Chapter 1: Introduction

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Executive Summary

Since the Fourth Assessment Report (AR4) of the IPCC, the scientific knowledge derived from observations, theoretical evidence, and modelling studies has continued to increase and to further strengthen the basis for human activities being the primary driver in climate change. At the same time, the capabilities of the observational and modelling tools have continued to improve.

As concluded in prior assessments, human activities are affecting the Earth's energy budget by changing the atmospheric concentrations of radiatively important gases and aerosols and by changing land surface properties. Multiple lines of evidence show 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, ocean and cryosphere systems. Incontrovertible evidence from in situ observations and ice core records shows that the atmospheric concentrations of important greenhouse gases such as carbon dioxide, methane, and nitrous oxides have increased over the last 200 years. Global mean atmospheric temperatures over land and oceans have increased over the last 100 years. The temperature measurements show a continuing increase in the heat content of the oceans, and analyses based on measurements of Earth's radiative budget suggest a small positive energy imbalance that serves to increase global heat content. Observations from satellites and in situ observations show a trend of significant reductions in most glaciers, in sea ice, and in ice sheets (especially in the Arctic region). Palaeoclimatic reconstructions have helped place ongoing climate change in the perspective of natural climate variability.

In the last few decades, new observational systems, especially satellite-based systems, have increased the number of observations 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 historical climate changes. At the same time, increases in computing speed and memory have led to the development of more sophisticated models which describe physical and chemical processes in greater detail. Finally, modelling strategies have been extended to provide estimates of the uncertainty in climate change projections.

The Earth's climate system is characterized by multiple spatial and temporal scales. Consequently, uncertainties are usually resolved at a variety of rates over multiple time scales rather than at a single, predictable rate: new observations may reduce the uncertainties surrounding short timescale processes quite rapidly, whereas processes that occur over longer time scales may require very long observational baselines before much progress can be made. 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., mechanistic understanding, theory, data, expert judgment) and the degree of agreement; and, (2) Likelihoods provide a quantified measures of uncertainty in a finding expressed probabilistically (based on statistical analysis of observations or model results, or on expert judgment).

Each IPCC assessment has provided new computer model projections of future climate change that have become more detailed as the models have become more advanced. The range of climate projections from the first IPCC assessment in 1990 to those in the 2007 AR4 provides an opportunity to compare the timespan of projections with the actually observed changes, thereby examining the capabilities of the projections over time. Globally-averaged temperature observations and carbon dioxide (CO_2) concentrations are generally well within the uncertainty range of the previous extent of the earlier IPCC projections. Observed methane (CH_4) and nitrous oxide (N_2O) concentrations are closer to the lower limit of the projections from the prior assessments.

Overall, the many notable scientific advances and associated peer-reviewed publications that have appeared since AR4 form the basis for the scientific assessment given in Chapters 2 through 14.

1.1 Chapter Preview

Chapter 1 in the AR4 provided a historical perspective on the understanding of climate science and the evidence regarding a human influence on the Earth's climate system. Since the last assessment, the scientific knowledge gained through observations, theoretical evidence, and modelling studies has continued to increase and to further strengthen the evidence that human activities are the primary driver in the ongoing changes in climate. Rather than repeating the historical analysis, this introductory chapter instead serves as a lead-in to the science presented in the rest of the AR5 assessment. It focuses on the concepts and definitions set up in the discussion of new findings found 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. Finally, the chapter discusses the directions and capabilities of current climate science, while the detailed discussion of new findings is covered in the rest of the assessment. .

1.2 Rationale and Key Concepts of the WGI Contribution

1.2.1 Setting the Stage for the Assessment

In light of the importance and potential policy implications of climate change, the scientific community invests substantial resources on the periodic assessment of the most recent research, in order to convey to the wider community the evolving state of knowledge. As discussed in the Working Group II report of AR4, climate change has potentially significant implications for humans and ecosystems. The goal of the Working Group I contribution to the IPCC Fifth Assessment Report is to assess the current state of the physical science with respect to climate change. The report is not a discussion of all relevant papers, as would be included in a review, but rather presents an assessment of the current state of research results. As such it seeks to make sure the range of scientific views, as represented in the evaluation of the peer-reviewed literature, is considered in the assessment, and that the state of the science is concisely and accurately presented. A transparent review process ensures that appropriate views are included.

Scientific hypotheses are contingent, and are always subject to revision in the 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 institutions such as peer review. At conferences and in the processes 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 (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. At any point in time some of the uncertainty regarding the state of knowledge of climate change arises from choices over which reasonable minds may disagree. Examples include how best to evaluate climate models relative to observations, how best to evaluate potential sea-level rise, and how to evaluate the probabilistic projections of climate change. In many cases there may be no definitive resolution 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 (see Box 1.1 for key findings from earlier IPCC assessments). In order to assess areas of scientific controversy, careful review of the peer-reviewed literature is conducted and evaluated (see later section on topical issues from other chapters). Not all papers on a controversial point can be included in an assessment, but all views represented in the peer-reviewed literature are considered in the assessment process.

The Earth sciences study the processes that shape our environment. Some of these processes can be understood through ideal laboratory experiments, altering a single element and then tracing through the effects of that controlled change. However, in common with Astronomy, aspects of Biology and much of Social Sciences, the openness of environmental systems, in terms of our lack of control of the boundaries of the system, their spatially and temporal multi-scale character and the complexity of interactions within many environmental systems often hamper scientists' ability to definitively isolate causal links, and this in turn places important limits on the understanding of many of the inferences in the Earth sciences (e.g., Oreskes et al., 1994). However, there are many cases where scientists may be able to make inferences using statistical tools with considerable evidential support and with high degrees of confidence.

[START BOX 1.1 HERE]

Box 1.1: Historical Overview of Major Conclusions of Previous IPCC Assessment Reports

In **1990**, the **First IPCC Assessment Report** (FAR) came to the conclusions:
- There is a natural greenhouse effect that 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
- The rate of increase of global mean temperature during the next century is about 0.3°C per decade.
- Land surfaces warm more rapidly than the ocean, and high northern latitudes warm more than the global mean in winter.
- The global mean sea level rise of about 6 cm per decade over the next century.

In **1995**, the **Second IPCC Assessment Report** (SAR) confirmed these statements and added some new aspects:
- Anthropogenic aerosols tend to produce negative radiative forcing.
- The balance of evidence suggests a discernible human influence on global climate.

The **Third Assessment Report** (TAR) in **2001** led to the following further conclusions:
- The global average surface temperature has increased over the 20th century by about 0.6°C.
- The temperatures have risen during the past four decades in the lowest 8 kilometres of the atmosphere.
- Snow cover and ice extent have decreased.
- Global average sea level has risen and ocean heat content has increased.
- Changes have also occurred in other important aspects of climate.
- Some important aspects of climate appear not to have changed.
- Natural factors have made small contributions to radiative forcing over the past century.
- Confidence in the ability of models to project future climate has increased.

Based on a growing body of evidence the **Fourth Assessment Report** (AR4) in **2007** also concluded that:
- The understanding of anthropogenic warming and cooling influences on climate has improved since the TAR.
- Some aspects of climate have not been observed to change.
- Palaeoclimatic information supports the interpretation that the warmth of the last half century is unusual in at least the previous 1,300 years.
- Analysis of climate models together with constraints from observations enables an assessed likely range to be given for climate sensitivity for the first time and provides increased confidence in the understanding of the climate system response to radiative forcing.
- Continued greenhouse gas emissions at or above current rates would cause further warming and induce many changes in the global climate system during the 21st century that would very likely be larger than those observed during the 20th century.
- 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 due to the time scales associated with climate processes and feedbacks, even if greenhouse gas concentrations were to be stabilised.

[END BOX 1.1 HERE]

1.2.2 Key Concepts in Climate

Here we describe briefly some of the key concepts affecting the Earth's climate; these are summarized more comprehensively in earlier IPCC assessments (Baede et al., 2001). First of all, 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 the temperature, humidity, pressure, and the occurrence of thunderstorms or rain. On the other hand, climate refers to the mean and the variability in the state of weather events at that location, in addition to including the state of the land surface, ocean and cryosphere, occurring on decadal to centennial time scales. Climate also includes not just the mean conditions, but also the associated statistics, including those of extreme events, such as heat waves or sustained heavy precipitation. 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). The bulk 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 generally be in balance with outgoing radiation. Since the average temperature of the Earth's surface is about 15°C (288 K), black body radiation theory indicates that the majority of the outgoing energy flux from the Earth is in the infrared part of the spectrum. Of the incoming shortwave radiation (SWR), about half is absorbed by the Earth's surface. The fraction of SWR reflected back to space by gases and particles, clouds and by the Earth's surface (albedo) is approximately 30%, and about 20% is absorbed in the atmosphere. The longwave radiation (LWR) emitted from the Earth's surface is absorbed and largely reradiated by certain atmospheric constituents (water vapour, CO_2, CH_4, N_2O and other greenhouse gases (GHG)) and by clouds through absorption and emission processes, adding heat to the lower layers of the atmosphere and warming the surface (greenhouse effect, GHE). The dominant energy loss of the infrared radiation from the Earth is from higher layers of the troposphere. The Sun primarily provides its energy to the Earth in the tropics and the subtropics; this energy is then partially redistributed to middle and high latitudes. Energy fluxes in the form of ocean currents and atmospheric transport processes redistributes the energy.

Fluctuations 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 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} (see Chapter 8 for a detailed discussion on the TSI). Variations of a few tenths of a percent are common, e.g., during the approximately 11 year sunspot solar cycle (see Chapter 5 and Chapter 8 for further details). Changes in LWR can result from changes in the temperature of the Earth's surface or changes in the emission of long wave radiation from either the atmosphere or the Earth's surface. For the atmosphere, these changes in emissivity are predominately due to changes in cloud cover, in greenhouse gases, and in particle concentrations. The radiative energy budget of the Earth is largely in balance (Figure 1.1), but satellite measurements indicate a small imbalance in the radiative budget (Hansen et al., 2011; Trenberth et al., 2009). This imbalance appears to be largely caused by the ongoing changes in the atmospheric composition (Hansen et al., 2011; Murphy et al., 2009).

In addition to changing the atmospheric concentrations of gases and aerosols, humans are affecting the energy budget of the planet by changing the land surface properties and changing the water budget with redistributions between latent and sensible heat fluxes (Chapter 2, Chapter 7 and Chapter 8). Land use changes such as the conversion of forests to agriculture, change the characteristics of vegetation, including its colour, seasonal growth and carbon content (Foley et al., 2005; Houghton, 2003). For example, clearing and burning a forest to prepare agricultural land reduces carbon storage in vegetation, adding CO_2 to the atmosphere, and changes the reflectivity of the land, rates of evapotranspiration and longwave emissions (Figure 1.1). Changes in land use can alter the Earth's reflectivity (surface albedo) in the SWR. In addition, some aerosols increase atmospheric reflectivity, while others (e.g., particulate black carbon) are strong absorbers and also modify SWR. Indirectly, aerosols also affect cloud albedo, because many aerosols serve as cloud condensation nuclei (CCN) or ice nuclei. This means that changes in particle types and distribution can result in small but important changes in cloud albedo. Clouds play a critical role in climate, since they not only can increase albedo, thereby cooling the planet, but also are important for their warming effects through infrared radiative transfer. Whether the net effect of a cloud warms or cools the planet depends on the cloud type and characteristics, the cloud height, and the nature of the CCN population. Humans enhance the greenhouse effect directly by emitting greenhouse gases such as CO_2, CH_4, and N_2O (Figure 1.1). In addition, pollutants such as carbon monoxide (CO), volatile organic compounds (VOC), nitrogen oxides (NO_x) and sulfur dioxide (SO_2), which by themselves are negligible GHGs, have an indirect effect on the GHE by altering, through atmospheric chemical reactions, the abundance of important gases to LWR such as CH_4 and O_3, and/or by acting as precursors of secondary aerosols. Since anthropogenic emission sources simultaneously can emit some chemicals that affect climate and others that affect air pollution, including some that affect both, air pollution science and climate science are intrinsically linked.

Changes in the atmosphere, land, ocean and cryosphere - both natural and manmade - can perturb the Earth's radiation budget, producing a radiative forcing (RF) that affects climate. 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). RF is a measure of the net change in the energy balance in response to some external perturbation. In addition to the RF as used in previous assessments, Chapters 7 and 8 introduce a new concept, adjusted forcing (AF) that allows for rapid response in the climate system. AF is defined as the change in net irradiance at the top of the atmosphere after allowing for atmospheric and land temperatures, water vapour, clouds and land albedo to adjust, but with sea surface temperatures (SST) and sea ice cover unchanged

[INSERT FIGURE 1.1 HERE]

Figure 1.1: Main drivers of climate change. The energy balance between incoming solar shortwave radiation (SWR) and outgoing longwave radiation (LWR) is influenced by global climate "drivers". Natural fluctuations in solar output (solar cycles) can cause changes in the energy balance (incoming SWR). Human activity changes the emissions of gases and particles, which are involved in atmospheric chemical reactions, resulting in modified O_3 and aerosol amounts. O_3 and aerosols scatter and reflect SWR, changing the energy balance. Some aerosol particles act as cloud condensation nuclei (CCN) modifying the properties of cloud droplets. Since cloud interactions with SWR and LWR are large, small changes in the properties of clouds have important implications for the radiative budget. Anthropogenic changes in greenhouse gases (e.g., CO_2, CH_4, N_2O, O_3, CFCs, etc.) and large aerosols modify the LWR by absorbing outgoing LWR and reemitting less energy at a lower temperature. Surface albedo is changed by changes in vegetation or land surface cover, snow or ice cover and ocean colour. These changes are driven by natural seasonal and diurnal changes (e.g., snow cover), as well as human influence (e.g., changes in vegetation height).

Once a forcing is applied, the climate feedbacks describe how the climate system responds(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 which describes the process whereby an increase in surface temperature enhances water evaporation and increases the amount of water vapour present in the atmosphere. Water vapour is a powerful greenhouse gas: increasing it enhances the greenhouse effect and leads to further surface warming. Another example is the ice-albedo feedback, where the albedo decreases as highly reflective ice and snow surfaces melt. In addition, some feedbacks operate quickly (seconds), while others develop over decades to centuries; in order to understand the full impact of a feedback mechanism, its time scale needs to be considered. Melting of land ice sheets can take decades to centuries. An example of a negative feedback is the increased loss of energy through longwave radiation as surface temperature increases (sometimes also referred to as blackbody radiation feedback).

An equilibrium climate experiment is an experiment in which a climate model is allowed to fully adjust to a change in radiative forcing. Such experiments provide information on the difference between the initial and final states of the model, but not on the time-dependent response. The equilibrium response to a doubling of atmospheric concentration of CO_2 above pre-industrial levels (e.g., Arrhenius, 1896; Callendar, 1938; Ekholm, 1901) has often been used as the basis for the concept of equilibrium climate sensitivity (ECS) (Hansen et al., 1981; Manabe and Wetherald, 1967; Newell and Dopplick, 1979; Schneider et al., 1980). The transient climate response (TCR) is defined as the change in global surface temperature in a global coupled ocean-atmosphere climate model in a 1% yr^{-1} CO_2 increase simulation at the time of atmospheric CO_2

doubling.TCR is a measure of the strength and rapidity of the surface temperature response to greenhouse gas forcing and can be both more meaningful for some problems as well as easier to derive from observations (see Figure 10.25; Chapter 9; Allen et al., 2006; Knutti et al., 2005; Chapter 12), but such experiments are not intended to replace more realistic scenario evaluations.

[INSERT FIGURE 1.2 HERE]

Figure 1.2: Climate feedbacks and timescales. The climate feedbacks from increasing carbon dioxide and rising temperature include negative feedbacks (–) such as longwave radiation, lapse rate, and ocean uptake of carbon dioxide feedbacks. Positive feedbacks (+) include water vapour and the snow/ice albedo feedbacks. Some feedbacks may be positive or negative (±): clouds, ocean circulation changes, air-land carbon dioxide exchange, and emissions of non-green house gases and aerosols from natural systems In the smaller box, the large difference in time scale for the various feedbacks is highlighted.

A summary of perturbations to the forcing of the climate system from changes in solar radiation, greenhouse gases, surface albedo, and aerosols are 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).

Climate processes exhibit considerable natural variability. Even in the absence of external forcing we observe periodic and chaotic variation on a vast range of spatial and temporal scales. Much of this variability can be represented by unimodal or power law distributions. But many components of the climate system also exhibit multiple states – for instance, the glacial-interglacial cycle and certain modes of internal variability such as ENSO. 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, non-additive combination of feedbacks and so on.

Climate change commitment is defined as future change to which the climate system is committed by virtue of past or current forcings. Components of the climate system respond on a large range of timescales, ranging from the essentially instantaneous responses that characterise some radiative feedbacks, through to millennial scale responses, such as those associated with the behaviour of the carbon cycle and ice-sheets (see Figure 1.2). Even if climate forcings were fixed at current values the climate system would continue to change until it came into equilibrium with those forcings. Because of the slow response time of some aspects of the climate system, equilibrium conditions will not be reached for many centuries, furthermore slow processes can sometimes only be constrained by data collected over long periods, giving a particular salience for equilibrium processes to paleoclimate data. Climate change commitment is indicative of aspects of inertia in the climate system, since it captures the on-going nature of some aspects of change. Related to commitment, multiple climate states, and hysteresis is the concept of irreversibility in the climate system. Where multiple states and irreversibility combine, a bifurcation of “tipping points” has been reached. 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. Though a small number of studies using simplified models find evidence for global-scale “tipping points” (e.g., Lenton et al., 2008) there is no evidence for global-scale tipping points in any of the most comprehensive models evaluated to date. There are arguments for the existence of regional tipping points, most notably in the Arctic(e.g., Duarte et al., 2012; Lenton et al., 2008; Wadhams, 2012), though 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 observations of the atmosphere, land, ocean and cryosphere systems (Figure 1.3). There is incontrovertible evidence from in situ observations and ice core records that atmospheric concentrations of greenhouse gases such as CO_2, CH_4, and N_2O have increased substantially over the last 200 years (Chapter 6, Chapter 8). In addition, instrumental observations show that land and sea surface temperatures have increased over the last 100 years (Chapter 2). Additional measurements from satellites allow a much broader spatial distribution of measurements, especially over the last 30 years. Measurements show that the upper ocean temperature has increased since at least 1950 (Willis et al., 2010). Ocean warming dominates the total energy change inventory, accounting for an estimated 90–93% average from 1970–2009 (Chapter 3). Observations from satellites and in situ observations suggest reductions in glaciers, sea ice and ice sheets (Chapter 4). Additionally, analyses based on measurements of the radiative budget and ocean heat content suggest a small imbalance (Chapter 2). 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 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 perspective on climate change (Chapter 9). These use our basic understanding of the Earth to provide self-consistent methodologies for calculating impacts of processes and changes. Numerical models include what we know about the laws of physics and chemistry, as well as hypotheses about how complicated processes such as cloud formation can occur. Since these models can only represent the existing state of knowledge and technology, they are not perfect; however, they are important tools for analyzing 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 empirical observations. This methodology is generally called detection and attribution in the climate change community (see Chapter 10). For example, climate models indicate that the temperature response to greenhouse gas increases is expected to be different than the effects from aerosols or from solar variability. In addition, satellite and radiosonde observations of atmospheric temperature show increases in tropospheric temperature and decreases in stratospheric temperatures, consistent with the increases in greenhouse gas effects found in climate model simulations (e.g., increases in CO_2, changes in ozone), but this behaviour would not be expected if the Sun was the main driver of current climate change (Hegerl et al., 2007).

