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 the concerns about climate change. At the same time, the capabilities of the observational and modelling tools have continued to improve.

Humans are changing the energy budget of the planet by changing the land surface properties as well as atmospheric concentrations of gases and aerosols. There are multiple lines of evidence that the climate is changing throughout our planet. The main line of evidence in assessing climate change is based on observations of the atmosphere, land, ocean and cryosphere system. In the atmosphere, there is solid evidence from in situ observations and ice core records that concentrations of greenhouse gases such as carbon dioxide, methane, nitrous oxides and chlorofluorocarbons have increased over the last 200 years. In addition, historical surface temperature, and sea surface temperature, have increased over the last 100 years. Ocean temperature measurements suggest increases in the large heat reservoir of the oceans. Observations from satellites and in situ observations suggest reductions in glaciers, sea ice and some changes in ice sheets. Additionally, analyses based on measurements of the radiative budget suggest a small imbalance. Palaeoclimatic reconstructions allow placing the ongoing climate change in the perspective of natural climate variability. Ecosystem indicators confirm the findings of the physical observations.

During recent years, new observational systems have increased the number of observations by orders of magnitude. Parallel to this, tools to analyse and process the data have been developed and enhanced to cope with the increase of information. Additionally, more proxy data have been acquired to complete our picture of climate changes in the past. At the same time, a greater availability of computing resources led to the development of more sophisticated models which resolve more processes in greater detail. Also the modelling strategy has been extended to give an estimate of the uncertainty of the climate projections.

Because environmental systems are characterized by multiple spatial and temporal scales, uncertainties do not usually resolve at a single, predictable rate: new observations may reduce the uncertainties surrounding short timescale processes quite rapidly, while longer timescale processes may require very long observational baselines before much progress can be made. All three IPCC Working Groups in the AR5 have agreed to use two metrics for communicating the degree of certainty in key findings: (1) 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; (2) Quantified measures of uncertainty (likelihoods) in a finding expressed probabilistically (based on statistical analysis of observations or model results, or expert judgment).

Each IPCC assessment, starting with the first in 1990, has provided a new set of projections of the climate change that have become more complex and detailed as the models have became more advanced. The timespan from the first projections published in 1990 to those in AR4 provides a unique opportunity to compare the projections with the actually observed changes during that time period, thereby assessing the reliability of the projections. The globally-averaged temperature observations are well within the uncertainty range of all previous IPCC projections, and generally are in the middle of the scenario ranges. The carbon dioxide (CO_2) observations follow the projections as well. Methane (CH_4) and nitrous oxide (N_2O) concentration are closer to the lower limit of the projections.

Overall, the many 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.

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 basis for human activities being the primary driver in the concerns about climate change. 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 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, without describing the detailed progress made in the science being covered throughout the rest of this assessment.

1.2 Rationale and Key Concepts of the WGI Contribution

1.2.1 Setting the Stage for the Assessment

Because of possible policy implications, the climate change research community expends a substantial amount of scientific resources on the periodic assessment of the state of the research to convey to the wider community the state of knowledge. As discussed in the Working Group II report, 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 state of the physical science with respect to climate change. The report represents an assessment of the current state of research, not a discussion of all relevant papers, as would be included in a review. As such it seeks to make sure the range of scientific views, as represented in the climate change peer-reviewed literature, is considered in the assessment, and the state of the science concisely and accurately presented.

Scientific hypotheses are contingent, and are always subject to revision in the light of new evidence and theory. In this sense the distinguishing feature of scientific enquiry is not its claims to truth, but its 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 analyzed and held up to scrutiny. Even after publication, findings are further analyzed 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 our state of knowledge of climate change arises from choices over which reasonable minds may disagree. Examples include how best to constrain climate models using observations, how best to evaluate potential sea-level rise and the appropriate choice of prior for probabilistic estimates 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 disagreement as well as consensus. In order to assess areas of scientific controversy, careful review of appropriate papers is conducted and evaluated. Not all papers on a controversial point end up being included in an assessment, but all views represented in the peer-reviewed literature are considered and presented in the assessment.

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, pressure, and the presence or absence of clouds, precipitation, snow, winds, etc. On the other hand, climate refers to the long-term mean and variations in the state of weather events at that location, in addition to including the state of the land surface, ocean and cryosphere. Climate also includes not just the mean conditions, but also the associated statistics, including those of extreme events, such as heat waves or droughts, and the persistence of extreme values.

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 science, the openness of environmental systems, in terms of our lack of control of the boundaries of the system, their multi-scale character and the complexity of interactions within many environmental systems often hampers our ability to definitively isolate causal links, and this in turn places important limits on the nature of many of the inferences in the Earth Sciences (e.g., Oreskes et al., 1994). However, there are many cases where we 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

The First and Second IPCC Assessment Reports (FAR and SAR) each delivered six main conclusions, with the SAR stating that "*the balance of evidence suggest a discernible human influence on global climate*." In one of its 16 conclusions, the IPCC Third Assessment Report (TAR) states that "*there is new and stronger evidence that most of the warming observed during the last 50 years is attributable to human activities*." The IPCC Fourth Assessment Report (AR4) has eight very detailed statements about climate changes found in numerous observed quantities. The key message here is that "*the global average effect of human activities since 1750 has been one of warming….Warming of the system is unequivocal, as now is evident from observations of increases of global average air and ocean temperatures, widespread melting of snow and ice, and rising global average sea level*."

[END BOX 1.1 HERE]

1.2.2 Discussion of 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). The Earth's climate system is powered by **solar radiation** (bold faced words are defined in the glossary) (Figure 1.1). The bulk of the energy is supplied in the visible part of the electromagnetic spectrum. Since the Earth has kept its temperature relatively constant over many centuries, the incoming solar energy must generally be in balance with outgoing radiation. Since the average temperature of the Earth is about 15°C (288 K), black body radiation theory indicates that the outgoing energy flux from the Earth is in the infrared part of the spectrum. Of the incoming solar radiation, about half is absorbed the surface. Another 30% is reflected back to space by either clouds or the Earth's surface, and around 20% is absorbed in the atmosphere. The **longwave radiation** (LWR) emitted from the surface is largely radiated back by atmosphere constituents (water vapour, CO_2, CH_4, N_2O and other **greenhouse gases (GHGs)** and 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 Earth gains energy in the tropics and the subtropics, but looses energy in the middle and high latitudes. An energy flux in form of ocean currents and transports within the atmosphere compensates the areas of energy loss and gain (Stackhouse et al., 2011).

Fluctuations in the **energy budget** derive from either changes in 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 solar radiation can only be made from space and the precise record extends back only to 1978. The generally accepted mean value is 1368 W m^{-2} with an accuracy of about 0.2%. Variations of a few tenths of a percent are common, usually associated with a passage of a **solar cycle** (see also Chapter 5). The solar cycle variation of **total solar irradiance** (TSI) is of the order of 0.1% (AMS, 2000). Changes in OLR can result from changes in the temperature of the planet or changes in the surface or atmosphere's emissivity of long wave radiation. For the atmosphere, these changes in emissivity are predominately due to changes in cloud cover or in

greenhouse gases (and/or particle) concentrations. The budget of the Earth is largely in balance (Figure 1.1), but a small imbalance in the radiative budget (on the order 0.59 ± 0.15 Wm−2 during the 6-year period 2005–2010, Hansen et al., 2011) largely caused by changes in the atmospheric composition is thought to be driving the observed changes in climate.

Humans are changing the energy budget of the planet by changing the land surface properties as well as atmospheric concentrations of gases and aerosols (Chapter 2 and Chapter 7). Land use changes such converting forests to agriculture, modify the characteristics of vegetation, including its colour, seasonality and carbon content. For example, converting a forest to agricultural land reduces carbon storage in vegetation, adding it to the atmosphere, while also changing the short wave albedo, rates of evapotranspiration and long wave emissions (Figure 1.1). The dominant source of albedo comes from the surface and from clouds, but aerosol particles can also enhance the reflectivity of the atmosphere. On the other hand, particulate black carbon is a strong absorber, and at present is considered the second most important anthropogenic warming agent after CO_2. Indirectly, aerosols also impact cloud albedo, because water vapor preferentially condenses onto particles (**cloud condensation 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, such that they not only 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, the cloud height, and the nature of the cloud condensation nuclei (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 (VOCs), nitrose 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 oxidation processes, the abundance of LWR active gases such as CH_4 and O_3 and/or by acting as precursors of secondary aerosols. Since anthropogenic emission sources simultaneously emit some chemicals that affect climate, others that affect air pollution, and others that affect both, air pollution and climate science are intrinsically linked.

The changes in atmospheric trace constituent concentration are modifying the radiative budget, and these changes in radiation are called **radiative forcing**. In addition to the traditional definition of **radiative forcing** (RF) as used in previous assessments, Chapter 7 and 8 introduce a new concept, **adjusted radiative forcing** (AF) that allows for rapid response in the climate system. AF is defined as the change in net (down minus up) irradiance (solar plus longwave; in W m^{-2}) at the top of the atmosphere (TOA) after allowing for atmospheric temperatures, water vapour and clouds to adjust, but with globally-averaged surface temperature unchanged.

[INSERT FIGURE 1.1 HERE]

Figure 1.1: Main drivers of climate change. **a)** Shows a schematic of the energy budget of the Earth, including incoming solar short wave radiation (SWR) and outgoing long wave radiation (LWR) Natural incoming solar radiation variations (solar cycles) can drive important changes in energy budget. **b)** Atmospheric short wave interactions are driven by clouds and atmospheric constituents (gas and particles). Green arrows indicate natural fluxes, while grey arrows indicate anthropogenic fluxes. **c)** Atmospheric long wave interactions, which cause the greenhouse effect, are driven predominately by clouds, water vapor with important smaller contributions from other greenhouse gases (e.g., CO_2, CH_4, N_2O, O_3, CFCs, etc.) and aerosol particles (mainly dust and sea spray). **d)** Although the atmosphere is largely transparent to incoming solar radiation, both short and long wave interactions are important for the energy balance. This balance can be affected by human land use as well as climate change.

Once a forcing is applied to the climate system, 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). For example, the water vapour feedback argues that higher temperatures will lead to more water vapour, thus more greenhouse gases in the atmosphere, and a positive feedback leading to further warming. Another example is the ice-albedo feedback, where the albedo decreases as ice surface melts. In addition, some feedbacks operate quickly (seconds), while others can take decades to centuries; the time scale of feedbacks is very important to understand the full impact of a feedback. For example the ocean uptake of heat can take centuries to equilibrate. Based on the equilibrium response to a doubling of atmospheric concentration of CO_2 above pre-industrial levels (e.g., Arrhenius, 1896; Callendar, 1938; Eckholm, 1901) the concept of **equilibrium**

climate sensitivity (ECS) has been developed (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 climate model in a 1% yr^{-1} CO_2 increase experiment at the time of atmospheric CO_2 doubling and can be both more meaningful for some problems as well as easier to derive from observations (see Figure 10.25; Chapter 9; Allen, 2006; Knutti et al., 2005; Chapter 12).

[INSERT FIGURE 1.2 HERE]

Figure 1.2: Climate feedbacks and timescales. The climate feedbacks of increasing carbon dioxide and rising temperature include negative feedbacks such as black body 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 time scale for the various feedbacks is highlighted.

Climate change commitment is defined as future change to which the climate system is committed by virtue of past or current forcings. 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. Commitment is indicative of aspects of inertia in the climate system. Related to commitment is the idea of **irreversibility** in the climate system. Once a **tipping point** has been reached, it is difficult if not impossible for the climate system to revert to its previous state, and the change is termed irreversible.

