

# **WORKING GROUP I CONTRIBUTION TO THE IPCC FIFTH ASSESSMENT REPORT CLIMATE CHANGE 2013: THE PHYSICAL SCIENCE BASIS**

## **Final Draft Underlying Scientific-Technical Assessment**

**A report accepted by Working Group I of the IPCC but not approved in detail.**

### **Note:**

The final draft Report, dated 7 June 2013, of the **Working Group I contribution to the IPCC 5th Assessment Report "Climate Change 2013: The Physical Science Basis"** was accepted but not approved in detail by the **12th Session of Working Group I and the 36th Session of the IPCC on 26 September 2013 in Stockholm, Sweden**. It consists of the full scientific and technical assessment undertaken by Working Group I.

The Report has to be read in conjunction with the document entitled "Climate Change 2013: The Physical Science Basis. Working Group I Contribution to the IPCC 5th Assessment Report - Changes to the underlying Scientific/Technical Assessment" to ensure consistency with the approved Summary for Policymakers (IPCC-XXVII/Doc.4) and presented to the Panel at its 36th Session. This document lists the changes necessary to ensure consistency between the full Report and the Summary for Policymakers, which was approved line-by-line by Working Group I and accepted by the Panel at the above-mentioned Sessions.

Before publication the Report will undergo final copyediting as well as any error correction as necessary, consistent with the IPCC Protocol for Addressing Possible Errors. Publication of the Report is foreseen in January 2014.

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**WORKING GROUP I CONTRIBUTION TO THE IPCC FIFTH ASSESSMENT  
REPORT (AR5), CLIMATE CHANGE 2013: THE PHYSICAL SCIENCE BASIS**

**Technical Summary - Final Draft Underlying Scientific-Technical Assessment**

(Submitted by the Co-Chairs of Working Group I)

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**NOTE:**

The Final Draft Underlying Scientific-Technical Assessment is submitted to the Twelfth Session of Working Group I for acceptance. The IPCC at its Thirty-sixth Session (Stockholm, 26 September 2013) will be informed of the actions of the Twelfth Session of Working Group I in this regard.

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## TS.1 Introduction

"*Climate Change 2013: The Physical Science Basis*" is the contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. This comprehensive assessment of the physical aspects of climate change puts a focus on those elements that are relevant to understand past, document current, and project future climate change. The assessment builds on the IPCC Fourth Assessment Report (AR4)<sup>1</sup> and the recent Special Report on Managing the Risk of Extreme Events and Disasters to Advance Climate Change Adaptation (SREX)<sup>2</sup> and is presented in 14 Chapters and 6 Annexes. The chapters cover direct and proxy observations of changes in all components of the climate system, they assess the current knowledge of various processes within, and interactions among, climate system components, which determine the sensitivity and response of the system to changes in forcing, and they quantify the link between the changes in atmospheric constituents, and hence radiative forcing<sup>3</sup>, and the consequent detection and attribution of climate change. Projections of changes in all climate system components are based on model simulations forced by a new set of scenarios. The report also provides a comprehensive assessment of past and future sea level change in a dedicated chapter. Regional climate change information is presented in the form of an Atlas of Global and Regional Climate Projections (Annex I). This is complemented by Annex II: Climate System Scenario Tables and Annex III: Glossary.

The primary purpose of this Technical Summary is to provide the link between the complete assessment of the multiple lines of independent evidence presented in the 14 chapters of the main report and the highly condensed summary prepared as the WGI Summary for Policymakers. The Technical Summary thus serves as a starting point for those readers who seek the full information on more specific topics covered by this assessment. This purpose is facilitated by including pointers to the chapters and sections where the full assessment can be found. Policy-relevant topics, which cut across many chapters and involve many interlinked processes in the climate system, are presented here as Thematic Focus Elements, allowing rapid access of this information.

An integral element of this report is the use of uncertainty language that permits a traceable account of the assessment (see Box TS.1). The degree of certainty in key findings in this assessment is based on the author teams' evaluations of underlying scientific understanding and is expressed as a level of confidence that results from the type, amount, quality, and consistency of evidence and the degree of agreement in the scientific studies considered<sup>4</sup>. Confidence is expressed qualitatively. Quantified measures of uncertainty in a finding are expressed probabilistically and are based on a combination of statistical analyses of observations or model results, or both, and expert judgment. Where appropriate, findings are also formulated as statements of fact without using uncertainty qualifiers (See Chapter 1 and Box TS.1 for more details).

[START BOX TS.1 HERE]

### Box TS.1: Treatment of Uncertainty

Based on the Guidance Note for Lead Authors of the IPCC Fifth Assessment Report on Consistent Treatment of Uncertainties, this WGI Technical Summary and the WGI Summary for Policymakers rely on two metrics for communicating the degree of certainty in key findings, which is based on author teams' evaluations of underlying scientific understanding:

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<sup>1</sup> IPCC, 2007: *Climate Change 2007: The Physical Science Basis*. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 996 pp.

<sup>2</sup> IPCC, 2012: *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation*. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change [Field, C.B., V. Barros, T.F. Stocker, D. Qin, D.J. Dokken, K.L. Ebi, M.D. Mastrandrea, K.J. Mach, G.-K. Plattner, S.K. Allen, M. Tignor, and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, UK, and New York, NY, USA, 582 pp.

<sup>3</sup> Radiative forcing (RF) is a measure of the net change in the energy balance of the Earth system in response to some external perturbation. It is expressed in Watts per square meter ( $W m^{-2}$ ), see Box TS.2.

<sup>4</sup> Mastrandrea, M.D., C.B. Field, T.F. Stocker, O. Edenhofer, K.L. Ebi, D.J. Frame, H. Held, E. Kriegler, K.J. Mach, P.R. Matschoss, G.-K. Plattner, G.W. Yohe, and F.W. Zwiers, 2010: *Guidance Note for Lead Authors of the IPCC Fifth Assessment Report on Consistent Treatment of Uncertainties*. Intergovernmental Panel on Climate Change (IPCC).

- 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).

The AR5 Guidance Note refines the guidance provided to support the IPCC Third and Fourth Assessment Reports. Direct comparisons between assessment of uncertainties in findings in this report and those in the IPCC Fourth Assessment Report and the IPCC Special Report on Managing the Risk of Extreme Events and Disasters to Advance Climate Change Adaptation (SREX) are difficult, because of the application of the revised guidance note on uncertainties, as well as the availability of new information, improved scientific understanding, continued analyses of data and models, and specific differences in methodologies applied in the assessed studies. For some climate variables, different aspects have been assessed and therefore a direct comparison would be inappropriate.

Each key finding is based on an author team's evaluation of associated evidence and agreement. The confidence metric provides a qualitative synthesis of an author team's judgment about the validity of a finding, as determined through evaluation of evidence and agreement. If uncertainties can be quantified probabilistically, an author team can characterize a finding using the calibrated likelihood language or a more precise presentation of probability. Unless otherwise indicated, high or very high confidence is associated with findings for which an author team has assigned a likelihood term.

The following summary terms are used to describe the available evidence: limited, medium, or robust; and for the degree of agreement: low, medium, or high. A level of confidence is expressed using five qualifiers very low, low, medium, high, and very high. Box TS.1, Figure 1 depicts summary statements for evidence and agreement and their relationship to confidence. There is flexibility in this relationship; for a given evidence and agreement statement, different confidence levels can be assigned, but increasing levels of evidence and degrees of agreement are correlated with increasing confidence.

**[INSERT BOX TS.1, FIGURE 1 HERE]**

**Box TS.1, Figure 1:** A depiction of evidence and agreement statements and their relationship to confidence. Confidence increases toward the top-right corner as suggested by the increasing strength of shading. Generally, evidence is most robust when there are multiple, consistent independent lines of high-quality. {Figure 1.11}

The following terms have been used to indicate the assessed likelihood:

<b>Term*</b>	<b>Likelihood of the outcome</b>
<i>Virtually certain</i>	99–100% probability
<i>Very likely</i>	90–100% probability
<i>Likely</i>	66–100% probability
<i>About as likely as not</i>	33–66% probability
<i>Unlikely</i>	0–33% probability
<i>Very unlikely</i>	0–10% probability
<i>Exceptionally unlikely</i>	0–1% probability

\* Additional terms (*extremely likely*: 95–100% probability, *more likely than not*: >50–100% probability, and *extremely unlikely*: 0–5% probability) may also be used when appropriate.

**[END BOX TS.1 HERE]**

The Technical Summary is structured into four main sections presenting the assessment results following the storyline of the WGI contribution to AR5: Section TS.2 covers the assessment of observations of changes in the climate system; Section TS.3 summarizes the information on the different drivers, natural and anthropogenic, expressed in terms of radiative forcing; Section TS.4 presents the assessment of the quantitative understanding of observed climate change; and Section TS.5 summarizes the assessment results

for projections of future climate change over the 21st century and beyond from regional to global scale. Section TS.6 combines and lists key uncertainties from the WGI assessment from Sections TS.2–TS.5. The overall nine Thematic Focus Elements (TFEs), cutting across the various components of the WGI AR5, are dispersed throughout the four main TS sections, are visually distinct from the main text, and should allow stand-alone reading.

The basis for substantive paragraphs in this Technical Summary can be found in the chapter sections of the underlying report. These references are given in curly brackets.

## TS.2 Observation of Changes in the Climate System

### TS.2.1 Introduction

Observations of the climate system are based on direct physical and biogeochemical measurements, remote sensing from ground stations and satellites; information derived from paleoclimate archives provides a long-term context. Global-scale observations from the instrumental era began in the mid-19th century, and paleoclimate reconstructions extend the record of some quantities back hundreds to millions of years. Together, they provide a comprehensive view of the variability and long-term changes in the atmosphere, the ocean, the cryosphere, and the land surface.

The assessment of observational evidence for climate change is summarized in this section. Substantial advancements in the availability, acquisition, quality and analysis of observational data sets in atmosphere, land surface, ocean, and cryosphere have occurred since the AR4. Many aspects of the climate system are showing evidence of a changing climate.

### TS.2.2 Changes in Temperature

#### TS.2.2.1 Surface

It is certain that Global Mean Surface Temperature (GMST) has increased since the late 19th century (Figure TS.1). Each of the past three decades has been warmer than all the previous decades in the instrumental record, and the decade of the 2000's has been the warmest. The global combined land and ocean temperature data show an increase of about 0.89°C [0.69–1.08]<sup>5</sup> over the period 1901–2012 and about 0.72°C [0.49–0.89] over the period 1951–2012 when described by a linear trend<sup>6</sup>. The warming from 1850–1900 (early-industrial) to 1986–2005 (reference period for the modelling chapters and the Atlas in Annex 1) is 0.61°C [0.55 to 0.67], when calculated using HadCRUT4 and its uncertainty estimates. It is also *virtually certain* that maximum and minimum temperatures over land have increased on a global scale since 1950. {2.4.1, 2.4.3, Supplementary Material 2.SM.3}

Despite the robust multi-decadal timescale warming, there exists substantial interannual to decadal variability in the rate of warming, with several periods exhibiting weaker trends (including the warming hiatus since 1998) (Figure TS.1). Although the trend uncertainty is large for short records, the rate of warming over the past 15 years (1998–2012; 0.05°C per decade [–0.05 to +0.15]) is smaller than the trend since 1951 (1951–2012; 0.12°C per decade [0.08 to 0.14])<sup>6</sup>. Several independently analysed data records of global and regional land surface air temperature obtained from station observations are in broad agreement that land surface air temperature s have increased. Sea surface temperatures have also increased. Intercomparisons of new sea surface temperature data records obtained by different measurement methods, including satellite data, have resulted in better understanding of errors and biases in the records. {2.4.1, 2.4.2, 2.4.3; Box 9.2}

<sup>5</sup> 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.

<sup>6</sup> The warming is reported as an unweighted average based upon linear trend estimates calculated from HadCRUT4, MLOST and GISS datasets (see Figure TS.2; Section 2.4.3)

**[INSERT FIGURE TS.1 HERE]**

**Figure TS.1:** Multiple complementary indicators of a changing global climate. Each line represents an independently-derived estimate of change in the climate element. The time series presented are assessed in chapters 2, 3, and 4. In each panel all datasets have been normalized to a common period of record. A full detailing of which source datasets go into which panel is given in Chapter 2, Supplementary Material 2.SM.5 and in the respective chapters (See also FAQ 2.1, Figure 1). {2.4, 2.5, 3.2, 3.7, 4.5.2, 4.5.3}

**[INSERT FIGURE TS.2 HERE]**

**Figure TS.2:** Change in surface temperature over 1901-2012 as determined by linear trend for three data sets. White areas indicate incomplete or missing data. Trends have been calculated only for those grid boxes with greater than 70% complete records and more than 20% data availability in the first and last 10% of the time period. Black plus signs (+) indicate grid boxes where trends are significant (i.e., a trend of zero lies outside the 90% confidence interval). Differences in coverage primarily reflect the degree of interpolation to account for data void regions undertaken by the dataset providers ranging from none beyond grid box averaging (HadCRUT4) to substantial (GISS). {Figure 2.21}

It is *unlikely* that any uncorrected urban heat-island effects and land use change effects have raised the estimated centennial globally averaged land surface air temperature trends by more than 10% of the reported trend. This is an average value; in some regions that have rapidly developed urban heat island and land use change impacts on regional trends may be substantially larger. {2.4.1}

There is *high confidence* that annual mean surface warming since the 20th century has reversed long-term cooling trends of the past 5,000 years in mid-to-high latitudes of the Northern Hemisphere. For average annual Northern Hemisphere temperatures, the period 1983–2012 was *very likely* the warmest 30-year period of the last 800 years (*high confidence*) and *likely* the warmest 30-year period of the last 1400 years (*medium confidence*). This is supported by comparison of instrumental temperatures with multiple reconstructions from a variety of proxy data and statistical methods, and is consistent with AR4. Continental-scale surface temperature reconstructions show, with *high confidence*, multidecadal intervals during the Medieval Climate Anomaly (950 to 1250) that were in some regions as warm as in the mid-20th century and in others as warm as in the late 20th century. With *high confidence*, these intervals were not as synchronous across seasons and regions as the warming since the mid-20th century. Based on the comparison between reconstructions and simulations, there is *high confidence* that not only external orbital, solar and volcanic forcing, but also internal variability, contributed substantially to the spatial pattern and timing of surface-temperature changes between the Medieval Climate Anomaly and the Little Ice Age (1450 to 1850). {5.3.5, 5.5.1}

*TS.2.2.2 Troposphere and Stratosphere*

Based upon multiple independent analyses of measurements from radiosondes and satellite sensors, it is *virtually certain* that globally the troposphere has warmed and the stratosphere has cooled since the mid-20th century (Figure TS.1). Despite unanimous agreement on the sign of the trends, substantial disagreement exists between available estimates as to the rate of temperature changes, particularly outside the Northern Hemisphere extra-tropical troposphere, which has been well sampled by radiosondes. Hence there is only *medium confidence* in the rate of change and its vertical structure in the Northern Hemisphere extra-tropical troposphere and *low confidence* elsewhere. {2.4.4}

*TS.2.2.3 Ocean*

It is *virtually certain* that the upper ocean (above 700 m) has warmed from 1971 to 2010, and *likely* that it has warmed from the 1870s to 1971 (Figure TS.1). There is less certainty in changes prior to 1971 because of relatively sparse sampling in earlier time periods. Instrumental biases in historical upper ocean temperature measurements have been identified and mitigated since AR4, reducing artificial decadal variation in temperature and upper ocean heat content, most prominent during the 1970s and 1980s. {3.2.1, 3.2.2, 3.2.3, 3.5.3}

It is *likely* that the ocean warmed between 700 and 2000 m from 1957 to 2010, based on five-year averages. It is *likely* that the ocean warmed from 3000 m to the bottom from 1992 to 2005, when sufficient observations became available for a global assessment. No significant trends in global average temperature



were observed between 2000 and 3000 m depth for either overlapping time period. The largest changes in deep ocean temperature have been observed close to the sources of deep and bottom water in the northern North Atlantic and especially in the Southern Ocean with anomaly amplitudes lessening along the routes through which these waters spread. {3.2.4, 3.5.1}

### **TS.2.3 Changes in Energy Budget and Heat Content**

Earth has been in radiative imbalance, with more energy from the sun entering than exiting the top of the atmosphere, since at least circa 1970. It is *virtually certain* that Earth has gained substantial energy from 1971–2010. The estimated increase in energy inventory between 1971 and 2010 is  $274 [196 \text{ to } 351] \times 10^{21}$  J, with a heating rate of  $213 \times 10^{12}$  W from a linear fit to the annual values over that time period (see also TFE.4).

Ocean warming dominates that total heating rate, with full ocean depth warming accounting for about 93% (and warming of the upper (0–700 m) ocean accounting for about 64%). Melting ice (including Arctic sea ice, ice sheets, and glaciers) and warming of the continents each account for 3 of the total. Warming of the atmosphere makes up the remaining 1%. The 1971–2010 estimated rate of ocean energy gain is  $199 \times 10^{12}$  W from a linear fit to data over that time period, equivalent to  $0.42 \text{ W m}^{-2}$  heating applied continuously over Earth's entire surface, and  $0.55 \text{ W m}^{-2}$  for the portion owing to ocean warming applied over the ocean's entire surface area. Earth's estimated energy increase from 1993–2010 is  $163 [127 \text{ to } 201] \times 10^{21}$  J with a trend estimate of  $275 \times 10^{15}$  W. The ocean portion of the trend for 1993–2010 is  $257 \times 10^{12}$  W, equivalent to a mean heat flux into the ocean of  $0.71 \text{ W m}^{-2}$ . {3.2.3, 3.2.4; Box 3.1}

The rate of ocean warming in some of the 0–700 m estimates was lower from 2003 to 2010 than in the previous decade (Figure TS.1); however, warming in the subsurface layer between 700 and 2000 m *likely* continued unabated during this period. {3.2.3, 3.2.4; Box 9.2}

### **TS.2.4 Changes in Circulation and Modes of Variability**

Large variability on interannual to decadal time scales hampers robust conclusions on long-term changes in atmospheric circulation in many instances. *Confidence* is *high* that the increase of the northern mid-latitude westerly winds and the NAO index from the 1950s to the 1990s, and the weakening of the Pacific Walker circulation from the late 19th century to the 1990s, have been largely offset by recent changes. With *high confidence*, decadal and multi-decadal changes in the winter North Atlantic Oscillation index (NAO) observed since the 20th century are not unprecedented in the context of the past 500 years. {2.7.2, 2.7.5, 2.7.8, 5.4; Box 2.5; Tables 2.12}

It is *likely* that circulation features have moved poleward since the 1970s, involving a widening of the tropical belt, a poleward shift of storm tracks and jet streams, and a contraction of the northern polar vortex. Evidence is more robust for the Northern Hemisphere. It is *likely* that the Southern Annular Mode has become more positive since the 1950s. The increase in the strength of the observed summer Southern Annular Mode since 1950 has been anomalous, with *medium confidence*, in the context of the past 400 years. {2.7.5, 2.7.6, 2.7.8, 5.4; Box 2.5; Tables 2.2–2.12}

New results from high-resolution coral records document with *high confidence* that the El Niño-Southern Oscillation (ENSO) system has remained highly variable throughout the past 7,000 years, showing no discernible evidence for an orbital modulation of ENSO. {5.4}

Recent observations have strengthened evidence for variability in major ocean circulation systems on time scales from years to decades. It is *very likely* that the subtropical gyres in the North Pacific and South Pacific have expanded and strengthened since 1993. Based on measurements of the full Atlantic Meridional Overturning Circulation (AMOC) and its individual components at various latitudes and different time periods, there is no evidence of a long-term trend. There is also no evidence for trends in the transports of the Indonesian Throughflow, the Antarctic Circumpolar Current (ACC), or in the transports between the Atlantic Ocean and Nordic Seas. However, a southward shift of the ACC by about  $1^\circ$  of latitude is observed in data spanning the time period 1950 to 2010 with *medium confidence*. {3.6}

## TS.2.5 Changes in the Water Cycle and Cryosphere

### TS.2.5.1 Atmosphere

*Confidence* in precipitation change averaged over global land areas is *low* prior to 1950 and *medium* afterwards because of insufficient data, particularly in the earlier part of the record (for an overview of observed and projected changes in the global water cycle see TFE.1). Available globally incomplete records show mixed and non-significant long-term trends in reported global mean changes. Further, when virtually all the land area is filled in using a reconstruction method, the resulting time series shows little change in land-based precipitation since 1900. Northern hemisphere mid-latitude land areas do show a *likely* overall increase in precipitation (*medium confidence* prior to 1950, but *high confidence* afterwards). {2.5.1}

It is *very likely* that global near surface and tropospheric air specific humidity have increased since the 1970s. However, during recent years the near-surface moistening trend over land has abated (*medium confidence*) (Figure TS.1). As a result, fairly widespread decreases in relative humidity near the surface are observed over the land in recent years. {2.4.4, 2.5.5, 2.5.6}

While trends of cloud cover are consistent between independent data sets in certain regions, substantial ambiguity and therefore *low confidence* remains in the observations of global-scale cloud variability and trends. {2.5.7}

### TS.2.5.2 Ocean and Surface Fluxes

It is *very likely* that regional trends have enhanced the mean geographical contrasts in sea surface salinity since the 1950s: saline surface waters in the evaporation-dominated mid-latitudes have become more saline, while relatively fresh surface waters in rainfall-dominated tropical and polar regions have become fresher. The mean contrast between high and low salinity regions increased by 0.13 [0.08 to 0.17] from 1950 to 2008. It is *very likely* that the inter-basin contrast in freshwater content has increased: the Atlantic has become saltier and the Pacific and Southern Oceans have freshened. While similar conclusions were reached in AR4, recent studies based on expanded data sets and new analysis approaches provide *high confidence* in this assessment. {3.3.2, 3.3.3, 3.9; FAQ 3.3}

The spatial patterns of the salinity trends, mean salinity and the mean distribution of evaporation minus precipitation are all similar (see also TFE.1, Figure 1). These similarities provide indirect evidence that the pattern of evaporation minus precipitation over the oceans has been enhanced since the 1950s (*medium confidence*). Uncertainties in currently available surface fluxes prevent the flux products from being reliably used to identify trends in the regional or global distribution of evaporation or precipitation over the oceans on the timescale of the observed salinity changes since the 1950s. {3.3.2, 3.3.3, 3.3.4, 3.4.2, 3.4.3, 3.9; FAQ 3.3}

### TS.2.5.3 Sea Ice

Continuing the trends reported in AR4, there is *very high confidence* that the Arctic sea ice extent (annual, multiyear and perennial) decreased over the period 1979–2012 (Figure TS.1). The rate of the annual decrease was *very likely* between 3.5 and 4.1% per decade. The average decrease in decadal extent of annual Arctic sea ice has been most rapid in summer and autumn (*high confidence*), but the extent has decreased in every season, and in every successive decade since 1979 (*high confidence*). The extent of Arctic perennial and multiyear ice decreased between 1979 and 2012 (*very high confidence*). The rates are *very likely* 11.5 [9.4 to 13.6] % per decade for the perennial sea ice area at summer minimum and *very likely* 13.5 [11 to 16] % per decade for multiyear ice. There is *medium confidence* from reconstructions that the 1980–2012 summer sea-ice retreat and increase in sea-surface temperatures in the Arctic are anomalous in the last 2,000 years. {4.2.2, 5.5.2}

