figure 1.14a and 1.14b show the large effect on surface representation from a horizontal grid spacing of 87.5 km (higher resolution than most current global models and similar to that used in today's highly resolved models) to a grid spacing of 30.0 km (similar to the current regional climate models).

Representations of Earth system processes are much more extensive and improved, particularly for the radiation and the aerosol cloud interactions and for the treatment of the cryosphere. The representation of the carbon cycle was added to a larger number of models and has been improved since AR4. A high-resolution stratosphere is now included in many models. Other ongoing process development in climate models includes the enhanced representation of nitrogen effects on the carbon cycle. As new processes or treatments are added to the models, they are also evaluated and tested relative to available observations (see Chapter 9 for more detailed discussion).

Ensemble techniques (multiple calculations to increase the statistical sample, to account for natural variability, and to account for uncertainty in model formulations) are being used more frequently, with larger samples and with different methods to generate the samples (different models, different physics, different initial conditions). Coordinated projects have been set up to generate and distribute large samples (ENSEMBLES, climateprediction.net, Program for Climate Model Diagnosis and Intercomparison).

The model comparisons with observations have pushed the analysis and development of the models. CMIP5, an important input to the AR5, has produced a multi-model data set that is designed to advance our understanding of climate variability and climate change. Building on previous CMIP efforts, such as the CMIP3 model analysis reported in AR4, CMIP5 includes 'long-term' simulations of 20th century climate and projections for the 21st century and beyond. See Chapters 9, 10, 11 and 12 for more details on the results derived from the CMIP5 archive.

Since AR4, the incorporation of 'long-term' paleoclimate simulations in the CMIP5 framework has allowed incorporation of information from paleoclimate data to inform projections. Within uncertainties associated with reconstructions of past climate variables from proxy records and forcings, paleoclimate information from the Mid Holocene, Last Glacial Maximum and Last Millennium have been used to test the ability of models to simulate realistically the magnitude and large-scale patterns of past changes (Section 5.3, Box 5.1 and 9.4).

The capabilities of ESMs continue to be enhanced. For example, there are currently extensive efforts towards developing advanced treatments for the processes affecting ice sheet dynamics. Other enhancements are being aimed at land surface hydrology, and the effects of agriculture and urban environments.

As part of the process of getting model analyses for a range of alternative assumptions about how the future may unfold, scenarios for future emissions of important gases and aerosols have been generated for the IPCC assessments (e.g., see the SRES scenarios used in TAR and AR4). The emissions scenarios represent various development pathways based on well-defined assumptions. The scenarios are used to calculate future changes in climate, and are then archived in the Climate Model Intercomparison Project (e.g., CMIP3 for AR4; CMIP5 for AR5). For CMIP5, four new scenarios, referred to as Representative Concentration Pathways (RCPs) were developed (Section 12.3; Moss et al., 2010). See Box 1.1 for a more thorough discussion of the RCP scenarios. Because results from both CMIP3 and CMIP5 will be presented in the later chapters (e.g., Chapters 8, 9, 11 and 12), it is worthwhile considering the differences and similarities between the SRES and the RCP scenarios. Figure 1.15, acting as a prelude to the discussion in Box 1.1, shows that the RF for several of the SRES and RCP scenarios are similar over time and thus should provide results that can be used to compare climate modelling studies.

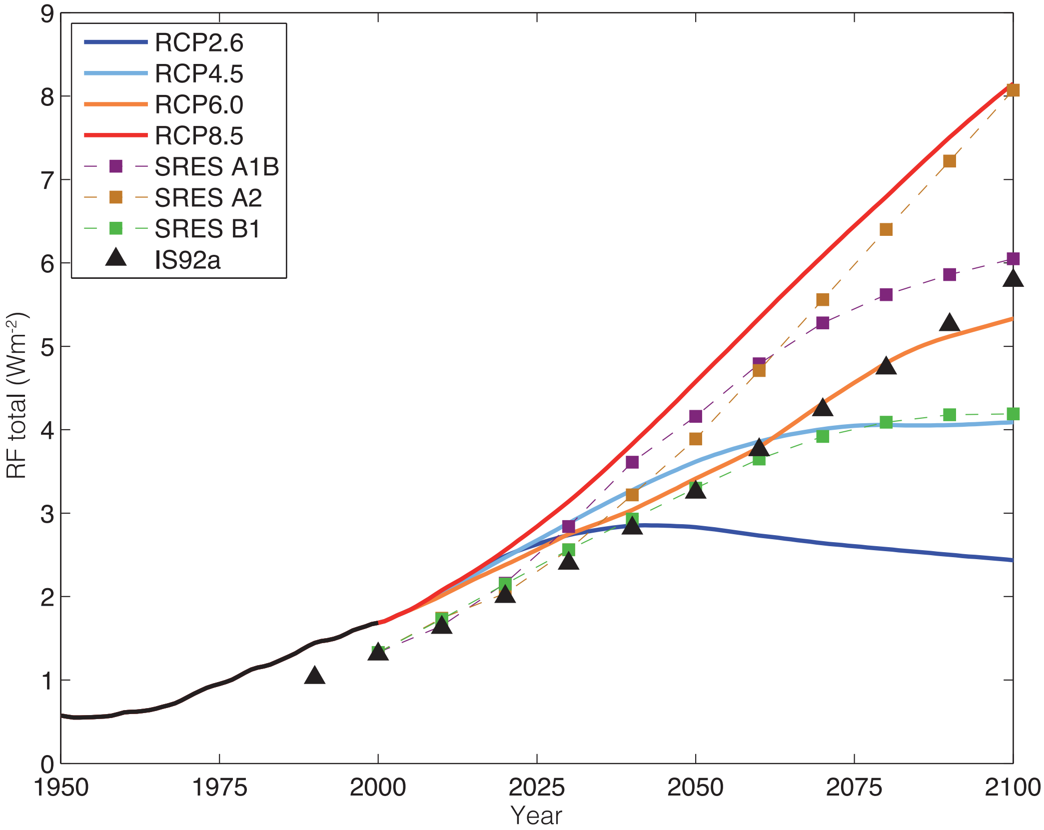


Figure 1.15 | Historical and projected total anthropogenic RF (W m^{-2}) relative to preindustrial (about 1765) between 1950 and 2100. Previous IPCC assessments (SAR IS92a, TAR/AR4 SRES A1B, A2 and B1) are compared with representative concentration pathway (RCP) scenarios (see Chapter 12 and Box 1.1 for their extensions until 2300 and Annex II for the values shown here). The total RF of the three families of scenarios, IS92, SRES and RCP, differ for example, for the year 2000, resulting from the knowledge about the emissions assumed having changed since the TAR and AR4.

Box 1.1 | Description of Future Scenarios

Long-term climate change projections require assumptions on human activities or natural effects that could alter the climate over decades and centuries. Defined scenarios are useful for a variety of reasons, e.g., assuming specific time series of emissions, land use, atmospheric concentrations or RF across multiple models allows for coherent climate model intercomparisons and synthesis. Scenarios can be formed in a range of ways, from simple, idealized structures to inform process understanding, through to comprehensive scenarios produced by Integrated Assessment Models (IAMs) as internally consistent sets of assumptions on emissions and socio-economic drivers (e.g., regarding population and socio-economic development).

Idealized Concentration Scenarios

As one example of an idealized concentration scenario, a 1% yr^{-1} compound increase of atmospheric CO_2 concentration until a doubling or a quadrupling of its initial value has been widely used in the past (Covey et al., 2003). An exponential increase of CO_2 concentrations induces an essentially linear increase in RF (Myhre et al., 1998) due to a 'saturation effect' of the strong absorbing bands. Such a linear ramp function is highly useful for comparative diagnostics of models' climate feedbacks and inertia. The CMIP5 intercomparison project again includes such a stylized pathway up to a quadrupling of CO_2 concentrations, in addition to an instantaneous quadrupling case.