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 includes 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 system (Figure 1.3a). In the atmosphere, there is solid evidence from in situ observations and ice core records that concentrations of greenhouse gases such as carbon dioxide, methane, nitrous oxides and chlorofluorocarbons have increased over the last 200 years (Chapter 8). In addition, historical surface temperature, and sea surface temperature have increased over the last 100 years (Chapter 2). Additional measurements from satellites allow a much broader spatial distribution, especially over the last 30 years. Ocean temperature measurements suggest increases in the large heat reservoir of the oceans (Chapter 3). Observations from satellites and in situ observations suggest reductions in glaciers, sea ice and some changes in ice sheets (Chapter 4). Additionally, analyses based on measurements of the radiative budget suggest a small imbalance (Chapter 2). These observations, 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, they are not perfect; however, they are important tools for analyzing uncertainties, 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 climate change involves the combination of models and observations, using statistical tools. This methodology is generally called detection and attribution in the climate change community (Chapter 10). Climate models indicate that the climate effects from greenhouse gas increases will have a different temperature distribution effect than aerosol or solar variability. For example satellite observations of atmospheric temperature show increases in tropospheric temperature and decreases in stratospheric temperatures, consistent with the increase in greenhouse gas effects found in climate model simulations, but which would not be expected if the Sun is driving the climate change (Hegerl et al., 2007).

Prior to the instrumental period, historical sources and natural archives provide quantitative information on past regional to global climate and atmospheric composition variability. Precise and quantitative reconstructions of key climate variables over a wide range of timescales provide information on the responses of the Earth system to a variety of external forcings and its internal variability (Hansen et al., 2006; Mann et al., 2008). Palaeoclimatic reconstructions thus allow placing the ongoing climate change in the perspective of natural climate variability. AR5 includes new information on external radiative forcings caused by variations in volcanic (e.g., Gao et al., 2008) and solar activity (e.g., Steinhilber et al., 2009). Extended data sets on past changes in atmospheric greenhouse gas (e.g., Lüthi et al., 2008) and mineral aerosol (Lambert et al., 2008) concentrations have also been used to assess past global temperature variations.

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 key climate and associated environmental parameters are presented in Figure 1.3 (which is updated from 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 discussed in other chapters. Throughout 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 many analyses shown provide a demonstration of the advancement of science through the comparisons with the past assessments.

[INSERT FIGURE 1.3 HERE]

Figure 1.3: a) Temperature indicators; **b)** Hydrological and storm related indicators. These two diagrams summarize many of the indicators showing that the system is changing.

1.3.1 Global and Regional Surface Temperatures

Observed changes in temperature since 1990 are shown in Figure 1.4. The globally and annually averaged 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 Brohan et al., 2006; data available at www.metoffice.gov.uk/hadobs). The anomalies are all relative to the 1961 to 1990 time period. 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. Also shown are the projected changes in temperature from the previous IPCC assessments out to 2015. The observations through 2010 fall within the upper range of the TAR projections (IPCC, 2001) and roughly in the middle of the AR4 model results. There are several additional points to consider about Figure 1.4: (1) the model analyses account for different emissions scenarios but do not fully account for natural variability; (2) the AR4 results for 1990–2000 accounts 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 represents the results from the 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 compare better with the observed temperatures than the previous assessments that did not include those effects.

Figure 1.5 similarly compares the globally and annually averaged temperature data with the AR4 model analyses for historical emissions and three of the SRES scenarios. There is very little difference between the model range for the different scenarios at this point (or even by 2015) and the observed data is typically in the middle of the projected ranges. Even though A1fi is the highest temperature scenario by the end of the century, A1T is higher during the earlier part of this century shown in Figure 1.5.

[INSERT FIGURE 1.4 HERE]

Figure 1.4: Estimated changes in the observed globally and annually averaged temperature (in °C) since 1990 compared with the range of projections from the previous IPCC assessments. Observed global annual temperature change, relative to 1961–1990, is shown as black points (average of 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 Brohan et al., 2006; data available at www.metoffice.gov.uk/hadobs) analyses). The black line is the observed temperature change smoothed with a 13-point binomial filter with ends reflected. The shading shows the projected range of global annual temperature change from 1990 to 2015 for models used in FAR, SAR, TAR, and AR4, but do not represent uncertainty estimates. Uncertainties in the observed temperatures are not shown.

[INSERT FIGURE 1.5 HERE]

Figure 1.5: Similar to Figure 1.4 except the focus is now on the range of scenario projection from AR4. The shading shows high, low and mid-range SRES scenarios from AR4 for the years 1990−2015 of global annual temperature change. SRES data was obtained from Figure 10.26 in Chapter 10 of AR4 and re-calculated to a baseline period of 1961−1990. Uncertainties in the observed temperatures are not shown.

1.3.2 Greenhouse Gas Concentrations

Another key indicator is the changing concentrations of the greenhouse gases that are driving the concerns about climate change. Figure 1.6 through Figure 1.8 show the recent observed trends for the gases of most concern, CO_2, CH_4, and N_2O (see Chapter 6 for more detailed discussion of these and other key gases). Measurements of these gases with long atmospheric lifetimes 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 projections from the First Assessment Report (FAR; IPCC, 1990) are much broader than those from the more recent assessments. The narrowest projection is from the most recent assessment, AR4.

As discussed in Dlugokencky et al. (2009), trends in CH_4 have slowed greatly in the last decade, although methane concentrations have increased the last two years. The projections all assumed 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: Estimated 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, www.esrl.noaa.gov/gmd/ccgg/trends). The shading shows the largest model projected range of global annual CO_2 concentrations from 1990 to 2015 from FAR, SAR, TAR, and AR4. Uncertainties in the observations are not shown.

[INSERT FIGURE 1.7 HERE]

Figure 1.7: Estimated 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). The shading shows the largest model projected range of global annual CH_4 concentrations from 1990–2015 from FAR, SAR, TAR, and AR4. Uncertainties in the observations are not shown.

[INSERT FIGURE 1.8 HERE]

Figure 1.8: 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). The shading shows the largest model projected range of global annual N_2O concentrations from 1990 to 2015 from FAR, SAR, TAR, and AR4. Uncertainties in the observations are not shown.

1.3.3 Extreme Events

Extreme weather or extreme climate events are defined as the occurrence of a value of a weather or climate variable that is either greater or equal a specific threshold, which is often defined in terms of the impact on the ecological, social or physical system, or at the tails of the observed range of the value (e.g., less than the fifth percentile or greater than the 95th percentile). For some climate extremes such as droughts or floods, several factors need to combine 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 distribution function (PDF) that for some variables is shaped similarly to a ‘Normal’ or ‘Gaussian’ curve (the familiar ‘bell’ curve). Simple statistical reasoning indicates that substantial changes in the frequency of extreme events (and in the maximum feasible extreme, e.g., the maximum possible 24-hour rainfall at a specific location) can result from a relatively small shift of 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 (corresponding to a small change in the average or centre of the distribution) 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) will often be accompanied by a decline in the opposite extreme (in this case the number of cold days such as frosts). Changes in the variability (Figure 1.9b and 1.9c) or shape of the distribution can complicate this simple picture.

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 was available, and climate models were being analyzed 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., daily 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 more robust information about PDFs and extremes. Subsequent to AR4 the IPCC decided to prepare a special report on extreme events that covers observed and projected changes of extremes (SREX).

Since the TAR, climate change detection and attribution studies focused on changes in the global statistics of extremes, which have been combined with the observed and projected changes in extremes in the so-called “extremes”-Table. The changes in this table are complemented by the assessment of the SREX and displayed in Figure 1.10. For the phenomena mentioned in all three reports (“higher maximum temperature”, “higher minimum temperature”, “more intense precipitation events”, “increase summer continental drying and associated risk of drought”) all reports confirmed a signal in the observations and in the projections. In the observations for the “higher maximum temperature” shifted from “likely” to “very likely”, and in the projections for the precipitation related phenomena the spatial relevance has been extended (these “uncertainty labels” are discussed in Section 1.4). The confidence in the higher maximum temperatures and lower minimum temperatures has increased. While the daily temperature range was assessed in the extremes-Table of the TAR, it was not included in the Table of AR4. Still, the daily temperature range was reported to increase in 21st century projections(IPCC, 2007). Moreover, confidence in an increase in the frequency of intense precipitation events in observations and projections has increased from the TAR to the AR4. However, confidence in projected increases were only assessed “Likely” in the SREX due biases and fairly large uncertainties in precipitation projections, while they were still assessed “Very Likely” in the AR4.

For some extremes (e.g., tropical cyclone wind speed to tropical cyclone intensity) the definition has changed between the TAR and the AR4 showing the progress made over the years. For example, 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. However, there remain key uncertainties. 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 a single, specific causal relationships are difficult to analyze. In some cases, however, it may be possible to estimate the human-related contribution to such changes in the probability of occurrence of extremes (for example see Min et al., 2011; Pall et al., 2011).

[INSERT FIGURE 1.9 HERE]

Figure 1.9: Schematic diagram showing the effect on extreme temperatures when **a)** the mean temperature increases, **b)** the variance increases, and **c)** when both the mean and variance increase for a normal distribution of temperature (based on TAR).

[INSERT FIGURE 1.10 HERE]

Figure 1.10: Change in the understanding of extreme events from TAR to SREX. Phenomena which are mentioned in all three reports are highlighted in green.

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

1.3.4.1 Sea Level

Sea level rise not only has a direct effect on coastal communities, but it is also an important indicator of climate change. 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. From the historical tide gauge record, we know that the 20th century rate of sea level rise is 1.7 ± 0.2 mm yr^{-1} (Holgate, 2007), but there is growing evidence that the rate since 1990 (3.3 ± 0.4 mm yr^{-1}) is significantly different from previous decades, with sea level trends in different ocean basins becoming more consistent over the last 20 years (Jevrejeva et al., 2006; Merrifield et al., 2009). Figure 1.11 compares the observed sea level rise relative to the projections from the IPCC assessments, showing 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. Along with the observed increase in atmospheric CO_2, there has so far been a corresponding decrease in oceanic pH by about 0.1, from an average of about 8.2 to 8.1 (Feely et al., 2004; Orr et al., 2005; Zeebe et al., 2008). In addition to other impacts of global climate change, ocean acidification poses potentially serious threats to the health of the world's ocean and its ecosystems.

[INSERT FIGURE 1.11 HERE]

Figure 1.11: Estimated changes in the observed global annual sea level (with seasonal signals removed) since 1990 based on annual averages from TOPEX and Jason satellites; http://sealevel.colorado.edu/results.php (black). Estimated changes in global annual sea level anomalies from tide gauge data (Church and White, 2011) (red). The shading shows the largest model projected range of global annual sea level rise from 1990 to 2015 for FAR, SAR, TAR and AR4. Data from AR4 was only presented in terms of long term projected change. However, SRES data for AR4 is available and was used in a special issue on sea level in "Oceanography" (Church et al., 2011). This data was used for the AR4 projections. Uncertainties in the observations are not shown.

1.3.4.3 Ice Indicators

Rapid sea ice loss is one of the most prominent indicators of global climate change. The trend of the pan-Arctic ice cover for the period 1978 to 2010 is about -4 % per decade 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 last five summers: 2007, 2011, 2008, 2009 and 2010 (http://nsidc.org). There is less multi-year sea ice and in some regions sea ice is thinning (Haas et al., 2008; Kwok et al., 2009). At the end of the summer 2010, under 15 % of the ice remaining in the Arctic was more than two years old, compared to 50−60 % during the 1980s (http://nsidc.org). Sea ice cover has been diminishing significantly faster than projected by climate models (IPCC, 2007), largely because basic physics of ice melting have not been well represented in models (SWIPA, 2011).