Prior to the instrumental period, historical sources, natural archives, and proxies for key climate variables (e.g., tree rings, ice cores, boreholes, etc.) can provide quantitative information on past regional to global climate and atmospheric composition variability. Reconstructions of key climate variables based on these datasets 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). Palaeoclimatic reconstructions thus provide a means for placing the current changes in climate in the perspective of natural climate variability. AR5 includes new information on external radiative forcings caused by variations in volcanic and solar activity (e.g., Steinhilber et al., 2009; see Chapter 9). Extended data sets on past changes in atmospheric concentrations and distributions of atmospheric greenhouse gases (e.g., Lüthi et al., 2008) and mineral aerosols (Lambert et al., 2008) concentrations have also been used to attribute reconstructed paleoclimate temperatures to past variations in external forcings.

1.3 Indicators of Climate Change

There are many indicators that the climate is changing throughout our planet. Some key examples of such changes in important climate parameters are discussed in this section. As was done to a more limited extent in AR4 (e.g., Figure 1.1 in IPCC, 2007), observations are compared with available model analyses from the previous assessments as a test of planetary-scale hypotheses of climate change – in other words, how well have the models used in the past assessments projected what has been observed. In the case of AR5, there are now five additional years of observations. The analyses presented in this section provide a demonstration of the advancement of science. Comparisons with the climate and associated environmental parameters are presented in Figure 1.3 (which is updated from the similar figure in IPCC, 2001). This section discusses recent changes in several indicators, but it is not the aim here to be comprehensive. Many of the indicators are more completely updated and discussed in other chapters. Note that a projection is not a prediction; the analyses presented only examine the short-term plausibility of the projections and models considered from the earlier assessment. Also, AR5 model results are not included in this section; other chapters will describe the findings from the new modelling studies.

[INSERT FIGURE 1.3 HERE]

Figure 1.3: Overview of observed climate variations since pre-industrial times unless stated otherwise (temperature: red; hydrological: blue; others: black).

1.3.1 Global and Regional Surface Temperatures

Observed changes in surface temperature since 1990 (as anomalies relative to 1961-1990) are shown in Figure 1.4. The globally and annually averaged surface temperatures are the average of the analyses of the land- and ocean-based measurements made by NASA (updated from Hansen et al., 2010; data available at http://data.giss.nasa.gov/gistemp/); NOAA (updated from Smith et al., 2008; data available at http://www.ncdc.noaa.gov/cmb-faq/anomalies.html#grid); and the UK Hadley Centre (updated from Morice et al., 2012; data available at http://www.metoffice.gov.uk/hadobs/hadcrut4/). These observations are discussed in more detail in Chapter 2. The black line is the observed temperature change smoothed with a 13-point binomial filter with ends reflected; this line is intended only as a rough indication of the long term trend. Uncertainties in the observed dataset are included from the analyses in Chapter 2. Also shown are the projected changes in temperature from the previous IPCC assessments out to 2015. Even though the projections from the models were never intended to be predictions over such a short time scale, the observations through 2010 generally fall well within the projections made in all of the past assessments. Note that before TAR the climate models did not include natural forcing, and even in AR4 some models did not have volcanic and solar forcing, and some also did not have aerosols. The projections are all scaled to give the same value for 1990. The scenarios considered for the projections from the earlier reports (FAR, SAR) had a much simpler basis than the SRES scenarios used in the later assessments. In addition, the scenarios were designed to span a broad range of plausible futures, but are not aimed at predicting the most likely outcome. There are several additional points to consider about Figure 1.4: (1) the model projections account for different emissions scenarios but do not fully account for natural variability; (2) the AR4 results for 1990–2000 account for the Mt. Pinatubo volcanic eruption, while the earlier assessments do not; (3) the TAR and AR4 results are based on MAGICC, a simple climate model that attempts to represent the results from more complex models, rather than the actual results from the full three-dimensional climate models; and (4) the bars on the side represent the range of results for the scenarios at the end of the time period and are not error bars. The AR4 model results that include effects of the 1991 Mt. Pinatubo eruption agree better with the observed temperatures than the previous assessments that did not include those effects. Analyses by Rahmstorf et al.(2012; submitted) show that accounting for ENSO events and solar cycle changes would enhance the comparison with the AR4 and earlier projections. In summary, the globally-averaged surface temperatures are well within the uncertainty range of all previous IPCC projections, and generally are in the middle of the scenario ranges. However, natural variability is likely the dominating effect in evaluating these early times in the scenario evaluations as noted by Hawkins and Sutton (2009).

Figure 1.5 similarly compares the globally and annually averaged temperature data with the AR4 model analyses for historical emissions and three of the Special Report on Emission Scenarios (SRES) scenarios (IPCC, 2000) that were extensively used in TAR and AR4. The three scenarios shown (A1B, A1FI, and A1T) are from the higher end of range of the SRES scenarios by 2100, but these are high, mid-range, and low for the period up to 2015. There is very little difference between the model range for the different scenarios at this point (or even by 2015) and the observed data are well within the projected ranges for each of the scenarios. Even though A1FI is the highest temperature scenario by the end of the century, A1T is higher during the earlier part of this century as shown in Figure 1.5.

[INSERT FIGURE 1.4 HERE]

Figure 1.4: [PLACEHOLDER FOR FINAL DRAFT: Observational datasets will be updated as soon as they become available] Estimated changes in the observed globally and annually averaged surface temperature (in °C) since 1990 compared with the range of projections from the previous IPCC assessments. Values are aligned to match the average observed value at 1990. Observed global annual temperature change, relative to 1961–1990, is shown as black squares (NASA (updated from Hansen et al., 2010; data available at http://data.giss.nasa.gov/gistemp/); NOAA (updated from Smith et al., 2008; data available at http://www.ncdc.noaa.gov/cmb-faq/anomalies.html#grid); and the UK Hadley Centre (Morice et al., 2012; data available at http://www.metoffice.gov.uk/hadobs/hadcrut4/) reanalyses). Whiskers indicate the 90% uncertainty range of the Morice et al. (2012) dataset from measurement and sampling, bias and coverage (see Appendix for methods). The coloured shading shows the projected range of global annual mean near surface temperature change from 1990 to 2015 for models used in FAR (Scenario D and business-as-usual), SAR (IS92c/1.5 and IS92e/4.5), TAR (full range of TAR Figure 9.13(b) based on the GFDL_R15_a and DOE PCM parameter settings), and AR4 (A1B and A1T). The 90% uncertainty estimate due to observational uncertainty and

internal variability based on the HadCRUT4 temperature data for 1951-1980 is depicted by the grey shading. Moreover, the publication years of the assessment reports and the scenario design are shown.

[INSERT FIGURE 1.5 HERE]

Figure 1.5: [PLACEHOLDER FOR FINAL DRAFT: Observational datasets will be updated as soon as they become available] Similar to Figure 1.4 except that the focus is now on the range of selected scenario projections from AR4. The shading shows high, low and mid-range SRES scenarios from AR4 for the years 1990–2015 of global annual mean near surface temperature change (note that these are high, mid-range, and low for this time period, not at end of the 21st century). SRES data was obtained from Figure 10.26 in Chapter 10 of AR4 and re-calculated to a baseline period of 1961–1990.

1.3.2 Greenhouse Gas Concentrations

Further key indicators are the changing concentrations of the radiatively important greenhouse gases that are important drivers in climate change (e.g., see IPCC, 2007). Figures 1.6 through 1.8 show the recent globally- and annually-averaged observed concentrations for the gases of most concern, CO_2, CH_4, and N_2O (see Chapter 6 and Chapter 8 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.

For CO_2, the recent observed trends tend to be in the middle of the model-based projections. The model results all assume historical emissions before 1990. The range of projections from the First Assessment Report (FAR, IPCC, 1990) is much larger than those from the scenarios used in more recent assessments. TAR and AR4 model concentrations after 1990 are based on the SRES scenarios but those model results may also account for historical emissions analyses.

As discussed in Dlugokencky et al. (2009), trends in CH_4 slowed greatly from 1998-2006, but CH_4 concentrations have been increasing again starting in 2007 (see Chapter 6 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 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.

Concentrations of N_2O have continued to increase at a nearly constant rate (Elkins and Dutton, 2010) for the 20 year period shown in Figure 1.8. Projections from TAR and AR4 compare well with the observed trends while the earlier assessments tended to assume higher growth in the concentrations than actually observed.

[INSERT FIGURE 1.6 HERE]

Figure 1.6: [PLACEHOLDER FOR FINAL DRAFT: Observational datasets will be updated as soon as they become available] Observed globally and annually averaged carbon dioxide concentrations in parts per million (ppm) since 1990 compared with projections from the previous IPCC assessments. Observed global annual CO_2 concentrations are shown in black (based on NOAA Earth System Research Laboratory measurements, http://www.esrl.noaa.gov/gmd/ccgg/trends/global.html). The uncertainty of the observed values is 0.1 ppm. The shading shows the largest model projected range of global annual CO_2 concentrations from 1990 to 2015 from FAR (Scenario D and business-as-usual), SAR (IS92c and IS92e), TAR (B2 and A1p), and AR4 (B2 and A1B). Moreover, the publication years of the assessment reports are shown.

[INSERT FIGURE 1.7 HERE]

Figure 1.7: [PLACEHOLDER FOR FINAL DRAFT: Observational datasets will be updated as soon as they become available] Observed globally and annually averaged methane concentrations in parts per billion (ppb) since 1990 compared with projections from the previous IPCC assessments. Estimated observed global annual CH_4 concentrations are shown in black (NOAA Earth System Research Laboratory measurements, updated from Dlugokencky et al., 2009 see http://www.esrl.noaa.gov/gmd). The shading shows the largest model projected range of global annual CH_4 concentrations from 1990–2015 from FAR (Scenario D and business-as-usual), SAR (IS92d and IS92e), TAR (B1p and A1p), and AR4 (B1 and A1B). Uncertainties in the observations are less than 1.5 ppb. Moreover, the publication years of the assessment reports are shown.

[INSERT FIGURE 1.8 HERE]

Figure 1.8: [PLACEHOLDER FOR FINAL DRAFT: Observational datasets will be updated as soon as they become available] Observed globally and annually averaged nitrous oxide (N_2O) concentrations in parts per billion (ppb) since

1990 compared with projections from the previous IPCC assessments. Observed global annual N_2O concentrations are shown in black (NOAA Earth System Research Laboratory measurements, updated from Elkins and Dutton, 2010; see http://www.esrl.noaa.gov/gmd/) with whiskers indicating the 1-σ error. The shading shows the largest model projected range of global annual N_2O concentrations from 1990 to 2015 from FAR (Scenario D and business-as-usual), SAR (IS92d and IS92e), TAR (B2 and A2), and AR4 (A1T and A2). Moreover, the publication years of the assessment reports are shown.

1.3.3 Extreme Events

Climate change, whether driven by natural or human forcings, can lead to changes in the likelihood of extreme weather events (see Chapter 3 of SREX, 2012; Seneviratne et al., 2012). Extreme events are defined as those that are "rare within their statistical reference distribution at a particular place. Definitions of 'rare' vary, but an extreme weather event would normally be as rare as or rarer than the 10th or 90th percentile. By definition, the characteristics of what is called 'extreme weather' may vary from place to place. For some climate extremes such as drought, floods and hot waves, several factors 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 1.9a 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 a decline in the opposite extreme (in this case the number of cold days such as frosts). Changes in the variability, skewness or the shape of the distribution can complicate this simple picture (Figure 1.9b, c and d).

The SAR noted that data and analyses of extremes related to climate change were sparse. By the time of the TAR, improved monitoring and data for changes in extremes were available, and climate models were being analysed to provide projections of extremes. In the AR4, the observational basis of analyses of extremes has increased substantially, so that some extremes have now been examined over most land areas (e.g., diurnal temperature and rainfall extremes). More models with higher resolution, and more regional models, have been used in the simulation and projection of extremes, and ensemble integrations now provide information about PDFs and extremes. Subsequent to AR4 the IPCC has prepared a special report on extreme events that covers observed and projected changes of extremes (IPCC, 2012).

Since the TAR, climate change studies have especially focused on changes in the global statistics of extremes, which have been compiled with the observed and projected changes in extremes to the so-called "Extremes"-Table (Figure 1.10). The changes in this table are complemented by the SREX assessment. For some of the phenomena ("higher maximum temperature", "higher minimum temperature", "precipitation extremes", "droughts or dryness") all reports found an increase in the observations and in the projections. In the observations for the "higher maximum temperature" the confidence 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. It was, however, reported to decrease in 21st century projections within the text of the AR4. In the projections for the precipitation related phenomena the spatial relevance has been improved from "over many Northern Hemisphere midlatitudes to high latitudes land areas" in the TAR to a "likely" for all regions (these "uncertainty labels" are discussed in Section 1.4). However, confidence in projected precipitation increases has been degraded to "likely" in the SREX from the "very likely" still perceived in the AR4. This is due to biases and fairly large spread in the precipitation projections. Consequently, less confidence has been attributed to the observations and estimates of droughts and dryness, moving from "likely" in the TAR to "medium confidence" in SREX.

For some extremes (e.g., "changes in tropical cyclone activity") the definition has changed between the TAR and the AR4 showing the progress made over the years. While the TAR only made a statement about the peak wind speed of tropical cyclones, the AR4 also stresses 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 deficiencies in the observational coverage. 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 the observations, and "very likely" for the climate projections reported in the SREX.

Some assessments still rely on simple reasoning about how extremes might be expected to change with climate change (e.g., warming could be expected to lead to more heat waves). Others rely on qualitative similarity between observed and simulated changes. 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 the combination of factors such as droughts, linking a particular extreme event to specific causal relationships are difficult to determine (e.g., difficult to establish the clear role of climate change in the event). 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).

[INSERT FIGURE 1.9 HERE]

Figure 1.9: 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, e.g., at the beginning of the 20th century, and solid lines a changed distribution, e.g., at end of 21st century. 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, 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 likely 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. Figure 1a-1c modified from IPCC (2001, Chapter 2) and Figure 1d modified from Peterson et al. (2008). See Zhang and Zwiers (2012).

[INSERT FIGURE 1.10 HERE]

Figure 1.10: Change in the confidence levels for extreme events based on the prior TAR, AR4, and SREX assessments. Phenomena which are mentioned in all three reports are highlighted in green. Confidence levels are defined in Section 1.4.

1.3.4 Integrative Climate Indicators (only in Terms of Data Indicating Climate Change)

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, in ocean acidification, and in the ice amounts on ocean and land. See also Chapters 3, 4 and 13 for detailed discussion.

1.3.4.1 Sea Level

A change in sea level is an important indicator of climate change (Chapters 3 and 13). 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. Absolute sea level is rising everywhere, but local processes (e.g., tectonic uplift) can lead to different interpretations on a local scale. From the historical tide gauge record, we know 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). While the rate since 1990 is significantly higher (3.2 ± 0.4 mm yr^{-1}), there is growing evidence that at least part of the increase is due to a multidecadal oscillation that has occurred previously between 1930 and 1950. There is, however, evidence of a small but positive acceleration in sea level at long tide gauge records and reconstructions of global mean sea level since the late 1800s. Figure 1.11 compares the observed sea level rise relative to the projections from the IPCC assessments. Earlier models did not include all of the forcings, so there is no reason that they should get the thermal expansion correct. Also, the projections for sea level were never made to be interpreted on these short timescales. Nonetheless, the results show that the actual change is in the middle of projected changes from the assessments.

1.3.4.2 Ocean Acidification

Ocean acidification is the ongoing decrease in the pH of the Earth's ocean, caused by its uptake of carbon dioxide from the atmosphere. Long time series from several ocean sites show declines in pH in the mixed layer between –0.03 and –0.06 since 1990, consistent with results from repeat pH measurements on ship transects spanning much of the globe (Byrne et al., 2010; Midorikawa et al., 2010). 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 WGII assessment).

[INSERT FIGURE 1.11 HERE]

Figure 1.11: [PLACEHOLDER FOR FINAL DRAFT: Observational datasets will be updated as soon as they become available] Estimated changes in the observed global annual sea level since 1990. Estimated changes in global annual sea level anomalies from tide gauge data (Church and White, 2011; available at http://www.cmar.csiro.au/sealevel/sl_data_cmar.html) (black error bars showing 1σ uncertainty) and based on annual averages from TOPEX and Jason satellites (Nerem et al., 2010; available at http://sealevel.colorado.edu/results.php) (blue dots) starting in 1992 (the values have been aligned to fit the 1993 value of the tide gauge data). The shading shows the largest model projected range of global annual sea level rise from 1990 to 2015 for FAR (Scenario D and business-as-usual), SAR (IS92c and IS92e), TAR (A2 and A1FI) and for Church et al. (2011) based on the CMIP3 model results available at the time of AR4 using the SRES A1B scenario.

1.3.4.3 Ice Indicators

Rapid sea ice loss is one of the most prominent indicators of Arctic climate change (see Chapter 4). The trend of the pan-Arctic sea ice area is a decrease of about 3% per decade from 1978–1996 and 10.7% per decade since 1996 (Comiso et al., 2008), with the trend in winter much less than that in summer. Summer sea ice extent has shrunk by more than 30% since 1979, with the lowest amounts of ice observed in the summers of 2007, 2011, 2008, 2010 and 2009, respectively (http://nsidc.org/arcticseaicenews/2011/09/). There is less multi-year sea ice and sea ice is thinning (Haas et al., 2008; Kwok et al., 2009). At the end of the summer of 2011, less than 30% of the ice remaining in the Arctic was more than two years old, compared to above 60% during the early 1980s (http://nsidc.org/arcticseaicenews/2011/10/). Sea ice cover has been diminishing significantly faster than projected by most of the AR4 climate models (SWIPA, 2011), largely because the basic physics of ice melting have not been well represented in models (Chapter 12).

Satellite data show that sea ice extent is increasing in the Antarctic by about 2 % per decade. The observed increase appears to be at least in part, an indirect result of stratospheric ozone depletion (see Chapter 4). Various studies 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; Turner et al., 2009b).