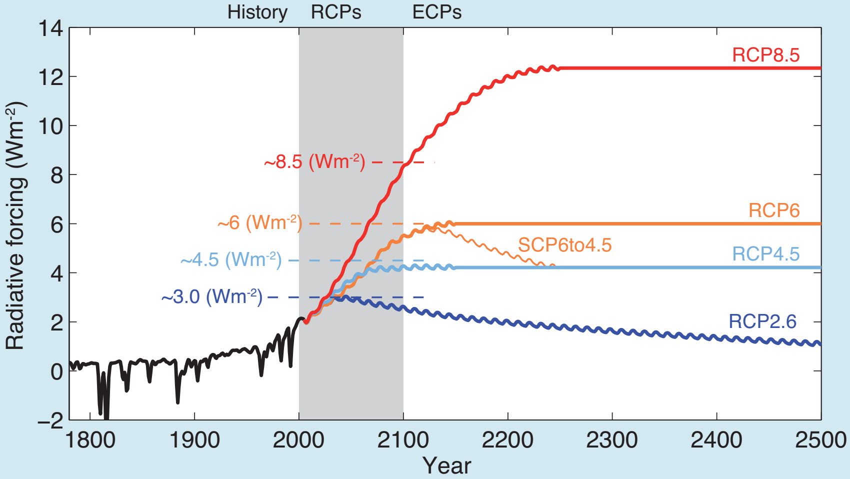
The Socio-Economic Driven SRES Scenarios

The SRES suite of scenarios were developed using IAMs and resulted from specific socio-economic scenarios from storylines about future demographic and economic development, regionalization, energy production and use, technology, agriculture, forestry and land use (IPCC, 2000). The climate change projections undertaken as part of CMIP3 and discussed in AR4 were based primarily on the SRES A2, A1B and B1 scenarios. However, given the diversity in models' carbon cycle and chemistry schemes, this approach implied differences in models' long lived GHG and aerosol concentrations for the same emissions scenario. As a result of this and other shortcomings, revised scenarios were developed for AR5 to allow atmosphere-ocean general circulation model (AOGCM) (using concentrations) simulations to be compared with those ESM simulations that use emissions to calculate concentrations.

Representative Concentration Pathway Scenarios and Their Extensions

Representative Concentration Pathway (RCP) scenarios (see Section 12.3 for a detailed description of the scenarios; Moss et al., 2008; Moss et al., 2010; van Vuuren et al., 2011b) are new scenarios that specify concentrations and corresponding emissions, but are not directly based on socio-economic storylines like the SRES scenarios. The RCP scenarios are based on a different approach and include more consistent short-lived gases and land use changes. They are not necessarily more capable of representing future developments than the SRES scenarios. Four RCP scenarios were selected from the published literature (Fujino et al., 2006; Smith and Wigley, 2006; Riahi et al., 2007; van Vuuren et al., 2007; Hijioka et al., 2008; Wise et al., 2009) and updated for use within CMIP5 (Masui et al., 2011; Riahi et al., 2011; Thomson et al., 2011; van Vuuren et al., 2011a). The four scenarios are identified by the 21st century peak or stabilization value of the RF derived by the reference model (in W m^{-2}) (Box 1.1, Figure 1): the lowest RCP, RCP2.6 (also referred to as

(continued on next page)

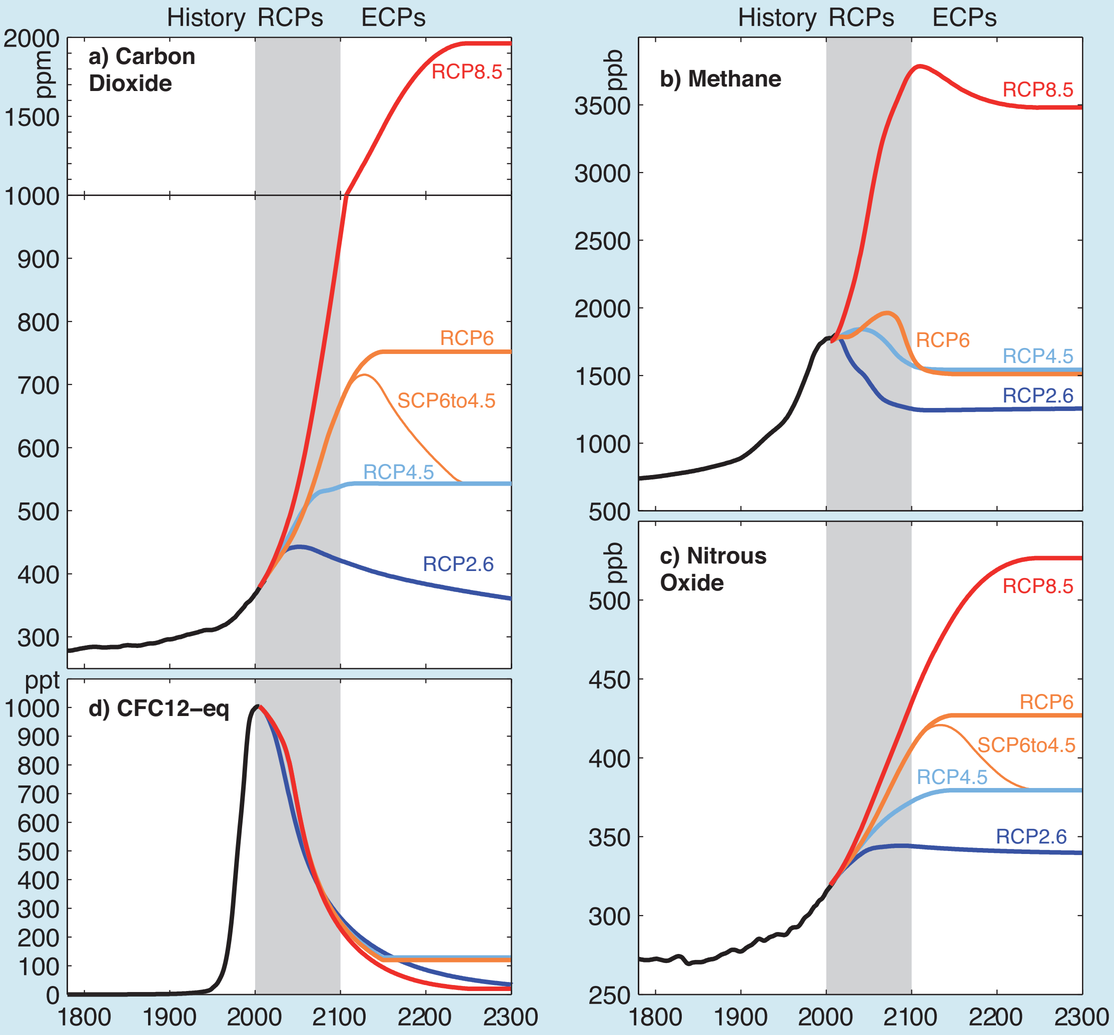


Box 1.1, Figure 1 | Total RF (anthropogenic plus natural) for RCPs and extended concentration pathways (ECP)—for RCP2.6, RCP4.5, and RCP6, RCP8.5, as well as a supplementary extension RCP6 to 4.5 with an adjustment of emissions after 2100 to reach RCP4.5 concentration levels in 2250 and thereafter. Note that the stated RF levels refer to the illustrative default median estimates only. There is substantial uncertainty in current and future RF levels for any given scenario. Short-term variations in RF are due to both volcanic forcings in the past (1800–2000) and cyclical solar forcing assuming a constant 11-year solar cycle (following the CMIP5 recommendation), except at times of stabilization. (Reproduced from Figure 4 in Meinshausen et al., 2011.)

Box 1.1 (continued)