Satellite data show the opposite direction for sea ice extent in the Antarctic where the trend is positive and about 2 % per decade. The reason for the positive trend may be in part due to the ozone hole, which may have resulted a deepening of the lows 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., 2009a).

The Greenland Ice Sheet is losing volume and mass, and at an increasingly higher rate over the last decade. Whereas the 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, with 2007 breaking the record for surface melt area, runoff, and mass loss (Mernild et al., 2009; Tedesco, 2007).

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 75–231 Gt in 1996 to 104–288 Gt in 2006, comparable to losses to the Greenland Ice Sheet (Rignot et al., 2008b). Significant mass loss have 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., 2009b).

Glaciers around the globe have been shrinking since the end of the Little Ice Age, with increasing rates of ice loss since the early 1980s. Over the last decades the greatest mass losses 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 to sea level rise (Zemp et al., 2009; Zemp et al., 2008). The Himalayas is among the regions with the least available data.

1.3.4.4 Ecosystem Indicators

Ecosystem indicators are covered more extensively in the Working Group II assessment; we just touch on a few of them here. Plant and animal species phenology, and the timing of natural events are strongly dependent on climate (e.g., Root et al., 2003). However, causal attribution of recent biological trends to climate change may not be straightforward since non-climatic influences could dominate local and short-term biological changes. Thus, any underlying signal from climate change is likely to be revealed by analyses that seek systematic trends across diverse species and geographic regions (Parmesan and Yohe, 2003). Many such studies have now demonstrated that ecological changes in the phenology and distribution of plants and animals are occurring in all well-studied marine, freshwater, and terrestrial groups (e.g., Parmesan, 2006). Overall, these observed changes are in line with the global climate trends and are linked to local or regional climate change (e.g., Menzel et al., 2006). In relationship to changes in growing season a change in leafing and blooming is occurring in a wide range of locations and affecting a wide range of species.

Birds are a strong indicator of recent climate change (e.g., Charmantier et al., 2008). The timing of bird migration and breeding is sensitive to changes in temperature, and global warming would be expected to lead to an earlier onset of those activities in the spring. Statistically significant trends toward earlier bird egg-laying and nesting have been reported for sites in Europe (Crick and Sparks, 1999; Crick et al., 1997) and the southern United States (Brown et al., 1999). The earlier nesting in Europe is attributed in part to earlier plant growth, which in turn causes earlier availability of the insects the birds feed upon (Crick et al., 1997).

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 conjectures. Climate science is no different in this regard to any other sort of biological or physical science, though the complexity of the climate system and the large range of processes involved do bring particular challenges.

Because environmental systems are characterized by multiple spatial and temporal scales, uncertainties do not usually resolve at a single, predictable rate: new observations may reduce the uncertainties surrounding short timescale processes quite rapidly, while longer timescale processes may require very long observational baselines before much progress can be made. Characterization of the interaction between processes, as quantified by models, can be improved by model development, or can shed light on new areas in which uncertainty is greater than previously thought. The fact that we have only a single realization of the climate, rather than a range of different climates from which to draw upon, 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 predictions of future states.

1.4.2 Characterizing Uncertainty

"Uncertainty" is a complicated concept, and can be used to characterize states of knowledge as diverse as near-but-not-complete certainty through to quite vague speculation. It 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.

Scientific uncertainty can be partitioned in various ways, and 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 predictions of future change. Uncertainty in measured quantities can arise from a range of sources, such as statistical variation, variability, inherent randomness, approximation, subjective judgment, and linguistic imprecision (Morgan and Henrion, 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 future emissions of greenhouse gases and other forcing agents; uncertainty associated with climate models; and internal variability or initial condition uncertainty (e.g., Collins and Allen, 2002; Yip et al., 2011). 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. Some scientific research areas, such as detection and attribution, incorporate significant elements of both observational and model-based science, and in these instances both sets of relevant uncertainties need to be incorporated.

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, so that 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 conditionalities 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 draw 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 high likelihood, then in the absence of additional qualifiers it should be taken as read that it is also 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 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.

Terma	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 and Henrion, 1990) and at the group level as people converge on a view and draw confidence in its reliability from each other. Nevertheless, in an assessment of the state of scientific knowledge across a field as large as that comprised by climate change, some degree of expert judgment is inevitable.

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 intention behind the guidance presented to chapter teams is to provide 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 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 for Observations

During recent years, new observational systems have increased the number of observations by orders of magnitude. 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 Earth's climate. Additionally, more proxy data have been acquired to complete our picture of climate changes in the past. At the same time, a greater availability of computing resources led to the development of more sophisticated models which resolve more processes in greater detail. The experimental strategy has been extended to give an estimate of the uncertainty of the climate projections.

Reanalysis products have played and will continue to play an important role in obtaining a consistent picture of the status of the climate system through the help of different types of observations assimilated, for example, in advanced weather prediction models, although its usefulness is detecting long term climate trend is limited. 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, comes from satellites (Figure 1.12). For example, information from GPS radio occultation measurements has increased significantly since 2007. It should be kept in mind that 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. For satellite data, the new generation satellite sensors such as the high spectral resolution infrared (IR) sounders (such as AIRS and IASI) now have better stability over time.

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 1500 meters 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). Satellite observations for sea level, sea ice, sea surface salinity and ocean colour have also been further developed over the past few years.

For observations on variables over land, progress has been made with regard to in-situ permafrost monitoring, and snow/ice, land surface, vegetation (including forests), soil moisture and fire monitoring from space.

[INSERT FIGURE 1.12 HERE]

Figure 1.12: Number of satellite instruments from which data have been assimilated in ECMWF's production streams for each year from 1996 to 2010. This figure demonstrates a fivefold increase in the usage or the satellite data over this time period.

1.5.2 Capabilities in Modelling

Four developments have especially pushed the capabilities in modelling forward over recent years (see Figure 1.13). First, 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 the parallel computer architecture. More regional models with higher resolution are available for more regions. Figure 1.14a and 1.14b show the large effect on surface representation from a horizontal resolution of 110 km (similar to the current global models) to a resolution of 30 km. Second, parameterization 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. It should also be recognized that the climate models used in future assessments will be further developed, for example to better represent nitrogen effects on the carbon cycle. Third, ensemble techniques 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 fifth phase of the Coupled Model Intercomparison Project (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 the CMIP5 developed from modelling studies from the AR5 assessment, four new scenarios, referred to as Representational Concentration Pathways (RCPs) were developed. Chapter 8 also provides 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, 11 and 12), it is worthwhile to consider the differences and similarities between the SRES and the RCP Scenarios. Figure 1.15, acting as a prelude to the discussion in Chapter 8, shows that the derived radiative forcing 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 1.13 HERE]

Figure 1.13: 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 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 1.14 HERE]

Figure 1.14: a) Illustration of the Eastern North American topography in a resolution of 110 km x 110 km. **b)** Illustration of the Eastern North American topography in a resolution of 30 km x 30 km. Geographic resolution characteristic in global illustration of the North American topography at the resolution of 110 km x 110 km typical of

AR5 and some global climate modelling studies in AR4 (Figure 1.14a) and of 30 km x 30 km as approximately used in some cases for AR5 (Figure 1.14b).

[INSERT FIGURE 1.15 HERE]

Figure 1.15: Projected total RF (W m^{-2}) from 2000 to 2100. Previous IPCC assessments (SAR IS92a, TAR/AR4 SRES A2 & B1) are compared with RCP scenarios reported as CO_2-equivalent (Meinshausen et al., 2011) and with those RCP emissions scenarios assessed here including uncertainties in natural emissions and atmospheric residence time. The uncertainty in RF for year 2000 (see Chapter 8) is not shown, nor projected here.

1.6 Summary 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 many 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): 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): Covers 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 the feedbacks on the climate system.

From Forcing to Attribution of Climate Change (Chapters 8, 9, 10): All the information on the different drivers (natural and anthropogenic) of climate change are 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) are 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): 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 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 Scenarios in Annex II.*

[START FAQ 1.1 HERE]

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

The uncertainties on projected change in global surface temperature for this assessment are similar to those from the first assessment. Given the amount of attention that climate change research has received over the last 30 years, an obvious question is why isn't the total uncertainty decreasing?

The continuing uncertainty is due to improvements in our understanding of processes previously ignored, uncertainties in feedbacks, uncertainties in climate forcings, and uncertainties in human actions in the future.

First, as we learn more about the climate system, we start to understand that assumptions we made previously were not so accurate (see Figure FAQ1.1). For example, for the first three assessments, we assumed that the fraction of carbon dioxide emitted by humans remaining in the atmosphere after the initial exchange with the land and ocean biosphere (about 50%) would stay the same in the future. However in the AR4, this number was assessed and the best modelling studies of the carbon cycle estimated that more might stay in the atmosphere than was originally anticipated. However, modelling of the carbon cycle continues to improve and these models are subject to their own uncertainties. Thus, our improved understanding of climate feedbacks onto climate suggests an additional source of uncertainty not previously included. One way to understand this is that there is a difference between our real uncertainty and our perceived uncertainty. The real uncertainty in our predictions may be reduced as we learn about new important processes; however, perceived (and reported) uncertainties may increase.

The second reason is due to the uncertainty in the feedbacks in the climate system. For example, an increase in surface warming causes a change in clouds, which in turn impacts surface warming, etc. Since many parts of the climate system have long lags in their response time (e.g., due to ocean or carbon cycle processes), this means that causing a change in the climate now will cause an impact in 20−200 years, increasing our difficulty in ascertaining the net impacts of changes in the atmospheric constituents or surface properties.

Third, our estimates of future climate prediction depend critically on the climate sensitivity, which is the response of the climate system to external forcings, such as those resulting from changes in the atmospheric concentrations of greenhouse gases. From observations, we can ascertain the surface temperature response; however we are forced to estimate the climate forcings due to human influence. Because some of the forcings are negative (e.g., aerosols) but not spatially well distributed, these partially "mask" the effects of the greenhouse gases and other human and natural forcings (Chapter 8).

Finally, our uncertainties remain high because we do not know what policy decisions humans will undertake. If humans decide to cut emissions drastically, this will have a different impact than if emission continue unabated. Thus, finding the true climate sensitivity requires understanding the delicate balance of the many changes in forcing by humans activity.

[INSERT FAQ 1.1, FIGURE 1 HERE]

FAQ 1.1, Figure 1: Schematic showing the evolution of uncertainties in a projection (e.g., global mean temperature) at 2100. The real uncertainties decrease as there is more data, better understanding and the time becomes closer. However, our perception of the uncertainties may not change as much with time (or even grow) as our understanding improves.