It is *likely* that the annual period of surface melt on Arctic perennial sea ice lengthened by 5.7 [4.8 to 6.6] days per decade over the period 1979–2012. Over this period, in the region between the East Siberian Sea and the western Beaufort Sea, the duration of ice-free conditions increased by nearly 2 months. {4.2.2}

There is *high confidence* that the average winter sea ice thickness within the Arctic Basin decreased between 1980 and 2008. The average decrease was *likely* between 1.3 m and 2.3 m. *High confidence* in this assessment is based on observations from multiple sources: submarine, electromagnetic probes, and satellite altimetry; and is consistent with the decline in multiyear and perennial ice extent. Satellite measurements made in the period 2010–2012 show a decrease in sea ice volume compared to those made over the period 2003–2008 (*medium confidence*). There is *high confidence* that in the Arctic, where the sea ice thickness has decreased, the sea ice drift speed has increased. {4.2.2}

It is *very likely* that the annual Antarctic sea ice extent increased at a rate of between 1.2 and 1.8% per decade between 1979 and 2012. There was a greater increase in sea ice area, due to a decrease in the percentage of open water within the ice pack. There is *high confidence* that there are strong regional differences in this annual rate, with some regions increasing in extent/area and some decreasing. {4.2.3}

#### TS.2.5.4 Glaciers and Ice Sheets

There is *very high confidence*—with a very few regional exceptions—that, since AR4, overall glaciers world-wide have continued to shrink as revealed by the time series of measured changes in glacier length, area, volume and mass (Figure TS.1, Figure TS.3). Measurements of glacier change have increased substantially in number since AR4. Most of the new datasets, along with a globally complete glacier inventory, have been derived from satellite remote sensing {4.3.1, 4.3.3}

There is *very high confidence* that, during the last decade, most ice was lost from glaciers in Alaska, the Canadian Arctic, the periphery of the Greenland ice sheet, the Southern Andes and the Asian mountains. Together these areas account for more than 80% of the total ice loss. Total mass loss from all glaciers in the world, excluding those on the periphery of the ice sheets, was *very likely* 226 [91 to 361] Gt yr<sup>-1</sup> (sea-level equivalent, 0.62 [0.25 to 0.99] mm yr<sup>-1</sup>) in the period 1971–2009, 275 [140 to 410] Gt yr<sup>-1</sup> (0.76 [0.39 to 1.13] mm yr<sup>-1</sup>) in the period 1993–2009, and 301 [166 to 436] Gt yr<sup>-1</sup> (0.83 [0.46 to 1.20] mm yr<sup>-1</sup>) between 2005 and 2009<sup>7</sup>. {4.3.3; Tables 4.4, 4.5}

There is *high confidence* that current glacier extents are out of balance with current climatic conditions, indicating that glaciers will continue to shrink in the future even without further temperature increase. {4.3.3}

There is *very high confidence* that the Greenland Ice Sheet has lost ice during the last two decades. Combinations of satellite and airborne remote sensing together with field data indicate with *high confidence* that the ice loss has occurred in several sectors and that large rates of mass loss have spread to wider regions than reported in AR4 (Figure TS.3). There is *high confidence* that the mass loss of the Greenland Ice Sheet has accelerated since 1992: the average rate has *very likely* increased from 34 [–6 to 74] Gt yr<sup>-1</sup> over the period 1992–2001 (sea-level equivalent, 0.09 [–0.02 to 0.20] mm yr<sup>-1</sup>), to 215 [157 to 274] Gt yr<sup>-1</sup> over the period 2002–2011 (0.59 [0.43 to 0.76] mm yr<sup>-1</sup>). There is *high confidence* that ice loss from Greenland resulted from increased surface melt and runoff, and increased outlet glacier discharge, and these occurred in similar amounts. There is *high confidence* that the area subject to summer melt has increased over the last two decades. {4.4.2, 4.4.3}

#### [INSERT FIGURE TS.3 HERE]

**Figure TS.3:** Upper panels: distribution of ice loss determined from GRACE time-variable gravity for (a) Antarctica and (b) Greenland, shown in centimetres of water per year (cm of water yr<sup>-1</sup>) for the period 2003 to 2012. Lower panel: the assessment of the total loss of ice from glaciers and ice sheets in terms of sea level equivalent (in mm). The contribution from glaciers excludes those on the periphery of the ice sheets. {4.3.4; Figures 4.12, 4.13, 4.14, 4.16, 4.17}

There is *high confidence* that the Antarctic Ice Sheet has been losing ice during the last two decades (Figure TS.3). There is *very high confidence* that these losses are mainly from the northern Antarctic Peninsula and the Amundsen Sea sector of West Antarctica, and *high confidence* that they result from the acceleration of outlet glaciers. The average rate of ice loss from Antarctica *likely* increased from 30 [–37 to 97] Gt yr<sup>-1</sup> (sea

<sup>7</sup> 100 Gt yr<sup>-1</sup> of ice loss corresponds to about 0.28 mm yr<sup>-1</sup> of sea level equivalent.

level equivalent, 0.08 [−0.10 to 0.27] mm yr<sup>−1</sup>) over the period 1992–2001, to 147 [72 to 221] Gt yr<sup>−1</sup> over the period 2002–2011 (0.40 [0.20 to 0.61] mm yr<sup>−1</sup>). {4.4.2, 4.4.3}

There is *high confidence* that in parts of Antarctica floating ice shelves are undergoing substantial changes. There is *medium confidence* that ice shelves are thinning in the Amundsen Sea region of West Antarctica, and *low confidence* that this is due to high ocean heat flux. There is *high confidence* that ice shelves around the Antarctic Peninsula continue a long-term trend of retreat and partial collapse that began decades ago. {4.4.2, 4.4.5}

#### TS.2.5.5 Snow Cover, Freshwater Ice and Frozen Ground

There is *very high confidence* that snow cover extent has decreased in the Northern Hemisphere, especially in spring (Figure TS.1). Satellite records indicate that over the period 1967–2012, snow cover extent *very likely* decreased; the largest change, −53% [−40% to −66%], occurred in June. No month had statistically significant increases. Over the longer period, 1922–2012, data are only available for March and April, but these show *very likely* a 7% [4.5% to 9.5%] decline and a negative correlation (−0.76) with March to April 40°N–60°N land temperature. In the Southern Hemisphere, evidence is too limited to conclude whether changes have occurred. {4.5.2, 4.5.3}

Permafrost temperatures have increased in most regions around the world since the early 1980s (*high confidence*). These increases were in response to increased air temperature, and changes in the timing and thickness of snow cover (*high confidence*). The temperature increase for colder permafrost was generally greater than for warmer permafrost (*high confidence*). {4.7.2, Table 4.8}

### TFE.1: Water Cycle Change

The water cycle describes the continuous movement of water through the climate system in its liquid, solid and vapour forms, and storage in the reservoirs of ocean, cryosphere, land surface and atmosphere. In the atmosphere, water occurs primarily as a gas, water vapour, but it also occurs as ice and liquid water in clouds. The ocean is primarily liquid water, but the ocean is partly covered by ice in Polar Regions. Terrestrial water in liquid form appears as surface water (lakes, rivers), soil moisture and groundwater. Solid terrestrial water occurs in ice sheets, glaciers, snow and ice on the surface and permafrost. The movement of water in the climate system is essential to life on land, since much of the water that falls on land as precipitation and supplies the soil moisture and river flow has been evaporated from the ocean and transported to land by the atmosphere. Water that falls as snow in winter can provide soil moisture in springtime and river flow in summer and is essential to both natural and human systems. The movement of fresh water between the atmosphere and the ocean can also influence oceanic salinity, which is an important driver of the density and circulation of the ocean. The latent heat contained in water vapour in the atmosphere is critical to driving the circulation of the atmosphere on scales ranging from individual thunderstorms to the global circulation of the atmosphere. {12.4.5; FAQ 3.3, FAQ 12.2}

#### Observations of Water Cycle Change

Because the saturation vapour pressure of air increases with temperature, it is expected that the amount of water vapour suspended in air will increase with a warming climate. Observations from surface stations, radiosondes, global positioning systems, and satellite measurements indicate increases in tropospheric water vapour at large spatial scales (TFE.1, Figure 1). It is *very likely* that tropospheric specific humidity has increased since the 1970s. The magnitude of the observed global change in water vapour of about 3.5% in the past 40 years is consistent with the observed temperature change of about 0.5°C during the same period, and the relative humidity has stayed approximately constant. The water vapour change can be attributed to human influence with *medium confidence*. {2.5.4, 10.3.2}

Changes in precipitation are harder to measure with the existing records, both because of the greater difficulty in sampling precipitation and also because it is expected that precipitation will have a smaller fractional change than the water vapour content of air as the climate warms. When virtually all the land area

is filled in using a reconstruction method, the resulting time series shows little change in land-based precipitation since 1900. At present there is *medium confidence* that there has been a significant human influence on global scale changes in precipitation patterns, including increases in northern hemisphere mid to high latitudes. Changes in the extremes of precipitation, and other climate extremes related to the water cycle are comprehensively discussed in TFE.9. {2.5.1, 10.3.2}

Although direct trends in precipitation and evaporation are difficult to measure with the available records, the observed oceanic surface salinity, which is strongly dependent on the difference between evaporation and precipitation, shows significant trends (TFE.1, Figure 1). The spatial patterns of the salinity trends since 1950, the mean salinity and the mean distribution of evaporation–precipitation are similar to each other: regions of high salinity where evaporation dominates have become more saline, while regions of low salinity where rainfall dominates have become fresher (TFE.1, Figure 1). This provides indirect evidence that the pattern of evaporation-precipitation over the oceans has been enhanced since the 1950s (*medium confidence*). The inferred changes in evaporation minus precipitation are consistent with the observed increased water vapour content of the warmer air. It is *very likely* that observed changes in surface and subsurface salinity are due in part to anthropogenic increases in forcings. {2.5, 3.3.2, 3.3.3, 3.3.4, 3.4, 3.9, 10.4.2; FAQ 3.3}

### [INSERT TFE.1, FIGURE 1 HERE]

**TFE.1, Figure 1:** Changes in sea surface salinity are related to the atmospheric patterns of Evaporation minus Precipitation (E-P) and trends in total precipitable water: (a) Linear trend (1988 to 2010) in total precipitable water (water vapor integrated from Earth’s surface up through the entire atmosphere) ( $\text{kg m}^{-2}$  per decade) from satellite observations. (b) The 1979–2005 climatological mean net evaporation minus precipitation ( $\text{cm yr}^{-1}$ ) from meteorological reanalysis data. (c) Trend (1950 to 2000) in surface salinity (PSS78 per 50years). (d) The climatological-mean surface salinity (PSS78) (blues <35; yellows-reds >35). (e) Global difference between salinity averaged over regions where the sea surface salinity is greater than the global mean sea surface salinity (“High Salinity”) and salinity averaged over regions values below the global mean (“Low Salinity”). Details of data sources: see Figure 3.21 and FAQ 3.3, Figure 1. {3.9}

In most regions analyzed, it is *likely* that decreasing numbers of snowfall events are occurring where increased winter temperatures have been observed. Both satellite and in-situ observations show significant reductions in the Northern Hemisphere snow cover extent over the past 90 years, with most of the reduction occurring in the 1980s. Snow cover decreased most in spring when the average extent decreased by around 8% (7 million  $\text{km}^2$ ) over the period 1970–2010 compared with the period 1922–1970. Because of earlier spring snowmelt, the duration of the Northern Hemisphere snow season has declined by 5.3 days per decade since the 1972/1973 winter. It is *likely* that there has been an anthropogenic component to these observed reductions in snow cover since the 1970s. {4.5.2, 10.5.1, 10.5.3}

The most recent and most comprehensive analyses of river runoff do not support the AR4 conclusion that global runoff has increased during the 20th century. New results also indicate that the AR4 conclusions regarding global increasing trends in droughts since the 1970s are no longer supported. {2.5.2, 2.6.2}

### *Projections of Future Changes*

Changes in the water cycle are projected to occur in a warming climate (TFE.1, Figure 2, see also TS 4.6, TS 5.6, Annex I). Global-scale precipitation is projected to gradually increase in the 21st century. It is *virtually certain*, that precipitation increase will be much smaller, approximately  $2\% \text{ K}^{-1}$ , than the rate of lower tropospheric water vapour increase ( $\sim 7\% \text{ K}^{-1}$ ), due to global energetic constraints. It is *virtually certain* that changes of average precipitation in a much warmer world will not be uniform, with some regions experiencing increases, and others with decreases or not much change at all. The high latitudes are *likely* to experience greater amounts of precipitation due to the additional water carrying capacity of the warmer troposphere. Many mid-latitude arid and semi-arid regions will *likely* experience less precipitation. The largest precipitation changes over northern Eurasia and North America are projected to occur during the winter. {12.4.5, Annex I}

### [INSERT TFE.1, FIGURE 2 HERE]

**TFE.1, Figure 2:** Annual mean changes in precipitation (P), evaporation (E), relative humidity, E-P, runoff and soil moisture, for 2081–2100 relative to 1986–2005 under the RCP8.5 scenario (see Box TS.6). The number of CMIP5

models to calculate the multi-model mean is indicated in the upper right corner of each panel. Hatching indicates regions where the multi model mean is less than one standard deviation of internal variability. Stippling indicates regions where the multi model mean is greater than two standard deviations of internal variability and where 90% of models agree on the sign of change (see Box 12.1). {Figures 12.25–12.27}

Regional to global-scale projections of soil moisture and drought remain relatively uncertain compared to other aspects of the water cycle. Nonetheless, drying in the Mediterranean, southwestern U.S. and south African regions are consistent with projected changes in Hadley circulation, so drying in these regions as global temperatures increase is *likely* for several degrees of warming under the RCP8.5 scenario. Decreases in runoff are *likely* in southern Europe and the Middle East. The high northern latitude runoff increases are likely and consistent with the projected precipitation increases. {12.4.5}

### TS.2.6 Changes in Sea Level

The primary contributions to changes in the volume of water in the ocean are the expansion of the ocean water as it warms and the transfer to the ocean of water currently stored on land, particularly from glaciers and ice sheets. Water impoundment in reservoirs and ground water depletion (and its subsequent run-off to the ocean) also affects sea level. Change in sea level relative to the land (relative sea level) can be significantly different from the global mean sea level (GMSL) change because of changes in the distribution of water in the ocean and vertical movement of the land. For an overview on the scientific understanding and uncertainties associated with recent (and projected) sea level change see TFE.2. {3.7.3, 13.1}

During the warm intervals of the middle Pliocene (3.3 to 3.0 million years ago), when there is *medium confidence* that global mean surface temperatures were 2°C to 3.5°C warmer than for pre-industrial climate and CO<sub>2</sub> levels were between 250 and 450 ppm, sedimentary records suggest periodic deglaciation of West Antarctica and parts of the East Antarctica. Ice-sheet models suggest near-complete deglaciation of the Greenland, West Antarctica and partial deglaciation of East Antarctica. Together, the evidence suggests that GMSL was above present levels at that time, but did not exceed 20 m above present (*high confidence*). {5.6.1, 13.2}

During the Last Interglacial Period (about 129,000 to 116,000 years ago) when peak global warmth was not more than 2°C above pre-industrial temperatures, and peak global annual sea surface temperatures were 0.7 [0.1 to 1.3] °C warmer (*medium confidence*), maximum GMSL was at least 5 m higher than at present (*very high confidence*), but did not exceed 10 m (*high confidence*). Based on ice-sheet model simulations consistent with elevation changes derived from a new Greenland ice core, the Greenland ice sheet *very likely* contributed between 1.4 m and 4.3 m sea level equivalent, implying with *medium confidence* a contribution from the Antarctic ice sheet to the global mean sea level during the last interglacial period. {5.6.2, 13.2}

Based on proxy data, the magnitude of centennial-scale global mean sea level variations did not exceed 0.25 m over the past few millennia (*medium confidence*). The current rate of global mean sea level change, starting in the late 19th-early 20th century, is, with *medium confidence*, unusually high in the context of centennial-scale variations of the last two millennia. Tide gauge data also indicate a *likely* acceleration during the last two centuries. Based on proxy and instrumental data, it is *virtually certain* that the rate of global mean sea level rise has accelerated during the last two centuries, marking the transition from relatively low rates of change during the late Holocene (order tenths of mm yr<sup>-1</sup>) to modern rates (order mm yr<sup>-1</sup>). {3.7, 5.6.3, 13.2}

Global mean sea level has risen by 0.19 [0.17 to 0.21] m, estimated from a linear trend over the period 1901–2010, based on tide gauge records and additionally on satellite data since 1993. It is *very likely* that the mean rate of sea level rise was 1.7 [1.5 to 1.9] mm yr<sup>-1</sup> between 1901 and 2010. Between 1993 and 2010, the rate was *very likely* higher at 3.2 [2.8 to 3.6] mm yr<sup>-1</sup>; similarly high rates *likely* occurred between 1930 and 1950. The rate of global mean sea level rise has *likely* increased since the early 1900 with estimates ranging from 0.000 to 0.013 [–0.002 to 0.019] mm yr<sup>-2</sup>. {3.7, 5.6.3, 13.2}

### TFE.2: Sea Level Change: Scientific Understanding and Uncertainties

After the Last Glacial Maximum, global mean sea levels reached close to present-day values several thousand years ago. Since then, it is *virtually certain* that the rate of global mean sea level rise has increased from low rates of sea level change during the late Holocene (order tenths of  $\text{mm yr}^{-1}$ ) to 20th century rates (order  $\text{mm yr}^{-1}$ , Figure TS1). {3.7, 5.6, 13.2}

Ocean thermal expansion and glacier mass loss are *very likely* the dominant contributors to global mean sea level rise during the 20th century. It is *very likely* that warming of the ocean has contributed 0.8 [0.5 to 1.1]  $\text{mm yr}^{-1}$  of sea level change during 1971–2010, with the majority of the contribution coming from the upper 700 m. The model-mean rate of ocean thermal expansion for 1971–2010 is close to observations. {3.7, 13.3}

Observations, combined with improved methods of analysis, indicate that the global glacier contribution (excluding the peripheral glaciers around Greenland and Antarctica) to sea level was 0.25 to 1.00  $\text{mm yr}^{-1}$  sea level equivalent during 1971–2010. *Medium confidence* in global glacier mass balance models used for projections of global changes arises from the ability of the models of the well-observed glaciers to reproduce time series of historical changes of those glaciers using observed climate input. A simulation using observed climate data shows a larger rate of glacier mass loss during the 1930s than the simulations using AOGCM input, possibly a result of an episode of warming in Greenland associated with unforced regional climate variability. {4.3, 13.3}

Observations indicate that the Greenland Ice Sheet has *very likely* experienced a net loss of mass due to both increased surface melting and run off, and increased ice discharge over the last two decades (Figure TS.3). Regional climate models indicate that Greenland ice-sheet surface mass balance showed no significant trend from the 1960s to the 1980s, but melting and consequent runoff has increased since the early 1990s. This tendency is related to pronounced regional warming, which may be attributed to a combination of anomalous regional variability in recent years and anthropogenic climate change. *High confidence* in projections of future warming in Greenland and increased surface melting is based on the qualitative agreements of models in projecting amplified warming at high northern latitudes for well-understood physical reasons. {4.4, 13.3}

There is *high confidence* that the Antarctic Ice Sheet is in a state of net mass loss and its contribution to sea level is also *likely* to have increased in the last two decades. Acceleration in ice outflow has been observed since the 1990s, especially in the Amundsen Sea sector of West Antarctica. Interannual variability in accumulation is large and as a result no significant trend is present in accumulation since 1979 in either models or observations. Surface melting is currently negligible in Antarctica. {4.4, 13.3}

Model-based estimates of climate-related changes in water storage on land (as snow cover, surface water, soil moisture and ground water) do not show significant long-term contributions to sea level change for recent decades. However, human-induced changes (reservoir impoundment and groundwater depletion) have each contributed at least several tenths of  $\text{mm yr}^{-1}$  to sea level change. Reservoir impoundment exceeded groundwater depletion for the majority of the 20th century but the rate of groundwater depletion has increased and now exceeds the rate of impoundment. Their combined net contribution for the 20th century is estimated to be small. {13.3}

#### [INSERT TFE.2, FIGURE 1 HERE]

**TFE.2, Figure 1:** Comparison of the observed global mean sea level rise from the sum of the modelled contributions from ocean thermal expansion, glaciers (excluding glaciers peripheral to the Antarctic ice sheet, PGs) and changes in land-water storage. In panels (a)-(d): the grey lines are results for individual CMIP5 AOGCMs; the black line is the model mean plus a correction for the omission of volcanic forcing in the AOGCM control experiments; the adjusted model mean (dashed black line) is the sum of the corrected model mean thermal expansion, the change in land-water storage, the glacier estimate using observed (rather than modelled) climate, and an illustrative long-term ice-sheet contribution (of 0.1  $\text{mm yr}^{-1}$ ); the adjusted model mean including the observed ice sheet contribution (dotted black line) begins in 1993 and includes the ice-sheet contributions, but excludes the glaciers peripheral to both the Greenland Ice Sheet and the Antarctic Ice Sheet, to avoid double counting because the observational ice-sheet estimates include the peripheral glaciers; three estimates of global mean sea level, with the shading indicating the uncertainty estimates (two standard deviations) are shown; the satellite altimeter data since 1993 are shown in red. The modelled sea level is given (a) for the period 1900 to 2010, (b) the rates of sea level change for the same period, with the satellite altimeter data shown as a red dot for the rate, (c) for 1961 to 2010 and (d) for 1990 to 2010. Panel (e) compares the sum of the observed contributions (orange) and the observed sea level from the satellite altimeter data (red). {13.3; Figure 13.7}

The observed global mean sea level (GMSL) rise for 1993–2010 is consistent with the sum of the observationally estimated contributions (TFE.2, Figure 1e). The closure of the observational budget for recent periods within uncertainties represents a significant advance since the AR4 in physical understanding of the causes of past GMSL change, and provides an improved basis for critical evaluation of models of these contributions in order to assess their reliability for making projections. {13.3}

The sum of modelled ocean thermal expansion and glacier contributions and the estimated change in land water storage (which is relatively small) accounts for about 65% of the observed GMSL rise for 1901–1990, and 90% for 1971–2010 and 1993–2010 (TFE.2, Figure 1). After inclusion of small long-term contributions from ice sheets and the possible greater mass loss from glaciers during the 1930s due to unforced climate variability, the sum of the modelled contribution is close to the observed rise. The addition of the observed ice sheet contribution since 1993 improves the agreement further between the observed and modelled sea level rise (TFE.2, Figure 1). The evidence now available gives a clearer account than in previous IPCC assessments of 20th century sea level change. {13.3}

When calibrated appropriately, recently improved dynamical ice-sheet models can reproduce the observed rapid changes in ice-sheet outflow for individual glacier systems (e.g., Pine Island Glacier in Antarctica; *medium confidence*). However, models of ice sheet response to global warming and particularly ice sheet-ocean interactions are incomplete and the omission of ice-sheet models, especially of dynamics, from the model budget of the past means that they have not been as critically evaluated as other contributions. {13.3, 13.4}