The Greenland Ice Sheet is losing mass, and the rate of decrease has increased over the last decade (see Chapter 4). Whereas the estimated annual net loss in 1995–2000 was 50 Gt, in 2003–2006 160 Gt was lost per year (AMAP, 2009; Mernild et al., 2009; Rignot et al., 2008a). 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 (Mernild et al., 2009; Tedesco, 2007), with 2010 breaking the record for surface melt area, runoff, and mass loss and the unprecedented retreat of the Greenland Ice Sheet in 2012 (http://www.nasa.gov/topics/earth/features/greenland-melt.html).

There are indications that the Antarctic continent is now experiencing a net loss of ice. Estimates show that annual mass loss in Antarctica has increased, from 112 ± 91 Gt in 1996 to 196 ± 92 Gt in 2006, comparable to losses to the Greenland Ice Sheet (Rignot et al., 2008b). Significant mass loss has been occurring in parts of West Antarctica, the Antarctic Peninsula, and limited parts of East Antarctica, while the ice sheet on the rest of the continent is relatively stable or thickening slightly due to increased accumulation (Lemke et al., 2007; Scott et al., 2009; Turner et al., 2009a).

Most glaciers around the globe have been shrinking since the end of the Little Ice Age (between 1550 AD and 1850 AD), with increasing rates of ice loss since the early 1980s. The vertical profiles of englacial temperature measured through the entire thickness of mountain cold glaciers, or through ice sheets, provide clear evidence of global warming over recent decades (e.g., Lüthi and Funk, 2001). Over the last decades the greatest mass losses, largely due to anthropogenic effects, per unit area have been observed in the European Alps, Patagonia, Alaska, north-western USA, and south-western Canada. Alaska and the Arctic are the most important regions with respect to total mass loss from glaciers, and thereby as contributors to sea level rise (Zemp et al., 2009; Zemp et al., 2008).

1.4 Treatment of Uncertainties

1.4.1 Uncertainty in Environmental Systems

Science always involves uncertainties. These arise at each step of the scientific method: in measurements, in the development of models or hypotheses, 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 do bring particular challenges.

The Earth's climate system is characterized by multiple spatial and temporal scales, and uncertainties do not usually reduce at a single, predictable rate: for example, new observations are likely to 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 we have 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 multi-faceted property, sometimes originating in a lack of information, 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 upon 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 taxonomy 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). In the modelling studies that underpin projections of future climate change, it is common to partition uncertainty into three main categories: scenario uncertainty, due to uncertainty of future emissions of greenhouse gases and other forcing agents; "model uncertainty" associated with climate models; and internal variability and initial condition uncertainty (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 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 studies use the phrase to represent the range of behaviour observed in ensembles of climate model (model spread), while other studies use it in more comprehensive senses (see Sections 9.2.2, 9.2.3, 11.2.1 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 we distinguish 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 functional forms of the model structure (see Section 12.2.1). 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.

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 upper endpoint of the uncertainty interval has a 95% likelihood of exceeding the value that is being estimated and the lower endpoint has a 95% likelihood of being less than that value. 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. Even 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, as well as specific procedures for the expression of uncertainty. 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 on-going challenges. In the wake of the TAR the IPCC formed a Cross-Working Group team charged with identifying the issues and providing 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., Broomell and Budescu, 2009; Budescu et al., 2009; Kandlikar et al., 2005; Morgan et al., 2009; Patt and Schrag, 2003; Risbey and Kandlikar, 2007) and expert advisory panels (InterAcademy Council, 2010; Morgan et al., 2009) 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. Additionally, 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 reasonably 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., mechanistic understanding, theory, data, 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 judgment).

A level of confidence synthesizes the author teams' judgments 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, since 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 at the very least where key variables are highly uncertain, presentation of the available evidence and scientific agreement in the literature regarding that variable should be 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 modeling, is important for evaluating the confidence level. Figure 1.12 shows how the combined evidence and agreement results in five levels for the confidence level used in this assessment.

[INSERT FIGURE 1.12]

Figure 1.12: The basis for the confidence level is given as a combination of evidence (limited, medium, robust) and agreement (low, medium, and high). The confidence level is given for five levels (very high, high, medium, low, and very low) and given in colours (IPCC, 2012).

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, e.g., a climate parameter, observed trend, or projected change 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 1.1 for the list of "likelihood" qualifiers to be used in AR5.

Table 1.1: 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:
(a) 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.

Many social science studies have found that the interpretation of uncertainty is contingent upon 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): a 10% chance of dying is interpreted more negatively than a 90% chance of surviving.

In addition, work examining expert judgment and decision making shows that people – including scientific experts – suffer from a range of heuristics and biases that affect their judgment (e.g., Kahneman et al., 1982). For example, in the case of expert judgments 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 judgment is inevitable (Mastrandrea et al., 2010).

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 we need to be concerned about is that translation of this assessment from English to other languages may lead to a possible loss of precision.

1.5 Advances in Measurement and Modelling Capabilities

Since AR4, measurement and modelling capabilities have continued to advance. 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 (ECV), that are technically and economically feasible to observe, but some of these 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 observed changes). 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. Additionally, more proxy 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).

Model-based reanalysis products play an important role in obtaining a consistent picture of the climate system through the use of different types of observations as assimilated, for example, in advanced weather prediction models. However, their usefulness in detecting long-term climate trends is currently limited and a systematic strategy is still needed to achieve appropriate quality (Thorne and Vose, 2010). Since 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 ERA-Interim since 2007 (Dee et al., 2011). The overwhelming majority of the data, and most of the increase over recent years, come from satellites (Figure 1.13). For example, information from GPS 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 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 (IR) sounders (such as AIRS and IASI) are instrumental to achieving a better temporal stability for recalibrating sensors like the HIRS. Few instruments (e.g., AVHRR) have now been in orbit for approx. three decades, but these have originally not been 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). 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 data have been identified and reduced, and new analytical approaches have been applied. 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. The spatial and temporal coverage of biogeochemical measurements in the ocean has also expanded. Satellite observations for sea level, sea ice, sea surface salinity and ocean colour have also been further developed over the past few years.

Progress has also been made with regard to observation of terrestrial ECVs. Major advances have been achieved in remote sensing of soil moisture due to the launch of the Soil Moisture and Oceanic Salinity mission (SMOS) 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 AVHRR-based NDVI data provide new information on the change in vegetation and suggest a greening of the planet (see Chapter 6). 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 4.6).

[INSERT FIGURE 1.13 HERE]

Figure 1.13: Development of Capabilities of Observations. Top (large figure): Changes in the mix and increasing diversity of observations over time create challenges for a consistent climate record (adapted from Brönnimann et al., 2008). Top (small figure): First year of temperature data in global historical climatology network daily database (available at http://www.ncdc.noaa.gov/oa/climate/ghcn-daily/; Menne et al., 2012). Bottom: Number of satellite instruments from which data have been assimilated in European Centre for Medium-Range Weather Forecasts' (ECMWF's) 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. Acronyms are spelled out in Table 1.2

Table 1.2: List of Acronyms used in Figure 1.13

Acronym	Full Spelling and References
SMOS	Soil Moisture and Ocean Salinity (see http://www.esa.int/esaLP/LPsmos.html for more information)
TERRA/AQUA AMV	atmospheric motion vector from the satellites TERRA and AQUA (see http://aqua.nasa.gov/ and http://terra.nasa.gov/ for more information)
GMS /MTSAT Rad	Geostationary Meteorological Satellite/ Multifunctional Transport Satellites radiation (see http://rammb.cira.colostate.edu/dev/hillger/gms.htm for more information)
GOES Rad	Geostationary Operational Environmental Satellite radiation (see http://goes.gsfc.nasa.gov/ for more information)
METEOSAT Rad	Meteorological satellite radiation (see http://www.eumetsat.int/Home/Main/Satellites/MeteosatThirdGeneration/index.htm?l=en for more information)
FY-2C/D AMV	Atmospheric Motion Vectors from Fengyún (chinese for "wind cloud") (see http://www.nsmc.cma.gov.cn/newsite/NSMC_EN/Channels/100096.html for more information)
GMS/MTSAT AMV	Geostationary Meteorological Satellite/ Multifunctional Transport Satellites atmospheric motion vectors (see http://rammb.cira.colostate.edu/dev/hillger/gms.htm for more information)

GOES AMV	Geostationary Operational Environmental Satellite atmospheric motion vectors (see http://goes.gsfc.nasa.gov/ for more information)
METEOSAT AMV	Meteorological satellite atmospheric motion vectors (see http://www.eumetsat.int/Home/Main/Satellites/MeteosatThirdGeneration/index.htm?l=en for more information)
Oceansat	satellite (see http://www.isro.org/satellites/irs-p4_oceansat.aspx for more information)
JASON-1/2/3	satellites (see http://ilrs.gsfc.nasa.gov/satellite_missions/list_of_satellites/jas2_general.html for more information)
QuikSCAT	Quick Scatterometer (see http://winds.jpl.nasa.gov/ for more information)
FY-3A/B	satellite mission (see http://www.nsmc.cma.gov.cn/newsite/NSMC_EN/Channels/100097.html for more information)
AURA	latin word for air, satellite (see http://aura.gsfc.nasa.gov/ for more information)
AQUA	latin word for water, satellite (see http://aqua.nasa.gov/ for more information)
TRMM	Tropical Rainfall Measuring Mission (see trmm.gsfc.nasa.gov for more information)
CHAMP/ GRACE	CHAllenging Minisatellite Payload/ Gravity Recovery and Climate Experiment (see http://op.gfz-potsdam.de/champ/ and http://op.gfz-potsdam.de/grace/main_GRACE.html for more information)
COSMIC	Constellation Observing System for Meteorology, Ionosphere, and Climate (see http://www.cosmic.ucar.edu/ for more information)
ENVISAT	Environmental Satellite (see https://earth.esa.int/web/guest/missions/esa-operational-eo-missions/envisat for more information)
ERS-1/2	European Remote Sensing (see https://earth.esa.int/web/guest/missions/esa-operational-eo-missions/ers for more information)
METOP	Meteorological Operational satellite (see http://www.eumetsat.int/Home/Main/Satellites/Metop/index.htm?l=en for more information)
DMSP	Defense Meteorological Satellite Program (see http://www.af.mil/information/factsheets/factsheet.asp?fsID=94 for more information)
NOAA	National Oceanic and Atmospheric Administration (see http://www.noaa.gov/satellites.html for more information)

1.5.2 Capabilities in Global Climate Modelling

Four developments have especially pushed the capabilities in modelling forward over recent years (see Figure 1.14 and a more detailed discussion in Chapter 6, Chapter 7 and Chapter 9).

- Firstly, 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 regional models with higher resolution are available for more regions. Figure 1.15a and 1.15b show the large effect on surface representation from a horizontal grid spacing of 110 km (similar to the current global models) to a grid spacing of 30 km.

- Secondly, representations of Earth system processes are much more extensive and improved, particularly the radiation and the aerosol cloud interactions and the treatment of the cryosphere. More models include better representation of the carbon cycle. 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.

- Thirdly, ensemble techniques (multiple calculations to account for natural variability) are being used more frequently, with larger samples and with different methods to generate the samples (different models, different physics, different initial conditions). International projects have been set up to generate and distribute large samples (ENSEMBLES, climateprediction.net, PCMDI).

- Fourth, model comparisons with observations have pushed the analysis and development of the models. The Coupled Model Intercomparison Project Phase 5 (CMIP5) done for AR5 has produced a state-of-the-art multi-model dataset that is designed to advance our knowledge of climate variability and climate change. Building on previous CMIP efforts, such as the CMIP3 model analysis done for 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 findings from CMIP5.

As part of the process of getting model analyses for a range of possible future conditions, 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 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 (CMIP3 for example for AR4). For CMIP5, four new scenarios, referred to as Representative Concentration Pathways (RCPs) were developed (Moss et al., 2010). See Box 1.2 for a more thorough discussion of the RCP scenarios. Since 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 1.16, acting as a prelude to the discussion in Box1.2, shows that the derived radiative forcing (RF) for several of the SRES and RCP scenarios are similar over time and thus should provide comparable results for comparing climate modelling studies.

[INSERT FIGURE 1.14 HERE]

Figure 1.14: The development of climate models over the last 35 years showing how the different components are coupled into comprehensive climate models. Note that in the same time the horizontal and vertical resolution has increased considerably for example for spectral models from T21L9 (roughly 500 km) in the 1970s to T95L95 (roughly 100 km) at present, and that now ensembles with at least three independent experiments can be considered as standard.

[INSERT FIGURE 1.15 HERE]

Figure 1.15: Horizontal resolutions considered in typical and higher resolution models. a) Illustration of the European topography at a resolution of 87.5 km x 87.5 km. b) Same but for a resolution of 30.0 km x 30.0 km.

[INSERT FIGURE 1.16 HERE]

Figure 1.16: Historical and projected total anthropogenic radiative forcing (W m^{-2}) relative to preindustrial (~1765) between 1950 and 2100. Previous IPCC assessments (SAR IS92a, TAR/AR4 SRES A1B, A2 and B1) are compared with RCP scenarios (see Chapter 12 for their extensions until 2300 and Annex II for the values shown here). The total radiative forcing of the three families of scenarios, IS92, SRES and RCP, differ for example for the year 2000 as the number of forcings and our knowledge about them have changed since the TAR.

[START BOX 1.2 HERE]

Box 1.2: Description of Future Scenarios

Long term climate change projections require assumptions about how human activities or natural effects 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 radiative forcing 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 emissions and socio-economic assumptions (e.g., regarding population and socio-economic development).

Idealized Concentration Scenarios

A 1%-per-annum 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 radiative forcing (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 primarily based on the SRES A2, A1B and B2 scenarios. However, given the diversity in models’ carbon cycle and chemistry schemes, this approach implied differences in models’ LLGHG and aerosol concentrations, for the same emissions scenario.

Representative Concentration Pathway Scenarios and their Extensions

Representative Concentration Pathways (RCPs) (Moss et al., 2010; Moss et al., 2008; van Vuuren et al., 2011b) are new scenarios that specify concentrations, rather than emissions. Four RCPs were selected from the published literature (Fujino et al., 2006; Hijioka et al., 2008; Riahi et al., 2007; Smith and Wigley, 2006; van Vuuren et al., 2007; 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). Three are identified by the 21st century peak or stabilization value of the radiative forcing (in Wm^{-2}) (Box 1.2, Figure 1): the lowest RCP, RCP2.6 (also referred as RCP3-PD) which peaks at 3 Wm^{-2} and then declines to approximately 2.6 Wm^{-2} by 2100; the medium-low RCP4.5 and the medium-high RCP6 aiming for stabilization at 4.5 and 6 Wm^{-2} respectively around 2100; and the highest one, RCP8.5, which implies a radiative forcing of 8.5 Wm^{-2} by 2100. Note that due to the substantial uncertainties in radiative forcing, these forcing values should be understood as comparative ‘labels’, not as exact definitions of the forcing that is effective in climate models. This is because concentrations or emissions (rather than the radiative forcing) are prescribed in the CMIP5 climate model runs.

[INSERT BOX 1.2, FIGURE 1 HERE]

Box 1.2, Figure 1: Total radiative forcing (anthropogenic plus natural) for RCPs − supporting the original names of the four pathways as there is a close match between peaking, stabilization and 2100 levels for RCP2.6, RCP4.5 & RCP6, as well as RCP8.5, respectively. Note that the stated radiative forcing levels refer to the illustrative default median estimates only. There is substantial uncertainty in current and future radiative forcing levels. Short-term variations in radiative forcing 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 Figure4 in Meinshausen et al., 2011).

Various steps were necessary to turn these selected ‘raw’ RCP emission scenarios from the IAMs to the datasets usable by the climate modelling community, including the extension with historical emissions (Granier et al., 2011; Meinshausen et al., 2011), the harmonization and gridding of land-use datasets (Hurtt et al., 2011), the provision atmospheric chemistry runs, particular for tropospheric ozone (Lamarque et al., 2011), and the harmonization of 2000-2005 GHG emission levels, extension of GHG concentrations with historical GHG concentrations and harmonization of 2000-2005 GHG concentrations levels (Meinshausen et al., 2011). The final RCP datasets comprise land-use data, harmonized GHG emissions and concentrations, gridded reactive gas and aerosol emissions, as well as ozone and aerosol abundance fields (Box1.2, Figure. 2 and Figure 3).

[INSERT BOX 1.2, FIGURE 2 HERE]

Box 1.2, Figure 2: Concentrations of GHG following the 4 RCPs and their extensions to 2300. (Reproduced from Figure 5 in Meinshausen et al., 2011).

[INSERT BOX 1.2, FIGURE 3 HERE]

Box 1.2, Figure 3: (a) Equivalent CO_2 concentration and (b) CO_2 emissions (except land use emissions) for the four RCP and 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 beyond 2100. 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 7 times the pre-industrial levels. As the RCP2.6 implies net negative 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 radiative forcing values that span a range larger than that of the three SRES scenarios used in CMIP3 (Figure 12.3.3). RCP4.5 is close to SRES B1, RCP6 is close to SRES A1B (more after 2100 than during 21st century) and RCP8.5 is somewhat higher than A2 at 2100 and close to the SRES A1FI scenario (Box 1.2, Figure 3). RCP2.6 is lower than any of the SRES scenarios (see also Figure 1.16).

[END BOX 1.2 HERE]

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. A variety of indicators show that the climate system is continuing to change. The notable scientific advances, and associated peer-reviewed publications since AR4 provide the basis for the rest of this assessment of the science as found in Chapters 2 through 14. Below we provide a quick summary of the basis for these chapters and their objectives.

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. It covers all relevant aspects of the atmosphere up to 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, 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, 10): In these chapters, all the information on the different drivers (natural and anthropogenic) of climate change is collected, expressed in terms of radiative forcing, 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 time scales 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, process understanding, and 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. Radiative forcings, 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, where questions have been raised that are being addressed through ongoing research. Table 1.3 provides a list of many of these issues and the chapters where they are discussed.

Table 1.3: Key topical issues discussed in the assessment.

Topics	Chapters
Climate sensitivity	5, 9, 10, 12
Decadal climate variability	5, 9, 10
Earth's Energy (trends, distribution and budget)	2, 3, 13
Abrupt change and irreversibility	5, 12, 13
Climate stabilization	6, 12
Temperature trends since 1998	2, 3, 10
Upper troposphere temperature trends	2, 9
Sea level change, including regional effects	3, 5, 13
Arctic sea ice change	4, 5, 9, 10
Climate change in Antarctica	5, 9, 10, 13
Changes in glaciers	4, 5, 10, 13
Ice-sheet dynamics and mass balance assessment	4, 5, 10, 13
Changes in permafrost	4, 6, 10
Ocean acidification	3, 6
Tropical cyclones	2, 10, 14
Role of aerosols in climate change	6, 7, 8, 11, 14
Cloud feedbacks	5, 7, 9, 11, 12
Cosmic ray effects on clouds	7
Changes in hydrological cycle	2, 3, 7, 10
Monsoons	5, 14
Climate-carbon feedbacks	2, 6, 12
Geoengineering	6, 7

[START FAQ 1.1 HERE]

FAQ 1.1: If Understanding of the Climate System Has Increased, Why Haven't the Uncertainties Decreased?