[END FAQ 1.1 HERE]

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Chapter 1: Introduction

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Figures

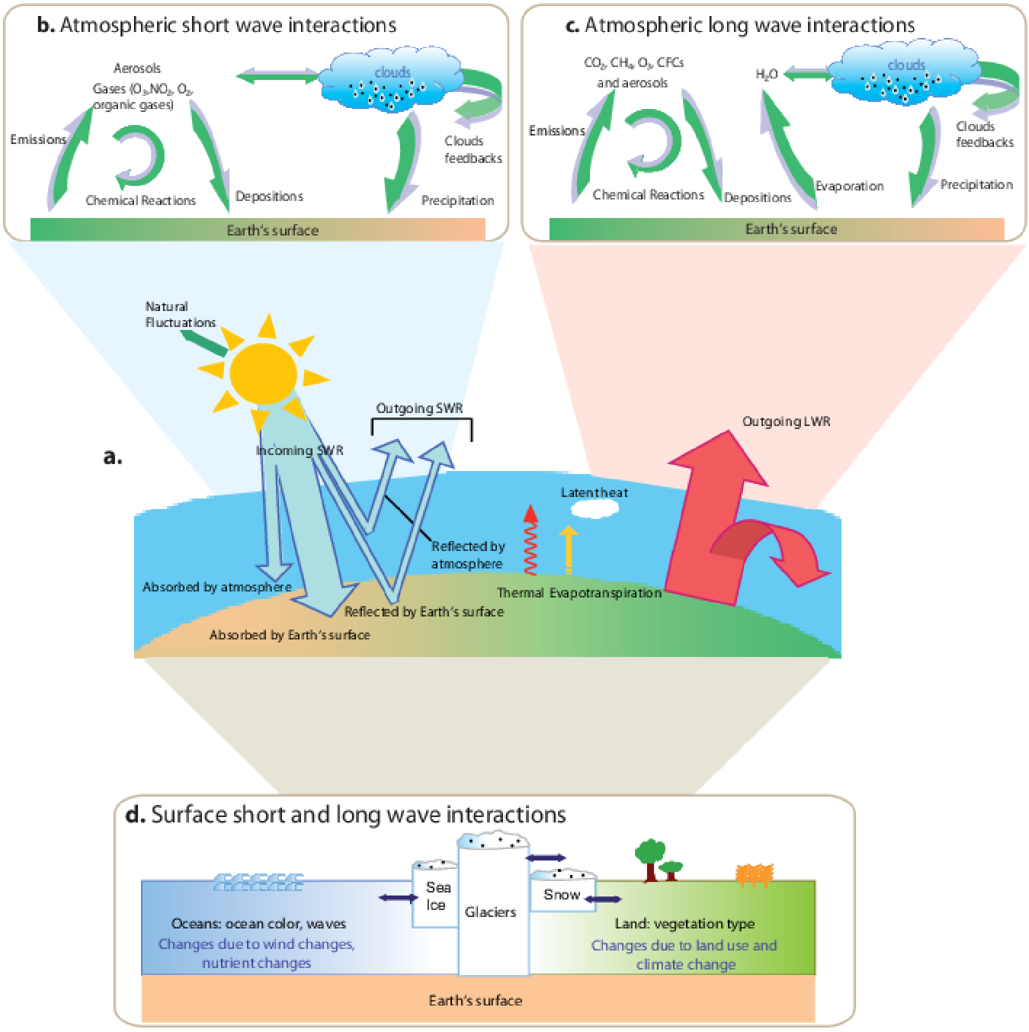


Figure 1.1: Main drivers of climate change. (a) Shows a schematic of the energy budget of the Earth, including incoming solar short wave radiation (SWR) and outgoing long wave radiation (LWR) Natural incoming solar radiation variations (solar cycles) can drive important changes in energy budget.(b) Atmospheric short wave interactions are driven by clouds and atmospheric constituents (gas and particles). Green arrows indicate natural fluxes, while grey arrows indicate anthropogenic fluxes. (c) Atmospheric long wave interactions, which cause the greenhouse effect, are driven predominately by clouds, water vapor with important smaller contributions from other greenhouse gases (e.g. CO_2, CH_4, N_2O, O_3, CFCs, etc.) and aerosol particles (mainly dust and sea spray). (d) Although the atmosphere is largely transparent to incoming solar radiation, both short and long wave interactions are important for the energy balance. This balance can be affected by human land use as well as climate change.

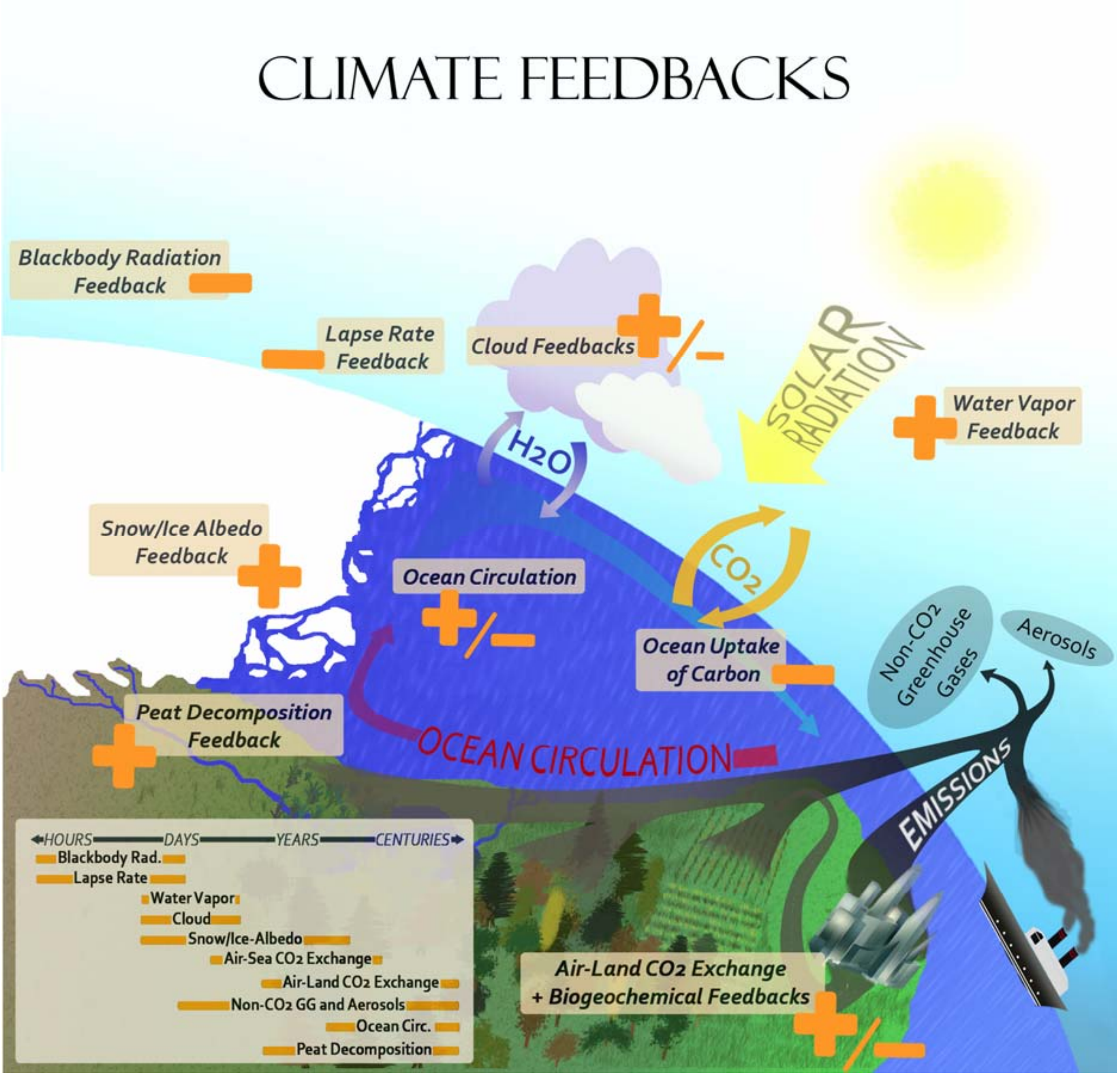
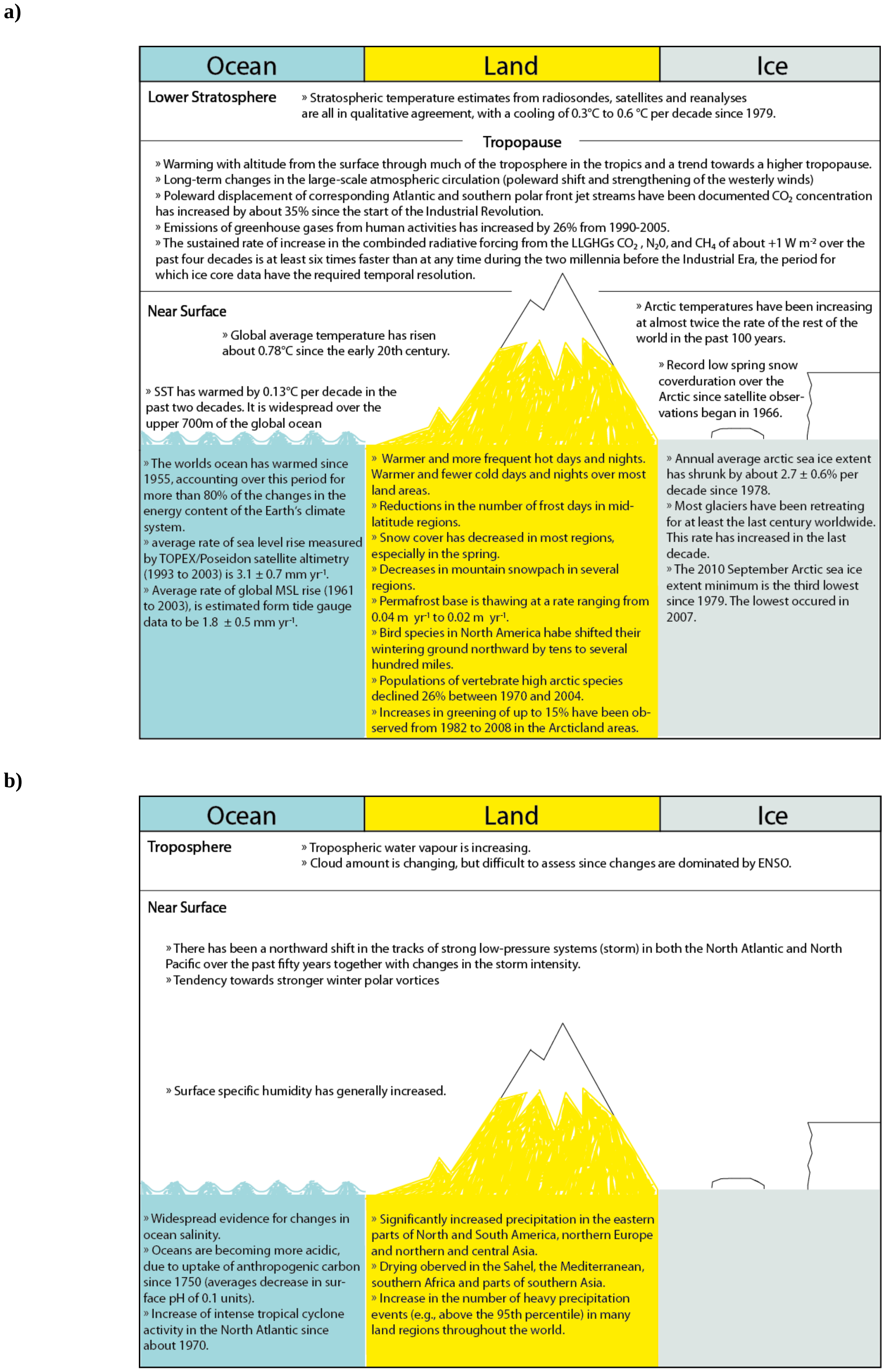


Figure 1.2: Climate feedbacks and timescales. The climate feedbacks of increasing carbon dioxide and rising temperature include negative feedbacks such as black body radiation, lapse rate, and ocean uptake of carbon dioxide feedbacks. Positive feedbacks include water vapour and the snow/ice albedo feedbacks. 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 time scale for the various feedbacks is highlighted.



» Stratospheric temperature estimates from radiosondes, satellites and reanalyses are all in qualitative agreement, with a cooling of 0.3°C to 0.6 °C per decade since 1979.