Global mean sea level rise for 2081–2100 (relative to 1986–2005) for the RCPs will *likely* be in the 5–95% ranges derived from CMIP5 climate projections in combination with process-based models (*medium confidence*), i.e., 0.26–0.54 m (RCP2.6), 0.32–0.62 m (RCP4.5), 0.33–0.62 m (RCP6.0), 0.45–0.81 (RCP8.5) m (see Table TS.1 and Figure TS.15 for RCP forcing). For RCP8.5 the range at 2100 is 0.53–0.97 m. Confidence in the projected *likely* ranges comes from the consistency of process-based models with observations and physical understanding. It is assessed that there is currently insufficient evidence to evaluate the probability of specific levels above the *likely* range. Based on current understanding, only the collapse of marine-based sectors of the Antarctic ice sheet, if initiated, could cause GMSL to rise substantially above the *likely* range during the 21st century. There is a lack of consensus on the probability for such a collapse, and the potential additional contribution to GMSL rise cannot be precisely quantified, but there is *medium confidence* that it would not exceed several tenths of a meter of sea level rise during the 21st century. It is *virtually certain* that global mean sea level rise will continue beyond 2100. {13.5.1, 13.5.3}

Many semi-empirical models projections of global mean sea level rise are higher than process-based model projections, but there is low agreement in semi-empirical model projections, and no consensus about their reliability. {13.5.2, 13.5.3}

TFE.2, Figure 2 combines the paleo, tide-gauge, and altimeter observations of sea level rise from 1700 with the projected global mean sea level change to 2100. {13.5, 13.7, 13.8}

### **[INSERT TFE.2, FIGURE 2 HERE]**

**TFE.2, Figure 2:** Compilation of paleo sea level data (purple), tide gauge data (blue, red and green), altimeter data (light blue), and central estimates and likely ranges for projections of global-mean sea level rise from the combination of CMIP5 and process-based models for RCP2.6 (blue) and RCP8.5 (red) scenarios, all relative to pre-industrial values. {Figures 13.3, 13.11, 13.27}

## **TS.2.7 Changes in Extremes**

### *TS.2.7.1 Atmosphere*

Recent analyses of extreme events generally support the AR4 and SREX conclusions (see TFE.9 and in particular TFE.9, Table 1, for a synthesis). It is *very likely* that the number of cold days and nights has decreased and the number of warm days and nights has increased on the global scale between 1951 and



2010. Globally, there is *medium confidence* that the length and frequency of warm spells, including heat waves, has increased since the middle of the 20th century mostly due to lack of data or studies in Africa and South America. However it is *likely* that heat wave frequency has increased over this period in large parts of Europe, Asia, and Australia. {2.6.1; Table 2.12, 2.13}

It is *likely* that since 1950 the number of heavy precipitation events over land has increased in more regions than it has decreased. Regional trends vary but confidence is *high* for North America with *very likely* trends towards heavier precipitation events. {2.6.2; Table 2.13}

There is *low confidence* in a global-scale observed trend in drought or dryness (lack of rainfall), due to lack of direct observations, dependencies of inferred trends on the index choice and geographical inconsistencies in the trends. However this masks important regional changes and, for example, the frequency and intensity of drought has *likely* increased in the Mediterranean and West Africa and *likely* decreased in Central North America and North-West Australia since 1950. {2.6.2; Table 2.13}

During the last millennium, there is *high confidence* for the occurrence of droughts of greater magnitude and longer duration than observed since 1900 in many regions. There is *medium confidence* that more megadroughts occurred in monsoon Asia and wetter conditions prevailed in arid Central Asia and the South American monsoon region during the Little Ice Age (1450–1850) compared to the Medieval Climate Anomaly (950–1250). {5.5.4, 5.5.5}

*Confidence* remains *low* for long-term (centennial) changes in tropical cyclone activity, after accounting for past changes in observing capabilities. However since the 1970s, it is *virtually certain* that the frequency and intensity of storms in the North Atlantic has increased although the reasons for this increase are debated (see TFE.9). There is *low confidence* of large-scale trends in storminess over the last century and there is still insufficient evidence to determine whether robust trends exist in small-scale severe weather events such as hail or thunder storms. {2.6.2, 2.6.3, 2.6.4}

With *high confidence*, past floods larger than recorded since the 20th century occurred during the past five centuries in northern and central Europe, the western Mediterranean region, and eastern Asia. There is *medium confidence* that in the Near East, India, central North America, modern large floods are comparable or surpass historical floods in magnitude and/or frequency. {5.5.5}

#### TS.2.7.2 Oceans

It is *likely* that the magnitude of extreme high sea level events has increased since 1970 (see TFE.9, Table 1). Most of the increase in extreme sea level can be explained by the mean sea level rise: changes in extreme high sea levels are reduced to less than 5 mm yr<sup>-1</sup> at 94% of tide gauges once the rise in mean sea level is accounted for. There is *medium confidence* based on reanalysis forced model hindcasts and ship observations that mean significant wave height has increased since the 1950s over much of the North Atlantic north of 45°N, with typical winter season trends of up to 20 cm per decade. {3.4.5, 3.7.5}

#### TS.2.8 Changes in Carbon and Other Biogeochemical Cycles

Concentrations of the atmospheric greenhouse gases carbon dioxide (CO<sub>2</sub>), methane (CH<sub>4</sub>), and nitrous oxide (N<sub>2</sub>O) in 2011, exceed the range of concentrations recorded in ice cores during the past 800,000 years. Past changes in atmospheric greenhouse-gas concentrations are determined with *very high confidence* from polar ice cores. Since AR4 these records have been extended from 650,000 years to 800,000 years ago. {5.2.2}

With *very high confidence*, the current rates of CO<sub>2</sub>, CH<sub>4</sub> and N<sub>2</sub>O rise in atmospheric concentrations and the associated increases in radiative forcing are unprecedented with respect to the “highest resolution” ice core records of the last 22,000 years. There is *medium confidence* that the rate of change of the observed greenhouse gas rise is also unprecedented compared with the lower resolution records of the past 800,000 years. {2.2.1, 5.2.2}

In several periods characterized by high atmospheric CO<sub>2</sub> concentrations, there is *medium confidence* that global mean temperature was significantly above pre-industrial level. During the mid-Pliocene (3.3 to 3.0 million years ago), atmospheric CO<sub>2</sub> concentration between 350 ppm and 450 ppm (*medium confidence*) occurred when global mean surface temperature was approximately 2°C to 3.5°C warmer (*medium confidence*) than for pre-industrial climate. During the Early Eocene (52 to 48 million years ago), atmospheric CO<sub>2</sub> concentration exceeded ~1000 ppm when global mean surface temperature was 9°C to 14°C higher (*medium confidence*) than for pre-industrial conditions. {5.3.1}

#### TS.2.8.1 CO<sub>2</sub>

Between 1750 and 2011, CO<sub>2</sub> emissions from fossil fuel combustion and cement production are estimated from energy and fuel use statistics to have released 365 [335 to 395] PgC<sup>8</sup>. In 2000–2009, average fossil fuel and cement manufacturing emissions were 7.8 [7.2 to 8.4] PgC yr<sup>-1</sup>, with an average growth rate of 3.2% yr<sup>-1</sup> (Figure TS.4). This rate of increase of fossil fuel emissions is higher than during the 1990's (1.0% yr<sup>-1</sup>). In 2011, fossil fuel emissions were 9.5 [8.7 to 10.3] PgC. {2.2.1, 6.3.1; Table 6.1}

#### [INSERT FIGURE TS.4 HERE]

**Figure TS.4:** Annual anthropogenic CO<sub>2</sub> emissions and their partitioning among the atmosphere, land and ocean (PgC yr<sup>-1</sup>) from 1750 to 2011. (Top) Fossil fuel and cement CO<sub>2</sub> emissions by category, estimated by the Carbon Dioxide Information Analysis Center (CDIAC). (Bottom) Fossil fuel and cement CO<sub>2</sub> emissions as above. CO<sub>2</sub> emissions from net land use change, mainly deforestation, are based on land cover change data (see Table 6.2). The atmospheric CO<sub>2</sub> growth rate prior to 1959 is based on a spline fit to ice core observations and a synthesis of atmospheric measurements from 1959. The fit to ice core observations does not capture the large interannual variability in atmospheric CO<sub>2</sub> and is represented with a dashed line. The ocean CO<sub>2</sub> sink is from a combination of models and observations. The residual terrestrial sink (term in green in the figure) is computed from the residual of the other terms. The emissions and their partitioning only include the fluxes that have changed since 1750, and not the natural CO<sub>2</sub> fluxes (e.g., atmospheric CO<sub>2</sub> uptake from weathering, outgassing of CO<sub>2</sub> from lakes and rivers, and outgassing of CO<sub>2</sub> by the ocean from carbon delivered by rivers; see Figure 6.1) between the atmosphere, land and ocean reservoirs that existed before that time and still exist today. The uncertainties in the various terms are discussed in chapter 6 and reported in Table 6.1 for decadal mean values. {Figure 6.8}

Between 1750 and 2011, land use change (mainly deforestation), derived from land cover data and modelling, is estimated to have released 180 [100 to 260] PgC. Land use change emissions between 2000 and 2009 are dominated by tropical deforestation, and are estimated at 1.1 [0.3 to 1.9] PgC yr<sup>-1</sup>, with possibly a small decrease from the 1990s due to lower reported forest loss during this decade. This estimate includes gross deforestation emissions of around 3 PgC yr<sup>-1</sup> compensated by around 2 PgC yr<sup>-1</sup> of forest regrowth in some regions, mainly abandoned agricultural land. {6.3.2; Table 6.2}

Of the 545 [460 to 630] PgC released to the atmosphere from fossil fuel and land use emissions from 1750 to 2011, 240 [230 to 250] PgC accumulated in the atmosphere, as estimated with very high accuracy from the observed increase of atmospheric CO<sub>2</sub> concentration from 278 [275 to 281] ppm<sup>9</sup> in 1750 to 390.5 ppm in 2011. The amount CO<sub>2</sub> in the atmosphere grew by 4.0 [3.8 to 4.2] PgC yr<sup>-1</sup> in the first decade of the 21st century. The distribution of observed atmospheric CO<sub>2</sub> increases with latitude clearly shows that the increases are driven by anthropogenic emissions which primarily occur in the industrialized countries north of the equator. Based on annual average concentrations, stations in the Northern Hemisphere show slightly higher concentrations than stations in the Southern Hemisphere. An independent line of evidence for the anthropogenic origin of the observed atmospheric CO<sub>2</sub> increase comes from the observed consistent decrease in atmospheric O<sub>2</sub> content and a decrease in the stable isotopic ratio of CO<sub>2</sub> (<sup>13</sup>C/<sup>12</sup>C) in the atmosphere (Figure TS.5). {2.2.1, 6.1.3}

The remaining amount of carbon released by fossil fuel and land-use emissions has been re-absorbed by the ocean and terrestrial ecosystems. Based on high agreement between independent estimates using different methods and data sets (e.g., oceanic carbon, oxygen, and transient tracer data), it is *very likely* that the global

<sup>8</sup> 1 Petagram of carbon = 1 PgC = 10<sup>15</sup> grams of carbon = 1 Gigatonne of carbon = 1 GtC. This corresponds to 3.67 GtCO<sub>2</sub>.

<sup>9</sup> ppm (parts per million) or ppb (parts per billion, 1 billion = 1,000 million) is the ratio of the number of greenhouse gas molecules to the total number of molecules of dry air. For example, 300 ppm means 300 molecules of a greenhouse gas per million molecules of dry air.

ocean inventory of anthropogenic carbon increased from 1994 to 2010. In 2011, it is estimated to be 155 [125 to 185] PgC. The annual global oceanic uptake rates calculated from independent data sets (from oceanic  $C_{\text{ant}}$  inventory changes, from atmospheric  $O_2/N_2$  measurements or from  $pCO_2$  data) and for different time periods agree with each other within their uncertainties, and *very likely* are in the range of 1.0–3.2 PgC  $yr^{-1}$ . Regional observations of the storage rate of anthropogenic carbon in the ocean are in broad agreement with the expected rate resulting from the increase in atmospheric  $CO_2$  concentrations, but with significant spatial and temporal variations. {3.8.1, 6.3}

#### [INSERT FIGURE TS.5 HERE]

**Figure TS.5:** Atmospheric concentration of  $CO_2$ , oxygen,  $^{13}C/^{12}C$  stable isotope ratio in  $CO_2$ , as well as  $CH_4$  and  $N_2O$  atmospheric concentrations and oceanic surface observations of  $pCO_2$  and pH, recorded at representative time series stations in the Northern and the Southern Hemispheres. MLO: Mauna Loa Observatory, Hawaii; SPO: South Pole; HOT: Hawaii Ocean Time-Series station; MHD: Mace Head, Ireland; CGO: Cape Grim, Tasmania; ALT: Alert, Northwest Territories, Canada. {Figure 6.3, FAQ 3.2, Figure 1}

Natural terrestrial ecosystems (those not affected by land use change) are estimated by difference from changes in other reservoirs to have accumulated 150 [60 to 240] PgC between 1750 and 2010. The gain of carbon by natural terrestrial ecosystems is estimated to take place mainly through the uptake of  $CO_2$  by enhanced photosynthesis at higher  $CO_2$  levels and nitrogen deposition, longer growing seasons in mid and high latitudes. Natural carbon sinks vary regionally due to physical, biological and chemical processes acting on different time scales. An excess of atmospheric  $CO_2$  absorbed by land ecosystems gets stored as organic matter in diverse carbon pools, from short lived (leaves, fine roots) to long-lived (stems, soil carbon). {6.3; Table 6.1}

#### TS.2.8.2 Carbon and Ocean Acidification

It is *very likely* that oceanic uptake of anthropogenic  $CO_2$  results in gradual acidification of the ocean. The  $pH^{10}$  of seawater has decreased by 0.1 since the beginning of the industrial era, corresponding to a 26% increase in hydrogen ion concentration. The observed pH trends range between  $-0.0014$  and  $-0.0024$  per year in surface waters. In the ocean interior, natural physical and biological processes, as well as uptake of anthropogenic  $CO_2$  can cause changes in pH over decadal and longer time scales. {3.8.2; Box 3.2; Table 3.2; FAQ 3.2}

#### TS.2.8.3 $CH_4$

The concentration of  $CH_4$  has increased by a factor of 2.5 since preindustrial times, from 720 [695 to 745] ppb in 1750 to 1803 [1799 to 1807] ppb in 2011 (Figure TS.5). There is *very high confidence* that the atmospheric  $CH_4$  increase during the Industrial Era is caused by anthropogenic activities. The massive increase in the number of ruminants, the emissions from fossil fuel extraction and use, the expansion of rice paddy agriculture and the emissions from landfills and waste, are the dominant anthropogenic  $CH_4$  sources. Anthropogenic emissions account for 50% to 65% of total emissions. By including natural geological  $CH_4$  emissions that were not accounted for in previous budgets, the fossil component of the total  $CH_4$  emissions (i.e., anthropogenic emissions related to leaks in the fossil fuel industry and natural geological leaks) is now estimated to amount to about 30% of the total  $CH_4$  emissions (*medium confidence*). {2.2.1, 6.1, 6.3.3}

In recent decades,  $CH_4$  growth in the atmosphere has been variable.  $CH_4$  concentrations were relatively stable for about a decade in the 1990s, but then started growing again starting in 2007. The exact drivers of this renewed growth are still debated. Climate driven fluctuations of  $CH_4$  emissions from natural wetlands ( $177$  to  $284 \times 10^{12}$  g ( $CH_4$ )  $yr^{-1}$  for 2000–2009 based on bottom-up estimates) are the main drivers of the global inter-annual variability of  $CH_4$  emissions (*high confidence*), with a smaller contribution from biomass burning emissions during high fire years {2.2.1, 6.3.3; Table 6.8}.

#### TS.2.8.4 Nitrogen

<sup>10</sup> pH is a measure of acidity : a decrease in pH value means an increase in acidity, i.e., acidification.

Since preindustrial times, the concentration of N<sub>2</sub>O in the atmosphere has increased by a factor of 1.2 (Figure TS.5). Changes in the nitrogen cycle, in addition to interactions with CO<sub>2</sub> sources and sinks, affect emissions of N<sub>2</sub>O both on land and from the ocean. {2.2.1, 6.4.6}

#### TS.2.8.5 Oceanic Oxygen

High agreement among analyses provides *medium confidence* that oxygen concentrations have decreased in the open ocean thermocline in many ocean regions since the 1960s. The general decline is consistent with the expectation that warming-induced stratification leads to a decrease in the supply of oxygen to the thermocline from near surface waters, that warmer waters can hold less oxygen, and that changes in wind-driven circulation affect oxygen concentrations. It is *likely* that the tropical oxygen minimum zones have expanded in recent decades. {3.8.3}

### TS.3 Drivers of Climate Change

#### TS.3.1 Introduction

Human activities have changed and continue to change the Earth's surface and atmospheric composition. Some of these changes have a direct or indirect impact on the energy balance of the Earth and are thus drivers of climate change. Radiative forcing (RF) is a measure of the net change in the energy balance of the Earth system in response to some external perturbation (see Box TS.2), with positive RF leading to a warming and negative RF to a cooling. The RF concept is valuable for comparing the influence on global mean temperature of most individual agents affecting Earth's radiation balance. The quantitative values provided in AR5 are consistent with those in previous IPCC reports, though there have been some important revisions (Figure TS.6). Effective radiative forcing (ERF) is now used to quantify the impact of some forcing agents that involve rapid adjustments of components of the atmosphere and surface that are assumed constant in the RF concept (see Box TS.2). RF and ERF are estimated from the change between 1750 and 2011, referred to as "industrial era", if other time periods are not explicitly stated. Uncertainties are given associated with the best estimates of RF and ERF, with values representing the 5–95% (90%) confidence range. {8.1, 7.1}

In addition to the global mean RF or ERF, the spatial distribution and temporal evolution of forcing, as well as climate feedbacks, play a role in determining the eventual impact of various drivers on climate. Land surface changes may also impact the local and regional climate through processes that are not radiative in nature {8.1, 8.3.5, 8.6}.

#### [START BOX TS.2 HERE]

#### Box TS.2: Radiative Forcing and Effective Radiative Forcing

Radiative Forcing (RF) and Effective Radiative Forcing (ERF) are used to quantify the change in Earth's energy balance that occurs as a result of an externally imposed change. They are expressed in Watts per square meter ( $\text{W m}^{-2}$ ). RF is defined in AR5, as in previous IPCC assessments, as the change in net downward flux (shortwave + longwave) at the tropopause after allowing for stratospheric temperatures to readjust to radiative equilibrium, while holding other state variables such as tropospheric temperatures, water vapor and cloud cover fixed at the unperturbed values (see Glossary). {8.1.1}

Although the RF concept has proved very valuable, improved understanding has shown that including rapid adjustments of the Earth's surface and troposphere can provide a better metric of climate response. These rapid adjustments occur over a variety of timescales, but are relatively distinct from responses to global mean surface temperature change. Aerosols in particular impact the atmosphere temperature profile and cloud properties on a time scale much shorter than adjustments of the ocean (even the upper layer) to forcings. The ERF concept defined in AR5 allows rapid adjustments to perturbations, for all variables except for global mean surface temperature or ocean temperature and sea ice cover. The ERF and RF values are significantly different for the anthropogenic aerosols, due to their influence on clouds and on snow or ice cover. For other components that drive the Earth energy balance, such as greenhouse gases, ERF and RF are fairly similar, and RF may have comparable utility given that it requires fewer computational resources to

calculate and is not affected by meteorological variability and hence can better isolate small forcings. In cases where RF and ERF differ substantially, ERF has been shown to be a better indicator of the global mean temperature response and is therefore emphasized in AR5. {7.1.3, 8.1; Box 8.1}

**[END BOX TS.2 HERE]**

### ***TS.3.2 Radiative Forcing from Greenhouse Gases***

Human activity leads to change in the atmospheric composition either directly (via emissions of gases or particles) or indirectly (via atmospheric chemistry). Anthropogenic emissions have driven the changes in well-mixed greenhouse gas (WMGHG) concentrations during the industrial era (see Section TS.2.8 and TFE.7). As historical WMGHG concentrations since the preindustrial are well known based on direct measurements and ice core records, and WMGHG radiative properties are also well known, the computation of RF due to concentration changes provides tightly constrained values (Figure TS.6). There has not been significant change in our understanding of WMGHG radiative impact, so that the changes in RF estimates relative to AR4 are due essentially to concentration increases. The best estimate for WMGHG ERF is the same as RF, but the uncertainty range is twice as large due to the poorly constrained cloud responses. Due to high-quality observations, it is certain that increasing atmospheric burdens of most WMGHGs, especially CO<sub>2</sub>, resulted in a further increase in their radiative forcing from 2005 to 2011. Based on concentration changes, the RF of all WMGHG in 2011 is 2.83 [2.54 to 3.12] W m<sup>-2</sup> (*very high confidence*). This is an increase since AR4 of 0.20 [0.18 to 0.22] W m<sup>-2</sup>, with nearly all of the increase due to the increase in the abundance of CO<sub>2</sub> since 2005. The industrial era RF for CO<sub>2</sub> alone is 1.82 [1.63 to 2.01] W m<sup>-2</sup>. Over the last 15 years, CO<sub>2</sub> has been the dominant contributor to the increase in RF from the WMGHGs, with RF of CO<sub>2</sub> having an average growth rate slightly less than 0.3 W m<sup>-2</sup> per decade. The uncertainty in the WMGHG RF is due in part to its radiative properties but mostly to the full accounting of atmospheric radiative transfer including clouds. {2.2.1, 5.2, 6.3, 8.3, 8.3.2; Table 6.1}

**[INSERT FIGURE TS.6 HERE]**

**Figure TS.6:** Radiative Forcing (RF) and Effective Radiative Forcing (ERF) of climate change during the industrial era. Top: Forcing by concentration change between 1750 and 2011 with associated uncertainty range (solid bars are ERF, hatched bars are RF, green diamonds and associated uncertainties are for RF assessed in AR4). Bottom: Probability Density Functions for the ERF, for the aerosol, well-mixed greenhouse gas (WMGHG) and total. The green lines show the AR4 RF 90% confidence intervals and can be compared with the red, blue and black lines which show the AR5 ERF 90% confidence intervals (although RF and ERF differ, especially for aerosols). The ERF from surface albedo changes and combined contrails and contrail induced cirrus is included in the total anthropogenic forcing, but not shown as a separate probability density function. For some forcing mechanisms (ozone, land use, solar) the RF is assumed to be representative of the ERF but an additional uncertainty of 17% is added in quadrature to the RF uncertainty. {Figures 8.15, 8.16}

After a decade of near stability, the recent increase of CH<sub>4</sub> concentration led to an enhanced RF compared to AR4 by 2% to 0.48 [0.43 to 0.53] W m<sup>-2</sup>. It is *very likely* that the RF from methane is now larger than that of all halocarbons combined. {2.2.1, 8.3}

Atmospheric N<sub>2</sub>O has increased by 6% since AR4 causing a RF of 0.17 [0.15 to 0.19] W m<sup>-2</sup>. N<sub>2</sub>O concentrations continue to rise while those of CFC-12, the third largest WMGHG contributor to RF for several decades, are decreasing due to phase-out of emissions of this chemical under the Montreal Protocol. N<sub>2</sub>O is now *likely* the third largest WMGHG contributor to RF. The RF from halocarbons is very similar to the value in AR4, with a reduced RF from CFCs but increases in many of their replacements. Four of the halocarbons (CFC-11, CFC-12, CFC-113, and HCFC-22) account for 85% of the total halocarbon RF. The former three compounds have declining RF over the last five years but are more than compensated for by the increased RF from HCFC-22. There is *high confidence* that the growth rate in RF from all WMGHG is weaker over the last decade than in the 1970s and 1980s owing to a slower increase in the non-CO<sub>2</sub> RF. {2.2.1, 8.3}