The continuing uncertainty in future climate projections is due to uncertainties arising from natural climate variability, around greenhouse gas and aerosol precursor emissions, and around the climate response to these emissions. Because of the chaotic nature of the climate system, uncertainty in long-term climate projections due to natural variability is unlikely to be reduced.

There is still considerable uncertainty around emissions, because we cannot accurately predict future social choices. Improved understanding, climate models and observational constraints will reduce uncertainty around the climate response, but the complexity of the climate system makes this is a slow process.

Projecting future climate is scientifically challenging. For the foreseeable future, imperfect understanding, and the approximations necessary for building climate models, will limit our ability to predict Earth's climate with high precision, particularly on regional and smaller scales.

Climate science has made many important advances since the last assessment report, due to improvements in measurements and data analysis in the cryosphere, atmosphere, land and ocean systems. We also have better understanding and modelling of clouds, sea ice, aerosols, small-scale ocean mixing, the carbon cycle and other processes. We can now better constrain projections, thanks to refinements in the way models are evaluated based on observations.

However, there are still considerable uncertainties around global and regional climate projections. Each uncertainty is specific to the variable being considered (precipitation vs. temperature, for example), the spatial and temporal scales involved (regional, monthly vs. local, daily), and the lead time of the projection (how far into the future we are looking). These uncertainty estimates are important because they allow other scientists and policy makers to understand the range of values that are consistent with the current understanding.

Uncertainty in projections is quantified in various ways. The aim is to capture the range of future possibilities that is consistent with current knowledge. However, there is no perfect method. In practice, almost all methods rely on climate models to some extent: as a result, estimates of uncertainty can change as models are developed – by including new processes, for instance. One can think of uncertainties as coming from known 'unknowns', where scientists are aware that they are poorly simulating processes, or from unknown 'unknowns', such as when a new process is discovered.

Uncertainties in climate projections arise from natural variability, uncertainty in emissions, and uncertainty in the climate's response to those emissions. There are fundamental limits to just how precisely the climate can be projected, because of the chaotic nature of the climate system. Furthermore, projections are sensitive to poorly-known current conditions, such as the temperature of the deep ocean.

Natural variability on decadal timescales arises from interactions between the ocean, atmosphere, land and cryosphere, and is also related to phenomena such as El Nino and the North Atlantic Oscillation. Volcanic eruptions and variations in the sun's output also contribute. This natural variability can be viewed as 'noise' in the climate record, which provides the backdrop against which the 'signal' of anthropogenic climate change is detected. Such uncertainties are inherent to the Earth system, and more knowledge will not eliminate them. Some progress is possible, however, particularly for predictions up to a few years ahead, which exploit advances in knowledge of the ocean state and processes. This is an area of active research.

Averaging global climate variables over decadal time scales or longer helps reduce the relative importance of internal variability, making emissions and response uncertainties more evident (FAQ1.1, Figure 1). However, regional to local scale natural variability tend to be larger than globally averaged variability and are unlikely to average out over 10 years. When we project climate, we need plausible estimates of human emissions of greenhouse gases and aerosol precursors, and of land use. Since the IPCC is intended to assist in policy making, and to show the consequences of different choices, several different scenarios of possible futures are simulated. These scenarios are designed to sample some of the future uncertainty in emissions, particularly that surrounding greenhouse gas emissions.

Scientists make assumptions about different pathways for human society in terms of population, economic and technological change, then estimate how these will impact emissions and land use. The scenarios illustrate just how political and social choices, along with technological developments, affect the large uncertainty in future climate. Projections for the next few years and decades are sensitive to emissions of short-lived species, such as aerosols and methane. Longer-term projections, however, are more sensitive to alternative scenarios for greenhouse gas emissions. These uncertainties will not reduced by improvements in climate science (FAQ 1.1, Figure 1).

Climate response is a measure of how the Earth's climate responds to anthropogenic emissions and land use change. Climate projections, based on given emissions and land use scenarios, are made using simulations by computer models. A few dozen global climate models have been developed, and these models project somewhat different future climates for a given scenario. To identify errors, and opportunities for improvements, these models are compared to existing observations in various innovative ways.

However, due to the complexity of the Earth system, there is still a considerable range of future climate that is consistent with current understanding and models. As observational records lengthen, and models improve, it is becoming possible to narrow some of the uncertainties in projections for the next few decades (FAQ 1.1, Figure 1). It is also possible to use information about the current state of the oceans to produce better predictions up to a few years ahead.

As the science improves, it also identifies new geophysical processes that should be added to the climate models, and improvements to the representation of those already included. Such developments can change model-derived estimates of climate response uncertainty. This uncertainty may appear to increase, but such increases merely reflect a quantification of previously unmeasured sources of uncertainty. (Figure FAQ1.1). As more and more important processes are added, the undermining influence of unquantified processes is diminished.

[INSERT FAQ1.1, FIGURE 1 HERE]

FAQ 1.1, Figure 1, a) Mean surface temperature change from historical record (black line), with climate model estimates of uncertainty for historical period (grey), along with future climate projections and uncertainty. Natural variability (orange) derives from model interannual variability from IPCC Fourth assessment Report (2007) (AR4). Emission uncertainty (green) is estimated as the model mean difference in projections from the AR4. Climate response uncertainty (blue-solid) is based on climate model spread from AR4, 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 (2009) and Huntingford et al.(2009). b) Climate response uncertainty can grow when a new process is discovered to be relevant, or c) can decrease with additional model improvements and observational constraints.

[END FAQ 1.1 HERE]

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

Figure 1.4

Documentation of Data Sources:

Observed Temperature

Hansen et al. (2010) updated: The data were downloaded at http://data.giss.nasa.gov/gistemp/tabledata_v3/GLB.Ts+dSST.txt in March 2012. There are no uncertainty estimates. Annual means are used (Januar to December) and anomalies calculated relative to 1961-1990.

Smith et al. (2008) updated: The data were downloaded at ftp://ftp.ncdc.noaa.gov/pub/data/anomalies/annual.land_ocean.90S.90N.df_1901-2000mean.dat in April 2012. There are no uncertainty estimates. Anomalies are calculated relative to 1961-1990.

Morice et al. (2012): The data were downloaded at http://www.metoffice.gov.uk/hadobs/hadcrut4/data/download.html in May 2012. To estimate the uncertainty of the observations the 95% uncertainty ranges from the combined effects of all the uncertainties (measurement and sampling, bias and coverage uncertainties) are used (see below for calculation of 90% uncertainty range).

IPCC Range of Projections

FAR: The data have been graphically traced from FAR Chapter 6 Figure 6.11 in 5 year increments as anomalies relative to 1990.

Year	Lower bound (Scenario D)	Upper bound (Business as Usual)
1990	0.00	0.00
1995	0.07	0.15
2000	0.14	0.31
2005	0.18	0.53
2010	0.22	0.73
2015	0.28	0.91

SAR: The data have been graphically traced from Figure 19 in 5 year increments as anomalies relative to 1990. The scenarios include changes on aerosols beyond 1990.

Year	Lower bound (IS92c/1.5)	Upper bound (IS92e/4.5)
1990	0.00	0.00
1995	0.04	0.09
2000	0.10	0.17
2005	0.15	0.28
2010	0.19	0.37
2015	0.24	0.47

TAR: The data have been graphically traced from Figure 9.13(b) in 5 year increments based on the GFDL_R15_a and DOE PCM parameter settings.

Year	Lower bound	Upper bound
1990	0.00	0.00
1995	0.05	0.09
2000	0.12	0.20
2005	0.14	0.35
2010	0.18	0.53
2015	0.22	0.69

AR4: The data used was obtained from Figure 10.26 in Chapter 10 of AR4 (provided by Malte Meinshausen). Annual means are used. The upper bound is given by the A1T scenario, the lower bound by the A1B scenario.

Data Processing

Observations
The observations are shown as annual means relative to 1961-1990. No smoothing is applied. Whiskers give the 90% uncertainty range of the Morice et al. (2012) dataset. These include the combined effects of all the uncertainties (measurement and sampling, bias and coverage uncertainties).

Projections
The projections have been aligned to match the mean observed value (averaged over the three observational data sets) for year 1990.

Uncertainty Band
To estimate natural variability the standard deviation of the annual means of the Morice et al. (2012) dataset is calculated for the period 1951-1980. It is assumed that this value includes both natural variability and observational uncertainty. Thus, natural variability is calculated by subtracting the variances reflecting the observational uncertainty from the variance of the annual means of the Morice et al. (2012) dataset for the period 1951-1980. The period 1951-1980 is chosen to minimize the influence of forced variability. Likewise the autocorrelation is calculated for this period to estimate the decorrelation time. To estimate the observational uncertainty the 95% uncertainty range of the Morice et al. (2012) dataset is used for the period 1990-2010 and divided by 1.96, which gives the standard deviation for normally distributed data.
The full 90% uncertainty band is given by

$$\mathrm{uncert}\ (t) = 1.645 \cdot \sqrt{2 \cdot \left(1 - \mathrm{autocorrelation}_{\mathrm{obs}}{}^{(t-1)}\right) \cdot \sigma_{\mathrm{nat.var}}{}^{2} + \sigma_{\mathrm{obs.uncert}}{}^{2}}$$

where t is 1 at 1990. For each year the uncertainty has been added to the maximum value and subtracted from the minimum value given by the range of projections.

Figure 1.5

Documentation of Data Sources:
For details on the sources of observed temperatures see technical details for Figure 1.4. The IPCC AR4 data were obtained from Figure 10.26 in Chapter 10 of AR4 (provided by Malte Meinshausen). Annual means of the A1B, A1T and A1FI scenarios are used.

Data Processing:
The observations are shown as annual means relative to 1961-1990. No smoothing is applied. Whiskers give the 90% uncertainty range of the Morice et al. (2012) dataset. These include the combined effects of all the uncertainties (measurement and sampling, bias and coverage uncertainties). The projections have been aligned to match the mean observed value (averaged over the three observational data sets) for year 1990. Details on the calculation of the uncertainty band are provided in the technical details for Figure 1.4.

Figure 1.6

Documentation of Data Sources:

Observed CO_2 Concentrations
Global annual mean CO2 concentrations are based on NOAA Earth System Research Laboratory measurements downloaded from www.esrl.noaa.gov/gmd/ccgg/trends in July 2012.

IPCC Range of Projections

FAR: The data have been graphically traced Figure A.3 from FAR SPM in 5 year increments.

Year	Lower bound (Scenario D)	Upper bound (Business as Usual)
1990	354.79	355.32
1995	363.40	365.17
2000	370.26	375.45
2005	375.34	388.42
2010	382.00	401.17
2015	388.84	414.48

SAR: The data have been graphically traced from Figure 5b in 5 year increments.

Year	Lower bound (IS92c)	Upper bound (IS92e)
1990	354.67	354.67
1995	359.22	362.17
2000	366.58	371.85
2005	374.32	382.74
2010	381.67	394.59
2015	390.96	408.38

TAR: The data were taken in 10 year increments from table Appendix II SRES Data Tables Table II.2.1 (ISAM model high and low setting). The upper bound is given by the A1p scenario, the lower bound by the B2 scenario.

AR4: The data used was obtained from Figure 10.26 in Chapter 10 of AR4 (provided by Malte Meinshausen). Annual means are used. The upper bound is given by the A1B scenario, the lower bound by the B2 scenario.

Data Processing:
The observations are shown as annual means. No smoothing is applied. The projections have been aligned to match the mean observed value for year 1990.

Figure 1.7

Documentation of Data Sources:

Observed CH_4 Concentrations
Global annual mean CH_4 concentrations and uncertainty estimates are based on NOAA Earth System Research Laboratory measurements provided by Ed Dlugokencky in June 2012. These are updated from Dlugokencky et al. (2009).

IPCC Range of Projections

FAR: The data have been graphically traced from FAR SPM Figure 5 in 5 year increments.

Year	Lower bound (Scenario D)	Upper bound (Business as Usual)
1990	1692.67	1765.91
1995	1736.99	1866.64
2000	1789.36	1978.08
2005	1793.71	2112.01
2010	1809.11	2232.88
2015	1823.93	2356.49

SAR: The data were taken in 5 year increments from table 2.5a in Chapter 2. The upper bound is given by the IS92e scenario, the lower bound by the IS92d scenario.

TAR: The data were taken in 10 year increments from table Appendix II SRES Data Tables Table II.2.2. 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 (provided by Malte Meinshausen). Annual means are used. The upper bound is given by the A1B scenario, the lower bound by the B1 scenario.

Data Processing:
The observations are shown as annual means. No smoothing is applied. The projections have been aligned to match the mean observed value for year 1990.

Figure 1.8

Documentation of Data Sources:

Observed N_2O Concentrations
Global annual mean N_2O concentrations and uncertainty estimates are based on NOAA Earth System Research Laboratory measurements downloaded from http://www.esrl.noaa.gov/gmd/hats/combined/N2O.html. These are provided as monthly data. Annual means were calculated from these. The whiskers show the 1-sigma error.

IPCC Range of Projections

FAR: The data have been graphically traced from FAR A3 in 5 year increments.

Year	Lower bound (Scenario D)	Upper bound (Business as Usual)
1990	306.569	307.000
1995	310.014	311.585
2000	313.298	315.942
2005	316.703	321.259
2010	320.027	326.356
2015	323.192	331.452

SAR: The data were taken in 5 year increments from table 2.5b in Chapter 2. The upper bound is given by the IS92e scenario, the lower bound by the IS92d scenario.

TAR: The data were taken in 10 year increments from table Appendix II SRES Data Tables Table II.2.3. The upper bound is given by the A2 scenario, the lower bound by the B2 scenario.

AR4: The data used was obtained from Figure 10.26 in Chapter 10 of AR4 (provided by Malte Meinshausen). Annual means are used. The upper bound is given by the A2 scenario, the lower bound by the A1T scenario.

Data Processing:
The observations are shown as annual means. No smoothing is applied. The projections have been aligned to match the mean observed value for year 1990.

Figure 1.11

Documentation of Data Sources:

Observed Global Mean Sea Level Rise

Tide gauge data (Church and White, 2011): The data were downloaded at http://www.cmar.csiro.au/sealevel/sl_data_cmar.html in July 2012. Anomalies were calculated relative to 1990. Uncertainty estimates are given.

Altimeter data: The data were downloaded at http://sealevel.colorado.edu/results.php in July 2012. There are no uncertainty estimates. All provided values for each year were averaged to calculate annual means.

IPCC Range of Projections

FAR: The data have been graphically traced from Chapter 9 Figure 9.6 for the upper bound and Figure 9.7 for the lower bound in 5 year increments as anomalies relative to 1990.

Year	Lower bound (Scenario D)	Upper bound (Business as Usual)
1990	0.00	0.00
1995	0.74	3.14
2000	1.83	6.12
2005	2.69	9.43
2010	3.54	13.14
2015	4.57	16.98

SAR: The data have been graphically traced from Figure 21 in 5 year increments as anomalies relative to 1990 (cm).

Year	Lower bound (IS92c/1.5)	Upper bound (IS92e/4.5)
1990	0.00	0.00
1995	0.53	2.58
2000	0.94	4.70
2005	1.43	7.16
2010	1.84	9.94
2015	2.17	13.21

TAR: The data are given in Table II.5.1 in 10 year increments.

AR4: Based on the CMIP3 model results available at the time of AR4 the SRES A1B scenario is used from Church et al (2011). The data start in 2001 and are given as anomalies with respect to 1990. Values for 1990-2000 have been linearly interpolated and thus do not account for variability.

Data Processing:
The global mean sea level reconstructions from tide gauges (Church and White, 2011) are shown as annual means relative to 1990. No smoothing is applied. Whiskers give the 1-σ uncertainty range. The altimeter data start in 1992 and were aligned to match the 1993 value of the reconstructions by Church and White (2011).

Chapter 1: Introduction

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Figures

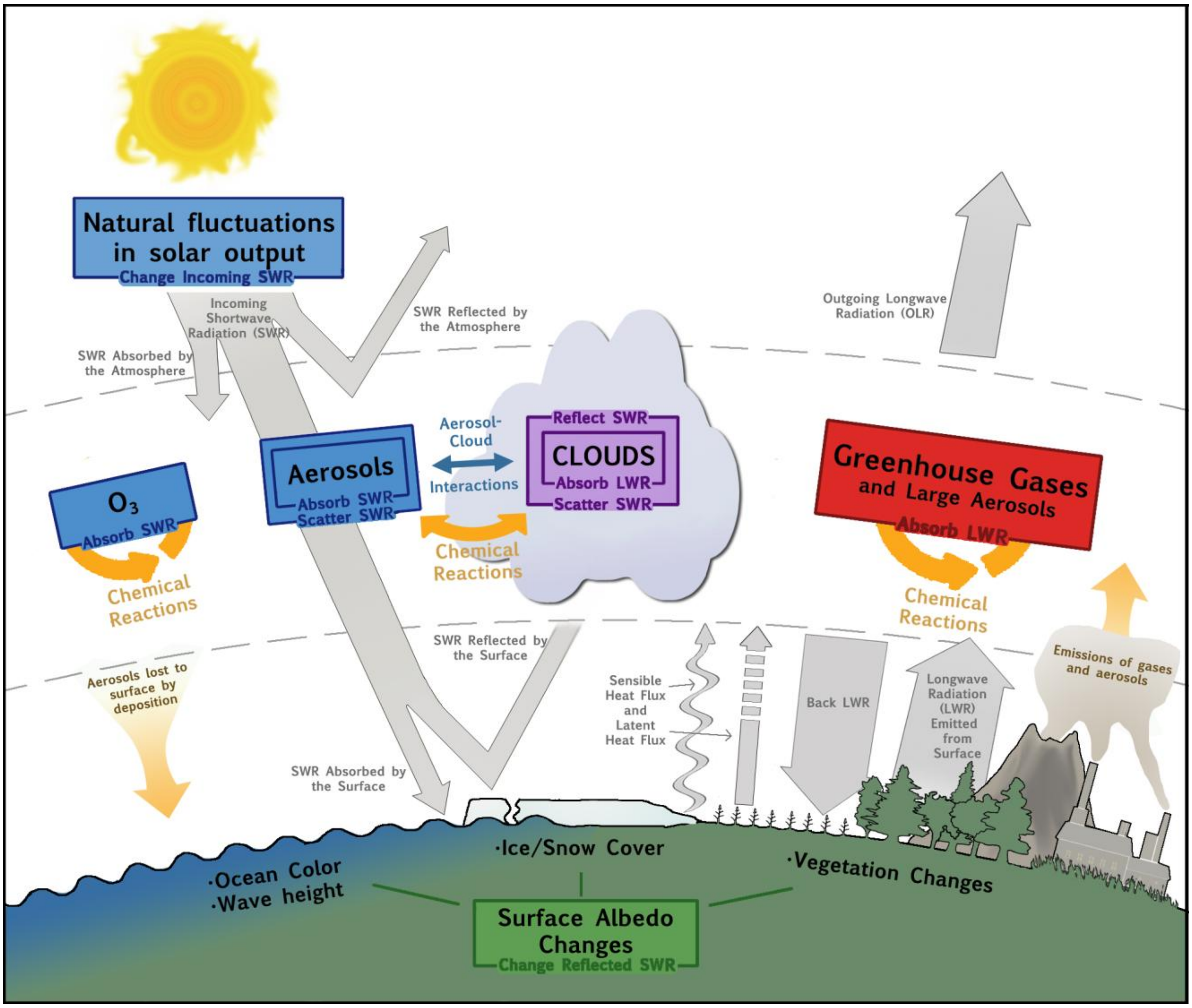


Figure 1.1: Main drivers of climate change. The energy balance between incoming solar shortwave radiation (SWR) and outgoing longwave radiation (LWR) is influenced by global climate "drivers". Natural fluctuations in solar output (solar cycles) can cause changes in the energy balance (incoming SWR). Human activity changes the emissions of gases and particles, which are involved in atmospheric chemical reactions, resulting in modified O_3 and aerosol amounts. O_3 and aerosols scatter and reflect SWR, changing the energy balance. Some aerosol particles act as cloud condensation nuclei (CCN) modifying the properties of cloud droplets. Since cloud interactions with SWR and LWR are large, small changes in the properties of clouds have important implications for the radiative budget. Anthropogenic changes in greenhouse gases (e.g., CO_2, CH_4, N_2O, O_3, CFCs, etc.) and large aerosols modify the LWR by absorbing outgoing LWR and reemitting less energy at a lower temperature. Surface albedo is changed by changes in vegetation or land surface cover, snow or ice cover and ocean colour. These changes are driven by natural seasonal and diurnal changes (e.g., snow cover), as well as human influence (e.g., changes in vegetation height).