» Warming with altitude from the surface through much of the troposphere in the tropics and a trend towards a higher tropopause.
» Long-term changes in the large-scale atmospheric circulation (poleward shift and strengthening of the westerly winds)
» Poleward displacement of corresponding Atlantic and southern polar front jet streams have been documented CO$_2$ concentration has increased by about 35% since the start of the Industrial Revolution.
» Emissions of greenhouse gases from human activities has increased by 26% from 1990-2005.
» The sustained rate of increase in the combined radiative forcing from the LLGHGs CO$_2$, N$_2$0, and CH$_4$ of about +1 W m^{-2} over the past four decades is at least six times faster than at any time during the two millennia before the Industrial Era, the period for which ice core data have the required temporal resolution.

» Global average temperature has risen about 0.78°C since the early 20th century.

» SST has warmed by 0.13°C per decade in the past two decades. It is widespread over the upper 700m of the global ocean

» Arctic temperatures have been increasing at almost twice the rate of the rest of the world in the past 100 years.

» Record low spring snow coverduration over the Arctic since satellite observations began in 1966.

» The worlds ocean has warmed since 1955, accounting over this period for more than 80% of the changes in the energy content of the Earth's climate system.
» average rate of sea level rise measured by TOPEX/Poseidon satellite altimetry (1993 to 2003) is 3.1 ± 0.7 mm yr^{-1}.
» Average rate of global MSL rise (1961 to 2003), is estimated form tide gauge data to be 1.8 ± 0.5 mm yr^{-1}.

» Warmer and more frequent hot days and nights. Warmer and fewer cold days and nights over most land areas.
» Reductions in the number of frost days in mid-latitude regions.
» Snow cover has decreased in most regions, especially in the spring.
» Decreases in mountain snowpach in several regions.
» Permafrost base is thawing at a rate ranging from 0.04 m yr^{-1} to 0.02 m yr^{-1}.
» Bird species in North America habe shifted their wintering ground northward by tens to several hundred miles.
» Populations of vertebrate high arctic species declined 26% between 1970 and 2004.
» Increases in greening of up to 15% have been observed from 1982 to 2008 in the Arcticland areas.

» Annual average arctic sea ice extent has shrunk by about 2.7 ± 0.6% per decade since 1978.
» Most glaciers have been retreating for at least the last century worldwide. This rate has increased in the last decade.
» The 2010 September Arctic sea ice extent minimum is the third lowest since 1979. The lowest occured in 2007.

» Tropospheric water vapour is increasing.
» Cloud amount is changing, but difficult to assess since changes are dominated by ENSO.

» There has been a northward shift in the tracks of strong low-pressure systems (storm) in both the North Atlantic and North Pacific over the past fifty years together with changes in the storm intensity.
» Tendency towards stronger winter polar vortices

» Surface specific humidity has generally increased.

» Widespread evidence for changes in ocean salinity.
» Oceans are becoming more acidic, due to uptake of anthropogenic carbon since 1750 (averages decrease in surface pH of 0.1 units).
» Increase of intense tropical cyclone activity in the North Atlantic since about 1970.

» Significantly increased precipitation in the eastern parts of North and South America, northern Europe and northern and central Asia.
» Drying oberved in the Sahel, the Mediterranean, southern Africa and parts of southern Asia.
» Increase in the number of heavy precipitation events (e.g., above the 95th percentile) in many land regions throughout the world.

Figure 1.3: a) Temperature indicators; **b)** Hydrological and storm related indicators. These two diagrams summarize many of the indicators showing that the system is changing.

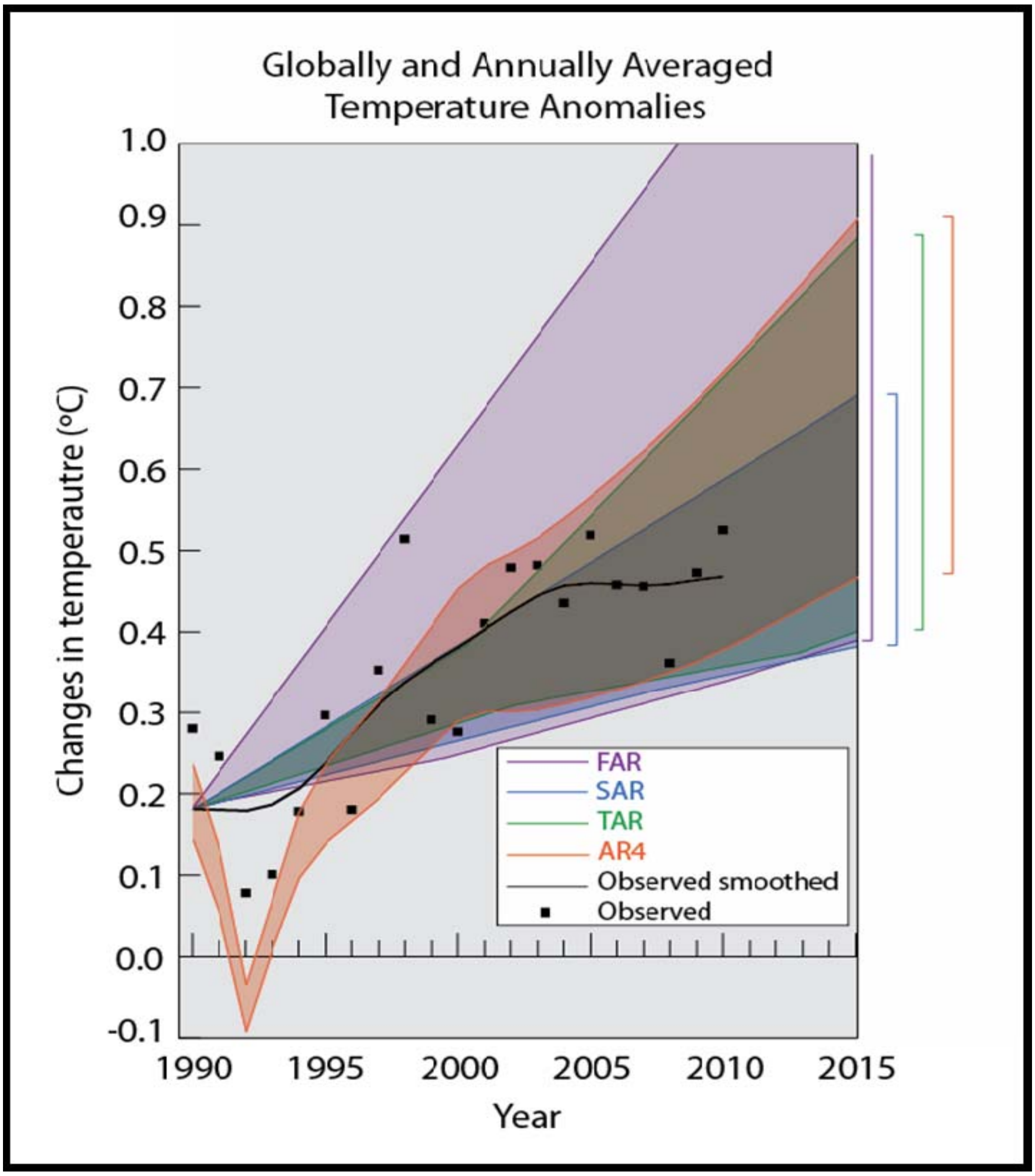


Figure 1.4: Estimated changes in the observed globally and annually averaged temperature (in °C) since 1990 compared with the range of projections from the previous IPCC assessments. Observed global annual temperature change, relative to 1961–1990, is shown as black points (average of NASA (updated from 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 Brohan et al., 2006; data available at www.metoffice.gov.uk/hadobs) analyses). The black line is the observed temperature change smoothed with a 13-point binomial filter with ends reflected. The shading shows the projected range of global annual temperature change from 1990 to 2015 for models used in FAR, SAR, TAR, and AR4, but do not represent uncertainty estimates. Uncertainties in the observed temperatures are not shown.

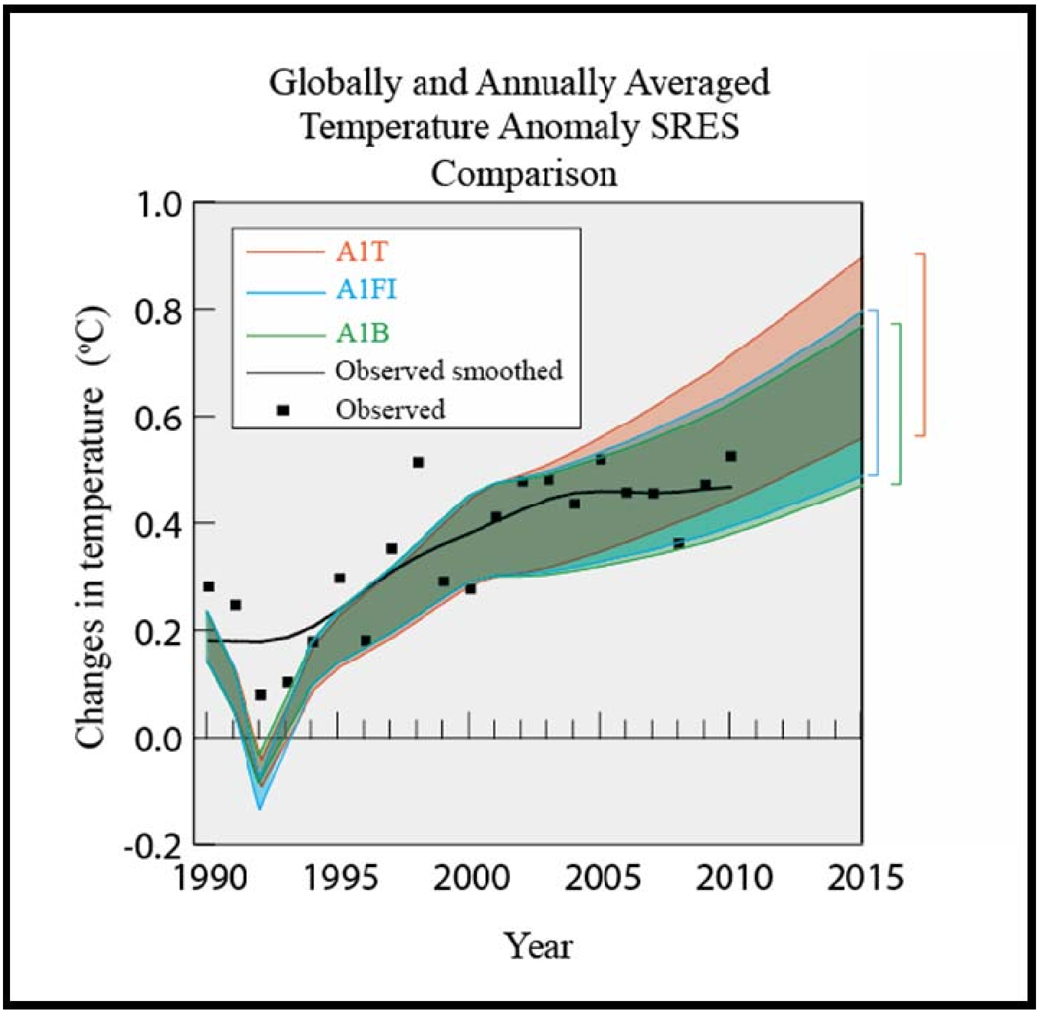


Figure 1.5: Similar to Figure 1.4 except the focus is now on the range of scenario projection from AR4. The shading shows high, low and mid-range SRES scenarios from AR4 for the years 1990−2015 of global annual temperature change. SRES data was obtained from Figure 10.26 in Chapter 10 of AR4 and re-calculated to a baseline period of 1961−1990. Uncertainties in the observed temperatures are not shown.