The short-lived GHGs ozone (O<sub>3</sub>) and stratospheric water vapour also contribute to anthropogenic forcing. Observations indicate that O<sub>3</sub> *likely* increased at many undisturbed (background) locations through the 1990s. These increases have continued mainly over Asia (though observations cover a limited area) and flattened over Europe during the last decade. The total RF due to changes in ozone is 0.35 [0.15 to 0.55] W

$\text{m}^{-2}$  (*high confidence*) (Figure TS.6), with RF due to tropospheric ozone of 0.40 [0.20 to 0.60]  $\text{W m}^{-2}$  (*high confidence*) and due to stratospheric ozone of  $-0.05$  [ $-0.15$  to  $+0.05$ ]  $\text{W m}^{-2}$  (*high confidence*). Ozone is not emitted directly into the atmosphere; instead it is formed by photochemical reactions. In the troposphere these reactions involve precursor compounds that are emitted into the atmosphere from a variety of natural and anthropogenic sources. Tropospheric ozone RF is largely attributed to increases in emissions of methane, carbon monoxide, volatile organics and nitrogen oxides, while stratospheric RF results primarily from ozone depletion by anthropogenic halocarbons. However, there is now strong evidence for substantial links between the changes in tropospheric and stratospheric ozone and a total ozone RF of 0.50 [0.30 to 0.70]  $\text{W m}^{-2}$  is attributed to tropospheric ozone precursor emissions and  $-0.15$  [ $-0.30$  to  $0.00$ ]  $\text{W m}^{-2}$  to ozone-depletion by halocarbons. There is strong evidence that tropospheric ozone also has a detrimental impact on vegetation physiology, and therefore on its  $\text{CO}_2$  uptake. This reduced uptake leads to an indirect increase in the atmospheric  $\text{CO}_2$  concentration. Thus a fraction of the  $\text{CO}_2$  RF should be attributed to ozone or its precursors rather than direct emission of  $\text{CO}_2$ , but there is a *low confidence* on the quantitative estimates. RF for stratospheric water vapour produced from  $\text{CH}_4$  oxidation is 0.07 [0.02 to 0.12]  $\text{W m}^{-2}$ . Other changes in stratospheric water vapour, and all changes in water vapour in the troposphere, are regarded as a feedback rather than a forcing. {2.2.2, 8.1, 8.2, 8.3; FAQ 8.1}

### TS.3.3 Radiative Forcing from Anthropogenic Aerosols

Anthropogenic aerosols are responsible for a radiative forcing of climate through multiple processes which can be loosely grouped into two types: aerosol-radiation interactions (ari) and aerosol-cloud interactions (aci) (Figure TS.6). There has been progress since AR4 on observing and modeling climate-relevant aerosol properties (including their size distribution, hygroscopicity, chemical composition, mixing state, optical and cloud nucleation properties) and their atmospheric distribution. Nevertheless, substantial uncertainties remain in assessments of long-term trends of global aerosol optical depth and other global properties of aerosols due to difficulties in measurement and lack of observations of some relevant parameters, high spatial and temporal variability and the relatively short observational records that exist. The anthropogenic  $\text{RF}_{\text{ari}}$  is given a best estimate of  $-0.35$  [ $-0.85$  to  $+0.15$ ]  $\text{W m}^{-2}$  (*high confidence*) using evidence from aerosol models and some constraints from observations. The  $\text{RF}_{\text{ari}}$  is caused by multiple aerosol types (see Section TS3.6). The rapid adjustment to  $\text{RF}_{\text{ari}}$  leads to further negative forcing, in particular through cloud adjustments. As a consequence, the  $\text{ERF}_{\text{ari}}$  is more negative than the  $\text{RF}_{\text{ari}}$  (*low confidence*) and given a best estimate of  $-0.45$  [ $-0.95$  to  $+0.05$ ]  $\text{W m}^{-2}$ . The assessment for  $\text{RF}_{\text{ari}}$  is less negative than reported in AR4 because of a re-evaluation of aerosol absorption. The uncertainty estimate is wider but more robust. {2.2.3, 7.3, 7.5.2}

Improved understanding of aerosol-cloud interactions has led to a reduction in the estimated magnitude of many global aerosol-cloud forcings estimates. The total effective radiative forcing due to aerosols ( $\text{ERF}_{\text{ari+aci}}$ , excluding the effect of absorbing aerosol on snow and ice) is assessed to be  $-0.9$  [ $-1.9$  to  $-0.1$ ]  $\text{W m}^{-2}$  (*medium confidence*). This estimate encompasses all rapid adjustments, including changes to the cloud lifetime and aerosol microphysical effects on mixed-phase, ice and convective clouds. This range was obtained by giving equal weight to satellite-based studies and estimates from climate models and inverse studies grouped together. It is consistent with multiple lines of evidence suggesting less negative estimates for aerosol-cloud interactions than those discussed in AR4. {7.4, 7.5}

The RF from black carbon (BC) on snow and ice is assessed to be 0.04 [0.02 to 0.09]  $\text{W m}^{-2}$  (*low confidence*). Unlike in the previous IPCC assessment, this estimate includes the effects on sea-ice, accounts for more physical processes, and incorporates evidence from both models and observations. This RF causes a 2–4 times larger global mean surface temperature change per unit forcing than  $\text{CO}_2$  primarily because all of the forcing energy is deposited directly into the cryosphere, whose evolution drives a positive albedo feedback on climate. This effect thus can represent a significant forcing mechanism in the Arctic and other snow or ice covered regions. {7.3, 7.5}

Despite the large uncertainty ranges on aerosol forcing, there is a *high confidence* that aerosols have offset a substantial portion of GHG forcing. Aerosol-cloud interactions can influence the character of individual storms, but evidence for a systematic aerosol effect on storm or precipitation intensity is more limited and ambiguous. {7.4, 7.6}

### ***TS.3.4 Radiative Forcing from Land Surface Changes and Contrails***

There is robust evidence that anthropogenic land use changes such as deforestation have increased the land surface albedo, which leads to a RF of  $-0.15$  [ $-0.25$  to  $-0.05$ ]  $\text{W m}^{-2}$  (Figure TS.6). There is still a large spread of quantitative estimates due to different assumptions for the albedo of natural and managed surfaces (e.g., croplands, pastures). In addition, the time evolution of the land use change, and in particular how much was already completed in the reference year 1750, are still debated. Furthermore, land use change causes other modifications that are not radiative but impact the surface temperature, including modifications in the surface roughness, latent heat flux, river runoff, and irrigation. These are more uncertain and they are difficult to quantify, but they tend to offset the impact of albedo changes at the global scale. As a consequence, there is low agreement on the sign of the net change in global mean temperature as a result of land use change. Land use change, and in particular deforestation, also has significant impacts on WMGHG concentrations. It contributes to the corresponding RF associated with  $\text{CO}_2$  emissions or concentration changes. {8.3}

Persistent contrails from aviation contribute a positive RF of  $0.01$  [ $0.005$  to  $0.03$ ]  $\text{W m}^{-2}$  (*medium confidence*) for year 2011, and the combined contrail and contrail-cirrus ERF from aviation is assessed to be  $0.05$  [ $0.02$  to  $0.15$ ]  $\text{W m}^{-2}$  (*low confidence*). This forcing can be much larger regionally but there is now *medium confidence* that it does not produce observable regional effects on either the mean or diurnal range of surface temperature. {7.2.7}

### ***TS.3.5 Radiative Forcing from Natural Drivers of Climate Change***

Solar and volcanic forcings are the two dominant natural contributors to global climate change during the industrial era. Satellite observations of total solar irradiance (TSI) changes since 1978 show quasi-periodic cyclical variation with a period of roughly 11 years. Longer-term forcing is typically estimated by comparison of solar minima (during which variability is least). This gives a RF change of  $-0.04$  [ $-0.08$  to  $0.00$ ]  $\text{W m}^{-2}$  between the most recent (2008) minimum and the 1986 minimum. There is some diversity in the estimated trends of the composites of various satellite data, however. Secular trends of TSI before the start of satellite observations rely on a number of indirect proxies. The best estimate of RF from TSI changes over the industrial era is  $0.05$  [ $0.00$  to  $0.10$ ]  $\text{W m}^{-2}$  (*medium confidence*), which includes greater RF up to around 1980 and then a small downward trend. This RF estimate is substantially smaller than the AR4 estimate due to the addition of the latest solar cycle and inconsistencies in how solar RF was estimated in earlier IPCC assessments. The recent solar minimum appears to have been unusually low and long-lasting and several projections indicate lower TSI for the forthcoming decades. However, current abilities to project solar irradiance are extremely limited so that there is *very low confidence* concerning future solar forcing. Nonetheless, there is a *high confidence* that 21st century solar forcing will be much smaller than the projected increased forcing due to GHGs. {5.2.1, 8.4; FAQ 5.1}

Changes in solar activity affect the cosmic ray flux impinging upon the Earth's atmosphere, which has been hypothesized to affect climate through changes in cloudiness. Cosmic rays enhance aerosol nucleation and thus may affect cloud condensation nuclei production in the free troposphere, but the effect is too weak to have any climatic influence during a solar cycle or over the last century (*medium evidence, high agreement*). No robust association between changes in cosmic rays and cloudiness has been identified. In the event that such an association exists, it is *very unlikely* to be due to cosmic ray-induced nucleation of new aerosol particles. {7.3, 7.4.6}

The RF of stratospheric volcanic aerosols is now well understood and there is a large RF for a few years after major volcanic eruptions (Box TS.5, Figure 1). While volcanic eruptions inject both mineral particles and sulphate aerosol precursors into the atmosphere, it is the latter, because of their small size and long lifetimes, which are responsible for radiative forcing important for climate. The emissions of  $\text{CO}_2$  from volcanic eruptions are at least 100 times smaller than anthropogenic emissions, and inconsequential for climate on century time scales. Large tropical volcanic eruptions have played an important role in driving annual to decadal scale climate change during the industrial era due to their sometimes very large negative RF. There has not been any major volcanic eruption since Mt. Pinatubo in 1991, which caused a one-year RF of about  $-3.7$   $\text{W m}^{-2}$ , but several smaller eruptions have caused a RF for the years 2008–2011 of  $-0.10$  [ $-0.13$  to  $-0.07$ ]  $\text{W m}^{-2}$  (*high confidence*), twice as strong in magnitude compared to 1999–2002. The smaller

eruptions have led to better understanding of the dependence of radiative forcing on the amount of material from and time of the year of high-latitude injections. {5.2.1, 5.3.5, 8.4; Annex II}

### TS.3.6 Synthesis of Forcings; Spatial and Temporal Evolution

A synthesis of the industrial era forcing finds that among the forcing agents, there is a *very high confidence* only for the WMGHG RF. Relative to AR4, the confidence level has been elevated for seven forcing agents due to improved evidence and understanding. {8.5; Figure 8.14}

The time evolution of the total anthropogenic RF shows a nearly continuous increase from 1750, primarily since about 1860. There is *very high confidence* that the total anthropogenic RF increase rate since 1960 has been much greater than during earlier industrial-era periods, driven primarily by the continuous increase in most WMGHG concentrations. There is still low agreement on the time evolution of the total aerosol ERF, which is the primary factor for the uncertainty in the total anthropogenic forcing. The fractional uncertainty in the total anthropogenic forcing decreases gradually after 1950 due to the smaller offset of positive WMGHG forcing by negative aerosol forcing. There is robust evidence and high agreement that natural forcing is a small fraction of the WMGHG forcing. Natural forcing changes over the last 15 years have *likely* offset a substantial fraction (10–95%) of the anthropogenic forcing increase during this period (Box TS.3). Forcing by CO<sub>2</sub> is the largest single contributor to the total forcing during the industrial era and during 1980 to 2011. Compared to the entire industrial era the dominance of CO<sub>2</sub> forcing is larger for 1980 to 2011 with respect to other WMGHG, and there is *high confidence* that the offset from aerosol forcing to WMGHG forcing during this period was much smaller than over the 1950–1980 period. {8.5.2}

Forcing can also be attributed to emissions rather than to the resulting concentration changes (Figure TS.7). Carbon dioxide is the largest single contributor to historical RF from either the perspective of changes in the atmospheric concentration of CO<sub>2</sub> or the impact of changes in net emissions of CO<sub>2</sub>. The relative importance of other forcing agents can vary markedly with the perspective chosen, however. In particular, methane emissions have a much larger forcing (~1.0 W m<sup>-2</sup> over the industrial era) than methane concentration increases (~0.5 W m<sup>-2</sup>) due to several indirect effects through atmospheric chemistry. In addition, carbon monoxide emissions have a clear positive forcing, while emissions of reactive nitrogen oxides *likely* cause a net negative forcing but uncertainties are large. Emissions of ozone-depleting halocarbons *very likely* cause a net positive forcing as their direct radiative effect is larger than the impact of the stratospheric ozone depletion that they induce. Emissions of SO<sub>2</sub>, organic carbon and ammonia cause a negative forcing, while emissions of black carbon lead to positive forcing via aerosol-radiation interactions. Note that mineral dust forcing may include a natural component or a climate feedback effect. {7.3, 7.5.2, 8.5.1}

#### [INSERT FIGURE TS.7 HERE]

**Figure TS.7:** Radiative forcing of climate change during the industrial era shown by emitted components from 1750 to 2011. The horizontal bars indicate the overall uncertainty, while the vertical bars are for the individual components (vertical bar lengths proportional to the relative uncertainty, with a total length equal to the bar width for a ±50% uncertainty). Best estimates for the totals and individual components (from left to right) of the response are given in the right column. Values are RF except for the ERF of aerosol-cloud interactions (ERF<sub>aci</sub>). An additional rapid adjustment to aerosol-radiation interactions of -0.1 [-0.3 to +0.1] W m<sup>-2</sup> is attributable primarily to black carbon (ERF<sub>ari</sub>-RF<sub>ari</sub> in Figure TS.6). CFCs= Chlorofluorocarbons, HCFCs= Hydrochlorofluorocarbons, HFCs=Hydrofluorocarbons, PFCs= Perfluorocarbons, NMVOC= Non-Methane Volatile Organic Compounds, BC= Black Carbon. {Figure 8.17}

Although the WMGHG show a spatially fairly homogeneous forcing, other agents such as aerosols, ozone and land-use changes are highly heterogeneous spatially. RF<sub>ari</sub> showed maximum negative values over eastern North America and Europe during the early 20th century, with large negative values extending to East and Southeast Asia, South America and central Africa by 1980. Since then, however, the magnitude has decreased over eastern North America and Europe due to pollution control and the peak negative forcing has shifted to South and East Asia primarily as a result of economic growth and the resulting increase in emissions in those areas. Total aerosol ERF shows similar behaviour for locations with maximum negative forcing, but also shows substantial positive forcing over some deserts and the Arctic. In contrast, the global mean whole atmosphere ozone forcing increased throughout the 20th century, and has peak positive amplitudes around 15°N–30°N but negative values over Antarctica. Negative land-use forcing by albedo changes has been strongest in industrialized and biomass burning regions. The inhomogeneous nature of



these forcings can cause them to have a substantially larger influence on the hydrologic cycle than an equivalent global mean homogeneous forcing. {8.3, 8.6}

Over the 21st century, there is *very high confidence* that the anthropogenic radiative forcing will increase. Simple model estimates of the RF resulting from the Representative Concentration Pathways (RCPs, see Box TS.6), which include WMGHG emissions spanning a broad range of possible futures, show anthropogenic RF relative to 1750 increasing to 3.0–4.8 W m<sup>-2</sup> in 2050, and 2.7–8.4 W m<sup>-2</sup> at 2100. In the near-term, the RCPs are quite similar to one another (and emissions of near-term climate forcings do not span the literature range of possible futures), with RF at 2030 ranging only from 2.9 to 3.3 W m<sup>-2</sup> (additional 2010 to 2030 RF of 0.7–1.1 W m<sup>-2</sup>), but they show highly diverging values for the second half of the 21st century driven largely by CO<sub>2</sub>. Results based on the RCP scenarios suggest only small changes in aerosol ERF between 2000 and 2030, followed by a strong reduction in the aerosols and a substantial weakening of the negative total aerosol ERF. Nitrate aerosols are an exception to this reduction with a substantially increased negative forcing which is a robust feature among the few available models. The divergence across the RCPs indicates that, although a certain amount of future climate change is already ‘in the system’ due to the current radiative imbalance caused by historical emissions and the long lifetime of some atmospheric forcing agents, societal choices can still have a very large effect on future radiative forcing, and hence on climate change. {8.2, 8.5, 8.6, 12.3}

### TS.3.7 Climate Feedbacks

Feedbacks will also play an important role in determining future climate change. Indeed, climate change may induce modification in the carbon, water and geochemical cycles which may reinforce (positive feedback) or dampen (negative feedback) the expected temperature increase. Snow and ice albedo feedbacks are known to be positive. The combined water vapor and lapse rate feedback is *extremely likely* and now fairly well quantified, while cloud feedbacks have larger uncertainties (see TFE.6). In addition, the new Coupled Model Intercomparison Project Phase 5 (CMIP5) models consistently estimate a positive carbon-cycle feedback, i.e. reduced natural sinks or increased natural CO<sub>2</sub> sources in response to future climate change. In particular, carbon-cycle feedbacks in the oceans are positive in the models. Carbon sinks in tropical land ecosystems are less consistent, and may be susceptible to climate change via processes such as drought and fire that are sometimes not yet fully represented. A key update since AR4 is the introduction of nutrient dynamics in some of the CMIP5 land carbon models, in particular the limitations on plant growth imposed by nitrogen availability. The net effect of accounting for the nitrogen cycle is a smaller projected land sink for a given trajectory of anthropogenic CO<sub>2</sub> emissions (see TFE.7). {6.3, 6.4; Box 6.1, 7.2}

Models and ecosystem warming experiments show high agreement that wetland CH<sub>4</sub> emissions will increase per unit area in a warmer climate, but wetland areal extent may increase or decrease depending on regional changes in temperature and precipitation affecting wetland hydrology, so that there is low confidence in quantitative projections of wetland CH<sub>4</sub> emissions. Reservoirs of carbon in hydrates and permafrost are very large, and thus could potentially act as very powerful feedbacks. Although poorly constrained, the 21st century global release of CH<sub>4</sub> from hydrates to the atmosphere is *likely* to be low due to the under-saturated state of the ocean, long-ventilation time of the ocean, and slow propagation of warming through the seafloor. Release of carbon from thawing permafrost is *very likely* to provide a positive feedback, but there is limited confidence in quantitative projections of its strength. {6.4}

Aerosol-climate feedbacks occur mainly through changes in the source strength of natural aerosols or changes in the sink efficiency of natural and anthropogenic aerosols; a limited number of modeling studies have assessed the magnitude of this feedback to be small with a *low confidence*. There is *medium confidence* for a weak feedback (of uncertain sign) involving dimethyl sulphide, cloud condensation nuclei, and cloud albedo due to a weak sensitivity of cloud condensation nuclei population to changes in dimethyl sulphide emissions. {7.3.5}

### TS.3.8 Emission Metrics

Different metrics can be used to quantify and communicate the relative and absolute contributions to climate change of emissions of different substances, and of emissions from regions/countries or sources/sectors. Up to AR4, the most common metric has been the Global Warming Potential (GWP) that integrates RF out to a

particular time horizon. This metric thus accounts for the radiative efficiencies of the various substances, and their lifetimes in the atmosphere, and gives values relative to those for the reference gas CO<sub>2</sub>. There is now increasing focus on the Global Temperature change Potential (GTP), which is based on the change in global mean surface temperature at a chosen point in time, again relative to that caused by the reference gas CO<sub>2</sub>, and thus accounts for climate response along with radiative efficiencies and atmospheric lifetimes. Both the GWP and the GTP use a time horizon (Figure TS.8 top), the choice of which is subjective and context-dependent. In general, GWPs for near-term climate forcers are higher than GTPs due to the equal time-weighting in the integrated forcing used in the GWP. Hence the choice of metric can greatly affect the relative importance of near-term climate forcers and WMGHGs, as can the choice of time horizon. Analysis of the impact of current emissions (one-year pulse of emissions) shows that near-term climate forcers, such as black carbon, sulfur dioxide or methane, can have contributions comparable to CO<sub>2</sub>'s for short time horizons (of either the same or opposite sign), but their impacts become progressively less for longer time horizons over which emissions of CO<sub>2</sub> dominate (Figure TS.8 top). {8.7}

### [INSERT FIGURE TS.8 HERE]

**Figure TS.8:** (Upper Panel) Global anthropogenic present-day emissions weighted by the Global Warming Potential (GWP) and the Global Temperature change Potential (GTP) for the chosen time horizons. Year 2008 (single-year pulse) emissions weighted by GWP, which is the global mean radiative forcing per unit mass emitted integrated over the indicated number of years relative to the forcing from CO<sub>2</sub> emissions, and GTP which estimates the impact on global mean temperature based on the temporal evolution of both radiative forcing and climate response per unit mass emitted relative to the impact of CO<sub>2</sub> emissions. The units are “CO<sub>2</sub> equivalents” which reflects equivalence only in the impact parameter of the chosen metric (integrated RF over the chosen time horizon for GWP; temperature change at the chosen point in time for GTP), given as Pg(CO<sub>2</sub>)eq (left axis) and PgCeq (right axis) (see footnote 5). (Bottom Panel) The Absolute GTP (AGTP) as a function of time multiplied by the present-day emissions of all compounds from the indicated sectors is used to estimate global mean temperature response (AGTP is the same as GTP, except is not normalized by the impact of CO<sub>2</sub> emissions). There is little change in the relative values for the sectors over the 60–100 year time horizon. The effects of aerosol-cloud interactions and aviation-induced cirrus are not included in the upper panel. {Figures 8.32, 8.33}

A large number of other metrics may be defined down the driver-response-impact chain. No single metric can accurately compare all consequences (i.e., responses in climate parameters over time) of different emissions, and a metric that establishes equivalence with regard to one effect will not give equivalence with regard to other effects. The choice of metric therefore depends strongly on the particular consequence one wants to evaluate. It is important to note that the metrics do not define policies or goals, but facilitate analysis and implementation of multi-component policies to meet particular goals. All choices of metric contain implicit value-related judgments such as type of effect considered and weighting of effects over time. While GWP integrates the effects up to a chosen time horizon (i.e. giving equal weight to all times up to the horizon and zero weight thereafter), the GTP gives the temperature just for one chosen year with no weight on years before or after. {8.7}

The GWP and GTP have limitations and suffer from inconsistencies related to the treatment of indirect effects and feedbacks, for instance if climate-carbon feedbacks are included for the reference gas CO<sub>2</sub> but not for the non-CO<sub>2</sub> gases. The uncertainty in the GWP increases with time horizon and for the 100-year GWP of WMGHGs the uncertainty can be as large as ±40%. Several studies also point out that this metric is not well suited for policies with a maximum temperature target. Uncertainties in GTP also increase with time as they arise from the same factors contributing to GWP uncertainties along with additional contributions from it being further down the driver-response-impact chain and including climate response. The GTP metric is better suited to target-based policies, but is again not appropriate for every goal. Updated metric values accounting for changes in knowledge of lifetimes and radiative efficiencies and for climate-carbon feedbacks are now available. {8.7}