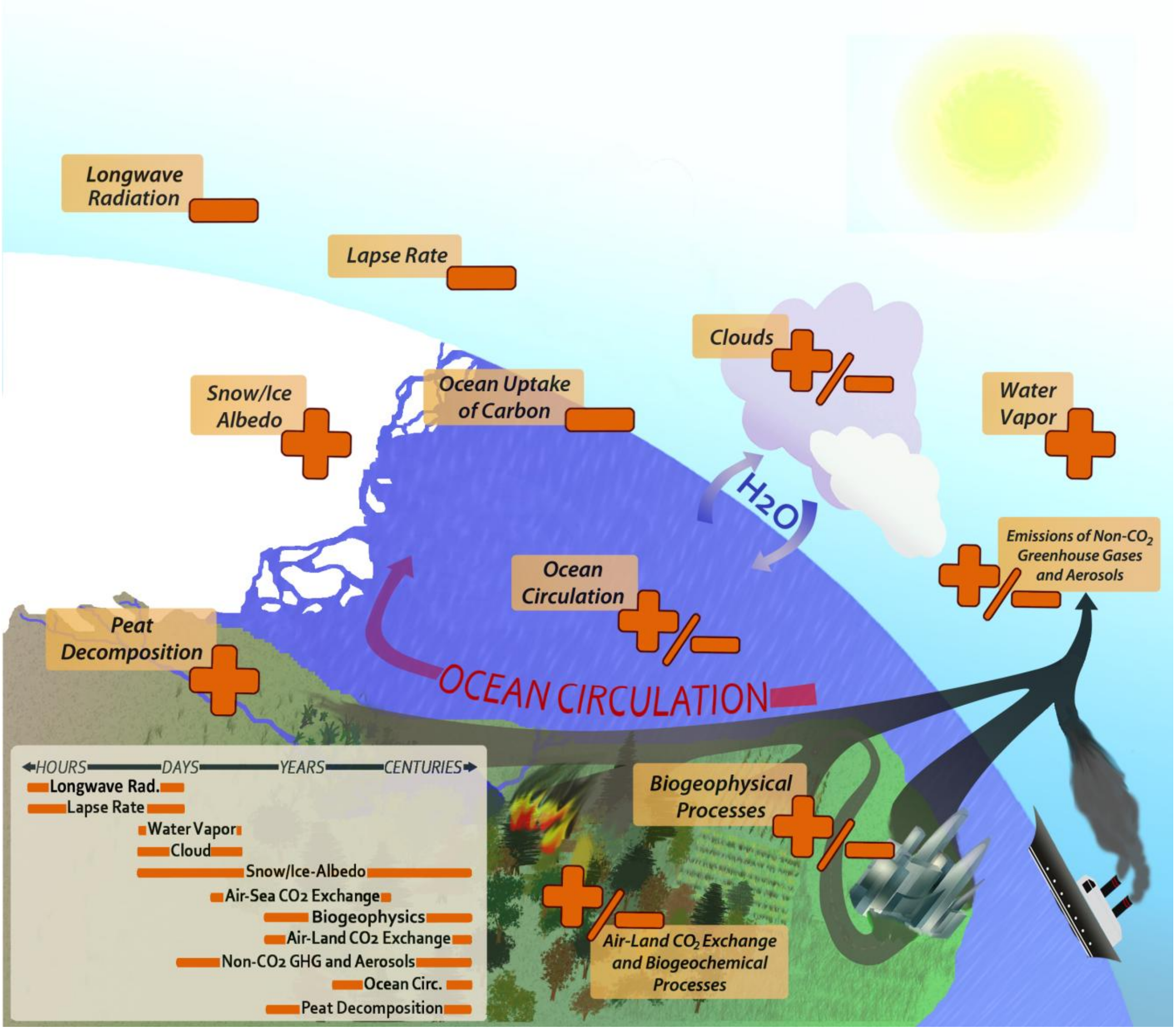
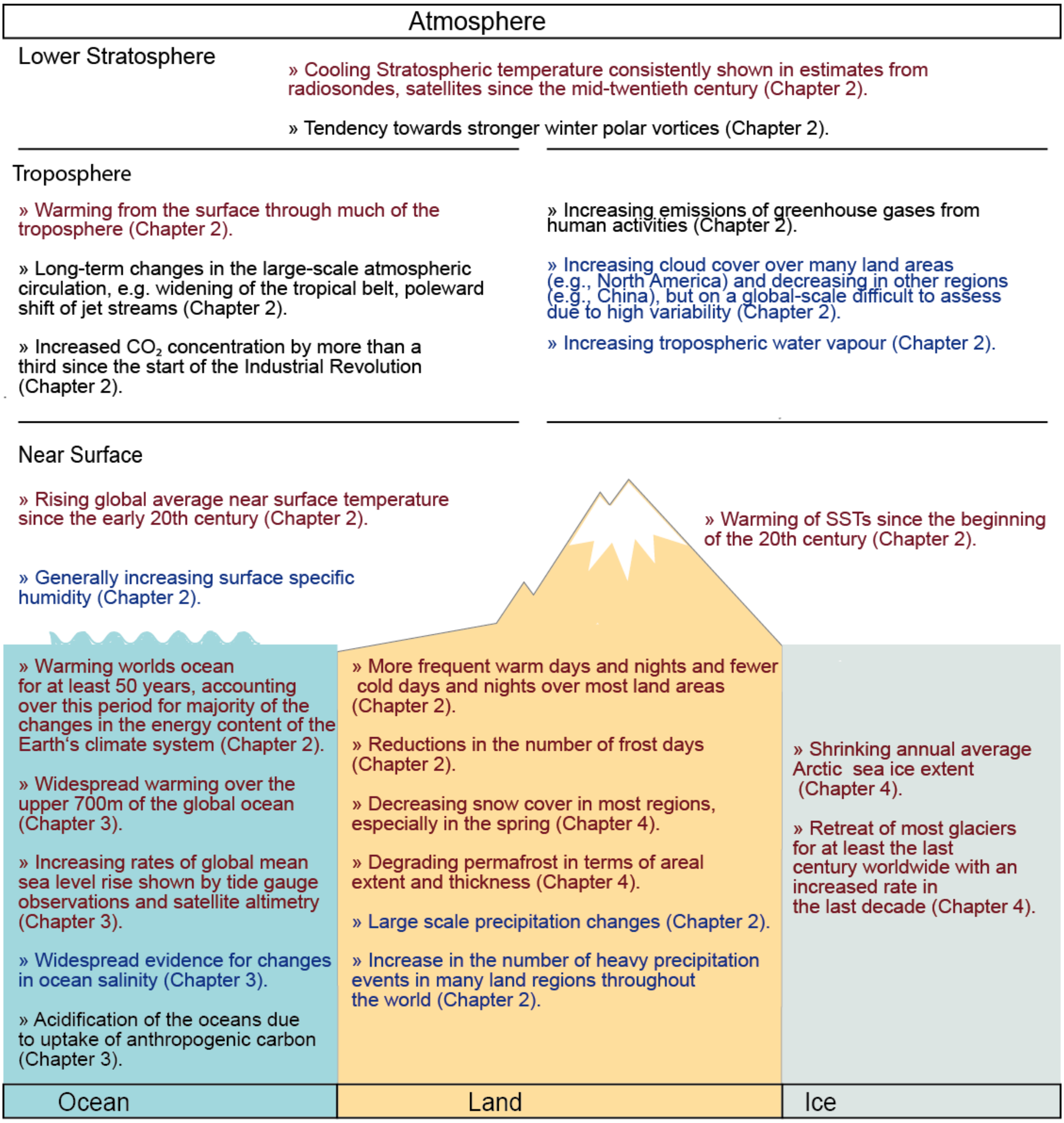


Figure 1.2: Climate feedbacks and timescales. The climate feedbacks from increasing carbon dioxide and rising temperature include negative feedbacks (–) such as longwave radiation, lapse rate, and ocean uptake of carbon dioxide feedbacks. Positive feedbacks (+) include water vapour and the snow/ice albedo feedbacks. Some feedbacks may be positive or negative (±): clouds, ocean circulation changes, air-land carbon dioxide exchange, and emissions of non-green house gases and aerosols from natural systems In the smaller box, the large difference in time scale for the various feedbacks is highlighted.



Atmosphere

Lower Stratosphere

» Cooling Stratospheric temperature consistently shown in estimates from radiosondes, satellites since the mid-twentieth century (Chapter 2).

» Tendency towards stronger winter polar vortices (Chapter 2).

Troposphere

» Warming from the surface through much of the troposphere (Chapter 2).

» Long-term changes in the large-scale atmospheric circulation, e.g. widening of the tropical belt, poleward shift of jet streams (Chapter 2).

» Increased CO_2 concentration by more than a third since the start of the Industrial Revolution (Chapter 2).

» Increasing emissions of greenhouse gases from human activities (Chapter 2).

» Increasing cloud cover over many land areas (e.g., North America) and decreasing in other regions (e.g., China), but on a global-scale difficult to assess due to high variability (Chapter 2).

» Increasing tropospheric water vapour (Chapter 2).

Near Surface

» Rising global average near surface temperature since the early 20th century (Chapter 2).

» Generally increasing surface specific humidity (Chapter 2).

» Warming of SSTs since the beginning of the 20th century (Chapter 2).

Ocean

» Warming worlds ocean for at least 50 years, accounting over this period for majority of the changes in the energy content of the Earth's climate system (Chapter 2).

» Widespread warming over the upper 700m of the global ocean (Chapter 3).

» Increasing rates of global mean sea level rise shown by tide gauge observations and satellite altimetry (Chapter 3).

» Widespread evidence for changes in ocean salinity (Chapter 3).

» Acidification of the oceans due to uptake of anthropogenic carbon (Chapter 3).

Land

» More frequent warm days and nights and fewer cold days and nights over most land areas (Chapter 2).

» Reductions in the number of frost days (Chapter 2).

» Decreasing snow cover in most regions, especially in the spring (Chapter 4).

» Degrading permafrost in terms of areal extent and thickness (Chapter 4).

» Large scale precipitation changes (Chapter 2).

» Increase in the number of heavy precipitation events in many land regions throughout the world (Chapter 2).

Ice

» Shrinking annual average Arctic sea ice extent (Chapter 4).

» Retreat of most glaciers for at least the last century worldwide with an increased rate in the last decade (Chapter 4).

Figure 1.3: Overview of observed climate variations since pre-industrial times unless stated otherwise (temperature: red; hydrological: blue; others: black).

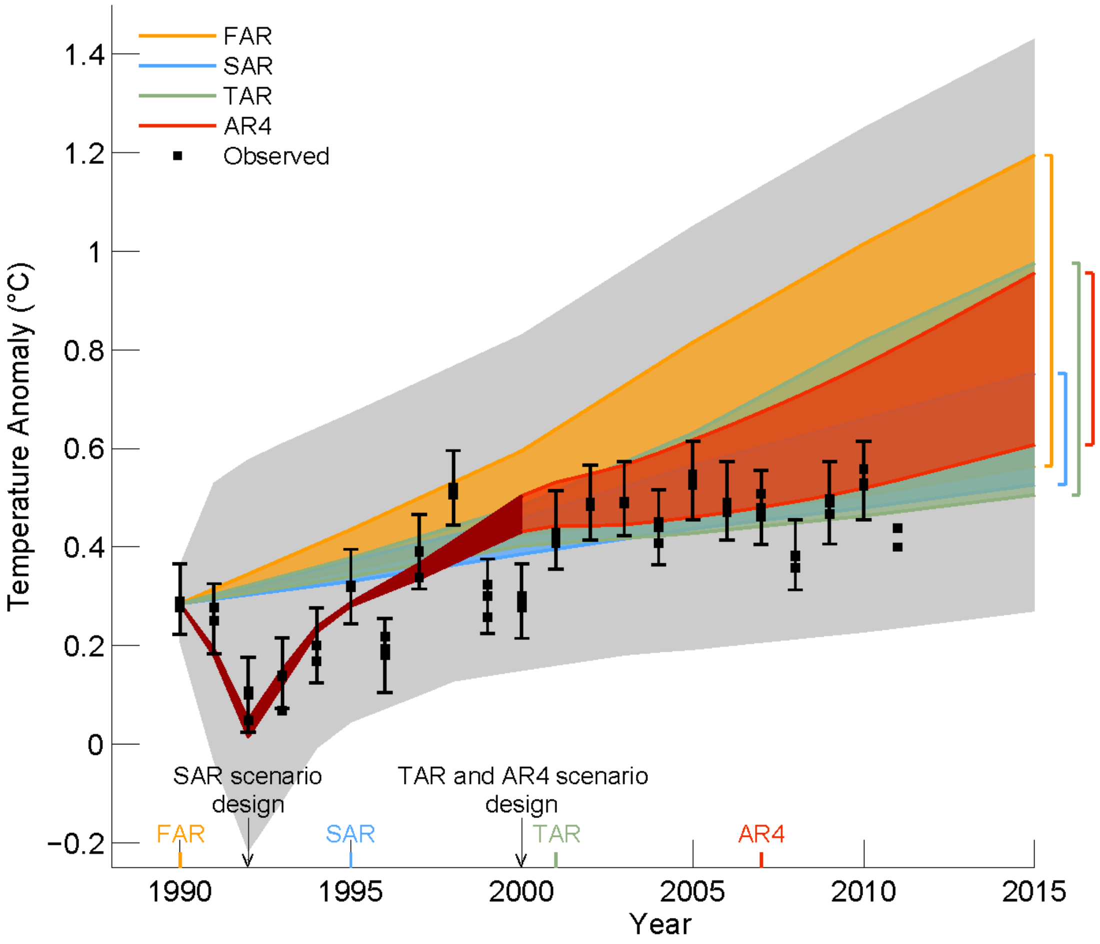


Figure 1.4: [PLACEHOLDER FOR FINAL DRAFT: Observational datasets will be updated as soon as they become available] Estimated changes in the observed globally and annually averaged surface temperature (in °C) since 1990 compared with the range of projections from the previous IPCC assessments. Values are aligned to match the average observed value at 1990. Observed global annual temperature change, relative to 1961–1990, is shown as black squares (NASA (updated from Hansen et al., 2010; data available at http://data.giss.nasa.gov/gistemp/); NOAA (updated from Smith et al., 2008; data available at http://www.ncdc.noaa.gov/cmb-faq/anomalies.html#grid); and the UK Hadley Centre (Morice et al., 2012; data available at http://www.metoffice.gov.uk/hadobs/hadcrut4/) reanalyses). Whiskers indicate the 90% uncertainty range of the Morice et al. (2012) dataset from measurement and sampling, bias and coverage (see Appendix for methods). The coloured shading shows the projected range of global annual mean near surface temperature change from 1990 to 2015 for models used in FAR (Scenario D and business-as-usual), SAR (IS92c/1.5 and IS92e/4.5), TAR (full range of TAR Figure 9.13(b) based on the GFDL_R15_a and DOE PCM parameter settings), and AR4 (A1B and A1T). The 90% uncertainty estimate due to observational uncertainty and internal variability based on the HadCRUT4 temperature data for 1951-1980 is depicted by the grey shading. Moreover, the publication years of the assessment reports and the scenario design are shown.