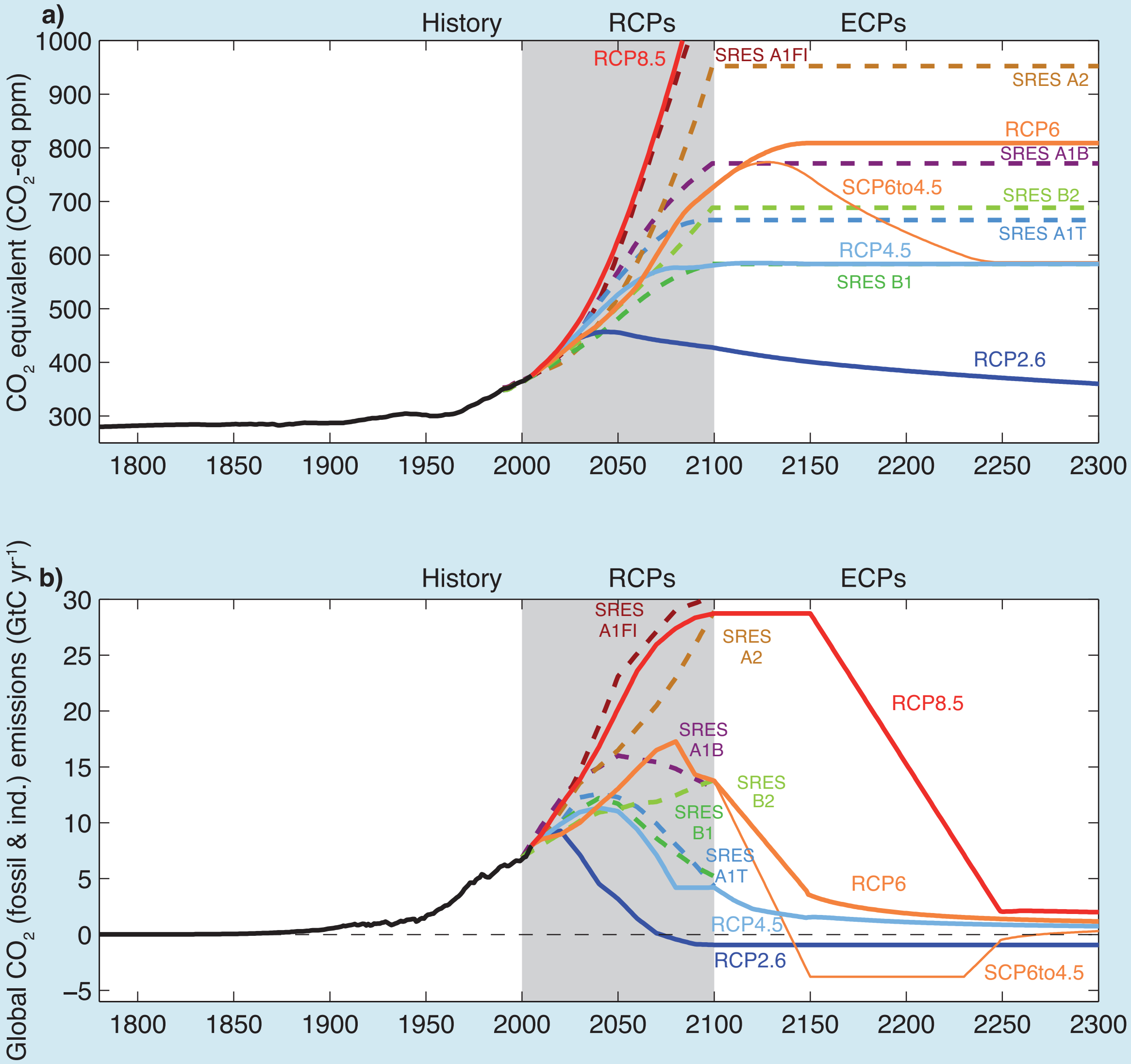
RCP3-PD) which peaks at 3 W m^{-2} and then declines to approximately 2.6 W m^{-2} by 2100; the medium-low RCP4.5 and the medium-high RCP6 aiming for stabilization at 4.5 and 6 W m^{-2}, respectively around 2100; and the highest one, RCP8.5, which implies a RF of 8.5 W m^{-2} by 2100, but implies rising RF beyond that date (Moss et al., 2010). In addition there is a supplementary extension SCP6to4.5 with an adjustment of emissions after 2100 to reach RCP 4.5 concentration levels in 2250 and thereafter. The RCPs span the full range of RF associated with emission scenarios published in the peer-reviewed literature at the time of the development of the RCPs, and the two middle scenarios where chosen to be roughly equally spaced between the two extremes (2.6 and 8.5 W m^{-2}). These forcing values should be understood as comparative labels representative of the forcing associated with each scenario, which will vary somewhat from model to model. This is because concentrations or emissions (rather than the RF) are prescribed in the CMIP5 climate model runs.

Various steps were necessary to turn the selected 'raw' RCPs into emission scenarios from IAMs and to turn these into data sets usable by the climate modelling community, including the extension with historical emissions (Granier et al., 2011; Meinshausen et al., 2011), the harmonization (smoothly connected historical reconstruction) and gridding of land use data sets (Hurtt et al., 2011), the provision of atmospheric chemistry modelling studies, particularly for tropospheric ozone (Lamarque et al., 2011), analyses of 2000–2005 GHG emission levels, and extension of GHG concentrations with historical GHG concentrations and harmonization with analyses of 2000–2005 GHG concentrations levels (Meinshausen et al., 2011). The final RCP data sets comprise land use data, harmonized GHG emissions and concentrations, gridded reactive gas and aerosol emissions, as well as ozone and aerosol abundance fields (Figures 2, 3, and 4 in Box 1.1). *(continued on next page)*



Box 1.1, Figure 2 | Concentrations of GHG following the 4 RCPs and their extensions (ECP) to 2300. (Reproduced from Figure 5 in Meinshausen et al., 2011.) Also see Annex II Table AII.4.1 for CO_2, Table AII.4.2 for CH_4, Table AII.4.3 for N_2O.

Box 1.1 (continued)



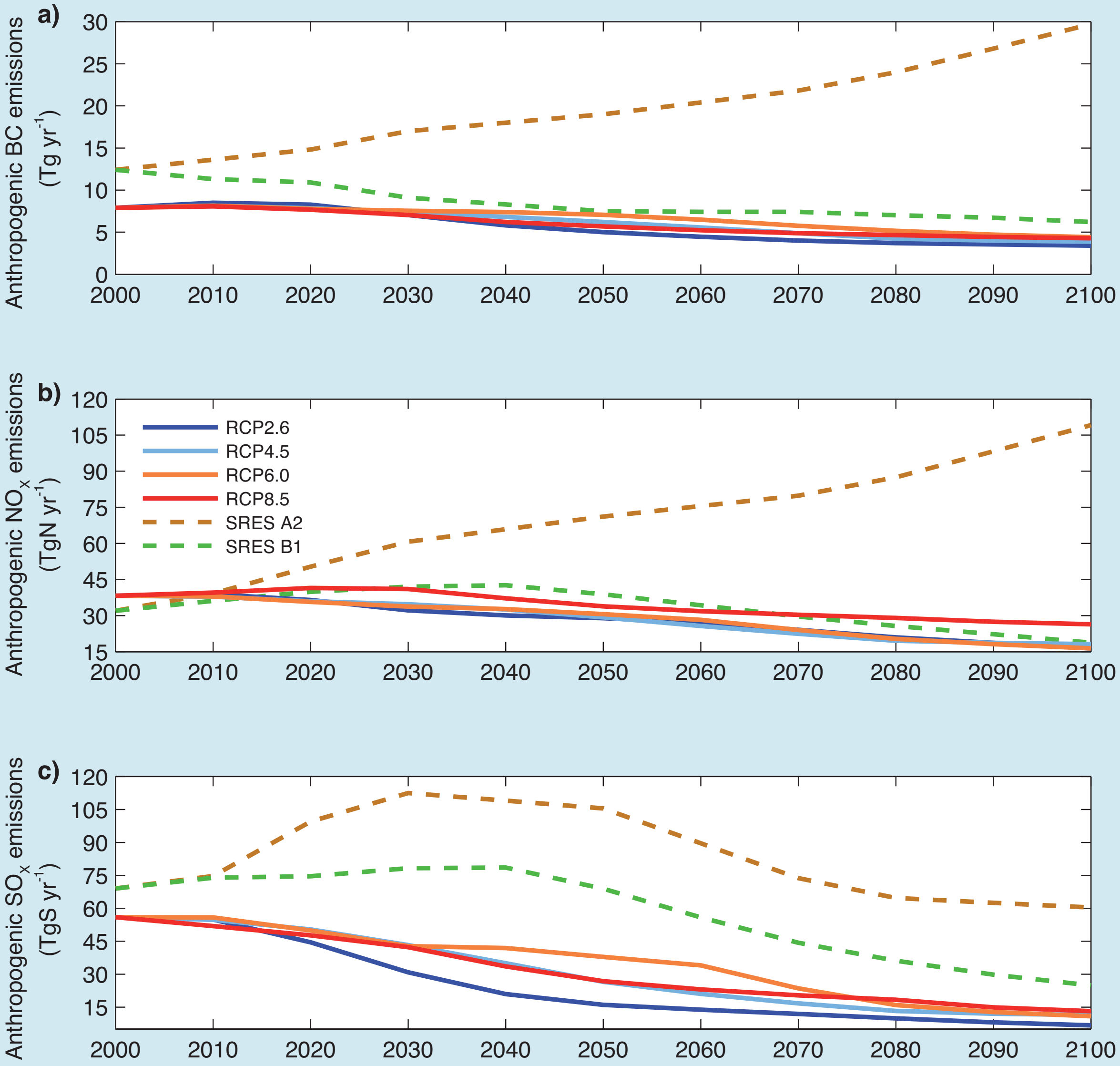
Box 1.1, Figure 3 | (a) Equivalent CO$_2$ concentration and (b) CO$_2$ emissions (except land use emissions) for the four RCPs and their ECPs as well as some SRES scenarios.

To aid model understanding of longer-term climate change implications, these RCPs were extended until 2300 (Meinshausen et al., 2011) under reasonably simple and somewhat arbitrary assumptions regarding post-2100 GHG emissions and concentrations. In order to continue to investigate a broad range of possible climate futures, the two outer RCPs, RCP2.6 and RCP8.5 assume constant emissions after 2100, while the two middle RCPs aim for a smooth stabilization of concentrations by 2150. RCP8.5 stabilizes concentrations only by 2250, with CO$_2$ concentrations of approximately 2000 ppm, nearly seven times the pre-industrial levels. As the RCP2.6 implies netnegative CO$_2$ emissions after around 2070 and throughout the extension, CO$_2$ concentrations are slowly reduced towards 360 ppm by 2300.