With these emission metrics, the climate impact of past or current emissions attributable to various activities can be assessed. Such activity-based accounting can provide additional policy-relevant information since these activities are more directly affected by particular societal choices than overall emissions. A single-year's worth of emissions (a pulse) is often used to quantify the impact on future climate. From this perspective and with the absolute GTP metric used to illustrate the results, energy and industry have the largest contributions to warming over the next 50–100 years (Figure TS.8 bottom). Household fossil and biofuel, biomass burning and on-road transportation are also relatively large contributors to warming over

these timescales, while current emissions from sectors that emit large amounts of methane (animal husbandry, waste/landfills and agriculture) are also important over shorter time horizons (up to ~20 years). Another useful perspective is to examine the effect of sustained current emissions. Since emitted substances are removed according to their residence time, short-lived species remain at nearly constant values while long-lived gases accumulate in this analysis. In both cases, the sectors that have the greatest long-term warming impacts (energy and industry) lead to cooling in the near-term (primarily due to SO<sub>2</sub> emissions), and thus emissions from those sectors can lead to opposite global mean temperature responses at short and long timescales. The relative importance of the other sectors depends upon the time and perspective chosen. As with RF or ERF, uncertainties in aerosol impacts are large, and in particular attribution of aerosol-cloud interactions to individual components is poorly constrained. {8.7}

## TS.4 Understanding the Climate System and its Recent Changes

### TS.4.1 Introduction

Understanding of the climate system results from combining observations, theoretical studies of feedback processes, and model simulations. Compared to AR4, more detailed observations and improved climate models (see Box TS.4) now enable the attribution of detected changes to human influences in more climate system components. The consistency of observed and modeled changes across the climate system, including regional temperatures, the water cycle, global energy budget, cryosphere and oceans (including ocean acidification), point to global climate change resulting primarily from anthropogenic increases in greenhouse gas concentrations. {10}

### TS.4.2 Surface Temperature

Several advances since the AR4 have allowed a more robust quantification of human influence on surface temperature changes. Observational uncertainty has been explored much more thoroughly than previously and the assessment now considers observations from the first decade of the 21st century and simulations from a new generation of climate models whose ability to simulate historical climate has improved in many respects relative to the previous generation of models considered in AR4. Observed global mean surface temperature anomalies relative to 1880-1919 in recent years lie well outside the range of temperature anomalies in CMIP5 simulations with natural forcing only, but are consistent with the ensemble of CMIP5 simulations including both anthropogenic and natural forcing (Figure TS.9) even though some individual models overestimate the warming trend, while others underestimate it. Simulations with greenhouse gas changes only, and no aerosol changes, generally exhibit stronger warming than has been observed (Figure TS.9). Observed temperature trends over the period 1951–2010, which are characterized by warming over most of the globe with the most intense warming over the Northern Hemisphere continents, are, at most observed locations, consistent with the temperature trends in CMIP5 simulations including anthropogenic and natural forcings and inconsistent with the temperature trends in CMIP5 simulations including natural forcings only. A number of studies have investigated the effects of the Atlantic Multidecadal Oscillation (AMO) on global mean surface temperature. While some studies find a significant role for the AMO in driving multi-decadal variability in GMST, the AMO exhibited little trend over the period 1951-2010 on which these assessments are based, and the AMO is assessed with *high confidence* to have made little contribution to the GMST trend between 1951 and 2010 (considerably less than 0.1°C). {2.4, 9.8.1, 10.3; FAQ 9.1}.

#### [INSERT FIGURE TS.9 HERE]

**Figure TS.9:** Three observational estimates of global mean surface temperature (black lines) from HadCRUT4, GISTEMP, and MLOST, compared to model simulations (CMIP3 models – thin blue lines and CMIP5 models – thin yellow lines) with anthropogenic and natural forcings (a), natural forcings only (b) and greenhouse gas forcing only (c). Thick red and blue lines are averages across all available CMIP5 and CMIP3 simulations respectively. All simulated and observed data were masked using the HadCRUT4 coverage (since this dataset has the most restricted spatial coverage), and global average anomalies are shown with respect to 1880–1919, where all data are first calculated as anomalies relative to 1961–1990 in each grid box. Inset to (b) shows the three observational datasets distinguished by different colours. {Figure 10.1}

It is *extremely likely* that human activities caused more than half of the observed increase in global average surface temperature from 1951 to 2010. This assessment is supported by robust evidence from multiple

studies using different methods. In particular, the temperature trend attributable to all anthropogenic forcings combined can be more closely constrained in multi-signal detection and attribution analyses. Uncertainties in forcings and in climate models' responses to those forcings, together with difficulty in distinguishing the patterns of temperature response due to greenhouse gases and other anthropogenic forcings prevent as precise a quantification of the temperature changes attributable to greenhouse gases and other anthropogenic forcings individually. Consistent with AR4, it is assessed that more than half of the observed increase in global average surface temperature from 1951 to 2010 is *very likely* due to the observed anthropogenic increase in greenhouse gas concentrations. Greenhouse gases contributed a global mean surface warming *likely* to be between 0.5°C and 1.3°C over the period between 1951 and 2010, with the contributions from other anthropogenic forcings *likely* to be between –0.6°C and 0.1°C and from natural forcings *likely* to be between –0.1°C and 0.1°C. Together these assessed contributions are consistent with the observed warming of approximately 0.6°C over this period (Figure TS.10). {10.3}

**[INSERT FIGURE TS.10 HERE]**

**Figure TS.10:** Assessed *likely* ranges (whiskers) and their midpoints (bars) for warming trends over the 1951–2010 period due to well-mixed greenhouse gases (GHG), anthropogenic forcings (ANT), anthropogenic forcings other than well-mixed greenhouse gases (OA), natural forcings (NAT), and internal variability. The trend in the HadCRUT4 observations is shown in black with its 5 to 95% uncertainty range due only to observational uncertainty in this record. {Figure 10.5}

Solar forcing is the only known natural forcing acting to warm the climate over the 1951–2010 period but it has increased much less than greenhouse gas forcing, and the observed pattern of long-term tropospheric warming and stratospheric cooling is not consistent with the expected response to solar irradiance variations. Considering this evidence together with the assessed contribution of natural forcings to observed trends over this period, it is assessed that the contribution from solar forcing to the observed global warming since 1951 is *extremely unlikely* to be larger than that from greenhouse gases. Since solar forcing has *very likely* decreased since the advent of direct satellite measurements of total solar irradiance in 1978, there is *high confidence* that changes in total solar irradiance have not contributed to global warming during that period. However, there is *medium confidence* that the 11-year cycle of solar variability influences decadal climate fluctuations in some regions through amplifying mechanisms. {8.4, 10.3; Box 10.2}

Observed warming over the past sixty years is far outside the range of internal climate variability estimated from pre-instrumental data, and it is also far outside the range of internal variability simulated in climate models. Model-based simulations of internal variability are assessed to be adequate to make this assessment. Further, the spatial pattern of observed warming differs from those associated with internal variability. Based on this evidence, the contribution of internal variability to the 1951–2010 global mean surface temperature trend was assessed to be *likely* between –0.1°C and 0.1°C, and it is *virtually certain* that warming since 1951 cannot be explained by internal variability alone. {9.5, 10.3, 10.7}

The instrumental record shows a pronounced warming during the first half of the 20th century. Consistent with AR4, it is assessed that the early 20th century warming is *very unlikely* to be due to internal variability alone. It remains difficult to quantify the contributions to this early century warming from internal variability, natural forcing and anthropogenic forcing, due to forcing and response uncertainties and incomplete observational coverage. {10.3}

**[START BOX TS.3 HERE]**

**Box TS.3: Climate Models and the Hiatus in Global-Mean Surface Warming of the Past 15 years**

The observed global-mean surface temperature (GMST) has shown a much smaller increasing linear trend over the past 15 years than over the past 30 to 60 years (Box TS.3, Figure 1a,c). Depending on the observational data set, the GMST trend over 1998–2012 is estimated to be around one-third to one-half of the trend over 1951–2012. For example, in HadCRUT4 the trend is 0.04°C per decade over 1998–2012, compared to 0.11°C per decade over 1951–2012. The reduction in observed GMST trend is most marked in Northern-Hemisphere winter. Even with this “hiatus” in GMST trend, the decade of the 2000s has been the warmest in the instrumental record of GMST. Nevertheless, the occurrence of the hiatus in GMST trend during the past 15 years raises the two related questions of what has caused it and whether climate models are able to reproduce it. {2.4.3, 9.4.1; Box 9.2; Table 2.7}

Fifteen-year-long hiatus periods are common in both the observed and CMIP5 historical GMST time series. However, an analysis of the full suite of CMIP5 historical simulations (augmented for the period 2006–2012 by RCP4.5 simulations) reveals that 111 out of 114 realisations show a GMST trend over 1998–2012 that is higher than the entire HadCRUT4 trend ensemble (Box TS.3, Figure 1a; CMIP5 ensemble-mean trend is  $0.21^{\circ}\text{C}$  per decade). This difference between simulated and observed trends could be caused by some combination of (a) internal climate variability, (b) missing or incorrect radiative forcing, and (c) model response error. These potential sources of the difference, which are not mutually exclusive, are assessed below, as is the cause of the observed GMST trend hiatus. {2.4.3, 9.3.2, 9.4.1; Box 9.2}

#### (a) *Internal Climate Variability*

Hiatus periods of 10–15 years can arise as a manifestation of internal decadal climate variability, which sometimes enhances and sometimes counteracts the long-term externally forced trend. Internal variability thus diminishes the relevance of trends over periods as short as 10 to 15 years for long-term climate change. Furthermore, the timing of internal decadal climate variability is not expected to be matched by the CMIP5 historical simulations, owing to the predictability horizon of at most 10 to 20 years (CMIP5 historical simulations are typically started around nominally 1850 from a control run). However, climate models exhibit individual decades of GMST trend hiatus even during a prolonged phase of energy uptake of the climate system, in which case the energy budget would be balanced by increasing subsurface-ocean heat uptake. {2.4.3, 9.3.2, 11.2.2; Box 2.2, 9.2}

Owing to sampling limitations, it is uncertain whether an increase in the rate of subsurface-ocean heat uptake occurred during the past 15 years. However, it is *very likely* that the climate system, including the ocean below 700 m depth, has continued to accumulate energy over the period 1998–2010. Consistent with this energy accumulation, global-mean sea level has continued to rise during 1998–2012, at a rate only slightly and insignificantly lower than during 1993–2012. The consistency between observed heat-content and sea-level changes yields *high confidence* in the assessment of continued ocean energy accumulation, which is in turn consistent with the positive radiative imbalance of the climate system. By contrast, there is *limited evidence* that the hiatus in GMST trend has been accompanied by a slower rate of increase in ocean heat content over the depth range 0 to 700 m, when comparing the period 2003–2010 against 1971–2010. There is *low agreement* on this slowdown, since three of five analyses show a slowdown in the rate of increase while the other two show the increase continuing unabated. {3.2.3, 3.2.4, 3.7, 8.5.1, 13.3; Box 3.1, 13.1}

During the 15-year period beginning in 1998, the ensemble of HadCRUT4 GMST trends lies below almost all model-simulated trends (Box TS.3, Figure 1a), whereas during the 15-year period ending in 1998, it lies above 93 out of 114 modelled trends (Box TS.3, Figure 1b; HadCRUT4 ensemble-mean trend  $0.26^{\circ}\text{C}$  per decade, CMIP5 ensemble-mean trend  $0.16^{\circ}\text{C}$  per decade). Over the 62-year period 1951–2012, observed and CMIP5 ensemble-mean trend agree to within  $0.02^{\circ}\text{C}$  per decade (Box TS.3, Figure 1c; CMIP5 ensemble-mean trend  $0.13^{\circ}\text{C}$  per decade). There is hence *very high confidence* that the CMIP5 models show long-term GMST trends consistent with observations, despite the disagreement over the most recent 15-year period. Due to internal climate variability, in any given 15-year period the observed GMST trend sometimes lies near one end of a model ensemble, an effect that is pronounced in Box TS.3, Figure 1a,b since GMST was influenced by a very strong El Niño event in 1998.

Unlike the CMIP5 historical simulations referred to above, some CMIP5 predictions were initialised from the observed climate state during the late 1990s and the early 21st century. There is *medium evidence* that these initialised predictions show a GMST lower by about  $0.05^{\circ}\text{C}$  to  $0.1^{\circ}\text{C}$  compared to the historical (uninitialised) simulations and maintain this lower GMST during the first few years of the simulation. In some initialised models this lower GMST occurs in part because they correctly simulate a shift, around 2000, from a positive to a negative phase of the Interdecadal Pacific Oscillation. However, the improvement of this phasing of the Interdecadal Pacific Oscillation through initialisation is not universal across the CMIP5 predictions. Moreover, while part of the GMST reduction through initialisation indeed results from initialising at the correct phase of internal variability, another part may result from correcting a model bias that was caused by incorrect past forcing or incorrect model response to past forcing, especially in the ocean. The relative magnitudes of these effects are at present unknown; moreover, the quality of a forecasting system cannot be evaluated from a single prediction (here, a ten-year prediction within the period 1998–

2012). Overall, there is *medium confidence* that initialisation leads to simulations of GMST during 1998–2012 that are more consistent with the observed trend hiatus than are the uninitialised CMIP5 historical simulations, and that the hiatus is in part a consequence of internal variability that is predictable on the multiyear timescale. {11.1, 11.2.3; Box 11.1, 11.2, 2.5, 9.2;}

### (b) Radiative Forcing

On decadal to interdecadal timescales and under continually increasing effective radiative forcing (ERF), the forced component of the GMST trend responds to the ERF trend relatively rapidly and almost linearly (*medium confidence*). The expected forced-response GMST trend is related to the ERF trend by a factor that has been estimated for the 1% per year CO<sub>2</sub> increases in the CMIP5 ensemble as 2.0 [1.3 to 2.7] W m<sup>-2</sup> °C<sup>-1</sup> (90% uncertainty range). Hence, an ERF trend can be approximately converted to a forced-response GMST trend, permitting an assessment of how much of the change in the GMST trends shown in Box TS.3, Figure 1 is due to a change in ERF trend. {Box 9.2}

The AR5 best-estimate ERF trend over 1998–2011 is 0.23 [0.12 to 0.34] W m<sup>-2</sup> per decade (90% uncertainty range), which is substantially lower than the trend over 1984–1998 (0.34 [0.24 to 0.44] W m<sup>-2</sup> per decade; note that there was a strong volcanic eruption in 1982) and the trend over 1951–2011 (0.30 [0.20 to 0.40] W m<sup>-2</sup> per decade; Box TS.3, Figure 1d–f; the end year 2011 is chosen because data availability is more limited than for GMST). The resulting forced-response GMST trend would approximately be 0.13 [0.06 to 0.31] °C per decade, 0.19 [0.10 to 0.40] °C per decade, and 0.17 [0.08 to 0.36] °C per decade for the periods 1998–2011, 1984–1998, and 1951–2011, respectively (the uncertainty ranges assume that the range of the conversion factor to GMST trend and the range of ERF trend itself are independent). The AR5 best-estimate ERF forcing trend difference between 1998–2011 and 1951–2011 thus might explain about one-half (0.04 °C per decade) of the observed GMST trend difference between these periods (0.06 to 0.08 °C per decade, depending on observational data set). {8.5.2}

The reduction in AR5 best-estimate ERF trend over 1998–2011 compared to both 1984–1998 and 1951–2011 is mostly due to decreasing trends in the natural forcings, -0.14 [-0.24 to -0.04] W m<sup>-2</sup> per decade over 1998–2011 compared to 0.0 [-0.01 to +0.01] W m<sup>-2</sup> per decade over 1951–2011. Solar forcing went from a relative maximum in 2000 to a relative minimum in 2009, with a peak-to-peak difference of around 0.15 W m<sup>-2</sup> and a linear trend over 1998–2011 of around -0.10 W m<sup>-2</sup> per decade. Furthermore, a series of small volcanic eruptions has increased the observed stratospheric aerosol loading after 2000, leading to an additional negative ERF linear-trend contribution of around -0.04 W m<sup>-2</sup> per decade over 1998–2011 (Box TS.3, Figure 1d,f). By contrast, satellite-derived estimates of tropospheric aerosol optical depth suggests little overall trend in global-mean aerosol optical depth over the last 10 years, implying little change in ERF due to aerosol-radiative interaction (*low confidence* because of *low confidence* in aerosol optical depth trend itself). Moreover, because there is only *low confidence* in estimates of ERF due to aerosol-cloud interaction, there is likewise *low confidence* in its trend over the last 15 years. {2.2.3, 8.4.2, 8.5.1, 8.5.2, 10.3.1; Box 10.2; Table 8.6, 8.7}

For the periods 1984–1998 and 1951–2011, the CMIP5 ensemble-mean ERF trend deviates from the AR5 best-estimate ERF trend by only 0.01 W m<sup>-2</sup> per decade (Box TS.3, Figure 1e, f). After 1998, however, some contributions to a decreasing ERF trend are missing in the CMIP5 models, such as the increasing stratospheric aerosol loading after 2000 and the unusually low solar minimum in 2009. Nonetheless, over 1998–2011 the CMIP5 ensemble-mean ERF trend is lower than the AR5 best-estimate ERF trend by 0.05 W m<sup>-2</sup> per decade (Box TS.3, Figure 1d). Furthermore, global-mean aerosol optical depth in the CMIP5 models shows little trend over 1998–2012, similar to the observations. Although the forcing uncertainties are substantial, there are no apparent incorrect or missing global-mean forcings in the CMIP5 models over the last 15 years that could explain the model–observations difference during the warming hiatus. {9.4.6}

### (c) Model Response Error

The discrepancy between simulated and observed GMST trends during 1998–2012 could be explained in part by a tendency for some CMIP5 models to simulate stronger warming in response to increases in greenhouse-gas concentration than is consistent with observations. Averaged over the ensembles of models assessed in Section 10.3.1.1.3, the best-estimate greenhouse-gas (GHG) and other anthropogenic (OA)

scaling factors are less than one (though not significantly so, Figure 10.4), indicating that the model-mean GHG and OA responses should be scaled down to best match observations. This finding provides evidence that some CMIP5 models show a larger response to greenhouse gases and other anthropogenic factors (dominated by the effects of aerosols) than the real world (*medium confidence*). As a consequence, it is argued in Chapter 11 that near-term model projections of GMST increase should be scaled down by about 10%. This downward scaling is, however, not sufficient to explain the model-mean overestimate of GMST trend over the hiatus period. {10.3.1; 11.3.6}

Another possible source of model error is the poor representation of water vapour in the upper atmosphere. It has been suggested that a reduction in stratospheric water vapour after 2000 caused a reduction in downward longwave radiation and hence a surface-cooling contribution, possibly missed by the models. However, this effect is assessed here to be small, because there was a recovery in stratospheric water vapour after 2005. {2.2.2, 9.4.1; Box 9.2}

In summary, the observed recent warming hiatus, defined as the reduction in GMST trend during 1998–2012 as compared to the trend during 1951–2012, is attributable in roughly equal measure to a cooling contribution from internal variability and a reduced trend in external forcing (expert judgment, *medium confidence*). The forcing trend reduction is primarily due to a negative forcing trend from both volcanic eruptions and the downward phase of the solar cycle. However, there is *low confidence* in quantifying the role of forcing trend in causing the hiatus, because of uncertainty in the magnitude of the volcanic forcing trend and *low confidence* in the aerosol forcing trend. {Box 9.2}

Almost all CMIP5 historical simulations do not reproduce the observed recent warming hiatus. There is *medium confidence* that the GMST trend difference between models and observations during 1998–2012 is to a substantial degree caused by internal variability, with possible contributions from forcing error and some CMIP5 models overestimating the response to increasing greenhouse-gas forcing. The CMIP5 model trend in effective radiative forcing (ERF) shows no apparent bias against the AR5 best estimate over 1998–2012. However, *confidence* in this assessment of CMIP5 ERF trend is *low*, primarily because of the uncertainties in model aerosol forcing and processes, which through spatial heterogeneity might well cause an undetected global-mean ERF trend error even in the absence of a trend in the global-mean aerosol loading. {Box 9.2}

The causes of both the observed GMST trend hiatus and of the model–observation GMST trend difference during 1998–2012 imply that, barring a major volcanic eruption, most 15-year GMST trends in the near-term future will be larger than during 1998–2012 (*high confidence*; see Section 11.3.6.3. for a full assessment of near-term projections of GMST). The reasons for this implication are fourfold: first, anthropogenic greenhouse-gas concentrations are expected to rise further in all RCP scenarios; second, anthropogenic aerosol concentration is expected to decline in all RCP scenarios, and so is the resulting cooling effect; third, the trend in solar forcing is expected to be larger over most near-term 15-year periods than over 1998–2012 (*medium confidence*), because 1998–2012 contained the full downward phase of the solar cycle; and fourth, it is *more likely than not* that internal climate variability in the near-term will enhance and not counteract the surface warming expected to arise from the increasing anthropogenic forcing. {Box 9.2}

### [INSERT BOX TS.3, FIGURE 1 HERE]

**Box TS.3, Figure 1:** Top: Observed and simulated GMST trends in °C per decade, over the periods 1998–2012 (a), 1984–1998 (b), and 1951–2012 (c). For the observations, 100 realisations of the HadCRUT4 ensemble are shown (red, hatched). The uncertainty displayed by the ensemble width is that of the statistical construction of the global average only, in contrast to the trend uncertainties quoted in Section 2.4.3, which include an estimate of internal climate variability. Here, by contrast, internal variability is characterised through the width of the model ensemble. For the models, all 114 available CMIP5 historical realisations are shown, extended after 2005 with the RCP4.5 scenario and through 2012 (grey, shaded). Bottom: Trends in effective radiative forcing (ERF, in  $\text{W m}^{-2}$  per decade) over the periods 1998–2011 (d), 1984–1998 (e), and 1951–2011 (f). The figure shows AR5 best-estimate ERF trends (red, hatched) and CMIP5 ERF (grey, shaded). Black lines are smoothed versions of the histograms. Each histogram is normalised so that its area sums up to one. {2.4.3, 8.5.2; Box 9.2; Figure 8.18, Box 9.2, Figure 1}

### [END BOX TS.3 HERE]

### TFE.3: Comparing Projections from Previous IPCC Assessments with Observations

Verification of projections is arguably the most convincing way of establishing the credibility of climate change science. Results of projected changes in CO<sub>2</sub>, global mean surface temperature and global mean sea level from previous IPCC assessment reports are quantitatively compared with the best available observational estimates. The comparison between the four previous reports highlights the evolution in our understanding of how the climate system responds to changes in both natural and anthropogenic forcing and provides an assessment of how the projections compare with observational estimates. TFE.3, Figure 1, for example, shows the projected and observed estimates of: (i) CO<sub>2</sub> changes (top row), (ii) global mean surface temperature anomaly relative to 1961–1990 (middle row) and (iii) global mean sea level relative to 1990 (bottom row). Results from previous assessment reports are in the left hand column, and for completeness results from current assessment are given in the right hand column. {2.4, 3.7, 6.3, 11.3, 13.3}