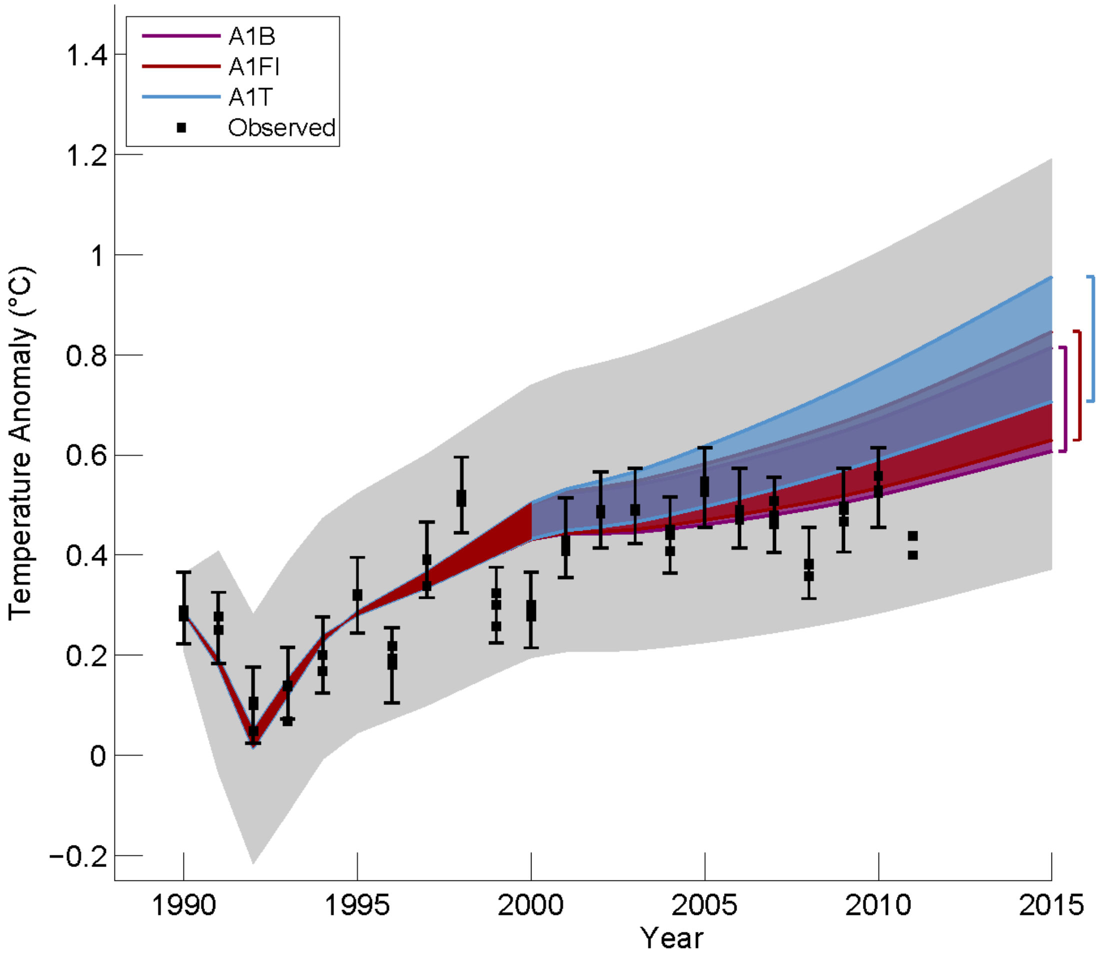


Figure 1.5: [PLACEHOLDER FOR FINAL DRAFT: Observational datasets will be updated as soon as they become available] Similar to Figure 1.4 except that the focus is now on the range of selected scenario projections from AR4. The shading shows high, low and mid-range SRES scenarios from AR4 for the years 1990–2015 of global annual mean near surface temperature change (note that these are high, mid-range, and low for this time period, not at end of the 21st century). SRES data was obtained from Figure 10.26 in Chapter 10 of AR4 and re-calculated to a baseline period of 1961–1990.

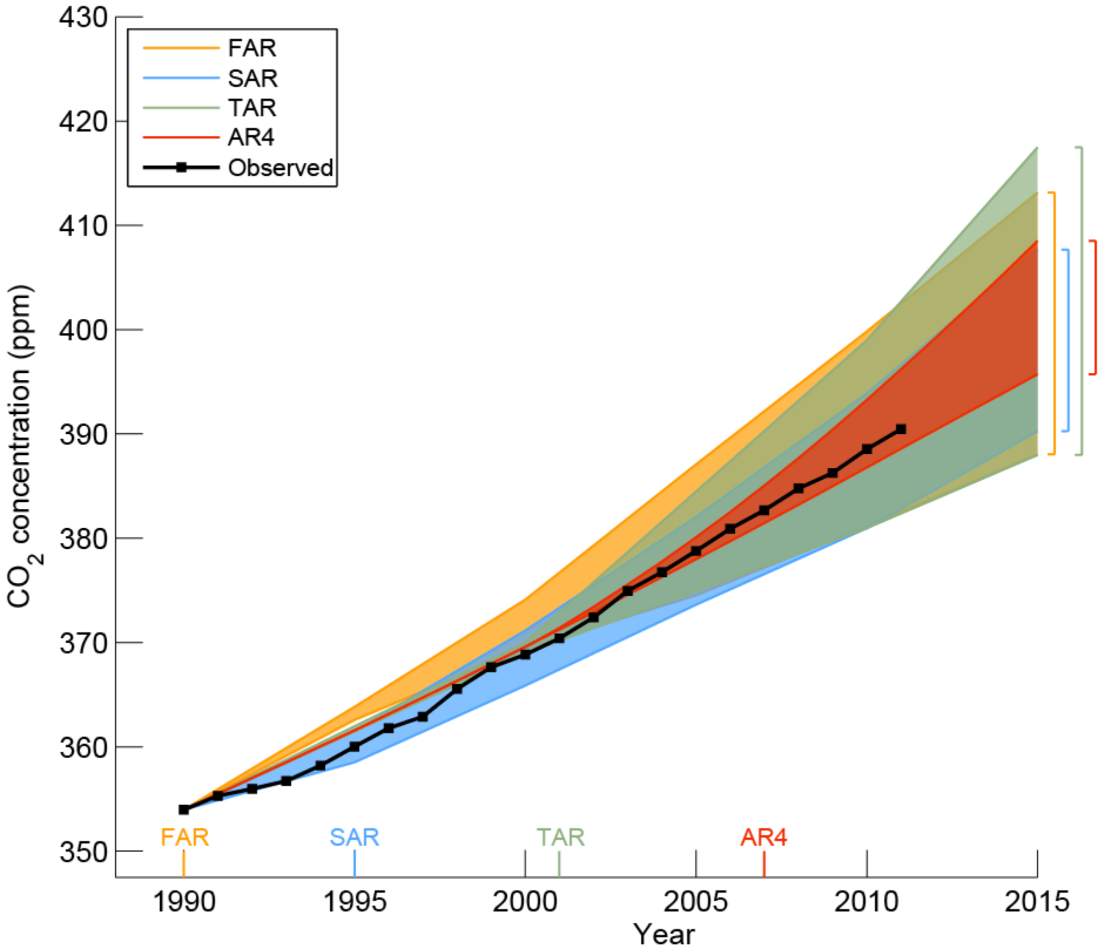


Figure 1.6: [PLACEHOLDER FOR FINAL DRAFT: Observational datasets will be updated as soon as they become available] Observed globally and annually averaged carbon dioxide concentrations in parts per million (ppm) since 1990 compared with projections from the previous IPCC assessments. Observed global annual CO$_2$ concentrations are shown in black (based on NOAA Earth System Research Laboratory measurements, http://www.esrl.noaa.gov/gmd/ccgg/trends/global.html). The uncertainty of the observed values is 0.1 ppm. The shading shows the largest model projected range of global annual CO$_2$ concentrations from 1990 to 2015 from FAR (Scenario D and business-as-usual), SAR (IS92c and IS92e), TAR (B2 and A1p), and AR4 (B2 and A1B). Moreover, the publication years of the assessment reports are shown.

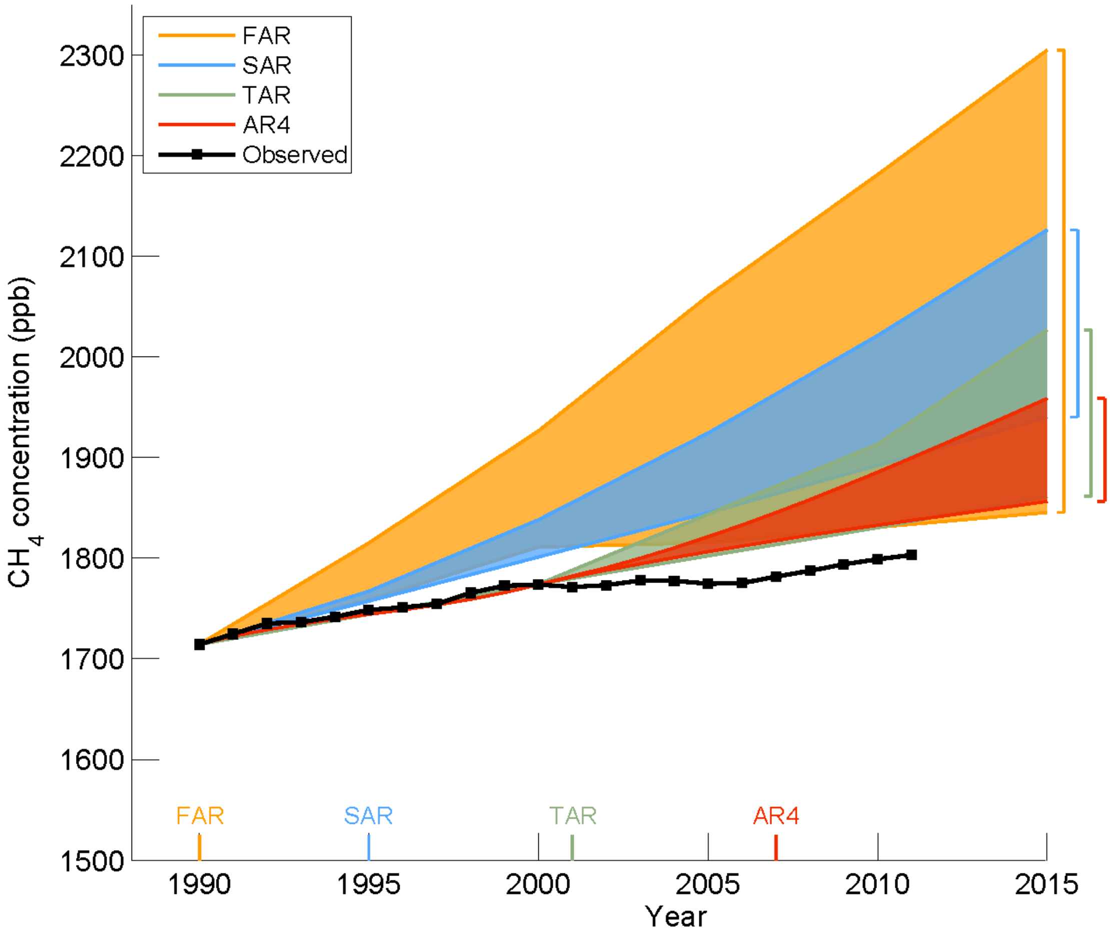


Figure 1.7: [PLACEHOLDER FOR FINAL DRAFT: Observational datasets will be updated as soon as they become available] Observed globally and annually averaged methane concentrations in parts per billion (ppb) since 1990 compared with projections from the previous IPCC assessments. Estimated observed global annual CH_4 concentrations are shown in black (NOAA Earth System Research Laboratory measurements, updated from Dlugokencky et al., 2009 see http://www.esrl.noaa.gov/gmd). The shading shows the largest model projected range of global annual CH_4 concentrations from 1990–2015 from FAR (Scenario D and business-as-usual), SAR (IS92d and IS92e), TAR (B1p and A1p), and AR4 (B1 and A1B). Uncertainties in the observations are less than 1.5 ppb. Moreover, the publication years of the assessment reports are shown.

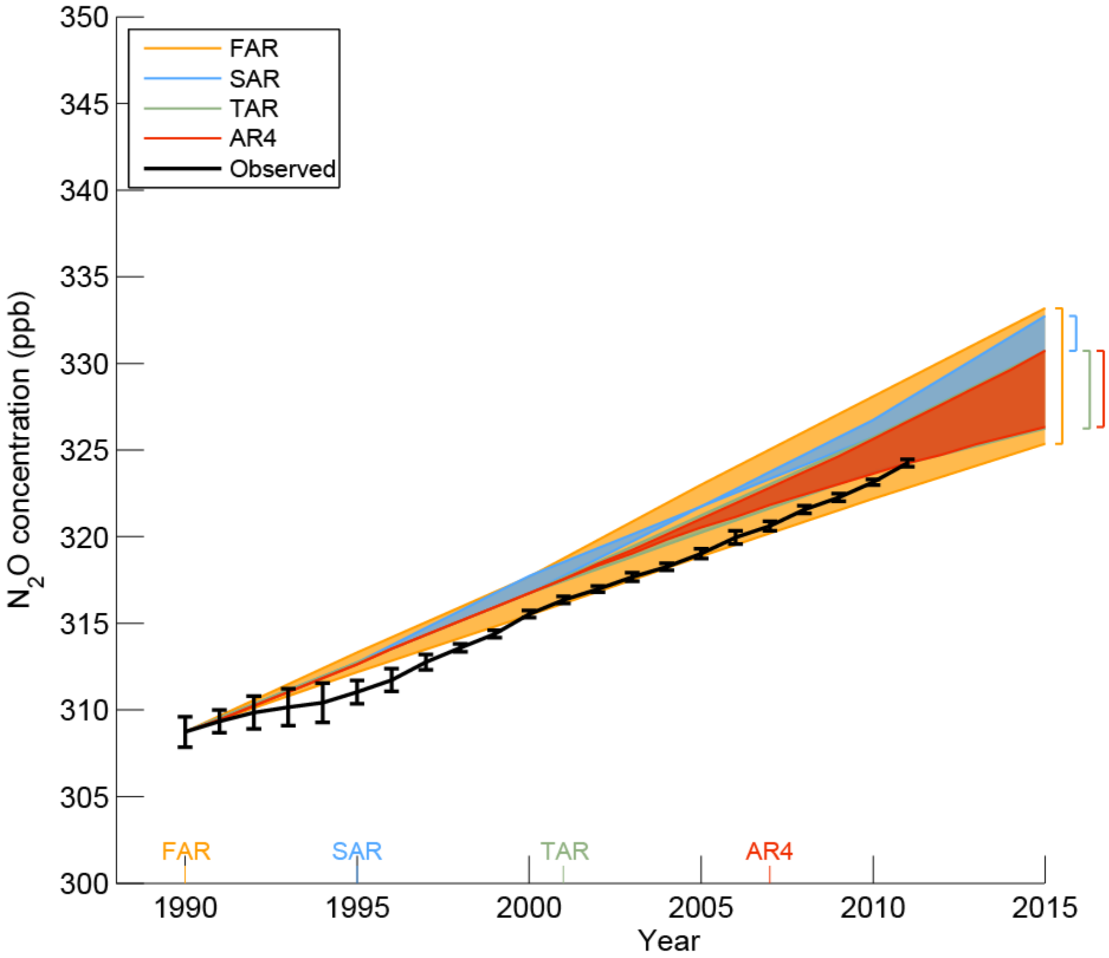


Figure 1.8: [PLACEHOLDER FOR FINAL DRAFT: Observational datasets will be updated as soon as they become available] Observed globally and annually averaged nitrous oxide (N_2O) concentrations in parts per billion (ppb) since 1990 compared with projections from the previous IPCC assessments. Observed global annual N_2O concentrations are shown in black (NOAA Earth System Research Laboratory measurements, updated from Elkins and Dutton, 2010; see http://www.esrl.noaa.gov/gmd/) with whiskers indicating the 1-σ error. The shading shows the largest model projected range of global annual N_2O concentrations from 1990 to 2015 from FAR (Scenario D and business-as-usual), SAR (IS92d and IS92e), TAR (B2 and A2), and AR4 (A1T and A2). Moreover, the publication years of the assessment reports are shown.

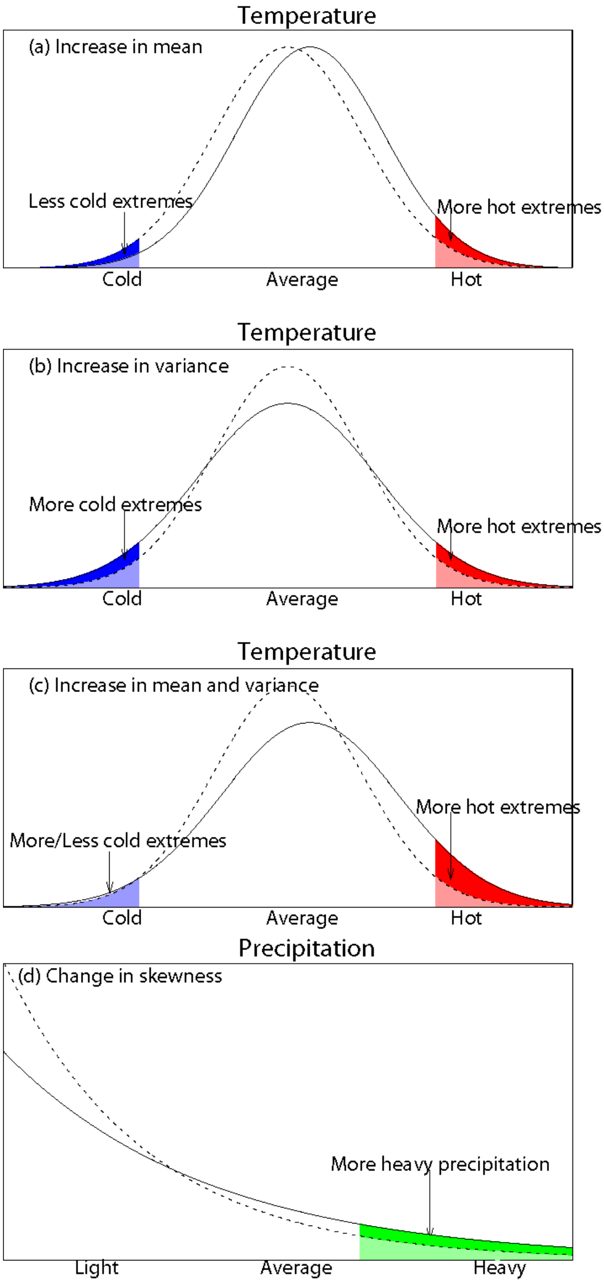
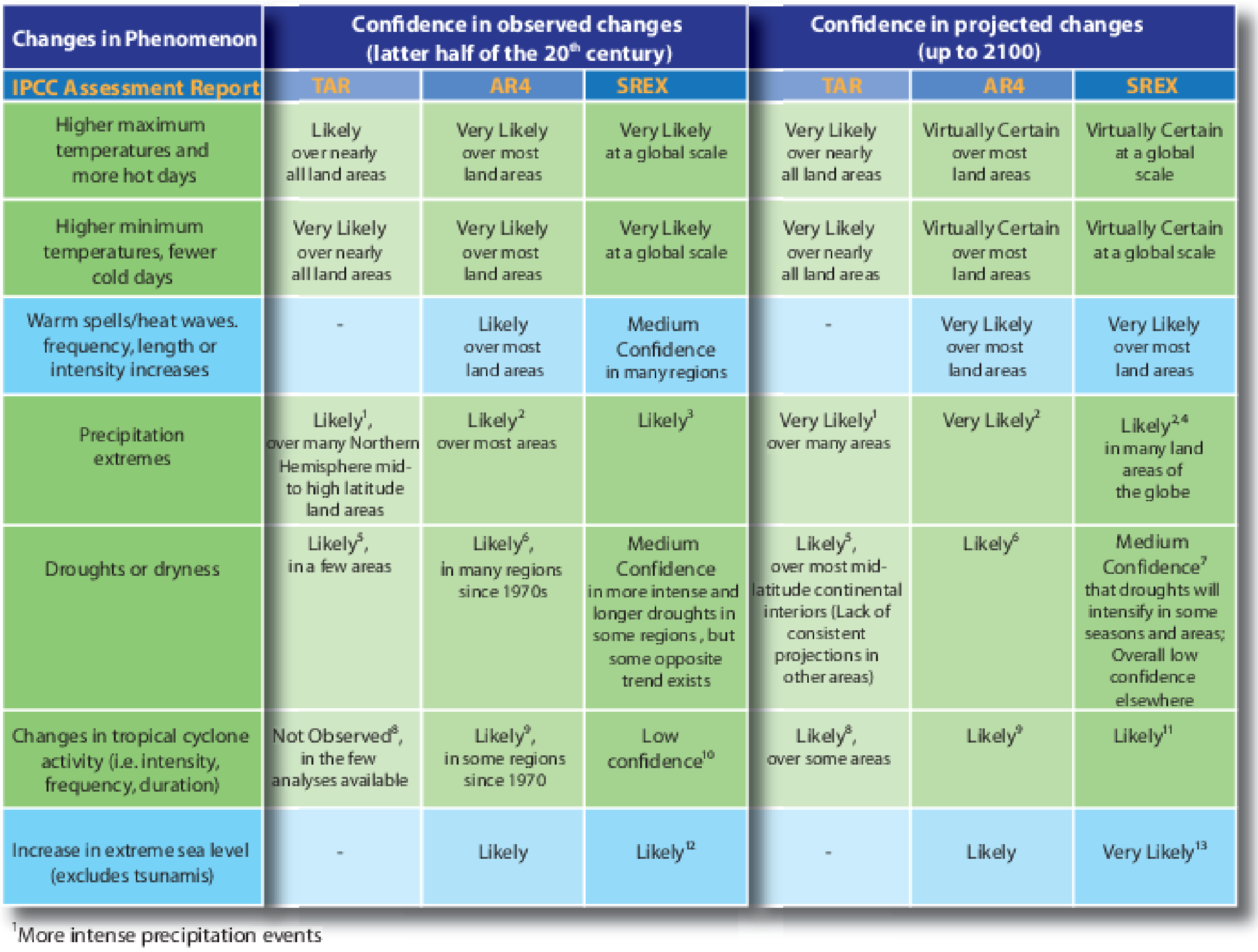


Figure 1.9: Schematic representations of the probability density function of daily temperature, which tends to be approximately Gaussian, and daily precipitation, which has a skewed distribution. Dashed lines represent a previous distribution, e.g., at the beginning of the 20th century, and solid lines a changed distribution, e.g., at end of 21st century. 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, 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 likely 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. Figure 1a-1c modified from IPCC (2001, Chapter 2) and Figure 1d modified from Peterson et al. (2008). See Zhang and Zwiers (2012).