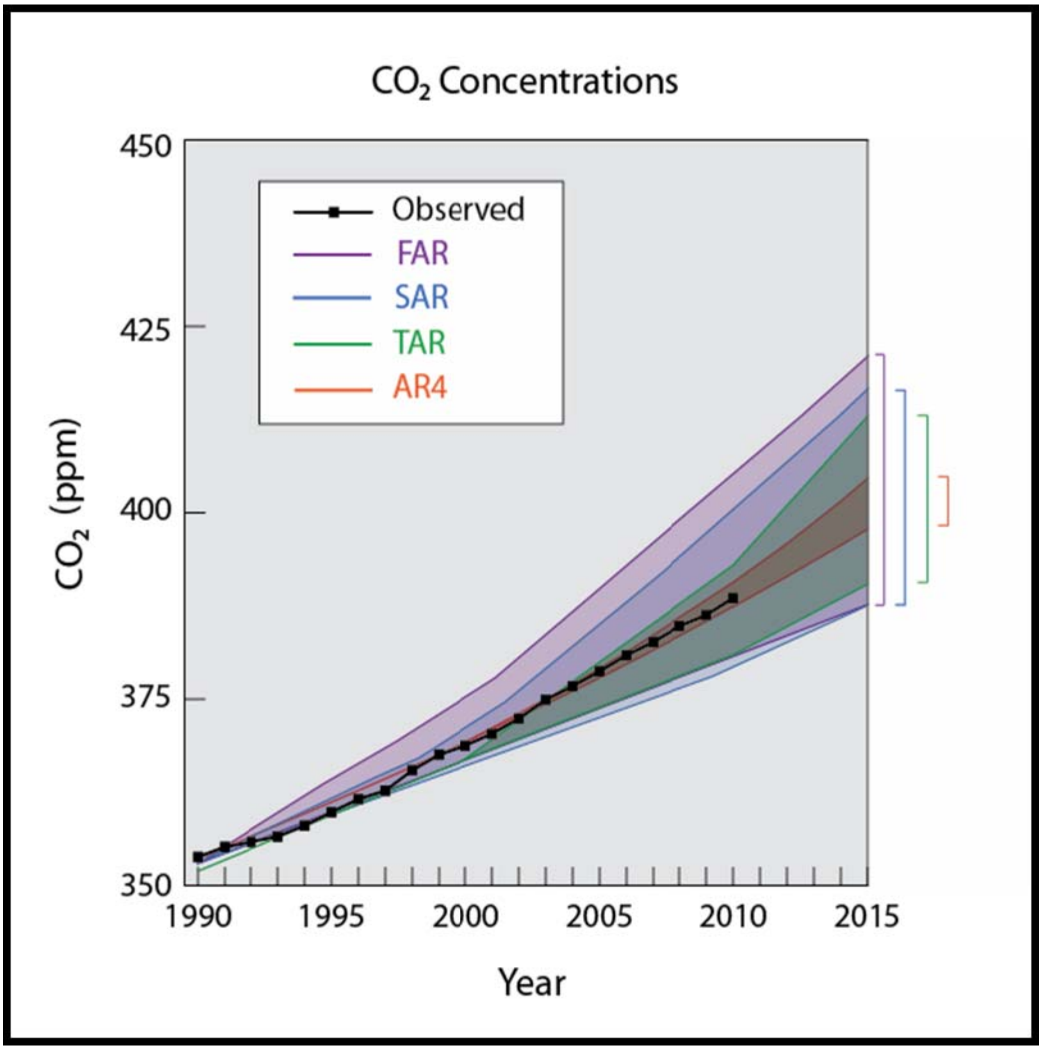


Figure 1.6: Estimated observed globally and annually averaged carbon dioxide concentrations in parts per million (ppm) since 1990 compared with projections from the previous IPCC assessments. Observed global annual CO_2 concentrations are shown in black (based on NOAA Earth System Research Laboratory measurements, www.esrl.noaa.gov/gmd/ccgg/trends). The shading shows the largest model projected range of global annual CO_2 concentrations from 1990 to 2015 from FAR, SAR, TAR, and AR4. Uncertainties in the observations are not shown.

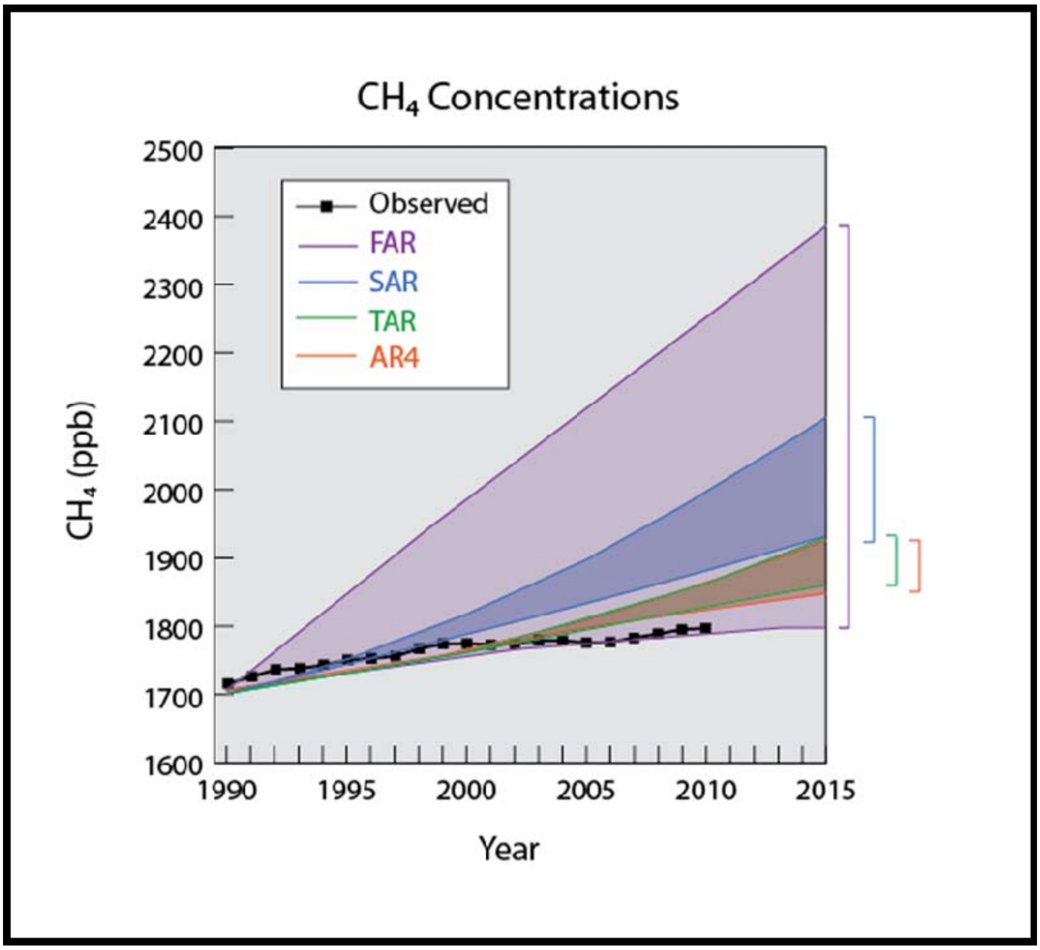


Figure 1.7: Estimated observed globally and annually averaged methane concentrations in parts per billion (ppb) since 1990 compared with projections from the previous IPCC assessments. Estimated observed global annual CH_4 concentrations are shown in black (NOAA Earth System Research Laboratory measurements, updated from Dlugokencky et al., 2009). The shading shows the largest model projected range of global annual CH_4 concentrations from 1990–2015 from FAR, SAR, TAR, and AR4. Uncertainties in the observations are not shown.

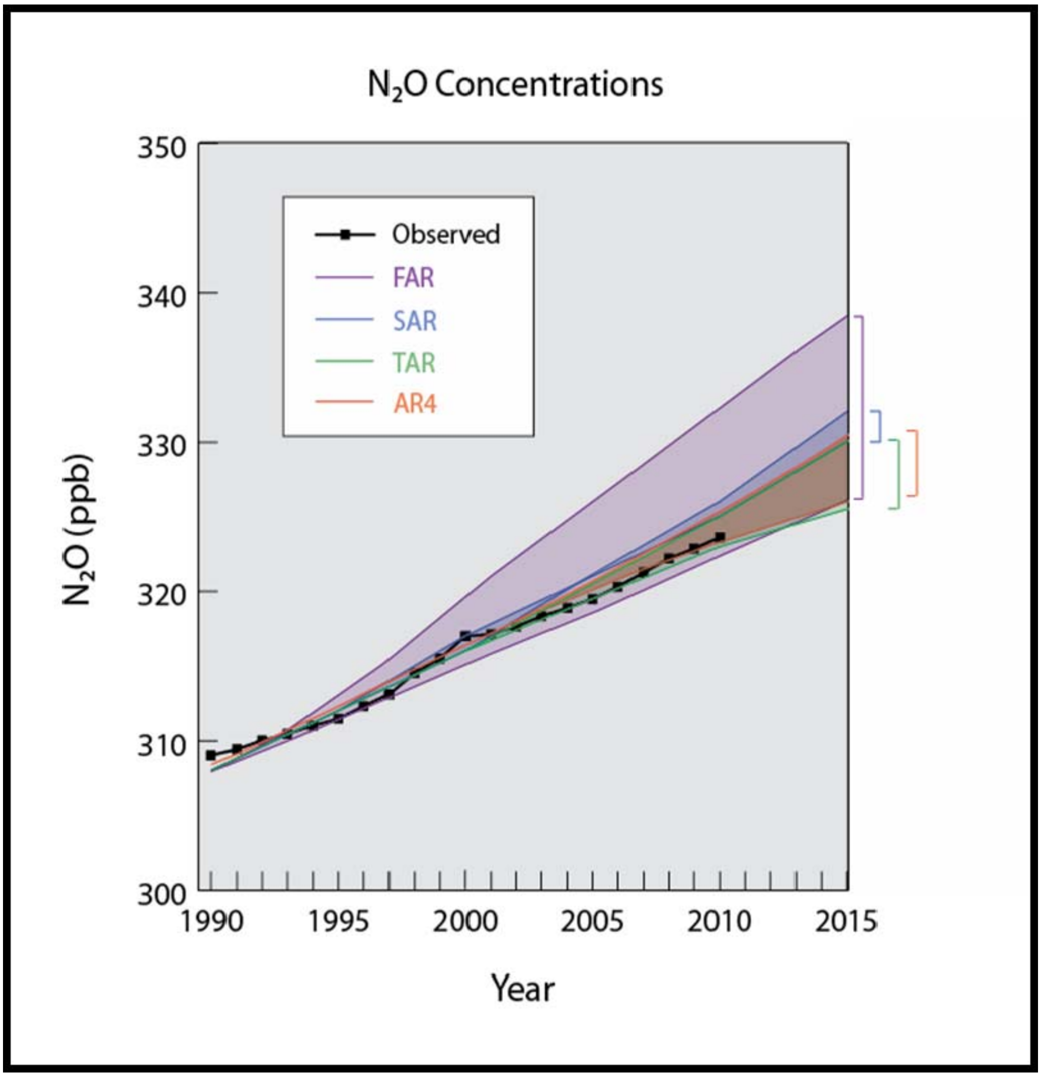


Figure 1.8: Observed globally and annually averaged nitrous oxide (N_2O) concentrations in parts per billion (ppb) since 1990 compared with projections from the previous IPCC assessments. Observed global annual N_2O concentrations are shown in black (NOAA Earth System Research Laboratory measurements, updated from Elkins and Dutton, 2010). The shading shows the largest model projected range of global annual N_2O concentrations from 1990 to 2015 from FAR, SAR, TAR, and AR4. Uncertainties in the observations are not shown.