#### [INSERT TFE.3, FIGURE 1 HERE]

**TFE.3, Figure 1:** (top: left) Observed globally and annually averaged CO<sub>2</sub> concentrations in parts per million (ppm) since 1950 compared with projections from the previous IPCC assessments. Observed global annual CO<sub>2</sub> concentrations are shown in dark blue. The shading shows the largest model projected range of global annual CO<sub>2</sub> concentrations from 1950 to 2035 from FAR (First Assessment Report; Figure A.3 in the Summary for Policymakers (SPM) of IPCC 1990), SAR (Second Assessment Report; Figure 5b in the TS of IPCC 1996), TAR (Third Assessment Report; Appendix II of IPCC 2001), and for the A2, A1B and B1 scenario presented in the AR4 (Fourth Assessment Report; Figure 10.26). (top: right) Same observed globally averaged CO<sub>2</sub> concentrations and the projections from this report. Only RCP8.5 has a range of values since the emission driven scenarios were only carried out for this RCP. For the other RCPs the best estimate is given. (middle: left) Estimated changes in the observed globally and annually averaged surface temperature anomaly relative to 1961–1990 (in °C) since 1950 compared with the range of projections from the previous IPCC assessments. Values are harmonized to start from the same value at 1990. Observed global annual temperature anomaly, relative to 1961–1990, from three datasets is shown as squares (NASA (dark blue), NOAA (warm mustard), and the UK Hadley Centre (bright green) data sets). The coloured shading shows the projected range of global annual mean near surface temperature change from 1990 to 2035 for models used in FAR (Figure 6.11), SAR (Figure 19 in the TS of IPCC 1996), TAR (full range of TAR, Figure 9.13(b)). TAR results are based on the simple climate model analyses presented in this assessment and not on the individual full three-dimensional climate model simulations. For the AR4 results are presented as single model runs of the CMIP3 ensemble for the historical period from 1950–2000 (light grey lines) and for three scenarios (A2, A1B and B1) from 2001–2035. For the three SRES scenarios the bars show the CMIP3 ensemble mean and the likely range given by -40 % to +60% of the mean as assessed in Meehl et al. (2007). The publication years of the assessment reports are shown. (middle: right) Projections of annual mean global mean surface air temperature (GMST) for 1950–2035 (anomalies relative to 1961–1990) under different RCPs from CMIP5 models (light grey and coloured lines, one ensemble member per model), and observational estimates the same as the middle left panel. The grey shaded region shows the indicative likely range for annual mean GMST during the period 2016–2035 for all RCPs (see Figure TS.14 for more details). The grey bar shows this same indicative likely range for the year 2035. (bottom: left) Estimated changes in the observed global annual mean sea level (GMSL) since 1950. Different estimates of changes in global annual sea level anomalies from tide gauge data (dark blue, warm mustard, dark green) and based on annual averages of altimeter data (light blue) starting in 1993 (the values have been aligned to fit the 1993 value of the tide gauge data). Squares indicate annual mean values, solid lines smoothed values. The shading shows the largest model projected range of global annual sea level rise from 1950 to 2035 for FAR (Figures 9.6 and 9.7), SAR (Figure 21 in TS of IPCC, 1996), TAR (Appendix II of IPCC, 2001; updated) based on the Coupled Model Intercomparison Project Phase 3 (CMIP3) model results available at the time of AR4 using the SRES A1B scenario. Note that in the AR4 no full range was given for the sea level projections for this period. Therefore, the figure shows results only for the SRES-A1B scenario that have been published subsequent to the AR4. The bars at the right hand side of each graph show the full range given for 2035 for each assessment report. The publication years of the assessment reports are shown. Appendix 1.A for details on the data and calculations used to create these figures. (bottom: right) Same observational estimate as bottom left. The bars are the "likely ranges (medium confidence) for global mean sea level rise at 2081–2100 with respect to 1986–2005 following the four RCPs. See Chapters 1, 11 and 13 for more details. {Figures 1.4, 1.5, 1.10, 11.9, 11.19, 11.25, 13.11}

#### CO<sub>2</sub> Changes

From 1950–2011 the observed concentrations of atmospheric CO<sub>2</sub> have steadily increased. Considering the period 1990–2011, the observed CO<sub>2</sub> concentration changes lie within the envelope of the scenarios used in the four assessment reports. As the most recent assessment, AR4 (TFE.3.Figure 1; top left) has the narrowest scenario range and the observed concentration follows this range. The AR5 results (TFE.3.Figure 1; top right) are consistent with AR4, and during 2002–2011, atmospheric CO<sub>2</sub> concentrations increased at a rate of 1.9 to 2.1 ppm yr<sup>-1</sup>. {2.2.1, 6.3; Table 6.1}



### ***Global Mean Temperature Anomaly***

Relative to the 1961–1990 mean, the global mean surface temperature anomaly has been positive and larger than 0.25°C since 2001. Overall the observed temperature record lies within the total range of uncertainty (i.e., the combined effects of scenario uncertainty, observational uncertainty and uncertainty due to natural variability; area enclosed colored wedges (TFE.3, Figure 1, middle left: FAR, SAR, TAR, AR4: B1, A1B, A2) and by individual CMIP3 simulations and projections). This is also true for the CMIP5 results (TFE.3, Figure 1; middle right) in the sense that the observed record lies within the range of the model projections, but on the lower end of the plume. Mount Pinatubo erupted in 1991 (see FAQ 11.2 for discussion of how volcanoes impact the climate system) leading to a brief period of relative global mean cooling during the early 1990's. The FAR, SAR and TAR did not include the effects of volcanic eruptions and thus failed to include the cooling associated with the Pinatubo eruption. AR4 and AR5, however, did include the effects from volcanoes and did simulate successfully the associated cooling. During 1995–2000 the global mean temperature anomaly was quite variable – a significant fraction of this variability was due to the large El Niño in 1997–1998 and the strong back-to-back La Niña's in 1999–2001. The projections associated with these assessment reports do not attempt to capture the actual evolution of these El Niño and La Niña events, but includes them as a source of uncertainty due to natural variability as encompassed by, for example, the range given by the individual CMIP3 and CMIP5 simulations and projection (TFE.3, Figure 1). The grey wedge in TFE.3, Figure 1 (middle right) corresponds to the indicative likely range for annual temperatures, which is determined from the all RCPs assessed value for the 20-year mean 2016–2035 (see discussion of Figure TS.14 and Section 11.3.6 for details). From 1998–2012 the observational estimates have largely been on the low end of the range given by the scenarios alone in previous assessment reports and CMIP3 and CMIP5 projections. {2.4; Box 9.2}

### ***Global Mean Sea Level***

Based on both tide gauge and satellite altimetry data, relative to 1990, the global mean sea level has continued to rise. While the increase is fairly steady, both observational records show short periods of either no change or a slight decrease. The observed estimates lie within the envelope of all the projections except perhaps in the very early 1990s. The sea level rise uncertainty due to scenario-related uncertainty is smallest for the most recent assessments (AR4 and AR5) and observed estimates lie well within this scenario-related uncertainty. It is *virtually certain* that over the 20th century that sea level rose. The mean rate of sea level increase was 1.7 mm yr<sup>-1</sup> with a *very likely* range between 1.5 to 1.9 between 1901 and 2010 and this rate increased to 3.2 with a *likely* range of 2.8 to 3.6 mm yr<sup>-1</sup> between 1993 and 2010 (see TFE.2). {3.7.2, 3.7.4}

### ***TS.4.3 Atmospheric Temperature***

A number of studies since the AR4 have investigated the consistency of simulated and observed trends in free tropospheric temperatures (see section TS.2). Most, though not all, CMIP3 and CMIP5 models overestimate the observed warming trend in the tropical troposphere during the satellite period 1979–2012. Roughly one-half to two-thirds of this difference from the observed trend is due to an overestimate of the sea surface temperature trend, which is propagated upward because models attempt to maintain static stability. There is *low confidence* in these assessments, however, due to the *low confidence* in observed tropical tropospheric trend rates and vertical structure. Outside the tropics, and over the period of the radiosonde record beginning in 1961, the discrepancy between simulated and observed trends is smaller. {2.4.4, 9.4, 10.3}

Analysis of both radiosonde and satellite datasets, combined with CMIP5 and CMIP3 simulations continues to find that observed tropospheric warming is inconsistent with internal variability and simulations of the response to natural forcings alone. Over the period 1961–2010 CMIP5 models simulate tropospheric warming driven by greenhouse gas changes, with only a small offsetting cooling due to the combined effects of changes in reflecting and absorbing aerosols and tropospheric ozone. Taking this evidence together with the results of multi-signal detection and attribution analyses, it is *likely* that anthropogenic forcings, dominated by greenhouse gases, have contributed to the warming of the troposphere since 1961. Uncertainties in radiosonde and satellite records makes assessment of causes of observed trends in the upper

troposphere less confident than an assessment of the overall atmospheric temperature changes. {2.4.4, 9.4, 10.3}

CMIP5 simulations including greenhouse gas, ozone and natural forcing changes broadly reproduce the observed evolution of lower stratospheric temperature, with some tendency to underestimate the observed cooling trend over the satellite era (see Section TS.2). New studies of stratospheric temperature, considering the responses to natural forcings, greenhouse gases and ozone-depleting substances, demonstrate that it is *very likely* that anthropogenic forcings, dominated by the depletion of the ozone layer due to ozone depleting substances have contributed to the cooling of the lower stratosphere since 1979. CMIP5 models simulate only a very weak cooling of the lower stratosphere in response to historical greenhouse gas changes, and the influence of greenhouse gases on lower stratospheric temperature has not been formally detected. Considering both regions together, it is *very likely* that anthropogenic forcing, particularly greenhouse gases and stratospheric ozone depletion, has led to a detectable observed pattern of tropospheric warming and lower stratospheric cooling since 1961. {2.4, 9.4, 10.3}

#### **TS.4.4 Oceans**

The observed upper-ocean warming during the late 20th and early 21st centuries and its causes have been assessed more completely since AR4 using updated observations and more simulations (see Section TS.2.2). The long term trends and variability in the observations are most consistent with simulations of the response to both anthropogenic forcing and volcanic forcing. The anthropogenic fingerprint in observed upper-ocean warming, consisting of global mean and basin-scale pattern changes, has also been detected. This result is robust to a number of observational, model and methodological or structural uncertainties. It is *very likely* that anthropogenic forcings have made a substantial contribution to upper ocean warming (above 700m) observed since the 1970s. This anthropogenic ocean warming has contributed to global sea level rise over this period through thermal expansion. {3.2.2, 3.2.3, 3.7.2, 10.4.1, 10.4.3; Box 3.1}

Observed surface salinity changes also suggest a change in the global water cycle has occurred (see TFE.1). The long term trends show that there is a strong positive correlation between the mean climate of the surface salinity and the temporal changes of surface salinity from 1950 to 2000. This correlation shows an enhancement of the climatological salinity pattern—so fresh areas have become fresher and salty areas saltier. The strongest anthropogenic signals are in the tropics (TRO, 30°S–30°N) and the Western Pacific. The salinity contrast between the Pacific and Atlantic oceans is also increased with significant contributions from anthropogenic forcing. {3.3, 10.3.2, 10.4.2; FAQ 3.3}

On a global scale, surface and subsurface salinity changes (1955–2004) over the upper 250m of the water column are very unlikely to be explained by natural variability. However, the observed salinity changes match the modelled distribution of forced changes (greenhouse gases and tropospheric aerosols). Natural external variability taken from the simulations with just the variations in solar and volcanic forcing do not match the observations at all, thus excluding the hypothesis that observed trends can be explained by just solar or volcanic variations. These lines of evidence and our physical understanding of the physical processes leads to the conclusions that it is *very likely* that anthropogenic forcings have made a discernable contribution to surface and subsurface oceanic salinity changes since the 1960's. {10.4.2; Table 10.1}

Oxygen is an important physical and biological tracer in the ocean. Global analyses of oxygen data from the 1960's to 1990's extend the spatial coverage from local to global scales and have been combined with attribution studies for a limited range of earth system models. It is concluded that there is *medium confidence* that the observed global pattern of decrease in dissolved oxygen in the oceans can be attributed in part to human influences. {3.8.3, 10.4.4; Table 10.1}

The observations show distinct trends for ocean acidification (which is observed to be between –0.0014 and –0.0024 pH units per year). It is *very likely* that oceanic uptake of anthropogenic carbon dioxide has resulted in the acidification of surface waters. {3.8.2, 10.4.4; Box 3.2; Table 10.1}

### **TFE.4: The Changing Energy Budget of the Global Climate System**

The global energy budget is a fundamental aspect of the Earth's climate system and depends on many phenomena within it. The ocean has stored about 93% of the increase in energy in the climate system over recent decades resulting in ocean thermal expansion and hence sea level rise. The rate of storage of energy in the Earth system must be equal to the net downward radiative flux at the top of the atmosphere, which is the difference between effective radiative forcing due to changes imposed on the system, and the radiative response of the system. There are also significant transfers of energy between components of the climate system and from one location to another. The focus here is on the Earth's global energy budget since 1970, when better global observational data coverage is available. {3.7, 9.4, 13.4; Box 3.1}

The effective radiative forcing of the climate system has been positive as a result of increases in well-mixed (long-lived) greenhouse gas concentrations, changes in short-lived greenhouse gases (tropospheric and stratospheric ozone and stratospheric water vapour), and an increase in solar irradiance (TFE.4, Figure 1a). This has been partly compensated by a negative contribution to the effective radiative forcing of the climate system as a result of changes in tropospheric aerosol, which predominantly reflect sunlight and furthermore enhance the brightness of clouds, although black carbon produces positive forcing. Explosive volcanic eruptions (such as El Chichón in Mexico in 1982 and Mount Pinatubo in the Philippines in 1991) can inject sulphur dioxide into the stratosphere, giving rise to stratospheric aerosol, which persists for several years. Stratospheric aerosol reflects some of the incoming solar radiation and thus gives a negative forcing. Changes in surface albedo from land-use change have also led to a greater reflection of shortwave radiation back to space and hence a negative forcing. Since 1970, the net effective radiative forcing of the climate system has increased, and the integrated impact of these forcings is an energy inflow over this period (TFE.4, Figure 1a). {2.3, 8.5; Box 13.1}

#### [INSERT TFE.4, FIGURE 1 HERE]

**TFE.4, Figure 1:** The Earth's energy budget from 1970 through 2011. (a) The cumulative energy inflow into the Earth system from changes in well-mixed and short-lived greenhouse gases, solar forcing, tropospheric aerosol forcing, volcanic forcing, and changes in surface albedo due to land-use change (all relative to 1860-1879) are shown by the coloured lines; these contributions are added to give the total energy inflow (black; contributions from black carbon on snow and contrails as well as contrail-induced cirrus are included but not shown separately). (b) The cumulative total energy inflow from (a, black) is balanced by the sum of the energy uptake of the Earth system (blue; energy absorbed in warming the ocean, the atmosphere, and the land, as well as in the melting of ice) and an increase in outgoing radiation inferred from changes in the global-mean surface temperature. The sum of these two terms is given for a climate feedback parameter  $\alpha$  of 2.47, 1.23, and 0.82  $\text{W m}^{-2} \text{ } ^\circ\text{C}^{-1}$ , corresponding to an equilibrium climate sensitivity of 1.5°C, 3.0°C, and 4.5°C, respectively; 1.5°C–4.5°C is assessed to be the *likely* range of equilibrium climate sensitivity. The energy budget would be closed for a particular value of  $\alpha$  if the corresponding line coincided with the total energy inflow. For clarity, all uncertainties (shading) shown are *likely* ranges. {Box 12.2; Box 13.1, Figure 1}

As the climate system warms, energy is lost to space through increased outgoing radiation. This radiative response by the system is predominantly due to increased thermal radiation, but it is modified by climate feedbacks such as changes in water vapour, clouds, and surface albedo, which affect both outgoing long-wave and reflected shortwave radiation. The top of the atmosphere fluxes have been measured by the Earth Radiation Budget Experiment (ERBE) satellites from 1985 to 1999 and the Cloud and the Earth's Radiant Energy System (CERES) satellites from March 2000 to the present. The top of the atmosphere radiative flux measurements are highly precise, allowing identification of changes in the Earth's net energy budget from year to year within the ERBE and CERES missions, but the absolute calibration of the instruments is not sufficiently accurate to allow determination of the absolute top of the atmosphere energy flux or to provide continuity across missions. TFE.4, Figure 1b relates the cumulative total energy change of the Earth system to the change in energy storage and the cumulative outgoing radiation. Calculation of the latter is based on the observed global-mean surface temperature multiplied by the climate feedback parameter  $\alpha$ , which in turn is related to the equilibrium climate sensitivity. The mid-range value for  $\alpha$ , 1.23  $\text{W m}^{-2} \text{ } ^\circ\text{C}^{-1}$ , corresponds to an effective radiative forcing for a doubled  $\text{CO}_2$  concentration of 3.7 [2.96 to 4.44]  $\text{W m}^{-2}$  combined with an equilibrium climate sensitivity of 3.0°C. The climate feedback parameter  $\alpha$  is *likely* to be in the range from 0.82  $\text{W m}^{-2} \text{ } ^\circ\text{C}^{-1}$  to 2.47  $\text{W m}^{-2} \text{ } ^\circ\text{C}^{-1}$  (corresponding to the *likely* range in equilibrium climate sensitivity of 1.5°C to 4.5°C). {9.7.1, Box 12.2}

If effective radiative forcing were fixed, the climate system would eventually warm sufficiently that the radiative response would balance the effective radiative forcing, and there would be no further change in energy storage in the climate system. However, the forcing is increasing, and the ocean's large heat capacity

means that the climate system is not in radiative equilibrium and its energy content is increasing (TFE.4, Figure 1b). This storage provides strong evidence of a changing climate. The majority of this additional heat is in the upper 700 m of the ocean, but there is also warming in the deep and abyssal ocean. The associated thermal expansion of the ocean has contributed about 40% of the observed sea level rise since 1970. A small amount of additional heat has been used to warm the continents, warm and melt glacial and sea ice, and warm the atmosphere. {13.4.2; Box 3.1, Box 13.1}

In addition to these forced variations in the Earth's energy budget, there is also internal variability on decadal time scales. Observations and models indicate that, because of the comparatively small heat capacity of the atmosphere, a decade of steady or even decreasing surface temperature can occur in a warming world. Climate model simulations suggest that these periods are associated with a transfer of heat from the upper to the deeper ocean, of the order  $0.1 \text{ W m}^{-2}$ , with a near-steady or an increased radiation to space, again of the order  $0.1 \text{ W m}^{-2}$ . While these natural fluctuations represent a large amount of heat, they are significantly smaller than the anthropogenic forcing of the Earth's energy budget, particularly on timescales of several decades or longer {9.4; Box 9.2, 13.1}.

The available independent estimates of effective radiative forcing, of observed heat storage, and of surface warming combine to give an energy budget for the Earth that is consistent with the assessed *likely* range of equilibrium climate sensitivity to within estimated uncertainties. Quantification of the terms in the Earth's energy budget and verification that these terms balance over recent decades provides strong evidence for our understanding of anthropogenic climate change {Box 13.1}.

#### ***TS.4.5 Cryosphere***

The reductions in Arctic sea ice extent and northern hemisphere snow cover extent and widespread glacier retreat and increased surface melt of Greenland (see TS.2) are all evidence of systematic changes in the cryosphere. All of these changes in the cryosphere have been linked to anthropogenic forcings. {4.2.2, 4.4, 4.5, 4.6, 10.5.1, 10.5.3; Table 10.1}

Attribution studies, comparing the seasonal evolution of Arctic sea ice extent from observations from the 1950s with those simulated by coupled model simulations, demonstrate that human influence on the sea ice extent changes can be robustly detected since the early 1990s. The anthropogenic signal is also detectable for individual months from May to December, suggesting that human influence, strongest in late summer, now also extends into colder seasons. From these simulations of sea-ice and observed sea-ice extent from the instrumental record with high agreement between studies, it is concluded that anthropogenic forcings are *very likely* to have contributed to Arctic sea ice loss since 1979 (Figure TS.12). {10.5.1}

For Antarctic sea ice extent, the shortness of the observed record and differences in simulated and observed variability preclude an assessment of whether or not the observed increase since 1979 is inconsistent with internal variability. Untangling the processes involved with trends and variability in Antarctica and surrounding waters remains complex and several studies are contradictory. In conclusion there is *low confidence* in the scientific understanding of the observed increase in Antarctic sea ice extent since 1979, due to the large differences between sea-ice simulations from CMIP5 models and to the incomplete and competing scientific explanations for the causes of change and *low confidence* in estimates of internal variability (Figure TS.12). {9.4.3, 10.5.1; Table 10.1}

The Greenland ice sheet shows recent major melting episodes in response to record temperatures relative to the 20th century associated with persistent shifts in early summer atmospheric circulation, and these shifts have become more pronounced since 2007. While many Greenland instrumental records are relatively short (two decades), regional modelling and observations tell a consistent story of the response of Greenland temperatures and ice sheet runoff to shifts in regional atmospheric circulation associated with larger scale flow patterns and global temperature increases. Mass loss and melt is also occurring in Greenland through the intrusion of warm water into the major fjords containing glaciers such as Jacobshaven Glacier. It is *likely* that anthropogenic forcing has contributed to surface melting of the Greenland ice sheet since 1990. {10.5.2; Table 10.1}

Estimates of ice mass in Antarctica since 2000 show that the greatest losses are at the edges. An analysis of observations underneath a floating ice shelf off West Antarctica leads to the conclusion that ocean warming in this region and increased transport of heat by ocean circulation are largely responsible for accelerating melt rates. The observational record of Antarctic mass loss is short and the internal variability of the ice sheet is poorly understood. These factors combined with incomplete models of Antarctic ice sheet mass loss result in *low confidence* in scientific understanding of this mass loss, and consequently the attribution of the decrease in mass of Antarctic ice sheet to human influence is premature. {3.2, 4.2, 4.4.3, 10.5.2}

The evidence for the retreat of glaciers due to warming and moisture change is now more complete than at the time of AR4. There is *high confidence* in the estimates of observed mass loss and the estimates of natural variations and internal variability from long term glacier records. Based on these factors and our understanding of glacier response to climatic drivers there is high confidence that a substantial part of the mass loss of glaciers is *likely* due to human influence. It is *likely* that there has been an anthropogenic component to observed reductions in northern hemisphere snow cover since 1970. {4.3.3, 10.5.2, 10.5.3; Table 10.1}

### **TFE.5: Irreversibility and Abrupt Change**

A number of components or phenomena within the climate system have been proposed as potentially exhibiting threshold behaviour. Crossing such thresholds can lead to an abrupt or irreversible transition into a different state of the climate system or some of its components.