Changes in Phenomenon	Confidence in observed changes (latter half of the 20th century)			Confidence 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 1.10: Change in the confidence levels for extreme events based on the prior TAR, AR4, and SREX assessments. Phenomena which are mentioned in all three reports are highlighted in green. Confidence levels are defined in Section 1.4.

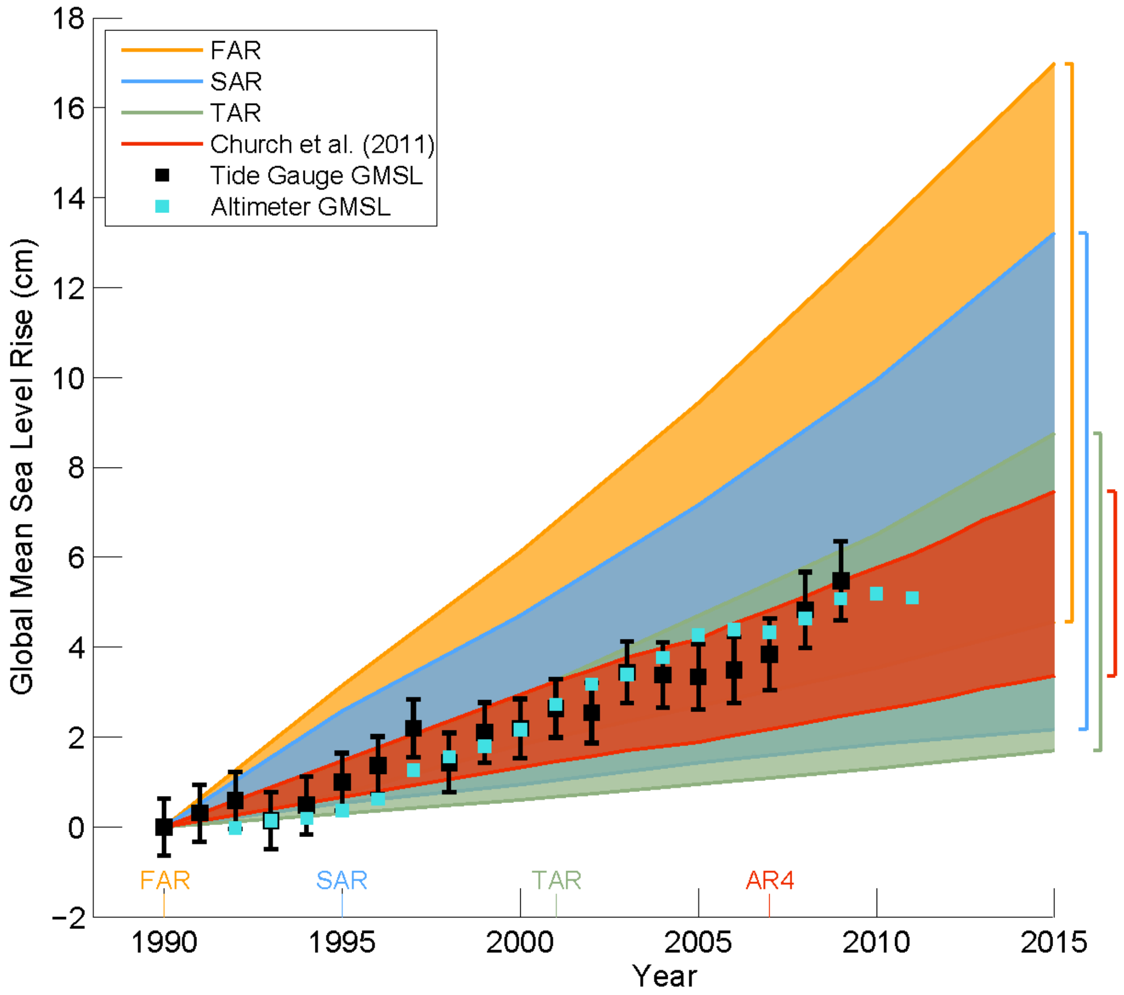


Figure 1.11: [PLACEHOLDER FOR FINAL DRAFT: Observational datasets will be updated as soon as they become available] Estimated changes in the observed global annual sea level since 1990. Estimated changes in global annual sea level anomalies from tide gauge data (Church and White, 2011; available at http://www.cmar.csiro.au/sealevel/sl_data_cmar.html) (black error bars showing 1σ uncertainty) and based on annual averages from TOPEX and Jason satellites (Nerem et al., 2010; available at http://sealevel.colorado.edu/results.php) (blue dots) starting in 1992 (the values have been aligned to fit the 1993 value of the tide gauge data). The shading shows the largest model projected range of global annual sea level rise from 1990 to 2015 for FAR (Scenario D and business-as-usual), SAR (IS92c and IS92e), TAR (A2 and A1FI) and for Church et al. (2011) based on the CMIP3 model results available at the time of AR4 using the SRES A1B scenario.

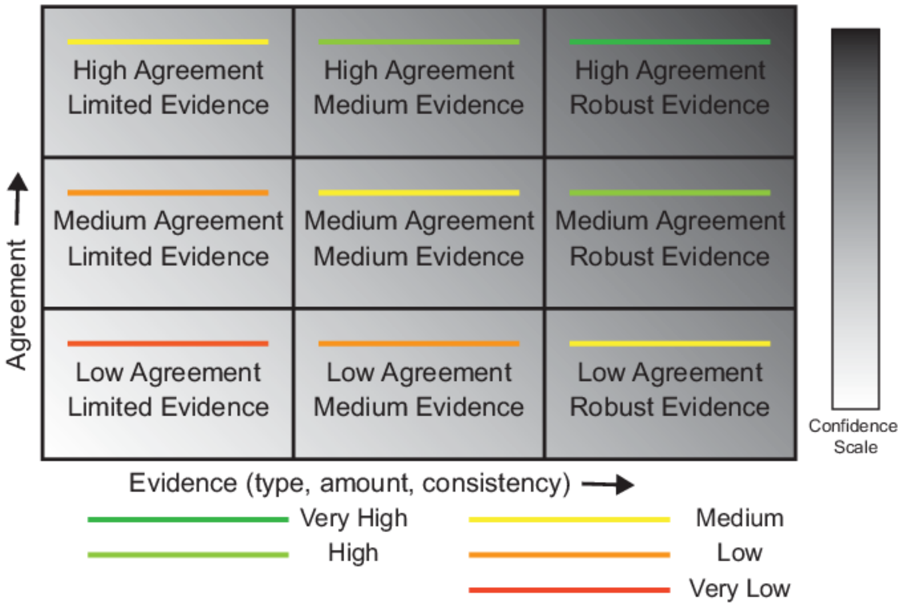


Figure 1.12: The basis for the confidence level is given as a combination of evidence (limited, medium, robust) and agreement (low, medium, and high). The confidence level is given for five levels (very high, high, medium, low, and very low) and given in colours (IPCC, 2012).

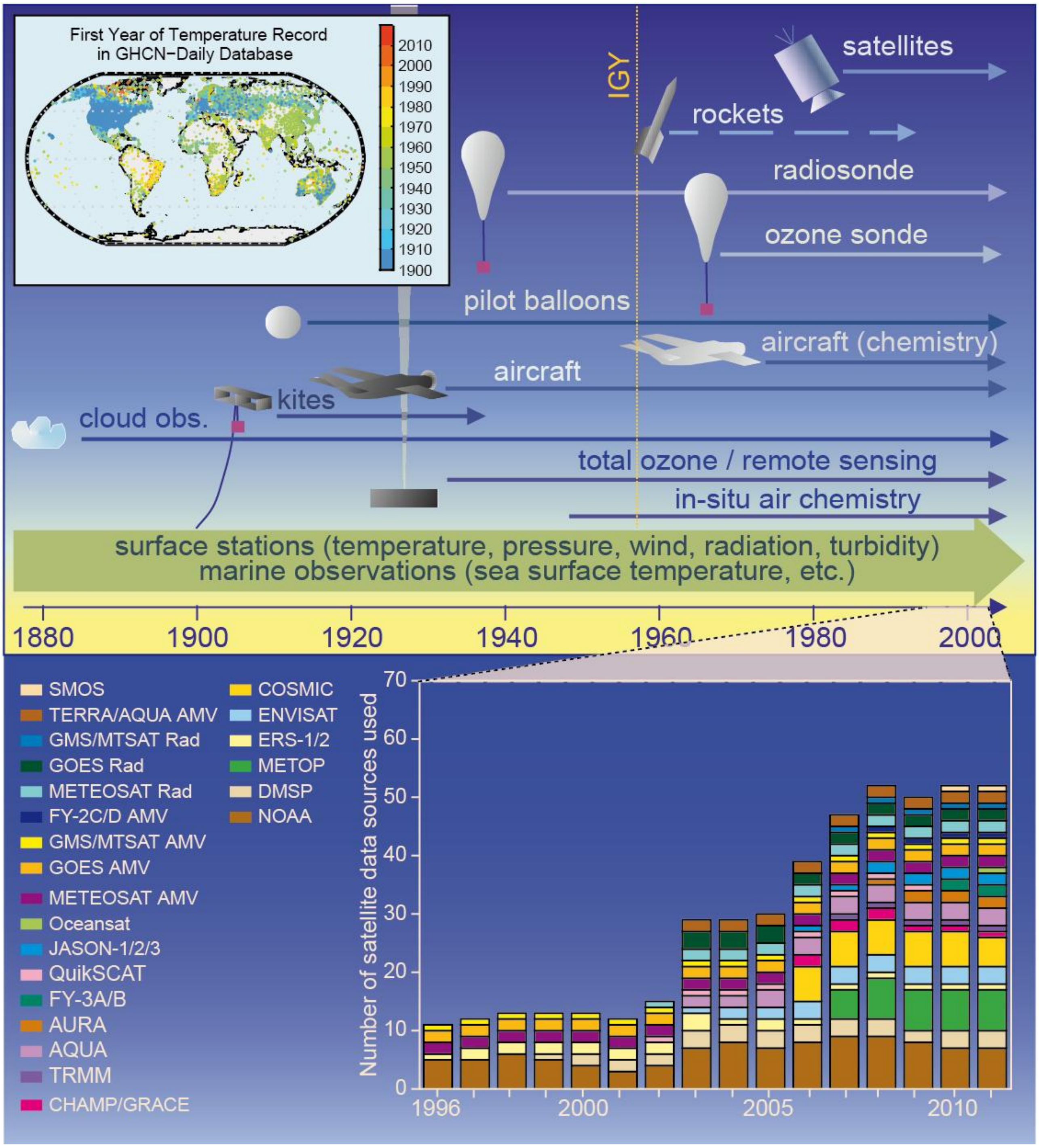


Figure 1.13: Development of Capabilities of Observations. Top (large figure): Changes in the mix and increasing diversity of observations over time create challenges for a consistent climate record (adapted from Brönnimann et al., 2008). Top (small figure): First year of temperature data in global historical climatology network daily database (available at http://www.ncdc.noaa.gov/oa/climate/ghcn-daily/; Menne et al., 2012). Bottom: Number of satellite instruments from which data have been assimilated in European Centre for Medium-Range Weather Forecasts' (ECMWF's) 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. Acronyms are spelled out in Table 1.2

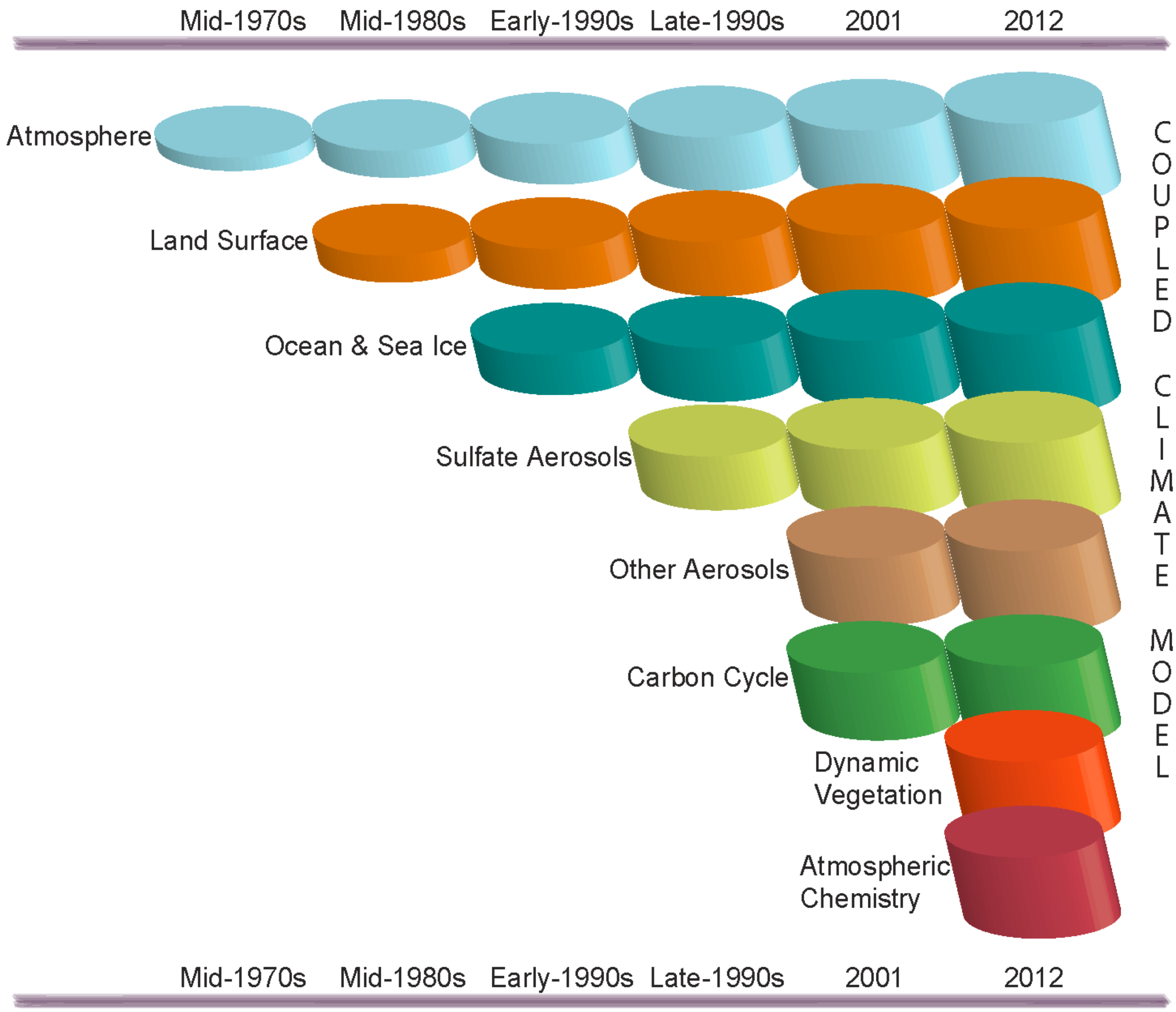
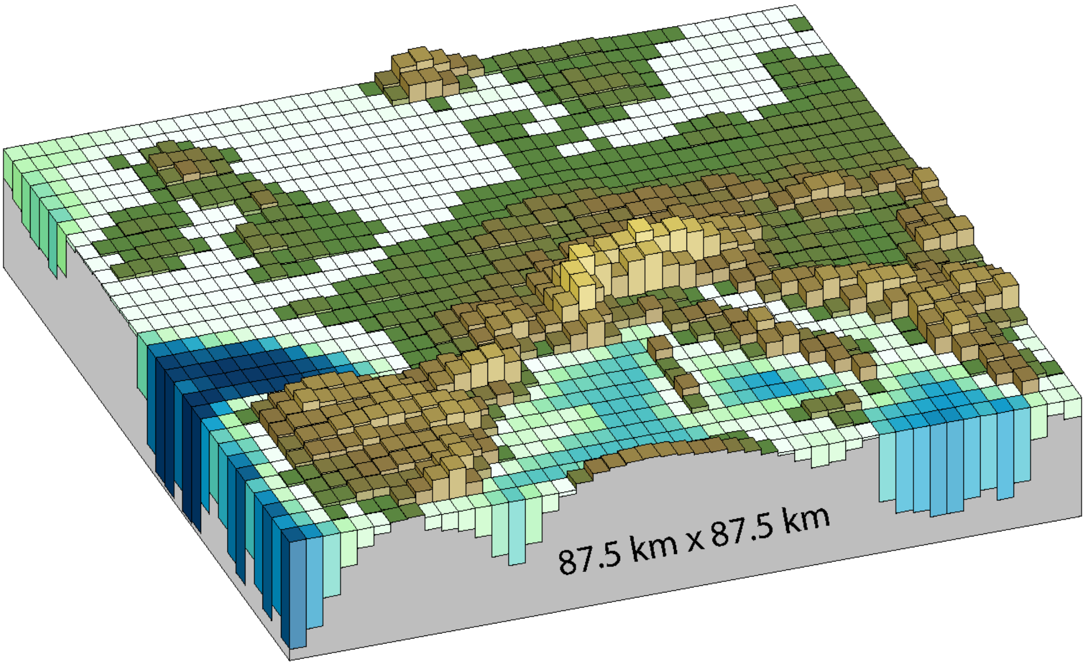