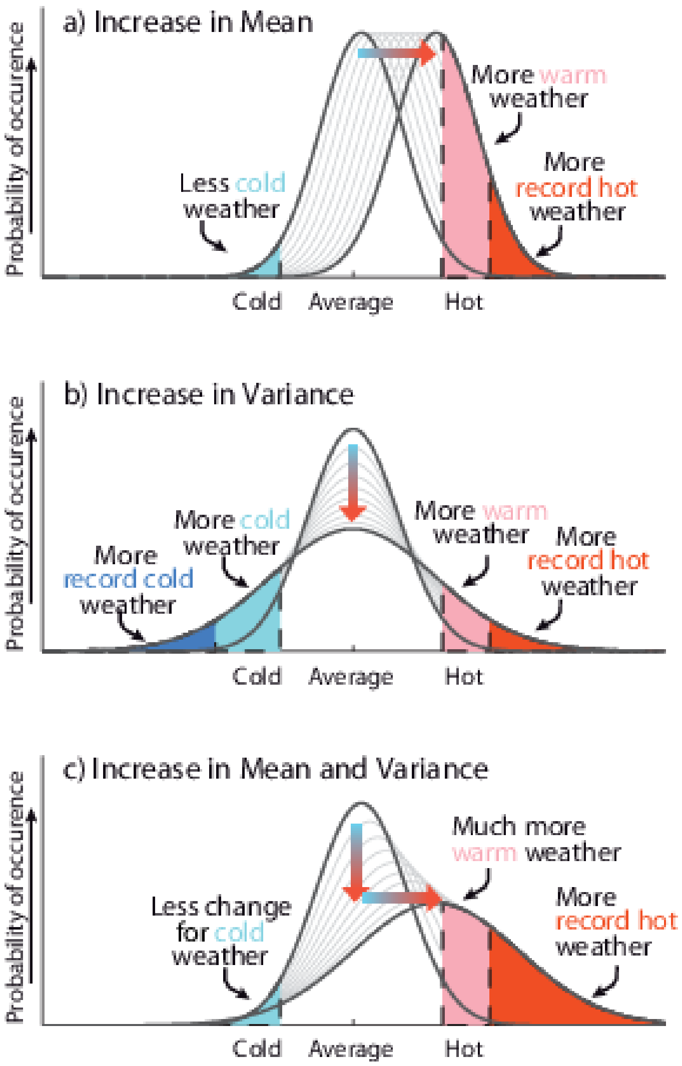


Figure 1.9: Schematic diagram showing the effect on extreme temperatures when (a) the mean temperature increases, (b) the variance increases, and (c) when both the mean and variance increase for a normal distribution of temperature (based on TAR).

Changes in Phenomenon	Confidence in observed changes (latter half of the 20th century)			Confidence in projected changes (during the 21st century)		
IPCC Assessment Report	TAR	AR4	SREX	TAR	AR4	SREX
Higher maximum temperatures and more hot days over nearly all land areas	Likely	Very Likely	Very Likely at a global scale	Very Likely	Virtually certain	Virtually certain
Higher minimum temperatures, fewer cold days and frost days over nearly all land areas	Very Likely	Very Likely	Very Likely at a global scale	Very Likely	Virtually certain	Virtually certain
Reduced diurnal temperature range over most land areas	Very Likely	-	-	Very Likely	-	-
Increase of heat index over land areas	Likely (over many areas)	-	-	Very Likely (over most areas)	-	-
Warm spells/heat waves. Frequency increases over most land areas	-	Likely	Likely	-	Very Likely	Very Likely
More intense precipitation events	Likely, over many Northern Hemisphere mid- to high latitude land areas	Likely	Likely	Very Likely over many areas	Very Likely	Likely
Increased summer continental drying and associated risk of drought	Likely, in a few areas	Likely, in many regions since 1970s	Medium confidence, since 1950 in some regiona , but some opposite trend exist	Likely, over most mid-latitude continental interiors (Lack of consistent projections in other areas)	Likely	Medium confidence, in increase of duration and intensity of drought
Increase in tropical cyclone peak wind intensities	Not observed in the few analyses available	-	-	Likely, over some areas	-	Likely, but not in all basins
Increase in tropical cyclone mean and peak precipitation intensities	Insufficient data for assessment	-	-	Likely, over some areas	-	Likely
Intense tropical cyclone activity increases	-	Likely. in some regions since 1970	Low confidence	-	Likely	Medium Confidence in some basins
Increased incidence of extreme high sea level (excludes tsunamis)	-	Likely	Likely	-	Likely	Very Likely

Figure 1.10: Change in the understanding of extreme events from TAR to SREX. Phenomena which are mentioned in all three reports are highlighted in green.

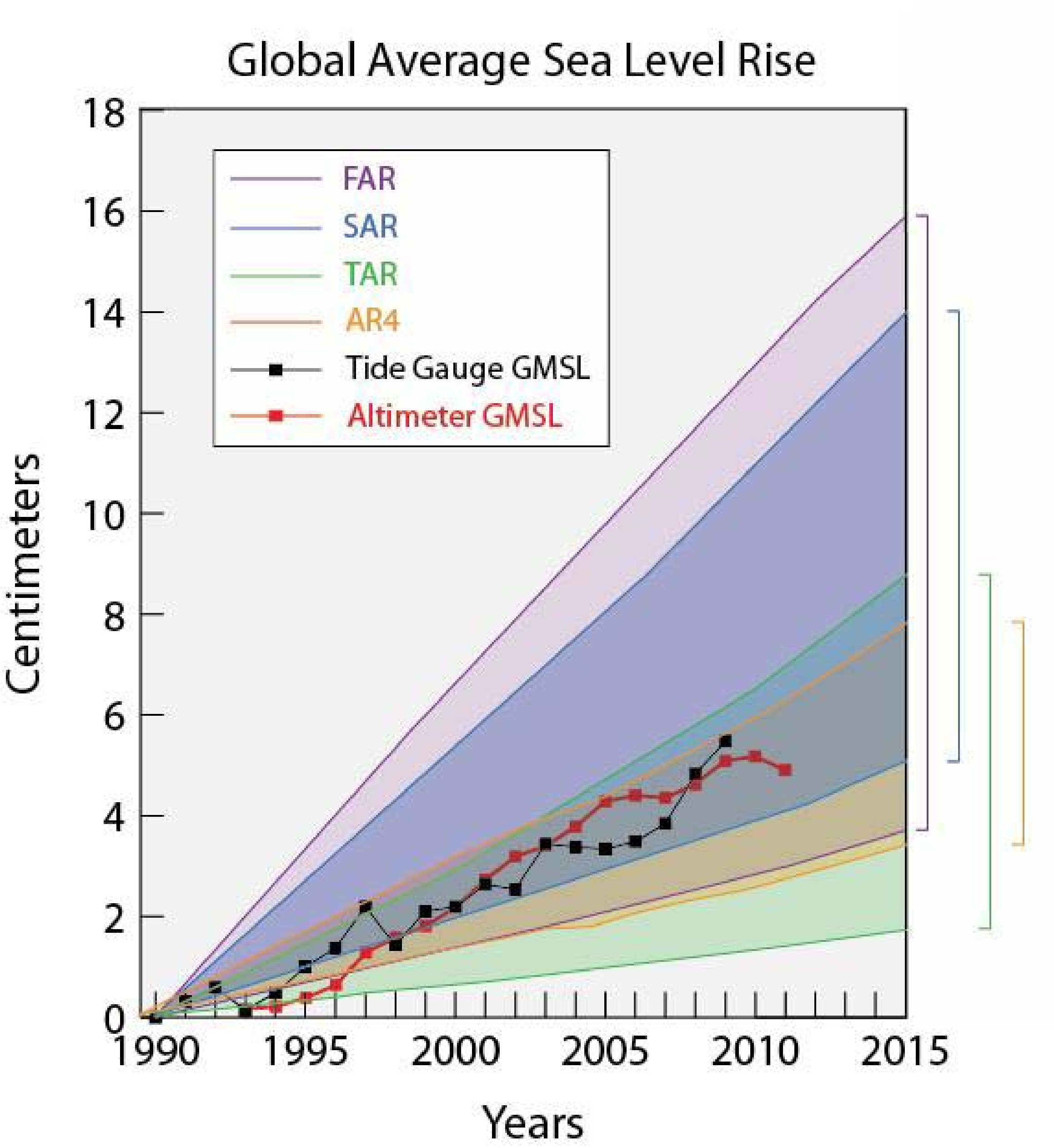


Figure 1.11: Estimated changes in the observed global annual sea level (with seasonal signals removed) since 1990 based on annual averages from TOPEX and Jason satellites; http://sealevel.colorado.edu/results.php (black). Estimated changes in global annual sea level anomalies from tide gauge data (Church and White, 2011) (red). The shading shows the largest model projected range of global annual sea level rise from 1990 to 2015 for FAR, SAR, TAR and AR4. Data from AR4 was only presented in terms of long term projected change. However, SRES data for AR4 is available and was used in a special issue on sea level in "Oceanography" (Church et al., 2011). This data was used for the AR4 projections. Uncertainties in the observations are not shown.

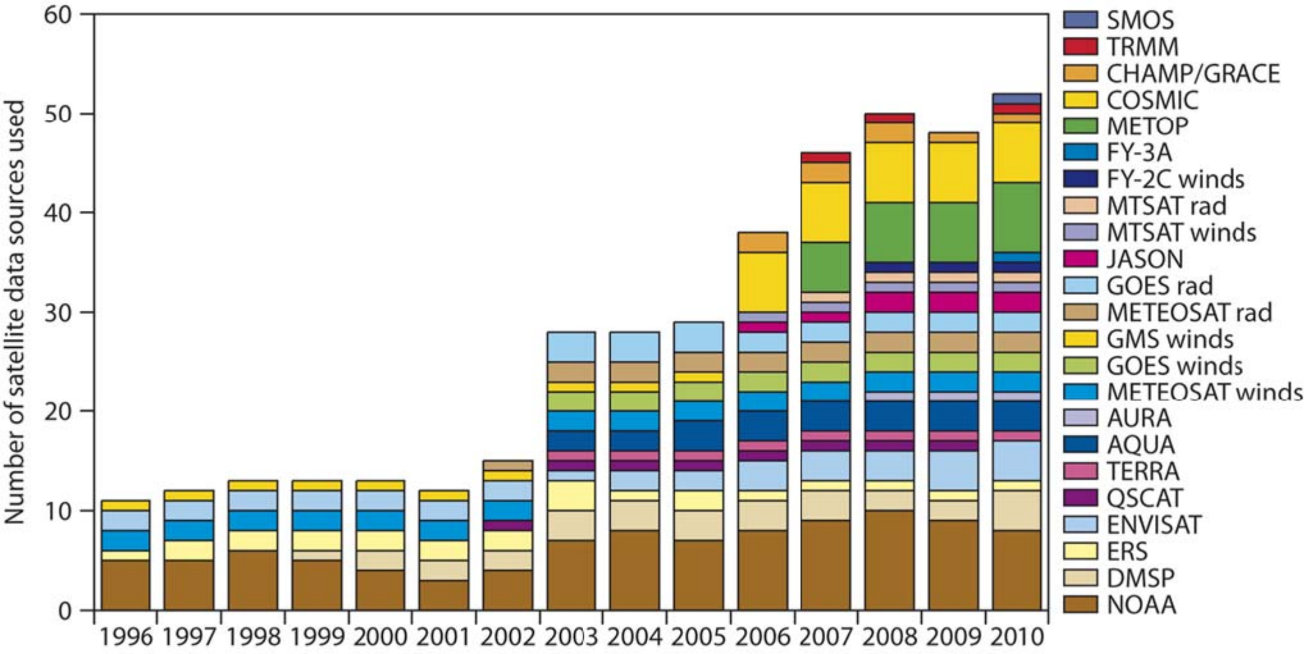


Figure 1.12: Number of satellite instruments from which data have been assimilated in ECMWF's production streams for each year from 1996 to 2010. This figure demonstrates a fivefold increase in the usage or the satellite data over this time period.