Comparison of SRES and RCP Scenarios

The four RCP scenarios used in CMIP5 lead to RF values that span a range larger than that of the three SRES scenarios used in CMIP3 (Figure 12.3). RCP4.5 is close to SRES B1, RCP6 is close to SRES A1B (more after 2100 than during the 21st century) and RCP8.5 is somewhat higher than A2 in 2100 and close to the SRES A1FI scenario (Figure 3 in Box 1.1). RCP2.6 is lower than any of the SRES scenarios (see also Figure 1.15). *(continued on next page)*

Box 1.1 (continued)



Note: Primary anthropogenic sulphur emissions as SO_2 measured here as Tg of S
(see Annex II Table AII.2.20)

Box 1.1, Figure 4 | (a) Anthropogenic BC emissions (Annex II Table AII.2.22), (b) anthropogenic NO_x emissions (Annex II Table AII.2.18), and (c) anthropogenic SO_x emissions (Annex II Table II.2.20).

1.6 Overview and Road Map to the Rest of the Report

As this chapter has shown, understanding of the climate system and the changes occurring in it continue to advance. The notable scientific advances and associated peer-reviewed publications since AR4 provide the basis for the assessment of the science as found in Chapters 2 to 14. Below a quick summary of these chapters and their objectives is provided.

Observations and Paleoclimate Information (Chapters 2, 3, 4 and 5): These chapters assess information from all climate system components on climate variability and change as obtained from instrumental records and climate archives. This group of chapters covers all relevant aspects of the atmosphere including the stratosphere, the land surface, the oceans and the cryosphere. Information on the water cycle, including evaporation, precipitation, runoff, soil moisture, floods, drought, etc. is assessed. Timescales from daily to decades (Chapters 2, 3 and 4) and from centuries to many millennia (Chapter 5) are considered.

Process Understanding (Chapters 6 and 7): These chapters cover all relevant aspects from observations and process understanding, to projections from global to regional scale. Chapter 6 covers the carbon cycle and its interactions with other biogeochemical cycles, in particular the nitrogen cycle, as well as feedbacks on the climate system. Chapter 7 treats in detail clouds and aerosols, their interactions and chemistry, the role of water vapour, as well as their role in feedbacks on the climate system.

From Forcing to Attribution of Climate Change (Chapters 8, 9 and 10): In these chapters, all the information on the different drivers (natural and anthropogenic) of climate change is collected, expressed in terms of RF, and assessed (Chapter 8). As part of this, the science of metrics commonly used in the literature to compare radiative effects from a range of agents (Global Warming Potential, Global Temperature Change Potential and others) is covered. In Chapter 9, the hierarchy of climate models used in simulating past and present climate change is assessed. Information regarding detection and attribution of changes on global to regional scales is assessed in Chapter 10.

Future Climate Change and Predictability (Chapters 11 and 12): These chapters assess projections of future climate change derived from climate models on timescales from decades to centuries at both global and regional scales, including mean changes, variability and extremes. Fundamental questions related to the predictability of climate as well as long-term climate change, climate change commitments and inertia in the climate system are addressed.

Integration (Chapters 13 and 14): These chapters integrate all relevant information for two key topics in WGI AR5: sea level change (Chapter 13) and climate phenomena across the regions (Chapter 14). Chapter 13 assesses information on sea level change ranging from observations and process understanding to projections from global to regional scales. Chapter 14 assesses the most important modes of variability in the climate system and extreme events. Furthermore, this chapter deals with interconnections between the climate phenomena, their regional expressions, and their relevance for future regional climate change. Maps produced and assessed in Chapter 14, together with Chapters 11 and 12, form the basis of the Atlas of Global and Regional Climate Projections in Annex I. RFs and estimates of future atmospheric concentrations from Chapters 7, 8, 11 and 12 form the basis of the Climate System Scenario Tables in Annex II.

1.6.1 Topical Issues

A number of topical issues are discussed throughout the assessment. These issues include those of areas where there is contention in the peer-reviewed literature and where questions have been raised that are being addressed through ongoing research. Table 1.3 provides a non-comprehensive list of many of these and the chapters where they are discussed.

Table 1.3 | Key topical issues discussed in the assessment.

Topic	Section
Abrupt change and irreversibility	5.7, 12.5, 13.4
Aerosols	6.4, 7.3, 7.4, 7.5, 7.6, 8.3, 11.3, 14.1
Antarctic climate change	5.8, 9.4, 10.3, 13.3
Arctic sea ice change	4.2, 5.5, 9.4, 10.3, 11.3, 12.4
Hydrological cycle changes	2.5, 2.6, 3.3, 3.4, 3.5, 7.6, 10.3, 12.4
Carbon-climate feedbacks	6.4, 12.4
Climate sensitivity	5.3, 9.7, 10.8, 12.5
Climate stabilization	6.3, 6.4, 12.5
Cloud feedbacks	5.3, 7.2, 9.7, 11.3, 12.4
Cosmic ray effects on clouds	7.4
Decadal climate variability	5.3, 9.5, 10.3
Earth's Energy (trends, distribution and budget)	2.3, 3.2, 13.3
El Niño-Southern Oscillation	2.7, 5.4, 9.4, 9.5, 14.4
Geo-engineering	6.4, 7.7
Glacier change	4.3, 5.5, 10.5, 13.3
Ice sheet dynamics and mass balance assessment	4.4, 5.3, 5.6, 10.5, 13.3
Monsoons	2.7, 5.5, 9.5, 14.2
Ocean acidification	3.8, 6.4
Permafrost change	4.7, 6.3, 10.5
Solar effects on climate change	5.2, 8.4
Sea level change, including regional effects	3.7, 5.6, 13.1
Temperature trends since 1998	2.4, 3.2, 9.4
Tropical cyclones	2.6, 10.6, 14.6
Upper troposphere temperature trends	2.4, 9.4

References

Allen, M. R., J. F. B. Mitchell, and P. A. Stott, 2013: Test of a decadal climate forecast. *Nature Geosci.*, **6**, 243–244.

AMAP, 2009: Summary – The Greenland Ice Sheet in a Changing Climate: Snow, Water, Ice and Permafrost in the Arctic (SWIPA). Arctic Monitoring and Assessment Programme (AMAP), 22 pp.

Armour, K. C., I. Eisenman, E. Blanchard-Wrigglesworth, K. E. McCusker, and C. M. Bitz, 2011: The reversibility of sea ice loss in a state-of-the-art climate model. *Geophys. Res. Lett.*, **38**.

Arrhenius, S., 1896: On the influence of carbonic acid in the air upon the temperature of the ground. *Philos. Mag.*, **41**, 237–276.

Baede, A. P. M., E. Ahlonsou, Y. Ding, and D. Schimel, 2001: The climate system: An overview. In: *Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change* [J. T. Houghton, Y. Ding, D. J. Griggs, M. Noquer, P. J. van der Linden, X. Dai, K. Maskell and C. A. Johnson (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Beerling, D. J., and D. L. Royer, 2011: Convergent Cenozoic CO_2 history. *Nature Geosci.*, **4**, 418–420.

Bretherton, F. P., K. Bryan, and J. D. Woodes, 1990: Time-dependent greenhouse-gas-induced climate change. In: *Climate Change: The IPCC Scientific Assessment* [J. T. Houghton, G. J. Jenkins and J. J. Ephraums (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 177–193.

Brönnimann, S., T. Ewen, J. Luterbacher, H. F. Diaz, R. S. Stolarski, and U. Neu, 2008: A focus on climate during the past 100 years. In: *Climate Variability and Extremes during the Past 100 Years* [S. Brönnimann, J. Luterbacher, T. Ewen, H. F. Diaz, R. S. Stolarski and U. Neu (eds.)]. Springer Science+Business Media, Heidelberg, Germany and New York, NY, USA, pp. 1–25.

Broomell, S., and D. Budescu, 2009: Why are experts correlated? Decomposing correlations between judges. *Psychometrika*, **74**, 531–553.

Brunet, M., and P. Jones, 2011: Data rescue initiatives: Bringing historical climate data into the 21st century. *Clim. Res.*, **47**, 29–40.

Budescu, D., S. Broomell, and H.-H. Por, 2009: Improving communication of uncertainty in the reports of the Intergovernmental Panel on Climate Change. *Psychol. Sci.*, **20**, 299–308.

Byrne, R., S. Mecking, R. Feely, and X. Liu, 2010: Direct observations of basin-wide acidification of the North Pacific Ocean. *Geophys. Res. Lett.*, **37**.

CCSP, 2009: *Best Practice Approaches for Characterizing, Communicating, and Incorporating Scientific Uncertainty in Climate Decision Making.* U.S. Climate Change Science Program, Washington, DC, USA, 96 pp.