*Abrupt climate change* is defined in AR5 as a large-scale change in the climate system that takes place over a few decades or less, persists (or is anticipated to persist) for at least a few decades, and causes substantial disruptions in human and natural systems. There is information on potential consequences of some abrupt changes, but in general there is *low confidence* and little consensus on the likelihood of such events over the 21st century. Examples of components susceptible to such abrupt change are the strength of the Atlantic Meridional Overturning Circulation (AMOC), clathrate methane release, tropical and boreal forest dieback, disappearance of summer sea ice in the Arctic Ocean, long-term drought and monsoonal circulation. {5.7, 6.4.7, 12.5.5; Table 12.4}

A change is said to be *irreversible* if the recovery timescale from this state due to natural processes is significantly longer than the time it takes for the system to reach this perturbed state. Such behaviour may arise because the timescales for perturbations and recovery processes are different, or because climate change may persist due to the long residence time of a CO<sub>2</sub> perturbation in the atmosphere (see TFE.8). While changes in Arctic- Ocean summer sea-ice extent, long-term droughts and monsoonal circulation are assessed to be reversible within years to decades, tropical or boreal forest dieback may only be reversible within centuries. Changes in clathrate methane and permafrost carbon release, Greenland and Antarctic ice sheet collapse may be irreversible during millennia after the causal perturbation. {5.8, 6.4.7, 12.5.5, 13.4.3, 13.4.4; Table 12.4}

#### ***Abrupt Climate Change Linked with AMOC***

New transient climate model simulations have confirmed with *high confidence* that strong changes in the strength of the AMOC produce abrupt climate changes at global scale with magnitude and pattern resembling past glacial Dansgaard-Oeschger events and Heinrich stadials. Confidence in the link between changes in North Atlantic climate and low-latitude precipitation has increased since AR4. From new paleoclimate reconstructions and modelling studies, there is *very high confidence* that a reduced strength of the AMOC and the associated surface cooling in the North Atlantic region caused southward shifts of the Atlantic intertropical convergence zone and affected the American (north and south), African and Asian monsoons. {5.7}

The interglacial mode of the AMOC can recover (*high confidence*) from a short-lived freshwater input into the subpolar North Atlantic. Approximately 8,200 years ago, a marked reduction in the strength of the AMOC was driven by a sudden freshwater release in the final stages of North American ice sheet melting.

Paleoclimate observations and model results indicate, with *high confidence*, that the circulation was restored within approximately 200 years after the perturbation. {5.8.1}

While many more model simulations have been conducted since AR4 under a wide range of future forcing scenarios, projections of the AMOC behaviour have not changed. It remains *very likely* that the AMOC will weaken over the 21st century relative to preindustrial values with a best estimate decrease in 2100 of about 20–30% for the RCP4.5 scenario and 36–44% for the RCP8.5 scenario, but there is *low confidence* on the magnitude of weakening. It also remains *very unlikely* that the AMOC will undergo an abrupt transition or collapse in the 21st century for the scenarios considered (*high confidence*) (TFE.5, Figure 1). For an abrupt transition of the AMOC to occur, the sensitivity of the AMOC to forcing would have to be far greater than seen in current models, or would require meltwater flux from the Greenland ice sheet greatly exceeding even the highest of current projections. While neither possibility can be excluded entirely, it is *unlikely* that the AMOC will collapse beyond the end of the 21st century for the scenarios considered but a collapse beyond the 21st century for large sustained warming cannot be excluded. There is *low confidence* in assessing the evolution of AMOC beyond the 21st century because of limited number of analyses and equivocal results. {12.4.7, 12.5.5}

#### **[INSERT TFE.5, FIGURE 1 HERE]**

**TFE.5, Figure 1:** Atlantic Meridional Overturning Circulation strength at 30°N (Sv) as a function of year, from 1850 to 2300 as simulated by different AOGCMs in response to scenario RCP2.6 (left) and RCP8.5 (right). The vertical black bar shows the range of AMOC strength measured at 26°N, from 2004 to 2011 {Figure 3.11, 12.35}

#### ***Potential Irreversibility of Changes in Permafrost, Methane Clathrates and Forests***

In a warming climate, permafrost thawing may induce decomposition of carbon accumulated in frozen soils which could persist for hundreds to thousands of years, leading to an increase of atmospheric CO<sub>2</sub> and/or CH<sub>4</sub> concentrations. The existing modelling studies of permafrost carbon balance under future warming that take into account at least some of the essential permafrost-related processes do not yield consistent results, beyond the fact that present-day permafrost will become a net emitter of carbon during the 21st century under plausible future warming scenarios (*low confidence*). This also reflects an insufficient understanding of the relevant soil processes during and after permafrost thaw, including processes leading to stabilization of unfrozen soil carbon, and precludes any quantitative assessment of the amplitude of irreversible changes in the climate system potentially related to permafrost degassing and associated feedbacks. {6.4.7, 12.5.5}

Anthropogenic warming will *very likely* lead to enhanced methane emissions from both terrestrial and oceanic clathrates. Deposits of methane clathrates below the sea floor are susceptible to destabilization via ocean warming. However, sea level rise due to changes in ocean mass enhances clathrate stability in the ocean. While difficult to formally assess, initial estimates of the 21st century feedback from methane clathrate destabilization are small but not insignificant. It is *very unlikely* that methane from clathrates will undergo catastrophic release during the 21st century (*high confidence*). On multi-millennial timescales, such methane emissions may provide a positive feedback to anthropogenic warming and may be irreversible, due to the difference between release and accumulation timescales. {6.4.7, 12.5.5}

The existence of critical climate change driven dieback thresholds in the Amazonian and other tropical rainforests purely driven by climate change remains highly uncertain. The possibility of a critical threshold being crossed in precipitation volume and duration of dry seasons cannot be ruled out. The response of boreal forest to projected climate change is also highly uncertain, and the existence of critical thresholds cannot at present be ruled out. There is *low confidence* in projections of the collapse of large areas of tropical and/or boreal forests. {12.5.5}

#### ***Potential Irreversibility of Changes in the Cryosphere***

The reversibility of sea ice loss has been directly assessed in sensitivity studies to CO<sub>2</sub> increase and decrease with AOGCMs or ESMs. None of them show evidence of an irreversible change in Arctic sea ice at any point. By contrast, as a result of the strong coupling between surface and deep waters in the Southern Ocean, the Antarctic sea ice in some models integrated with ramp-up and ramp-down atmospheric CO<sub>2</sub> concentration exhibits some hysteresis behaviour. {12.5.5}

At present, both the Greenland and Antarctic ice sheets have a positive surface mass balance (snowfall exceeds melting), although both are losing mass because ice outflow into the sea exceeds the net surface mass balance. A positive feedback operates to reduce ice sheet volume and extent when a decrease of the surface elevation of the ice sheet induces a decreased surface mass balance. This arises generally through increased surface melting, and therefore applies in the 21st century to Greenland, but not to Antarctica, where surface melting is currently very small. Surface melting in Antarctica is projected to become important after several centuries under high WMGHG radiative forcing scenarios. {4.4, 13.4.4; Box 5.2, 13.2}

Abrupt change in ice-sheet outflow to the sea may be caused by unstable retreat of the grounding line in regions where the bedrock is below sea level and slopes downwards towards the interior of the ice sheet. This mainly applies to West Antarctica, but also to parts of East Antarctica and Greenland. Grounding line retreat can be triggered by ice-shelf decay, due to warmer ocean water under ice shelves enhancing submarine ice-shelf melt, or melt water ponds on the surface of the ice shelf promoting ice-shelf fracture. Because ice sheet growth is a slow process, such changes would be irreversible in the definition adopted here. {4.4.5, Box 13.2}

There is *high confidence* that the volumes of the Greenland and West Antarctic ice sheets were reduced during periods of the past few million years that were globally warmer than present. Ice sheet model simulations and geological data suggest that the West Antarctic ice sheet is very sensitive to subsurface ocean warming and imply *with medium confidence* a West Antarctic ice sheet retreat if atmospheric CO<sub>2</sub> concentration remains above approximately 400 ppm for several millennia. {5.8, 13.4.4; Box 13.2}

The available evidence indicates that global warming beyond a threshold would lead to the near-complete loss of the Greenland Ice Sheet over a millennium or longer, causing a global mean sea level rise of approximately 7 m. Studies with fixed present-day ice sheet topography indicate that the threshold is greater than 2°C but less than 4°C of global mean surface temperature rise with respect to preindustrial. Taking into account the increased vulnerability of the ice sheet as the surface elevation decreases due to the loss of ice, a study with a dynamical ice sheet suggests the threshold could be as low as 1°C. Considering the present state of scientific uncertainty, a *likely* range cannot be quantified. The complete loss of the Greenland ice sheet is not inevitable because this would take a millennium or more; if temperatures decline before the ice sheet has completely vanished, the ice sheet might regrow. However, some part of the mass loss might be irreversible, depending on the duration and degree of exceedance of the threshold, because the ice sheet may have multiple steady states, due to its interaction with regional climate. {13.4.3, 13.4.4}

#### **TS.4.6 Water Cycle**

Since the AR4, new evidence has emerged of a detectable human influence on several aspects of the water cycle. There is *medium confidence* that observed changes in near-surface specific humidity since 1973 contain a detectable anthropogenic component. The anthropogenic water vapour fingerprint simulated by an ensemble of climate models has been detected in lower tropospheric moisture content estimates derived from SSM/I data covering the period 1988–2006. An anthropogenic contribution to increases in tropospheric specific humidity is found with *medium confidence*. {2.5, 10.3}

Attribution studies of global zonal mean terrestrial precipitation and Arctic precipitation both find a detectable anthropogenic influence. Overall there is *medium confidence* in a significant human influence on global scale changes in precipitation patterns, including increases in northern hemisphere mid to high latitudes. Remaining observational and modeling uncertainties and the large effect of internal variability on observed precipitation preclude a more confident assessment. {2.5, 7.6, 10.3}

Based on the collected evidence for attributable changes (with varying levels of confidence and likelihood) in specific humidity, terrestrial precipitation, and ocean surface salinity through its connection to precipitation and evaporation, and from physical understanding of the water cycle, it is *likely* that human influence has affected the global water cycle since 1960. This is a major advance since AR4. {2.4, 2.5, 3.3, 9.4.1, 10.3, 10.4.2; Table 10.1; FAQ 3.3}

### TS.4.7 *Climate Extremes*

Several new attribution studies have found a detectable anthropogenic influence in the observed increased frequency of warm days and nights and decreased frequency of cold days and nights. Since the AR4 and SREX, there is new evidence for detection of human influence on extremely warm daytime temperature and there is new evidence that the influence of anthropogenic forcing may be detected separately from the influence of natural forcing at global scales and in some continental and sub-continental regions. This strengthens the conclusions from both AR4 and SREX, and it is now *very likely* that anthropogenic forcing has contributed to the observed changes in the frequency and intensity of daily temperature extremes on the global scale since the mid-20th century. It is *likely* that human influence has significantly increased the probability of occurrence of heat waves in some locations. See TFE.9 and TFE.9, Table 1 for a summary of the assessment of extreme weather and climate events. {10.6}

Since the AR4, there is some new limited direct evidence for an anthropogenic influence on extreme precipitation, including a formal detection and attribution study and indirect evidence that extreme precipitation would be expected to have increased given the evidence of anthropogenic influence on various aspects of the global hydrological cycle and *high confidence* that the intensity of extreme precipitation events will increase with warming, at a rate well exceeding that of the mean precipitation. . In land regions where observational coverage is sufficient for assessment, there is *medium confidence* that anthropogenic forcing has contributed to a global-scale intensification of heavy precipitation over the second half of the 20th century. {7.6, 10.6}

Globally, there is *low confidence* in attribution of changes in tropical cyclone activity to human influence. This is due to insufficient observational evidence, lack of physical understanding of the links between anthropogenic drivers of climate and tropical cyclone activity, and the low level of agreement between studies as to the relative importance of internal variability, and anthropogenic and natural forcings. In the North Atlantic region there is *medium confidence* that a reduction in aerosol forcing over the North Atlantic has contributed at least in part to the observed increase in tropical cyclone activity there since the 1970s. There remains substantial disagreement on the relative importance of internal variability, greenhouse gas forcing, and aerosols for this observed trend. {2.6, 10.6, 14.6}

While the AR4 concluded that it is *more likely than not* that anthropogenic influence has contributed to an increased risk of drought in the second half of the 20th century, an updated assessment of the observational evidence indicates that the AR4 conclusions regarding global increasing trends in hydrological droughts since the 1970s are no longer supported. Owing to the *low confidence* in observed large-scale trends in dryness combined with difficulties in distinguishing decadal-scale variability in drought from long-term climate change, there is now *low confidence* in the attribution of changes in drought over global land since the mid-20th century to human influence. {2.6, 10.6}

### TS.4.8 *From Global to Regional*

Taking a longer term perspective shows the substantial role played by external forcings in driving climate variability on hemispheric scales in pre-industrial times (Box TS.5). It is *very unlikely* that Northern Hemisphere temperature variations from 1400 to 1850 can be explained by internal variability alone. There is *medium confidence* that external forcing contributed to Northern Hemispheric temperature variability from 850 to 1400 and that external forcing contributed to European temperature variations over the last 5 centuries. {5.3.3, 5.5.1, 10.7.2, 10.7.5; Table 10.1}

Changes in atmospheric circulation are important for local climate change since they could lead to greater or smaller changes in climate in a particular region than elsewhere. It is *likely* that human influence has altered sea level pressure patterns globally. There is *medium confidence* that stratospheric ozone depletion has contributed to the observed poleward shift of the southern Hadley Cell border during Austral summer. It is *likely* that stratospheric ozone depletion has contributed to the positive trend in the Southern Annular Mode seen in Austral summer since the mid-20th century which corresponds to sea level pressure reductions over the high latitudes and increase in the subtropics (Figure TS.11). {10.3}



**[INSERT FIGURE TS.11 HERE]**

**Figure TS.11:** Simulated and observed 1951–2011 trends in the Southern Annular Mode (SAM) index by season. The SAM index is a difference between zonal mean sea level pressure (SLP) at 40°S and 65°S. The SAM index is defined without normalization, so that the magnitudes of simulated and observed trends can be compared. Black lines show observed trends from the HadSLP2r dataset (solid), and the 20th century Reanalysis (dotted). Grey bars show 5th–95th percentile ranges of control trends, and red boxes show the 5th–95th percentile range of trends in historical simulations including anthropogenic and natural forcings. Coloured bars show ensemble mean trends and their associated 5–95% confidence ranges simulated in response to greenhouse gas (light green), aerosol (dark green), ozone (magenta) and natural forcing changes (blue) in CMIP5 individual-forcing simulations. {Figure 10.13b}

The evidence is stronger that observed changes in the climate system can now be attributed to human activities on global and regional scales in many components (Figure TS.12). Observational uncertainty has been explored much more thoroughly than previously, and fingerprints of human influence have been deduced from a new generation of climate models. There is improved understanding of ocean changes, including salinity changes, that are consistent with large scale intensification of the water cycle predicted by climate models. The changes in near surface temperatures, free atmosphere temperatures, ocean temperatures, and Northern Hemisphere snow cover and sea ice extent, when taken together, show not just global mean changes, but distinctive regional patterns consistent with the expected fingerprints of change from anthropogenic forcings and the expected responses from volcanic eruptions (Figure TS.12). {10.3–10.6, 10.9}

Human influence has been detected in nearly all of the major assessed components of the climate system (Figure TS.12). Taken together, the combined evidence increases the overall level of confidence in the attribution of observed climate change, and reduces the uncertainties associated with assessment based on a single climate variable. From this combined evidence it is *virtually certain* that human influence has warmed the global climate system. Anthropogenic influence has been identified in changes in temperature near the surface of the earth, in the atmosphere and in the oceans, as well as changes in the cryosphere, the water cycle and some extremes. There is strong evidence that excludes solar forcing, volcanoes, and internal variability as the strongest drivers of warming since 1950. {10.9; Table 10.1; FAQ 5.1}

**[INSERT FIGURE TS.12 HERE]**

**Figure TS.12:** Detection and attribution signals (decadal averages) in the climate system, at regional scales (top panels) and global scales (bottom 4 panels). Brown panels are land surface temperature time series, blue panels are ocean heat content time series, and white panels are sea-ice time series. Each panel shows observations (black or black and shades of grey), and the 5–95% range of the simulated response to natural forcings (blue shading) and natural and anthropogenic forcings (pink shading), together with the corresponding ensemble means (dark blue and dark red respectively). The observed surface temperature is from HadCRUT4. Three observed records of ocean heat content (OHC) are shown. Sea-ice anomalies (rather than absolute values) are plotted and based on models in Figure 10.16. The observations are either solid or dashed and indicate the quality of the observations and estimates. For land and ocean surface temperatures panels and precipitation panels, solid observation lines indicate where spatial coverage of areas being examined, is above 50% coverage and dashed observation lines where coverage is below 50%. For example, data coverage of Antarctica never goes above 50% of the land area of the continent. For ocean heat content and sea-ice panels the solid observations line is where the coverage of data is good and higher in quality, and the dashed line is where the data coverage is only adequate.<sup>11</sup> This figure is based in Figure 10.21 except presented as decadal averages rather than yearly averages. {Figure 10.21}

Over every continent except Antarctica, anthropogenic influence has *likely* made a substantial contribution to surface temperature increases since the mid-20th century (Figure TS.12). It is *likely* that there has been significant anthropogenic contribution to the very substantial warming in Arctic land surface temperatures over the past 50 years. For Antarctica large observational uncertainties result in *low confidence* that anthropogenic influence has contributed to observed warming averaged over available stations. Detection and attribution at regional scales is complicated by the greater role played by dynamical factors (circulation

<sup>11</sup> For surface temperature, the blue shaded band is based on 52 simulations from 17 climate models using only natural forcings, while the red shaded band is based on 147 simulations from 44 climate models using natural and anthropogenic forcings. For ocean heat content, 10 simulations from 10 models, and 13 simulations from 13 models were used respectively. For sea ice extent, a subset of models are considered that simulated the mean and seasonal cycle of the sea ice extent within 20% of the observed sea-ice climatology for the period 1981–2005 (Arctic: 24 simulations from 11 models for both red and blue shaded bands, Antarctic: 21 simulations from 6 models for both red and blue shaded bands).

changes), a greater range of forcings that may be regionally important, and the greater difficulty of modelling relevant processes at regional scales. Nevertheless, human influence has *likely* contributed to temperature increases in many sub-continental regions. {10.3, Box 5.1}

The coherence of observed changes with simulations of anthropogenic and natural forcing in the physical system is remarkable (Figure TS.12), particularly for temperature related variables. Surface temperature and ocean heat content show emerging anthropogenic and natural signals in both records, and a clear separation from the alternative hypothesis of just natural variations. These signals do not just appear in the global means, but also appear at regional scales on continents and in ocean basins in each of these variables. Sea-ice extent emerges clearly from the range of internal variability for the Arctic. At sub-continental scales human influence is *likely* to have substantially increased the probability of occurrence of heat waves in some locations. {Table 10.1}

## [START BOX TS.4 HERE]

### Box TS.4: Model Evaluation

Climate models have continued to be improved since the AR4, and many models have been extended into Earth System Models by including the representation of biogeochemical cycles important to climate change. Box TS.4, Figure 1 provides a partial overview of model capabilities as assessed in this report, including improvements or lack thereof relative to models that were assessed in the AR4 or that were available at the time of the AR4. {9.1, 9.8.1; Box 9.1}

The ability of climate models to simulate surface temperature has improved in many, though not all, important aspects relative to the generation of models assessed in the AR4. There continues to be *very high confidence* that models reproduce the observed large-scale time-mean surface temperature patterns (pattern correlation of ~0.99), although systematic errors of several degrees Celsius are found in some regions. There is *high confidence* that on the regional scale (sub-continental and smaller), time-mean surface temperature is better simulated than at the time of the AR4; however, confidence in model capability is lower than for the large scale. Models are able to reproduce the magnitude of the observed global-mean or northern-hemisphere-mean temperature variability on interannual to centennial time scales. Models are also able to reproduce the large-scale patterns of temperature during the Last Glacial Maximum (Section 9.4.1.5) indicating an ability to simulate a climate state much different from the present (see also Box TS.5). {9.4.1, 9.6.1}

There is *very high confidence* that models reproduce the general features of the global and annual mean surface temperature changes over the historical period, including the warming in the second half of the 20th century and the cooling immediately following large volcanic eruptions. Most simulations of the historical period do not reproduce the observed reduction in global-mean surface warming trend over the last 10–15 years (see Box TS.3). There is *medium confidence* that the trend difference between models and observations during 1998–2012 is to a substantial degree caused by internal variability, with possible contributions from forcing inadequacies in models and some models overestimating the response to increasing greenhouse-gas forcing. Most, though not all, models overestimate the observed warming trend in the tropical troposphere over the last 30 years, and tend to underestimate the long-term lower-stratospheric cooling trend. {9.4.1; Box 9.2}

The simulation of large-scale patterns of precipitation has improved somewhat since the AR4, although models continue to perform less well for precipitation than for surface temperature. The spatial pattern correlation between modelled and observed annual mean precipitation has increased from 0.77 for models available at the time of the AR4 to 0.82 for current models. At regional scales, precipitation is not simulated as well, and the assessment remains difficult owing to observational uncertainties. {9.4.1, 9.6.1}

Many models are able to reproduce the observed changes in upper-ocean heat content from 1960 to present. The time series of the multi-model mean falls within the range of the available observational estimates for most of the period. {9.4.2}

There is robust evidence that the downward trend in Arctic summer sea-ice extent is better simulated than at the time of the AR4. About one-quarter of the models show a trend as strong as, or stronger, than the trend in observations over the satellite era 1979–2012. Most models simulate a small decreasing trend in Antarctic sea-ice extent, albeit with large inter-model spread, in contrast to the small increasing trend in observations. {9.4.3}

There has been substantial progress since the AR4 in the assessment of model simulations of extreme events. Changes in the frequency of extreme warm and cold days and nights over the second half of the 20th century are consistent between models and observations, with the ensemble-mean global-mean time series generally falling within the range of observational estimates. The majority of models underestimate the sensitivity of extreme precipitation to temperature variability or trends, especially in the tropics. {9.5.4}

In about two-thirds of the models that include an interactive carbon cycle, the simulated global land and ocean carbon sinks over the latter part of the 20th century fall within the range of observational estimates. However, models systematically underestimate the northern-hemisphere land sink implied by atmospheric inversion techniques. {9.4.5}

Regional downscaling methods provide climate information at the smaller scales needed for many climate impact studies. There is *high confidence* that downscaling adds value both in regions with highly variable topography and for various small-scale phenomena. {9.6.4}

The model spread in equilibrium climate sensitivity ranges from 2.1°C to 4.7°C and is very similar to the assessment in the AR4. There is *very high confidence* that the primary factor contributing to the spread in equilibrium climate sensitivity continues to be the cloud feedback. This applies to both the modern climate and the last glacial maximum. There is likewise *very high confidence* that, consistent with observations, models show a strong positive correlation between tropospheric temperature and water vapour on regional to global scales, implying a positive water-vapour feedback in both models and observations. {5.3.3, 9.4.1, 9.7}

Climate models are based on physical principles, and they reproduce many important elements of observed climate. Both aspects contribute to our confidence in the models' suitability for their application in detection and attribution studies (see Chapter 10) and for quantitative future predictions and projections (see Chapters 11–14). There is increasing evidence that some elements of observed variability or trends are well correlated with inter-model differences in model projections for quantities such as Arctic summer sea-ice trends, the snow–albedo feedback, and the carbon loss from tropical land. However, there is still no universal strategy for transferring a model's past performance to a relative weight of this model in a multi-model-ensemble mean of climate projections. {9.8.3}

#### [INSERT BOX TS.4, FIGURE 1 HERE]

**Box TS.4, Figure1:** Summary of how well the current-generation climate models simulate important features of the climate of the 20th century. Confidence in the assessment increases towards the right as suggested by the increasing strength of shading. Model quality increases from bottom to top. The colour coding indicates improvements from the models available at the time of the AR4 to the current assessment. There have been a number of improvements since the AR4, and some some modelled quantities are not better simulated. The major climate quantities are listed in this summary and none shows degradation. The assessment is mostly based on the multi-model mean, not excluding that deviations for individual models could exist. Assessed model quality is simplified for representation in this figure; details of each assessment are found in Chapter 9. {9.8.1; Figure 9.44}