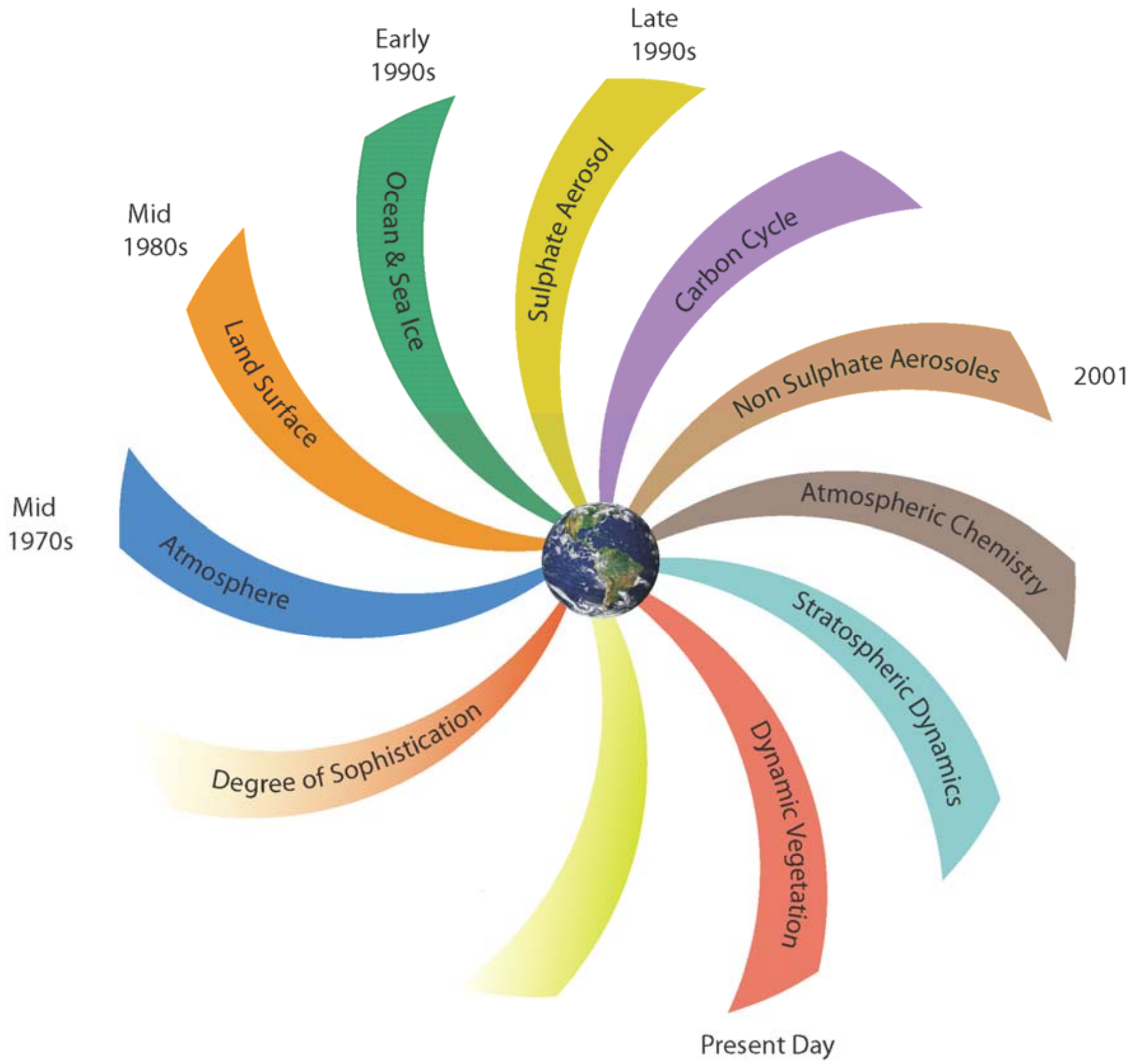


Figure 1.13: The development of climate models over the last 35 years showing how the different components are coupled into comprehensive climate models. Note that in the same time the horizontal and vertical resolution has increased considerably from T21L9 (roughly 500 km) in the 1970s to T95L95 (roughly 100 km) at present, and that now ensembles with at least three independent experiments can be considered as standard.

a)

b)

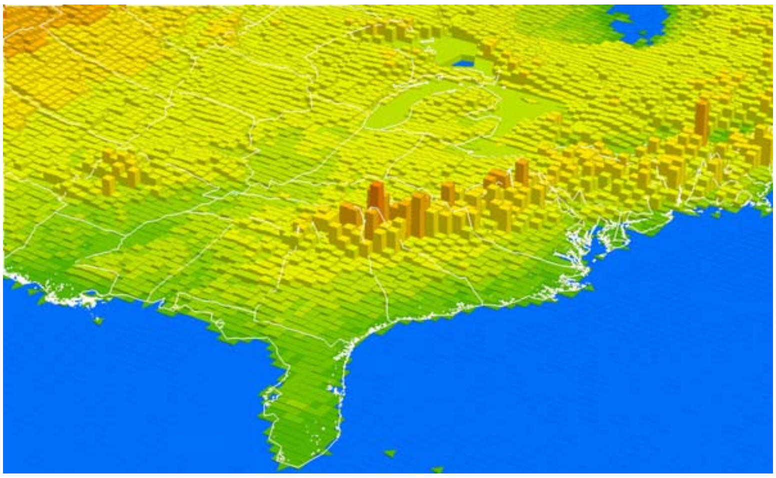


Figure 1.14: a) Illustration of the Eastern North American topography in a resolution of 110 km x 110 km. **b)** Illustration of the Eastern North American topography in a resolution of 30 km x 30 km. Geographic resolution characteristic in global illustration of the North American topography at the resolution of 110 km x 110 km typical of AR5 and some global climate modelling studies in AR4 (Figure 1.14a) and of 30 km x 30 km as approximately used in some cases for AR5 (Figure 1.14b).

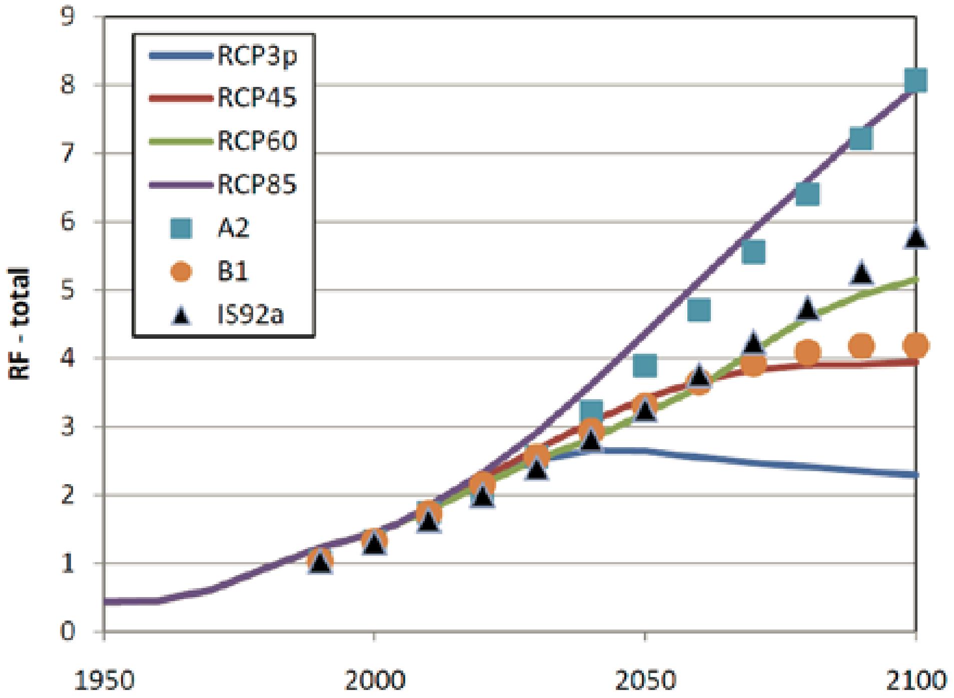
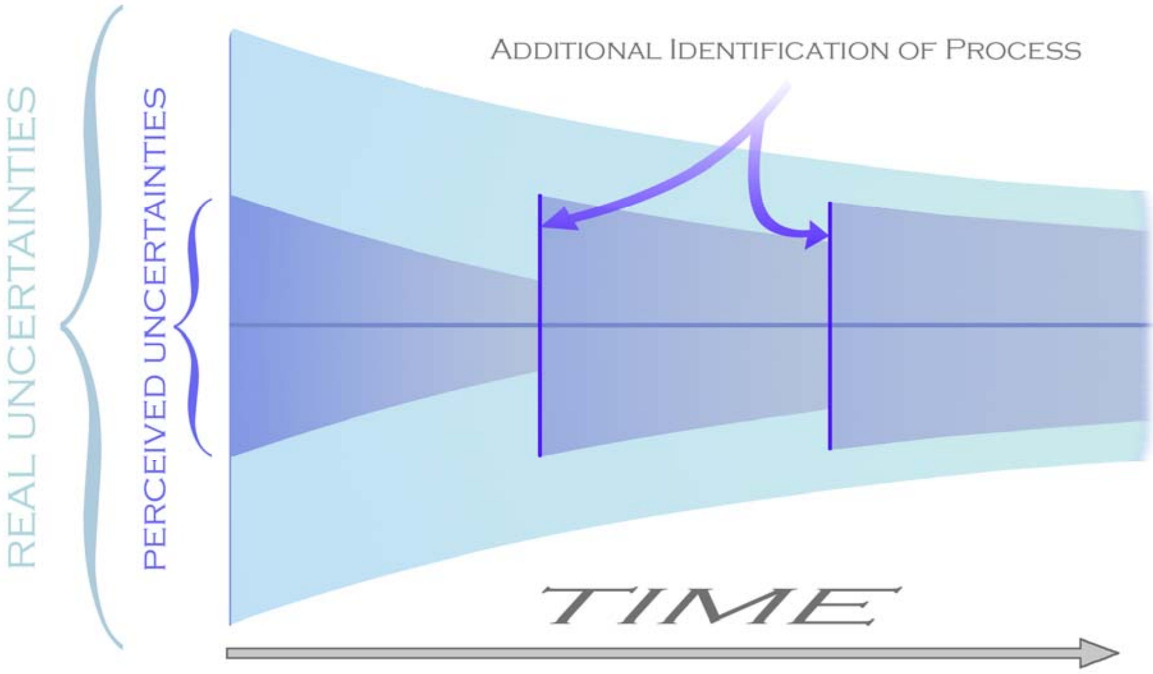


Figure 1.15: Projected total RF (W m^{-2}) from 2000 to 2100. Previous IPCC assessments (SAR IS92a, TAR/AR4 SRES A2 & B1) are compared with RCP scenarios reported as CO_2-equivalent (Meinshausen et al., 2011) and with those RCP emissions scenarios assessed here including uncertainties in natural emissions and atmospheric residence time. The uncertainty in RF for year 2000 (see Chapter 8) is not shown, nor projected here.



FAQ 1.1, Figure 1: Schematic showing the evolution of uncertainties in a projection (e.g., global mean temperature) at 2100. The real uncertainties decrease as there is more data, better understanding and the time becomes closer. However, our perception of the uncertainties may not change as much with time (or even grow) as our understanding improves.