Church, J. A., and N. J. White, 2011: Sea-level rise from the late 19th to the early 21st century. *Surv. Geophys.*, **32**, 585–602.

Church, J. A., J. M. Gregory, N. J. White, S. M. Platten, and J. X. Mitrovica, 2011: Understanding and projecting sea level change. *Oceanography*, **24**, 130–143.

Cleveland, W. S., 1979: Robust locally weighted regression and smoothing scatterplots. *J. Am. Stat. Assoc.*, **74**, 829–836.

Collins, M., and M. R. Allen, 2002: Assessing the relative roles of initial and boundary conditions in interannual to decadal climate predictability. *J. Clim.*, **15**, 3104–3109.

Covey, C., et al., 2003: An overview of results from the Coupled Model Intercomparison Project. *Global Planet. Change*, **37**, 103–133.

Cubasch, U., et al., 2001: Projections of future climate change. In: *Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change* [J. T. Houghton, Y. Ding, D. J. Griggs, M. Noquer, P. J. van der Linden, X. Dai, K. Maskell and C. A. Johnson (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 527–582.

Dee, D. P., et al., 2011: The ERA-Interim reanalysis: Configuration and performance of the data assimilation system. *Q. J. R. Meteorol. Soc.*, **137**, 553–597.

Denman, K. L., et al., 2007: Couplings between changes in the climate system and biogeochemistry. In: *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M. Tignor and H. L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 501–587.

Dlugokencky, E. J., et al., 2009: Observational constraints on recent increases in the atmospheric CH_4 burden. *Geophys. Res. Lett.*, **36**, L18803.

Duarte, C. M., T. M. Lenton, P. Wadhams, and P. Wassmann, 2012: Commentary: Abrupt climate change in the Arctic. *Nature Clim. Change*, **2**, 60–62.

Easterling, D. R., and M. F. Wehner, 2009: Is the climate warming or cooling? *Geophys. Res. Lett.*, **36**, L08706.

Elkins, J., and G. Dutton, 2010: Nitrous oxide and sulfur hexaflouride. Section in State of the Climate in 2009. *Bull. Am. Meteorol. Soc.*, **91**, 44–45.

Ettema, J., M. R. van den Broeke, E. van Meijgaard, W. J. van de Berg, J. L. Bamber, J. E. Box, and R. C. Bales, 2009: Higher surface mass balance of the Greenland ice sheet revealed by high-resolution climate modeling. *Geophys. Res. Lett.*, **36**, L12501.

Foley, J., et al., 2005: Global consequences of land use. *Science*, **309**, 570–574.

Folland, C. K., et al., 2001: Observed climate variability and change. In: *Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change* [J. T. Houghton, Y. Ding, D. J. Griggs, M. Noquer, P. J. van der Linden, X. Dai, K. Maskell and C. A. Johnson (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 101–181.

Forest, C. E., P. H. Stone, and A. P. Sokolov, 2008: Constraining climate model parameters from observed 20th century changes. *Tellus A*, **60**, 911–920.

Forster, P., et al., 2007: Changes in atmospheric constituents and in radiative forcing. In: *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M. Tignor and H. L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 131–234.

Frame, D. J., and D. A. Stone, 2013: Assessment of the first consensus prediction on climate change. *Nature Clim. Change*, **3**, 357–359.

Frame, D. J., D. A. Stone, P. A. Stott, and M. R. Allen, 2006: Alternatives to stabilization scenarios. *Geophys. Res. Lett.*, **33**.

Fujino, J., R. Nair, M. Kainuma, T. Masui, and Y. Matsuoka, 2006: Multi-gas mitigation analysis on stabilization scenarios using aim global model. *Energy J.*, **0**, 343–353.

GCOS, 2009: Progress Report on the Implementation of the Global Observing System for Climate in Support of the UNFCCC 2004–2008, GCOS-129 (WMO/TD-No. 1489; GOOS-173; GTOS-70) , Geneva, Switzerland.

GCOS , 2011: Systematic Observation Requirements for Satellite-based Products for Climate Supplemental details to the satellite-based component of the Implementation Plan for the Global Observing System for Climate in Support of the UNFCCC – 2011 Update, (GCOS-154) – December 2011, Geneva, Switzerland.

Goosse, H., W. Lefebvre, A. de Montety, E. Crespin, and A. H. Orsi, 2009: Consistent past half-century trends in the atmosphere, the sea ice and the ocean at high southern latitudes. *Clim. Dyn.*, **33**, 999–1016.

Granier, C., et al., 2011: Evolution of anthropogenic and biomass burning emissions of air pollutants at global and regional scales during the 1980–2010 period. *Clim. Change*, **109**, 163–190.

Haas, C., A. Pfaffling, S. Hendricks, L. Rabenstein, J. L. Etienne, and I. Rigor, 2008: Reduced ice thickness in Arctic Transpolar Drift favors rapid ice retreat. *Geophys. Res. Lett.*, **35**, L17501.

Hansen, J., D. Johnson, A. Lacis, S. Lebedeff, P. Lee, D. Rind, and G. Russell, 1981: Climate impact of increasing atmospheric carbon dioxide. *Science*, **213**, 957–966.

Hansen, J., M. Sato, R. Ruedy, K. Lo, D. W. Lea, and M. Medina-Elizade, 2006: Global temperature change. *Proc. Natl. Acad. Sci. U.S.A.*, **103**, 14288–14293.

Hansen, J., R. Ruedy, M. Sato, and K. Lo, 2010: Global surface temperature change. *Rev. Geophys.*, **48**, RG4004.

Hansen, J., M. Sato, P. Kharecha, and K. von Schuckmann, 2011: Earth's energy imbalance and implications. *Atmos. Chem. Phys.*, **11**, 13421–13449.

Hawkins, E., and R. Sutton, 2009: The potential to narrow uncertainty in regional climate predictions. *Bull. Am. Meteorol. Soc.*, **90**, 1095–1107.

Hawkins, E., and R. Sutton, 2011: The potential to narrow uncertainty in projections of regional precipitation change. *Clim. Dyn.*, **37**, 407–418.

Hegerl, G. C., et al., 2007: Understanding and attributing climate change. In: *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M. Tignor and H. L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 665–745.

Hijioka, Y., Y. Matsuoka, H. Nishomoto, M. Masui, and M. Kainuma, 2008: Global GHG emission scenarios under GHG concentration stabilization targets. *JGEE*, **13**, 97–108.

Hoelzle, M., G. Darms, M. P. Lüthi, and S. Suter, 2011: Evidence of accelerated englacial warming in the Monte Rosa area, Switzerland/Italy. *Cryosphere*, **5**, 231–243.

Houghton, R., 2003: Revised estimates of the annual net flux of carbon to the atmosphere from changes in land use and land management 1850–2000. *Tellus B*, **55**, 378–390.

Huntingford, C., J. Lowe, B. Booth, C. Jones, G. Harris, L. Gohar, and P. Meir, 2009: Contributions of carbon cycle uncertainty to future climate projection spread. *Tellus B*, doi:10.1111/j.1600–0889.2009.00414.x, 355–360.

Hurtt, G. C., et al., 2011: Harmonization of land-use scenarios for the period 1500–2100: 600 years of global gridded annual land-use transitions, wood harvest, and resulting secondary lands. *Clim. Change*, **109**, 117–161.

InterAcademy Council, 2010: Climate change assessments. In: *Review of the Processes and Procedures of the IPCC*, Amsterdam, The Netherlands.

IPCC, 1990: *Climate Change: The IPCC Scientific Assessment* [J. T. Houghton, G. J. Jenkins and J. J. Ephraums (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 212 pp.

IPCC , 1996: *Climate Change 1995: The Science of Climate Change. Contribution of Working Group I to the Second Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 584 pp.

IPCC , 2000: IPCC Special Report on Emissions Scenarios. Prepared by Working Group III of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambrudge, United Kingdom, pp 570.

IPCC , 2001: *Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change* [J. T. Houghton, Y. Ding, D. J. Griggs, M. Noquer, P. J. van der Linden, X. Dai, K. Maskell and C. A. Johnson (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 881 pp.

IPCC , 2007: *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC)* [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M. Tignor and H. L. Miller (eds.)]. Cambridge University Press, 996 pp.

IPCC , 2012a: Procedures for the preparation, review, acceptance, adoption, approval and publication of IPCC reports. Appendix A to the Principles Governing IPCC Work, Geneva, Switzerland, 6-9 June 2012, 29 pp.

IPCC , 2012b: *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. Special Report of the Intergovernmental Panel on Climate Change*. [Field, C. B., V. Barros, T. F. Stocker, D. Qin, D. J. Dokken, K. L. Ebi, M. D. Mastrandrea, K. J. Mach, G.-K. Plattner, S. K. Allen, M. Tignor, and P. M. Midgley (Eds.)]. Cambridge University Press, Cambridge, United Kingdom, 582 pp.