Figure 1.14: The development of climate models over the last 35 years showing how the different components are coupled into comprehensive climate models. Note that in the same time the horizontal and vertical resolution has increased considerably for example for spectral models from T21L9 (roughly 500 km) in the 1970s to T95L95 (roughly 100 km) at present, and that now ensembles with at least three independent experiments can be considered as standard.

a)



b)

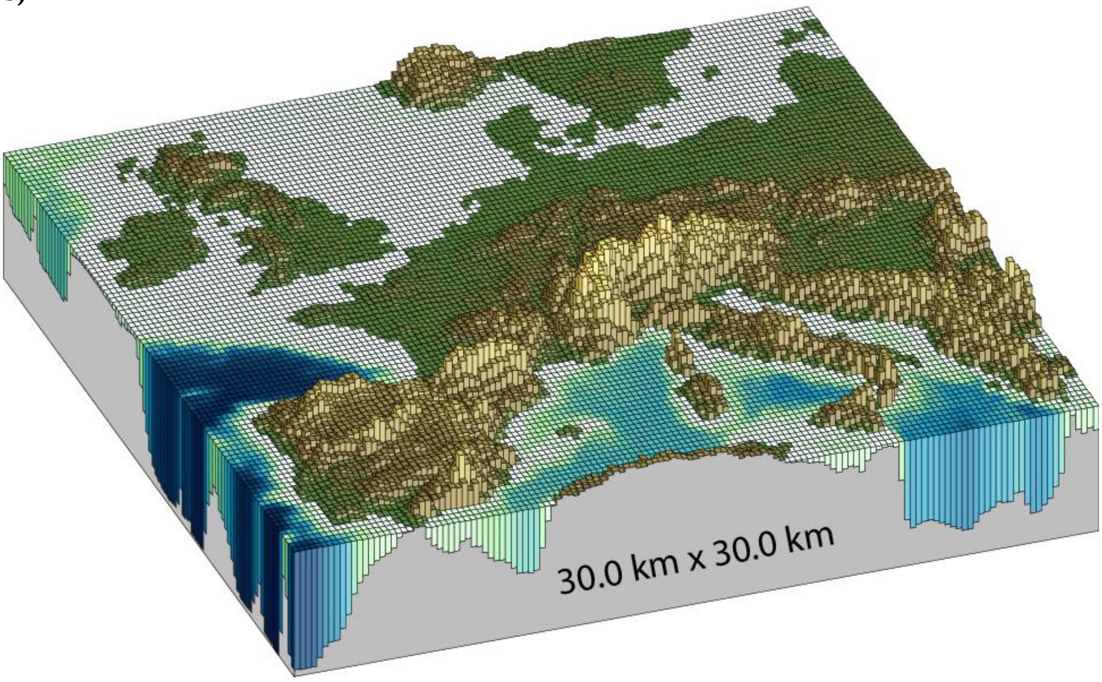


Figure 1.15: Horizontal resolutions considered in typical and higher resolution models. a) Illustration of the European topography at a resolution of 87.5 km x 87.5 km. b) Same but for a resolution of 30.0 km x 30.0 km.

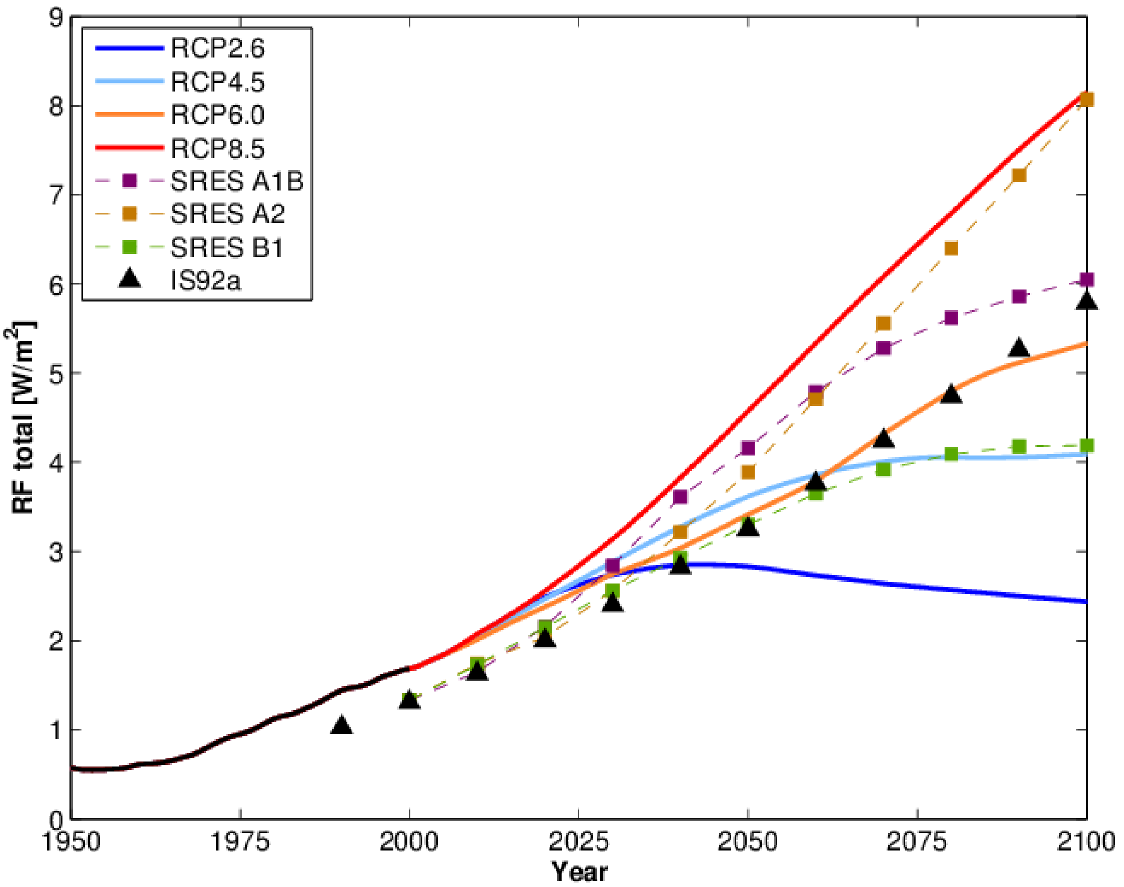
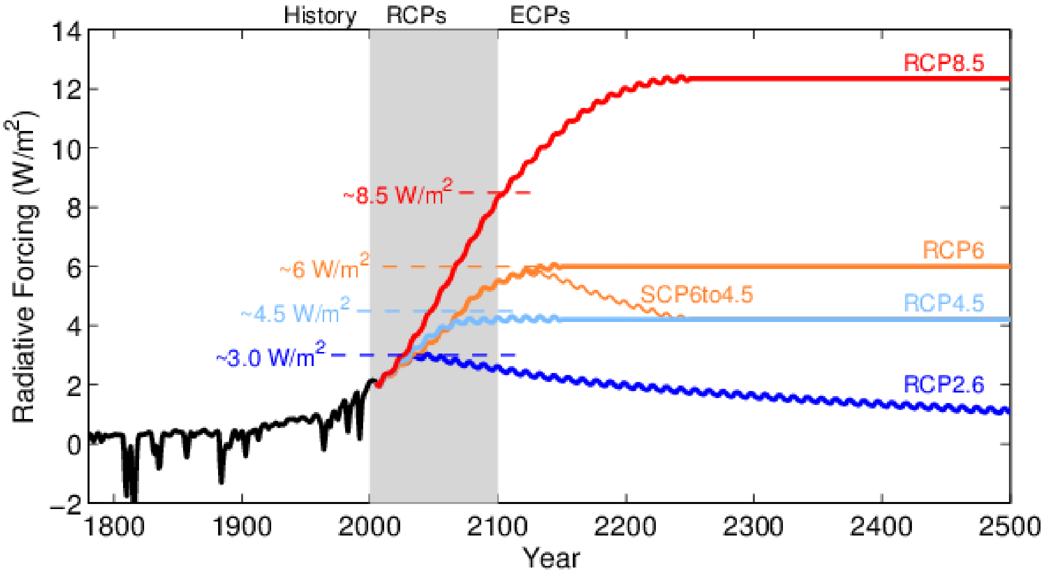
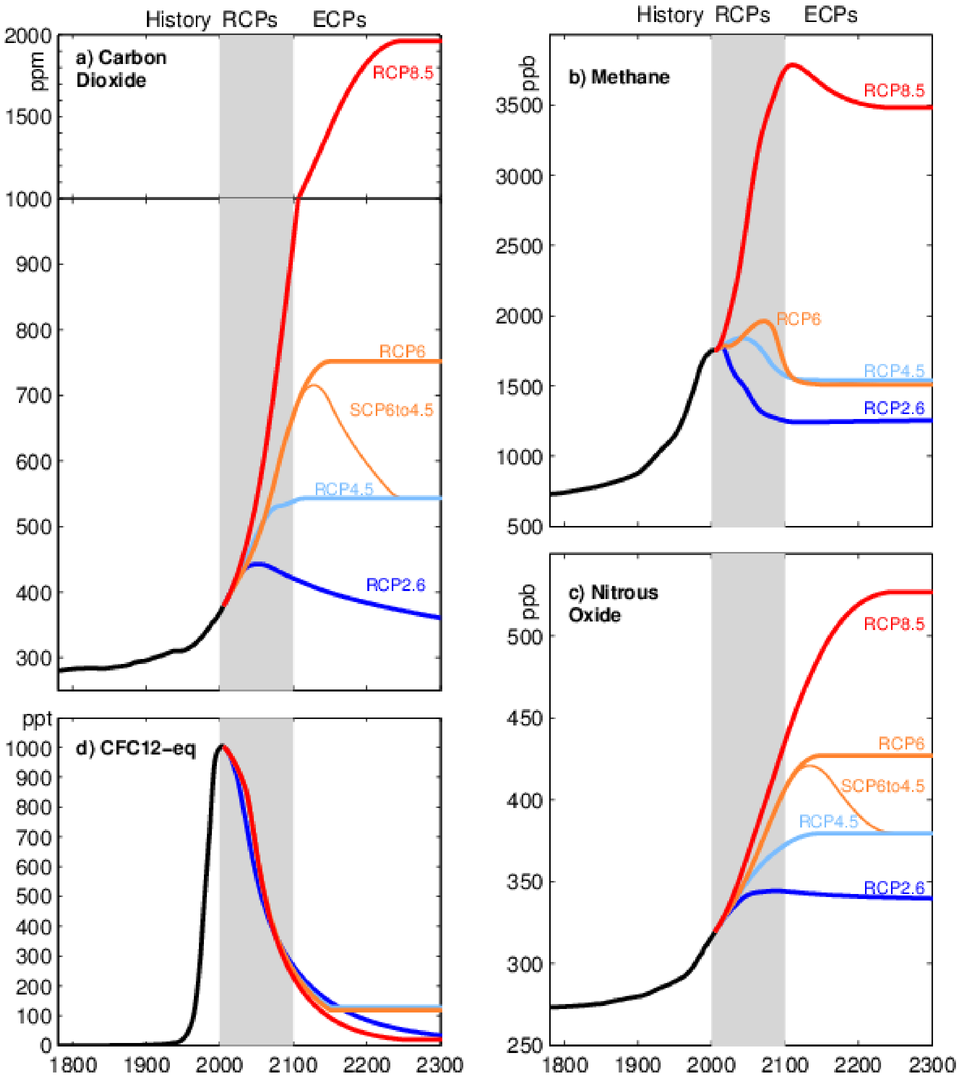


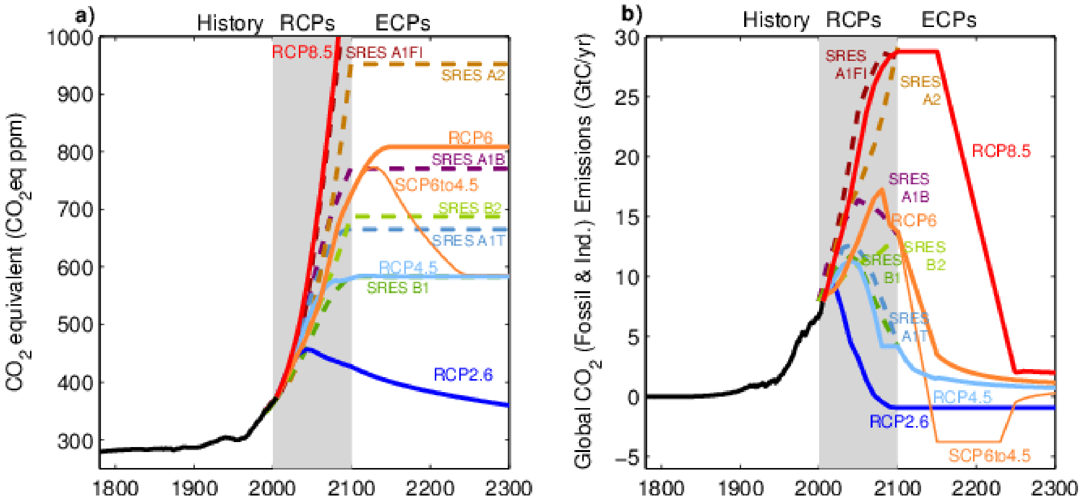
Figure 1.16: Historical and projected total anthropogenic radiative forcing (W m^{-2}) relative to preindustrial (~1765) between 1950 and 2100. Previous IPCC assessments (SAR IS92a, TAR/AR4 SRES A1B, A2 and B1) are compared with RCP scenarios (see Chapter 12 for their extensions until 2300 and Annex II for the values shown here). The total radiative forcing of the three families of scenarios, IS92, SRES and RCP, differ for example for the year 2000 as the number of forcings and our knowledge about them have changed since the TAR.



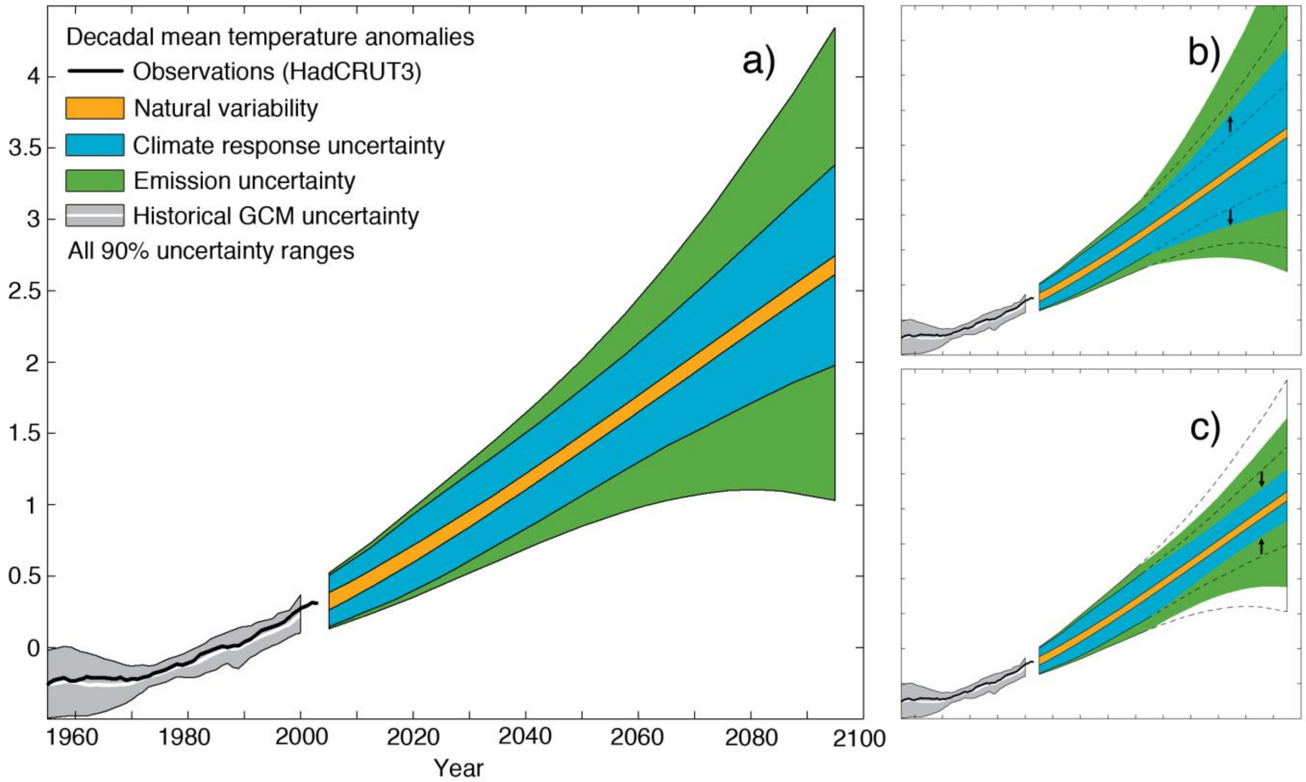
Box 1.2, Figure 1: Total radiative forcing (anthropogenic plus natural) for RCPs − supporting the original names of the four pathways as there is a close match between peaking, stabilization and 2100 levels for RCP2.6, RCP4.5 & RCP6, as well as RCP8.5, respectively. Note that the stated radiative forcing levels refer to the illustrative default median estimates only. There is substantial uncertainty in current and future radiative forcing levels. Short-term variations in radiative forcing 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 Fig.4 in Meinshausen et al., 2011).



Box 1.2, Figure 2: Concentrations of GHG following the 4 RCPs and their extensions to 2300. (Reproduced from Fig. 5 in Meinshausen et al., 2011).



Box 1.2, Figure 3: (a) Equivalent CO$_2$ concentration and (b) CO$_2$ emissions (except land use emissions) for the four RCP and some SRES scenarios.



FAQ 1.1, Figure 1: a) Mean surface temperature change from historical record (black line), with climate model estimates of uncertainty for historical period (grey), along with future climate projections and uncertainty. Natural variability (orange) derives from model interannual variability from IPCC Fourth assessment Report (2007) (AR4). Emission uncertainty (green) is estimated as the model mean difference in projections from the AR4. Climate response uncertainty (blue-solid) is based on climate model spread from AR4, 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 (2009) and Huntingford et al.(2009). b) Climate response uncertainty can grow when a new process is discovered to be relevant, or c) can decrease with additional model improvements and observational constraints.