JCGM, 2008: JCGM 100: 2008. GUM 1995 with minor corrections. Evaluation of measurement data—Guide to the expression of uncertainty in measurement. Joint Committee for Guides in Metrology.

Jevrejeva, S., J. C. Moore, A. Grinsted, and P. L. Woodworth, 2008: Recent global sea level acceleration started over 200 years ago? *Geophys. Res. Lett.*, **35**, L08715.

Kahneman, D., and A. Tversky, 1979: Prospect theory: An analysis of decision under risk. *Econometrica*, **47**, 263–291.

Kahneman, D., P. Slovic, and A. Tversky, Eds., 1982: *Judgment under Uncertainty: Heuristics and Biases*. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 544 pp.

Kandlikar, M., J. Risbey, and S. Dessai, 2005: Representing and communicating deep uncertainty in climate-change assessments. *C. R. Geosci.*, **337**, 443–455.

Knutti, R., F. Joos, S. A. Müller, G. K. Plattner, and T. F. Stocker, 2005: Probabilistic climate change projections for CO_2 stabilization profiles. *Geophys. Res. Lett.*, **32**, L20707.

Knutti, R., et al., 2008: A review of uncertainties in global temperature projections over the twenty-first century. *J. Clim.*, **21**, 2651–2663.

Kopp, G., and J. L. Lean, 2011: A new, lower value of total solar irradiance: Evidence and climate significance. *Geophys. Res. Lett.*, **38**, L01706.

Kwok, R., G. F. Cunningham, M. Wensnahan, I. Rigor, H. J. Zwally, and D. Yi, 2009: Thinning and volume loss of the Arctic Ocean sea ice cover: 2003–2008. *J. Geophys. Res. Oceans*, **114**, C07005.

Lamarque, J. F., et al., 2011: Global and regional evolution of short-lived radiatively-active gases and aerosols in the Representative Concentration Pathways. *Clim. Change*, **109**, 191–212.

Lambert, F., et al., 2008: Dust-climate couplings over the past 800,000 years from the EPICA Dome C ice core. *Nature*, **452**, 616–619.

Lemke, P., et al., 2007: Observations: Changes in snow, ice and frozen ground. In: *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M. Tignor and H. L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 339–383.

Lenton, T., H. Held, E. Kriegler, J. Hall, W. Lucht, S. Rahmstorf, and H. Schellnhuber, 2008: Tipping elements in the Earth's climate system. *Proc. Natl. Acad. Sci.U.S.A.*, **105**, 1786–1793.

Le Treut, H., et al., 2007: Historical Overview of Climate Change. In: *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M. Tignor and H. L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 94–127.

Lüthi, M., and M. Funk, 2001: Modelling heat flow in a cold, high-altitude glacier: Interpretation of measurements from Colle Gnifetti, Swiss Alps. *J. Glaciol.*, **47**, 314–324.

Lüthi, D., et al., 2008: High-resolution carbon dioxide concentration record 650,000–800,000 years before present. *Nature*, **453**, 379–382.

Mann, M., Z. Zhang, M. Hughes, R. Bradley, S. Miller, S. Rutherford, and F. Ni, 2008: Proxy-based reconstructions of hemispheric and global surface temperature variations over the past two millennia. *Proc. Natl. Acad. Sci. U.S.A.*, **105**, 13252–13257.

Manning, M., et al., 2004: *IPCC workshop Report: Describing scientific uncertainties in climate change to support analysis of risk and of options* [IPCC IPCC Working Group I Technical Support Unit (ed.)]. Available at http://www.ipcc.ch/ (accessed 07-10-2013), 138.

Masson, D., and R. Knutti, 2011: Climate model genealogy. *Geophys. Res. Lett.*, **38**, L08703.

Mastrandrea, M. D., et al., 2010: Guidance notes for lead authors of the IPCC Fifth Assessment Report on Consistent Treatment of Uncertainties. Available at http://www.ipcc.ch (accessed 07-10-2013).

Masui, T., et al., 2011: An emission pathway for stabilization at 6 Wm^{-2} radiative forcing. *Clim. Change*, **109**, 59–76.

Matthews, H. D., and A. J. Weaver, 2010: Committed climate warming. *Nature Geosci.*, **3**, 142–143.

Meehl, G. A., et al., 2007: Global climate projections. In: *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M. Tignor and H. L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 749–845.

Meinshausen, M., et al., 2011: The RCP greenhouse gas concentrations and their extensions from 1765 to 2300. *Clim. Change*, **109**, 213–241.

Menne, M. J., I. Durre, R. S. Vose, B. E. Gleason, and T. G. Houston, 2012: An overview of the Global Historical Climatology Network-Daily Database. *J. Atmos. Ocean. Technol.*, **29**, 897–910.

Mernild, S. H., G. E. Liston, C. A. Hiemstra, K. Steffen, E. Hanna, and J. H. Christensen, 2009: Greenland ice sheet surface mass-balance modelling and freshwater flux for 2007, and in a 1995–2007 perspective. *Hydrol. Proc,*, **23**, 2470–2484.

Midorikawa, T., et al., 2010: Decreasing pH trend estimated from 25-yr time series of carbonate parameters in the western North Pacific. *Tellus B*, **62**, 649–659.

Morgan, M. G., M. Henrion, and M. Small, 1990: *Uncertainty: A Guide to Dealing with Uncertainty in Quantitative Risk and Policy Analysis.* Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 332 pp.

Morice, C. P., J. J. Kennedy, N. A. Rayner, and P. D. Jones, 2012: Quantifying uncertainties in global and regional temperature change using an ensemble of observational estimates: The HadCRUT4 data set. *J. Geophys. Res. Atmos.*, **117**, D08101.

Moss, R. H., and S. H. Schneider, 2000: Uncertainties in the IPCC TAR: Recommendations to lead authors for more consistent assessment and reporting. In: *Guidance Papers on the Cross Cutting Issues of the Third Assessment Report of the IPCC*. World Meteorological Organization, Geneva, pp. 33–51.

Moss, R., et al., 2008: *Towards New Scenarios for Analysis of Emissions, Climate Change, Impacts, and Response Strategies*. Geneva, Intergovernmental Panel on Climate Change, 132 pp.

Moss, R., et al., 2010: The next generation of scenarios for climate change research and assessment. *Nature*, **463**, 747–756.

Murphy, D., S. Solomon, R. Portmann, K. Rosenlof, P. Forster, and T. Wong, 2009: An observationally based energy balance for the Earth since 1950. *J. Geophys. Res. Atmos.*, **114**, D17107.

Myhre, G., E. Highwood, K. Shine, and F. Stordal, 1998: New estimates of radiative forcing due to well mixed greenhouse gases. *Geophys. Res. Lett.*, **25**, 2715–2718.

Nghiem, S. V., et al., 2012: The extreme melt across the Greenland ice sheet in 2012. *Geophys. Res. Lett.*, **39**, L20502.

Oreskes, N., K. Shrader-Frechette, and K. Belitz, 1994: Verification, validation, and confirmation of numerical models in the earth sciences. *Science*, 263, 641–646.

Pall, P., et al., 2011: Anthropogenic greenhouse gas contribution to flood risk in England and Wales in autumn 2000. *Nature*, **470**, 382–385.

Patt, A. G., and D. P. Schrag, 2003: Using specific language to describe risk and probability. *Clim. Change*, 61, 17–30.

Patt, A. G., and S. Dessai, 2005: Communicating uncertainty: Lessons learned and suggestions for climate change assessment. *C. R. Geosci.*, **337**, 425–441.

Pennell, C., and T. Reichler, 2011: On the effective number of climate models. *J. Clim.*, **24**, 2358–2367.

Peterson, T. C., P. A. Stott, and S. Herring, 2012: Explaining extreme events of 2011 from a climate perspective. *Bull. Am. Meteorol. Soc.*, **93**, 1041–1067.

Peterson, T. C., et al., 2008: Why weather and climate extremes matter. In: *Weather and Climate Extremes in a Changing Climate. Regions of Focus: North America, Hawaii, Caribbean, and U.S. Pacific Islands*, [Karl, T. R., G. A. Meehl, C. D. Miller, S. J. Hassol, A. M. Waple, and W. L. Murray (eds.)]. A Report by the U.S.Climate Change Science Program and the Subcommittee on Global Change Research, Washington, DC., USA, 11–33.

Rahmstorf, S., G. Foster, and A. Cazenave, 2012: Comparing climate projections to observations up to 2011. *Environ. Res. Lett.*, **7**, 044035.

Ray, R. D., and B. C. Douglas, 2011: Experiments in reconstructing twentieth-century sea levels. *Prog. Oceanogr.*, **91**, 496–515.

Riahi, K., A. Grübler, and N. Nakicenovic, 2007: Scenarios of long-term socio-economic and environmental development under climate stabilization. *Technol. ForecastSoc Change*, **74**, 887–935.

Riahi, K., et al., 2011: RCP 8.5–A scenario of comparatively high greenhouse gas emissions. *Clim. Change*, **109**, 33–57.

Risbey, J. S., and M. Kandlikar, 2007: Expressions of likelihood and confidence in the IPCC uncertainty assessment process. *Clim. Change*, **85**, 19–31.

Schimel, D., et al., 1996: Radiative forcing of climate change. In: *Climate Change 1995: The Science of Climate Change, Contribution of Working Group I to the Second Assessment Report of the Intergovernmental Panel on Climate Change* [J. T. Houghton, L. G. Meiro Filho, B. A. Callander, N. Harris, A. Kattenburg and K. Maskell (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 69–131.

Scott, J. T. B., G. H. Gudmundsson, A. M. Smith, R. G. Bingham, H. D. Pritchard, and D. G. Vaughan, 2009: Increased rate of acceleration on Pine Island Glacier strongly coupled to changes in gravitational driving stress. *The Cryosphere*, **3**, 125–131.

Seneviratne, S., et al., 2010: Investigating soil moisture-climate interactions in a changing climate: A review. *Earth-Sci. Rev.*, **99**, 125–161.

Seneviratne, S. I., et al., 2012: Chapter 3: Changes in climate extremes and their Impacts on the Natural Physical Environment. In: *SREX: Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation* [C. B. Field, et al. (eds.]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp.109–230.

Smith, S., and T. Wigley, 2006: Multi-gas forcing stabilization with Minicam. *Energy J.*, 373–391.

Smith, T. M., R. W. Reynolds, T. C. Peterson, and J. Lawrimore, 2008: Improvements to NOAA's historical merged land-ocean surface temperature analysis (1880–2005). *J. Clim.*, **21**, 2283–2296.

Steinhilber, F., J. Beer, and C. Fröhlich, 2009: Total solar irradiance during the Holocene. *Geophys. Res. Lett.*, **36**, L19704.

SWIPA, 2011: Snow, water, ice and permafrost in the Arctic. SWIPA 2011 Executive Summary. AMAP, Oslo, Norway, 16 pp.

Taylor, K. E., R. J. Stouffer, and G. A. Meehl, 2012: An overview of CMIP5 and the experiment design. *Bull. Am. Meteorol. Soc.*, **93**, 485–498.

Tedesco, M., 2007: A new record in 2007 for melting in Greenland. *EOS, Trans. Am. Geophys. Union*, **88**, 383.

Thomson, A. M., et al., 2011: RCP4.5: A pathway for stabilization of radiative forcing by 2100. *Clim. Change*, **109**, 77–94.

Tietsche, S., D. Notz, J. H. Jungclaus, and J. Marotzke, 2011: Recovery mechanisms of Arctic summer sea ice. *Geophys. Res. Lett.*, **38**, L02707.

Trenberth, K. E., J. T. Fasullo, and J. Kiehl, 2009: Earth's global energy budget. *Bull. Am. Meteorol. Soc.*, **90**, 311–323.

Turner, J., and J. E. Overland, 2009: Contrasting climate change in the two polar regions. *Polar Res.*, **28**, 146–164.

Turner, J., et al., 2009: Antarctic Climate Change and the environment. Scientific Committee on Antarctic Research, Cambridge, United Kingdom, 526 pp.

van Vuuren, D., et al., 2007: Stabilizing greenhouse gas concentrations at low levels: An assessment of reduction strategies and costs. *Clim. Change*, **81**, 119–159.

van Vuuren, D. P., et al., 2011a: RCP2.6: Exploring the possibility to keep global mean temperature increase below 2°C. *Clim. Change*, **109**, 95–116.

van Vuuren, D. P., et al., 2011b: The representative concentration pathways: An overview. *Clim. Change*, **109**, 5–31.

Wadhams, P., 2012: Arctic ice cover, ice thickness and tipping points. *Ambio*, **41**, 23–33.

Warrick, R., and J. Oerlemans, 1990: Sea level rise. In: *Climate Change: The IPCC Scientific Assessment* [J. T. Houghton, G. J. Jenkins and J. J. Ephraums (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 261–281.

Wigley, T. M. L., 2005: The climate change commitment. *Science*, 307, 1766–1769.

Willis, J. K., J. M. Lyman, G. C. Johnson, and J. Gilson, 2009: In situ data biases and recent ocean heat content variability. *J. Atmos. Ocean. Technol.*, **26**, 846–852.

Willis, J., D. Chambers, C. Kuo, and C. Shum, 2010: Global sea level rise recent progress and challenges for the decade to come. *Oceanography*, **23**, 26–35.

Wise, M., et al., 2009: Implications of limiting CO_2 concentrations for land use and energy. *Science*, **324**, 1183–1186.

Yip, S., C. A. T. Ferro, D. B. Stephenson, and E. Hawkins, 2011: A simple, coherent framework for partitioning uncertainty in climate predictions. *J. Climate*, **24**, 4634–4643.

Zemp, M., I. Roer, A. Kääb, M. Hoelzle, F. Paul, and W. Haeberli, 2008: Global glacier changes: Facts and figures. United Nations Environment Programme and World Glacier Monitoring Service, 88 pp.

Zemp, M., M. Hoelzle, and W. Haeberli, 2009: Six decades of glacier mass-balance observations: A review of the worldwide monitoring network. *Ann. Glaciol.*, **50**, 101–111.

Zhang, X., and F. Zwiers, 2012: Statistical indices for the diagnosing and detecting changes in extremes. In: *Extremes in a Changing Climate: Detection, Analysis and Uncertainty* [A. AghaKouchak, D. Easterling, K. Hsu, S. Schubert, and S. Sorooshian (eds.)]. Springer Science+Business Media, Heidelberg, Germany and New York, NY, USA, 1–14.

Appendix 1.A: Notes and Technical Details on Figures Displayed in Chapter 1

Figure 1.4: Documentation of Data Sources

Observed Temperature

NASA GISS evaluation of the observations: Hansen et al. (2010) updated: The data were downloaded from http://data.giss.nasa.gov/gistemp/tabledata_v3/GLB.Ts+dSST.txt. Annual means are used (January to December) and anomalies are calculated relative to 1961–1990.

NOAA NCDC evaluation of the observations: Smith et al. (2008) updated: The data were downloaded from ftp://ftp.ncdc.noaa.gov/pub/data/anomalies/annual.land_ocean.90S.90N.df_1901–2000mean.dat. Annual mean anomalies are calculated relative to 1961–1990.

Hadley Centre evaluation of the observations: Morice et al. (2012): The data were downloaded from http://www.metoffice.gov.uk/hadobs/hadcrut4/data/current/download.html#regional_series. Annual mean anomalies are calculated relative to 1961–1990 based on the ensemble median.

IPCC Range of Projections

Table 1.A.1 | FAR: The data have been digitized using a graphics tool from FAR Chapter 6, Figure 6.11 (Bretherton et al., 1990) in 5-year increments as anomalies relative to 1990 (°C).

Year	Lower Bound (Scenario D)	Upper Bound (Business as Usual)
1990	0.00	0.00
1995	0.09	0.14
2000	0.15	0.30
2005	0.23	0.53
2010	0.28	0.72
2015	0.33	0.91
2020	0.39	1.11
2025	0.45	1.34
2030	0.52	1.58
2035	0.58	1.86

Table 1.A.2 | SAR: The data have been digitized using a graphics tool from Figure 19 of the TS (IPCC, 1996) in 5-year increments as anomalies relative to 1990. The scenarios include changes in aerosols beyond 1990 (°C).

Year	Lower Bound (IS92c/1.5)	Upper Bound (IS92e/4.5)
1990	0.00	0.00
1995	0.05	0.09
2000	0.11	0.17
2005	0.16	0.28
2010	0.19	0.38
2015	0.23	0.47
2020	0.27	0.57
2025	0.31	0.67
2030	0.36	0.79
2035	0.41	0.92

Table 1.A.3 | TAR: The data have been digitized using a graphics tool from Figure 9.13(b) (Cubasch et al., 2001) in 5-year increments based on the GFDL_R15_a and DOE PCM parameter settings (°C).

Year	Lower Bound	Upper Bound
1990	0.00	0.00
1995	0.05	0.09
2000	0.11	0.20
2005	0.14	0.34
2010	0.17	0.52
2015	0.22	0.70
2020	0.28	0.87
2025	0.37	1.08
2030	0.43	1.28
2035	0.52	1.50

AR4: The temperature projections of the AR4 are presented for three SRES scenarios: B1, A1B and A2. Annual mean anomalies relative to 1961–1990 of the individual CMIP3 ensemble simulations (as used in AR4 SPM Figure SPM5) are shown. One outlier has been eliminated based on the advice of the model developers because of the model drift that leads to an unrealistic temperature evolution. As assessed by Meehl et al. (2007), the *likely* range for the temperature change is given by the ensemble mean temperature change +60% and –40% of the ensemble mean temperature change. Note that in the AR4 the uncertainty range was explicitly estimated for the end of the 21st century results. Here, it is shown for 2035. The time dependence of this range has been assessed in Knutti et al. (2008). The relative uncertainty is approximately constant over time in all estimates from different sources, except for the very early decades when natural variability is being considered (see Figure 3 in Knutti et al., 2008).

Data Processing

Observations

The observations are shown from 1950 to 2012 as annual mean anomaly relative to 1961–1990 (squares). For smoothing, first, the trend of each of the observational data sets was calculated by locally weighted scatter plot smoothing (Cleveland, 1979; f = 1/3). Then, the 11-year running means of the residuals were determined with reflected ends for the last 5 years. Finally, the trend was added back to the 11-year running means of the residuals.

Projections

For FAR, SAR and TAR, the projections have been harmonized to match the average of the three smoothed observational data sets at 1990.

Figure 1.5: Documentation of Data Sources

Observed CO_2 Concentrations

Global annual mean CO_2 concentrations are presented as annual mean values from Annex II Table AII.1.1a.

IPCC Range of Projections

Table 1.A.4 | FAR: The data have been digitized using a graphics tool from Figure A.3 (Annex, IPCC, 1990) as anomalies compared to 1990 in 5-year increments (ppm) and the observed 1990 value (353.6) has been added.

Year	Lower Bound (Scenario D)	Upper Bound (Business as Usual)
1990	353.6	353.6
1995	362.8	363.7
2000	370.6	373.3
2005	376.5	386.5
2010	383.2	401.5
2015	390.2	414.3
2020	396.6	428.8
2025	401.5	442.0
2030	406.0	460.7
2035	410.0	480.3

Table 1.A.5 | SAR: The data have been digitized using a graphics tool from Figure 5b in the TS (IPCC, 1996) in 5-year increments (ppm) as anomalies compared to 1990 and the observed 1990 value (353.6) has been added.

Year	Lower Bound (IS92c)	Upper Bound (IS92e)
1990	353.6	353.6
1995	358.4	359.0
2000	366.8	369.2
2005	373.7	380.4
2010	382.3	392.9
2015	391.4	408.0
2020	400.7	423.0
2025	408.0	439.6
2030	416.9	457.7
2035	424.5	477.7

TAR: The data were taken in 10-year increments from table Appendix II (IPCC, 2001) SRES Data Tables Table II.2.1 (ISAM model high and low setting). The scenarios that give the upper bound or lower bound respectively vary over time.

AR4: The data used was obtained from Figure 10.26 in Chapter 10 of AR4 (Meehl et al., 2007, provided by Malte Meinshausen). Annual means are used.

Data Processing

The projections have been harmonized to start from the observed value in 1990.

Figure 1.6: Documentation of Data Sources

Observed CH_4 Concentrations

Global annual mean CH_4 concentrations are presented as annual mean values from Annex II Table AII.1.1a.

IPCC Range of Projections

Table 1.A.6 | FAR: The data have been digitized using a graphics tool from FAR SPM Figure 5 (IPCC, 1990) in 5-year increments (ppb) as anomalies compared to 1990 the observed 1990 value (1714.4) has been added.

Year	Lower Bound (Scenario D)	Upper Bound (Business as Usual)
1990	1714.4	1714.4
1995	1775.7	1816.7
2000	1809.7	1938.7
2005	1819.0	2063.8
2010	1823.1	2191.1
2015	1832.3	2314.1
2020	1847.7	2441.3
2025	1857.9	2562.3
2030	1835.3	2691.6
2035	1819.0	2818.8

SAR: The data were taken in 5-year increments from Table 2.5a (Schimel et al., 1996). The scenarios that give the upper bound or lower bound respectively vary over time.

TAR: The data were taken in 10-year increments from Appendix II SRES Data Tables Table II.2.2 (IPCC, 2001). The upper bound is given by the A1p scenario, the lower bound by the B1p scenario.

AR4: The data used was obtained from Figure 10.26 in Chapter 10 of AR4 (Meehl et al., 2007, provided by Malte Meinshausen). Annual means are used.

Data Processing

The observations are shown as annual means. The projections have been harmonized to start from the same value in 1990.

Figure 1.7: Documentation of Data Sources

Observed N_2O Concentrations

Global annual mean N_2O concentrations are presented as annual mean values from Annex II Table AII.1.1a.

IPCC Range of Projections

Table 1.A.7: FAR | The data have been digitized using a graphics tool from FAR A.3 (Annex, IPCC, 1990) in 5-year increments (ppb) as anomalies compared to 1990 and the observed 1990 value (308.7) has been added.

Year	Lower Bound (Scenario D)	Upper Bound (Business as Usual)
1990	308.7	308.7
1995	311.7	313.2
2000	315.4	317.7
2005	318.8	322.9
2010	322.1	328.0
2015	325.2	333.0
2020	328.2	337.9
2025	331.7	343.0
2030	334.0	348.9
2035	336.1	354.1

SAR: The data were taken in 5-year increments from Table 2.5b (Schimel et al., 1996). The upper bound is given by the IS92e and IS92f scenario, the lower bound by the IS92d scenario.

TAR: The data were taken in 10-year increments from Appendix II SRES Data Tables Table II.2.3 (IPCC, 2001). The upper bound is given by the A1FI scenario, the lower bound by the B2 and A1T scenario.

AR4: The data used was obtained from Figure 10.26 in Chapter 10 of AR4 (Meehl et al., 2007, provided by Malte Meinshausen). Annual means are used.

Data Processing

The observations are shown as annual means. No smoothing is applied. The projections have been harmonized to start from the same value in 1990.

Figure 1.10: Documentation of Data Sources

Observed Global Mean Sea Level Rise

Three data sets based on tide gauge measurements are presented: Church and White (2011), Jevrejeva et al. (2008), and Ray and Douglas (2011). Annual mean anomalies are calculated relative to 1961–1990.

Estimates based on sea surface altimetry are presented as the ensemble mean of five different data sets (Section 3.7, Figure 3.13, Section 13.2, Figure 13.3) from 1993 to 2012. Annual means have been calculated. The data are harmonized to start from the mean of the three tide gauge based estimates (see above) at 1993.

IPCC Range of Projections

Table 1.A.8 | FAR: The data have been digitized using a graphics tool from Chapter 9, Figure 9.6 for the upper bound and Figure 9.7 for the lower bound (Warrick and Oerlemans, 1990) in 5-year increments as anomalies relative to 1990 (cm) and the observed anomaly relative to 1961–1990 (2.0 cm) has been added.

Year	Lower Bound (Scenario D)	Upper Bound (Business as Usual)
1990	2.0	2.0
1995	2.7	5.0
2000	3.7	7.9
2005	4.6	11.3
2010	5.5	15.0
2015	6.3	18.7
2020	6.9	22.8
2025	7.7	26.7
2030	8.4	30.9
2035	9.2	35.4

Table 1.A.9 | SAR: The data have been digitized using a graphics tool from Figure 21 (TS, IPCC, 1996) in 5-year increments as anomalies relative to 1990 (cm) and the observed anomaly relative to 1961–1990 (2.0 cm) has been added.

Year	Lower Bound (IS92c/1.5)	Upper Bound (IS92e/4.5)
1990	2.0	2.0
1995	2.4	4.3
2000	2.7	6.5
2005	3.1	9.0
2010	3.4	11.7
2015	3.8	14.9
2020	4.4	18.3
2025	5.1	21.8
2030	5.7	25.4
2035	6.4	29.2

TAR: The data are given in Table II.5.1 in 10-year increments. They are harmonized to start from mean of the observed anomaly relative to 1961–1990 at 1990 (2.0 cm).

AR4: The AR4 did not give a time-dependent estimate of sea level rise. These analyses have been conducted post AR4 by Church et al. (2011) based on the CMIP3 model results that were available at the time of AR4. Here, the SRES B1, A1B and A2 scenarios are shown from Church et al. (2011). The data start in 2001 and are given as anomalies with respect to 1990. They are displayed from 2001 to 2035, but the anomalies are harmonized to start from mean of the observed anomaly relative to 1961–1990 at 1990 (2.0 cm).

Data Processing

The observations are shown from 1950 to 2012 as the annual mean anomaly relative to 1961–1990 (squares) and smoothed (solid lines). For smoothing, first, the trend of each of the observational data sets was calculated by locally weighted scatterplot smoothing (Cleveland, 1979; f = 1/3). Then, the 11-year running means of the residuals were determined with reflected ends for the last 5 years. Finally, the trend was added back to the 11-year running means of the residuals.