The figure highlights the following key features, with the sections that back up the assessment added in brackets:

#### (a) Trends in:

AntSIE:	Antarctic sea-ice extent {9.4.3}
ArctSIE:	Arctic sea-ice extent {9.4.3}
fgCO <sub>2</sub> :	Global ocean carbon sink {9.4.5}
LST:	Lower-stratospheric temperature {9.4.1.}
NBP:	Global land carbon sink {9.4.5}
OHC:	Global ocean heat content {9.4.2}
TotalO <sub>3</sub> :	Total-column ozone {9.4.1}
TAS:	Surface air temperature {9.4.1}
TTT:	Tropical tropospheric temperature {9.4.1}

**(b) Extremes:**

Droughts	Droughts {9.5.4}
Hurric-hr	Year-to-year count of Atlantic hurricanes in high-resolution AGCMs {9.5.4}
PR_ext	Global distribution of precipitation extremes {9.5.4}
PR_ext-hr	Global distribution of precipitation extremes in high-resolution AGCMs {9.5.4}
PR_ext-t	Global trends in precipitation extremes {9.5.4}
TAS_ext	Global distributions of surface air temperature extremes {9.5.4}
TAS_ext-t	Global trends in surface air temperature extremes {9.5.4}
TC	Tropical cyclone tracks and intensity {9.5.4}
TC-hr	Tropical cyclone tracks and intensity in high-resolution AGCMs {9.5.4}

[END BOX TS.4 HERE]

[START BOX TS.5 HERE]

**Box TS.5: Paleoclimate**

Reconstructions from paleoclimate archives allow current changes in atmospheric composition, sea level and climate (including extreme events such as droughts and floods), as well as future projections, to be placed in a broader perspective of past climate variability (see Section TS.2). {5, 5.5.5, 10.5.5}

Past climate information also documents the behaviour of slow components of the climate system including the carbon cycle, ice sheets and the deep ocean for which instrumental records are short compared to their characteristic time scales of responses to perturbations, thus informing on mechanisms of abrupt and irreversible changes. Together with the knowledge of past external climate forcings, syntheses of paleoclimate data have documented polar amplification, characterized by enhanced temperature changes in the Arctic compared to the global mean, in response to high or low CO<sub>2</sub> concentrations. {5.2.1, 5.2.2, 5.6, 5.7, 5.8, 6.2, 8.4.2, 13.2.1, 13.4; Box 5.1, 5.2}

Since AR4, the inclusion of paleoclimate simulations in the PMIP3 (Paleoclimate Modelling Intercomparison Project)/CMIP5 framework has enabled paleoclimate information to be more closely linked with future climate projections. Paleoclimate information for the mid-Holocene (6,000 years ago), the Last Glacial Maximum (approximately 21,000 years ago), and last millennium has been used to test the ability of models to simulate realistically the magnitude and large-scale patterns of past changes. Combining information from paleoclimate simulations and reconstructions enables the response of the climate system to radiative perturbations to be quantified, constraints to be placed on the range of equilibrium climate sensitivity, and past patterns of internal climate variability to be documented on inter-annual to multi-centennial scales. {5.3.1, 5.3.2, 5.3.3, 5.3.4, 5.3.5, 5.4, 5.5.1, 9.4.1, 9.4.2, 9.5.3, 9.7.2, 10.7.2, 14.2.2}

Box TS.5, Figure 1 illustrates the comparison between the last millennium PMIP3/CMIP5 simulations and reconstructions, together with the associated solar, volcanic and well-mixed greenhouse gas radiative forcings. For average annual Northern Hemisphere temperatures, the period 1983–2012 was *very likely* the warmest 30-year period of the last 800 years (*high confidence*) and *likely* the warmest 30-year period of the last 1400 years (*medium confidence*). This is supported by comparison of instrumental temperatures with multiple reconstructions from a variety of proxy data and statistical methods, and is consistent with AR4. In response to solar, volcanic and anthropogenic radiative changes, climate models simulate multi-decadal temperature changes in the last 1200 years in the Northern Hemisphere that are generally consistent in magnitude and timing with reconstructions, within their uncertainty ranges. Continental-scale temperature reconstructions show, with *high confidence*, multi-decadal intervals during the Medieval Climate Anomaly (ca. 950 to 1250) that were in some regions as warm as the mid-20th century and in others as warm as in the late 20th century. With *high confidence*, these intervals were not as synchronous across seasons and regions as the warming since the mid-20th century. Based on the comparison between reconstructions and simulations, there is *high confidence* that not only external orbital, solar and volcanic forcing but also internal variability contributed substantially to the spatial pattern and timing of surface temperature changes between the Medieval Climate Anomaly and the Little Ice Age (ca. 1450 to 1850). However, there is only *very low confidence* in quantitative estimates of their relative contributions. It is very unlikely that northern hemisphere temperature variations from 1400 to 1850 can be explained by internal variability alone. There is

*medium confidence* that external forcing contributed to Northern Hemispheric temperature variability from 850 to 1400 and that external forcing contributed to European temperature variations over the last 5 centuries. {5.3.5, 5.5.1, 10.7.2, 10.7.5; Table 10.1}

### **[INSERT BOX TS.5, FIGURE 1 HERE]**

**Box TS.5, Figure 1:** Last-millennium simulations and reconstructions. (a) 850–2000 PMIP3/CMIP5 radiative forcing due to volcanic, solar and well mixed greenhouse gas. Different colors illustrate the two existing datasets for volcanic forcing (CEA and GRA) and the four estimates of solar forcing (DB, MEA, SBF and VSK). For solar forcing, solid (dashed) lines stand for reconstruction variants in which background changes in irradiance are (not) considered; (b) 850–2000 PMIP3/CMIP5 simulated (red) and reconstructed (shading) NH temperature changes. The thick red line depicts the multi-model mean while the thin red lines show the multi-model 90% range. The overlap of reconstructed temperatures is shown by grey shading; all data are expressed as anomalies from their 1500–1850 mean and smoothed with a 30-year filter. Note that some reconstructions represent a smaller spatial domain than the full NH or a specific season, while annual temperatures for the full NH mean are shown for the simulations. (c), (d), (e) and (f) Arctic and North America annual mean temperature, and Europe and Asia June-July-August (JJA) temperature, from 950 to 2000 from reconstructions (black line), and PMIP3/CMIP5 simulations (thick red, multi-model mean; thin red 90% multi-model range). All red curves are expressed as anomalies from their 1500–1850 mean and smoothed with a 30-year filter. The shaded envelope depicts the uncertainties from each reconstruction (Arctic: 90% confidence bands, North American:  $\pm 2$  standard deviation. Asia:  $\pm 2$  root mean square error. Europe: 95% confidence bands). For comparison with instrumental record, the CRUTEM4 dataset is shown (yellow line). All lines are smoothed by applying a 30 year moving average. Map shows the individual regions for each reconstruction. {5.3.5; Table 5.A.1; Figures 5.1, 5.8, 5.12}

## **TS.5 Projections of Global and Regional Climate Change**

### ***TS.5.1 Introduction***

Projections of changes in the climate system are made using a hierarchy of climate models ranging from simple climate models, to models of intermediate complexity, to comprehensive climate models, and Earth System Models. These models simulate changes based on a set of scenarios of anthropogenic forcings. A new set of scenarios, the Representative Concentration Pathways (RCPs), was used for the new climate model simulations carried out under the framework of the Coupled Model Intercomparison Project Phase 5 (CMIP5) of the World Climate Research Programme. A large number of comprehensive climate models and Earth System Models have participated in CMIP5, whose results form the core of the climate system projections.

This section summarizes the assessment of these climate change projections. First, future forcing and scenarios are presented. The following subsections then address various aspects of projections of global and regional climate change, including near-term (up to about mid-century) and long-term (end of the 21st century) projections in the atmosphere, ocean and cryosphere; projections of carbon and other biogeochemical cycles; projections in sea level change; and finally changes to climate phenomena and other aspects of regional climate over the 21st century. Projected changes are given relative to the 1986–2005 average unless indicated otherwise. Projections of climate change on longer term and information on climate stabilization and targets are provided in TFE.8. Methods to counter climate change, termed geoengineering, have been proposed and an overview is provided in Box TS.7. {11.3, 12.3–12.5, 13.5–13.7, 14.1–14.6, Annex I}

### ***TS.5.2 Future Forcing and Scenarios***

In this assessment report a series of new Representative Concentration Pathways (RCP) are used that largely replace the SRES scenarios (see Box TS.6; see Annex II for Climate System Scenario Tables). They produce a range of responses from ongoing warming, to approximately stabilized forcing, to a stringent mitigation scenario (RCP2.6) that stabilizes and then slowly reduces the radiative forcing after mid-21st century. In contrast to the AR4, the climate change from the RCP scenarios in the AR5 is framed as a combination of adaptation and mitigation. Mitigation actions starting now in the various RCP scenarios do not produce discernibly different climate change outcomes for the next 30 years or so, while long-term climate change after mid-century is appreciably different across the RCPs. {Box 1.1}

### **[START BOX TS.6 HERE]**

**Box TS.6: The New RCP Scenarios and CMIP5 Models**

Future anthropogenic emissions of greenhouse gases (GHG), aerosol particles and other forcing agents such as land use change are dependent on socio-economic factors, and may be affected by global geopolitical agreements to control those emissions to achieve mitigation. AR4 made extensive use of the SRES scenarios that do not include additional climate initiatives, which means that no scenarios were included that explicitly assume implementation of the United Nations Framework Convention on Climate Change (UNFCCC) or the emissions targets of the Kyoto Protocol. However, GHG emissions are directly affected by non-climate change policies designed for a wide range of other purposes. The SRES scenarios were developed using a sequential approach, i.e., socio-economic factors fed into emissions scenarios, which were then used in simple climate models to determine concentrations of greenhouse gases, and other agents required to drive the more complex atmosphere-ocean global climate models (AOGCMs). In this report, outcomes of climate simulations that use new scenarios (some of which include implied policy actions to achieve mitigation) referred to as “Representative Concentration Pathways” (RCPs) are assessed. These RCPs represent a larger set of mitigation scenarios and were selected to have different targets in terms of radiative forcing at 2100 (about 2.6, 4.5, 6.0 and 8.5 W m<sup>-2</sup>; see Figure TS.15). The scenarios should be considered plausible and illustrative, and do not have probabilities attached to them. {12.3.1; Box 1.1}

The RCPs were developed using Integrated Assessment Models (IAMs) that typically include economic, demographic, energy, and simple climate components. The emission scenarios they produce are then run through a simple model to produce time series of greenhouse gas concentrations that can be run in AOGCMs. The emission time series from the RCPs can then be used directly in Earth System Models (ESMs) that include interactive biogeochemistry (at least a land and ocean carbon cycle).

The CMIP5 multi-model experiment (coordinated through the World Climate Research Programme) presents an unprecedented level of information on which to base assessments of climate variability and change. CMIP5 includes new ESMs in addition to AOGCMs, new model experiments, and more diagnostic output. CMIP5 is much more comprehensive than the preceding CMIP3 multi-model experiment that was available at the time of the IPCC AR4. CMIP5 has more than twice as many models, many more experiments (that also include experiments to address understanding of the responses in the future climate change scenario runs), and nearly  $2 \times 10^{15}$  bytes of data (as compared to over  $30 \times 10^{12}$  bytes of data in CMIP3). A larger number of forcing agents are treated more completely in the CMIP5 models, with respect to aerosols and land use particularly. Black carbon aerosol is now a commonly included forcing agent. Considering CO<sub>2</sub>, both ‘concentrations-driven’ projections and ‘emissions-driven’ projections are assessed from CMIP5. These allow quantification of the physical response uncertainties as well as climate-carbon cycle interactions. {1.5.2}

The assessment of the mean values and ranges of global mean temperature changes in AR4 would not have been substantially different if the CMIP5 models had been used in that report. The differences in global temperature projections can largely be attributed to the different scenarios. The global mean temperature response simulated by CMIP3 and CMIP5 models is very similar, both in the mean and the model range, transiently and in equilibrium. The range of temperature change across all scenarios is wider because the RCPs include a strong mitigation scenario (RCP2.6) that had no equivalent among the SRES scenarios used in CMIP3. For each scenario, the 5–95% range of the CMIP5 projections is obtained by approximating the CMIP5 distributions by a normal distribution with same mean and standard deviation and assessed as being “likely” for projections of global temperature change for the end of the 21st century. Probabilistic projections with simpler models calibrated to span the range of equilibrium climate sensitivity assessed by the AR4 provide uncertainty ranges that are consistent with those from CMIP5. In AR4 the uncertainties in global temperature projections were found to be approximately constant when expressed as a fraction of the model mean warming (constant fractional uncertainty). For the higher RCPs, the uncertainty is now estimated to be smaller than with the AR4 method for long-term climate change, because the carbon cycle climate feedbacks are not relevant for the concentration driven RCP projections (in contrast, the assessed projection uncertainties of global temperature in AR4 did account of carbon cycle climate feedbacks, even though these were not part of the CMIP3 models). When forced with RCP8.5, CO<sub>2</sub> emissions, as opposed to the RCP8.5 CO<sub>2</sub> concentrations, CMIP5 Earth System Models (ESMs) with interactive carbon cycle simulate, on average, a 50 (–140 to +210) ppm (CMIP5 model spread) larger atmospheric CO<sub>2</sub> concentration and 0.2°C larger global surface temperature increase by 2100. For the low RCPs the fractional uncertainty is

larger because internal variability and non-CO<sub>2</sub> forcings make a larger relative contribution to the total uncertainty. {12.4.1, 12.4.9}

There is overall consistency between the projections of temperature and precipitation based on CMIP3 and CMIP5, both for large-scale patterns and magnitudes of change (Box TS.6, Figure 1). Model agreement and confidence in projections depends on the variable and on spatial and temporal averaging, with better agreement for larger scales. Confidence is higher for temperature than for those quantities related to the water cycle or atmospheric circulation. Improved methods to quantify and display model robustness have been developed to indicate where lack of agreement across models on local trends is a result of internal variability, rather than models actually disagreeing on their forced response. Understanding of the sources and means of characterizing uncertainties in long-term large scale projections of climate change has not changed significantly since AR4, but new experiments and studies have continued to work towards a more complete and rigorous characterization. {9.7.3, 12.2, 12.4.1, 12.4.4, 12.4.5, 12.4.9; Box 12.1}

The well-established stability of geographical patterns of temperature and precipitation change during a transient experiment remains valid in the CMIP5 models (see Box TS.6, Figure 1). Patterns are similar over time and across scenarios and to first order can be scaled by the global mean temperature change. There remain limitations to the validity of this technique when it is applied to strong mitigation scenarios, to scenarios where localized forcing (e.g., aerosols) are significant and vary in time and for variables other than average seasonal mean temperature and precipitation {12.4.2}.

**[INSERT BOX TS.6, FIGURE 1 HERE]**

**Box TS.6, Figure 1:** Patterns of temperature (left column) and percent precipitation change (right column) for the CMIP3 models average (first row) and CMIP5 models average (second row), scaled by the corresponding global average temperature changes. The patterns are computed in both cases by taking the difference between the averages over the last twenty years of the 21st century experiments (2080–2099 for CMIP3 and 2081–2100 for CMIP5) and the last twenty years of the historic experiments (1980–1999 for CMIP3, 1986–2005 for CMIP5) and rescaling each difference by the corresponding change in global average temperature. This is done first for each individual model, then the results are averaged across models. Stippling indicates a measure of significance of the difference between the two corresponding patterns obtained by a bootstrap exercise. Two subsets of the pooled set of CMIP3 and CMIP5 ensemble members of the same size as the original ensembles, but without distinguishing CMIP3 from CMIP5 members, were randomly sampled 500 times. For each random sample the corresponding patterns and their difference are computed, then the true difference is compared, grid-point by grid-point, to the distribution of the bootstrapped differences, and only grid-points at which the value of the difference falls in the tails of the bootstrapped distribution (less than the 2.5 percentiles or the 97.5 percentiles) are stippled. {Figure 12.41}

**[END BOX TS.6 HERE]**

The range in anthropogenic aerosol emissions across all scenarios has a larger impact on near-term climate projections than the corresponding range in long-lived greenhouse gases, particularly on regional scales and for hydrological cycle variables. The RCP scenarios do not span the range of future aerosol emissions found in the SRES and alternative scenarios (see Box TS.6). {11.3.1, 11.3.6}

If rapid reductions in sulphate aerosol are undertaken for improving air quality or as part of decreasing fossil-fuel CO<sub>2</sub> emissions, then there is *medium confidence* that this could lead to rapid near-term warming. There is robust evidence that accompanying controls on methane (CH<sub>4</sub>) emissions would offset some of this sulphate-induced warming, although the cooling from methane mitigation will emerge more slowly than the warming from sulphate mitigation due to the different timescales over which atmospheric concentrations of these substances decrease in response to decreases in emissions. While removal of black carbon aerosol could also counter warming associated with sulphate removal, uncertainties are too large to constrain the net sign of the global temperature response to black carbon emission reductions, which depends on reduction of co-emitted (reflective) aerosols and on aerosol indirect effects. {11.3.6}

Including uncertainties in projecting the chemically reactive greenhouse gases methane (CH<sub>4</sub>) and nitrous oxide (N<sub>2</sub>O) from RCP emissions gives a range in abundance pathways that is *likely* 30% larger than the range in RCP concentrations used to force the CMIP5 climate models. Including uncertainties in emission estimates from agricultural, forest, and land-use sources, in atmospheric lifetimes, and in chemical feedbacks, results in a much wider range of abundances for N<sub>2</sub>O, CH<sub>4</sub>, and HFCs and their radiative forcing.

In the case of CH<sub>4</sub> it *likely* extends the range up to 500 ppb above RCP8.5 and 270 ppb below RCP2.6 through to 2100, with smaller ranges in the near term. {11.3.5}

There is *low confidence* in projections of natural forcing. Major volcanic eruptions cause a negative radiative forcing up to several W m<sup>-2</sup>, with a typical lifetime of one year, but the possible occurrence and timing of future eruptions is unknown. Except for the 11-year solar cycle, changes in the total solar irradiance are uncertain. Except where explicitly indicated, future volcanic eruptions and changes in total solar irradiance additional to a repeating 11 year solar cycle are not included in the projections of near- and long-term climate assessed. {8, 11.3.1}

### TS.5.3 Quantification of Climate System Response

Estimates of the Equilibrium Climate Sensitivity (ECS) based on observed climate change, climate models and feedback analysis, as well as paleoclimate evidence indicate that ECS is positive, *likely* in the range 1.5°C to 4.5°C with *high confidence*, *extremely unlikely* less than 1°C (*high confidence*) and *very unlikely* greater than 6°C (*medium confidence*). Earth system sensitivity over millennia timescales including long-term feedbacks not typically included in models could be significantly higher than ECS (see TFE.6 for further details). {5.3.1, 10.8; Box 12.2}

With *high confidence* the transient climate response (TCR) is positive, *likely* in the range 1°C to 2.5°C and *extremely unlikely* greater than 3°C, based on observed climate change and climate models (see TFE.6 for further details). {10.8; Box 12.2}

The ratio of global mean surface temperature change to total cumulative anthropogenic carbon emissions is relatively constant and independent of the scenario, but is model dependent, as it is a function of the model cumulative airborne fraction of carbon and the transient climate response. For any given temperature target, higher emissions in earlier decades therefore imply lower emissions by about the same amount later on. The transient climate response to cumulative carbon emission (TCRE) is *likely* between 0.8°C to 2.5°C per 1000 PgC (*high confidence*), for cumulative carbon emissions less than about 2000PgC until the time at which temperatures peak (see TFE.8 for further details). {10.8, 12.5.4; Box 12.2}

### TS.5.4 Near-Term Climate Change

Near-term decadal climate prediction provides information not available from existing seasonal to interannual (months to a year or two) predictions or from long-term (mid 21st century and beyond) climate change projections. Prediction efforts on seasonal to interannual timescales require accurate estimates of the initial climate state with less focus extended to changes in external forcing<sup>12</sup>, while long-term climate projections rely more heavily on estimations of external forcing with little reliance on the initial state of internal variability. Estimates of near-term climate depend on the committed warming (caused by the inertia of the oceans as they respond to historical external forcing) the time evolution of internally-generated climate variability, and the future path of external forcing. Near-term predictions out to about a decade (Figure TS.13) depend more heavily on an accurate depiction of the internally generated climate variability. {11.1, 12, 14}

#### [INSERT FIGURE TS.13 HERE]

**Figure TS.13:** Decadal prediction forecast quality of several climate indices. Top row: Time series of the 2–5 year average ensemble-mean initialized hindcast anomalies and the corresponding non-initialized experiments for three climate indices: Global Mean Surface Temperature (GMST, left) and the Atlantic Multidecadal Variability (AMV, right). The observational time series, GISS global-mean temperature and ERSST for the AMV, are represented with dark grey (positive anomalies) and light grey (negative anomalies) vertical bars, where a four-year running mean has been applied for consistency with the time averaging of the predictions. Predicted time series are shown for the CMIP5 Init (solid) and NoInit (dotted) simulations with hindcasts started every five years over the period 1960–2005. The lower and upper quartile of the multi-model ensemble are plotted using thin lines. The AMV index was computed as the sea surface temperature anomalies averaged over the region Equator –60°N and 80°W–0°W minus the sea surface temperature anomalies averaged over 60°S–60°N. Note that the vertical axes are different for each time series. Middle row: Correlation of the ensemble-mean prediction with the observational reference along the forecast time for four-year

<sup>12</sup> Seasonal-to-interannual predictions typically include the impact of external forcing.



averages of the three sets of CMIP5 hindcasts for Init (solid) and NoInit (dashed). The one-sided 95% confidence level with a t distribution is represented in grey. The effective sample size has been computed taking into account the autocorrelation of the observational time series. A two-sided t test (where the effective sample size has been computed taking into account the autocorrelation of the observational time series) has been used to test the differences between the correlation of the initialized and non-initialized experiments, but no differences were found statistically significant with a confidence equal or higher than 90%. Bottom row: Root mean square error (RMSE) of the ensemble-mean prediction along the forecast time for four-year averages of the CMIP5 hindcasts for Init (solid) and NoInit (dashed). A two-sided F test (where the effective sample size has been computed taking into account the autocorrelation of the observational time series) has been used to test the ratio between the RMSE of the Init and NoInit, and those forecast times with differences statistically significant with a confidence equal or higher than 90% are indicated with an open square. {Figure 11.3}

Further near-term warming from past emissions is unavoidable due to thermal inertia of the oceans. This warming will be increased by ongoing emissions of GHGs over the near term, and the climate observed in the near term will also be strongly influenced by the internally generated variability of the climate system. Previous IPCC Assessments only described climate-change projections wherein the externally forced component of future climate was included but no attempt was made to initialize the internally generated climate variability. Decadal climate predictions, on the other hand, are intended to predict both the externally forced component of future climate change, and the internally generated component. Near-term predictions do not provide detailed information of the evolution of weather. Instead they can provide estimated changes in the time evolution of the statistics of near-term climate. {11.1, 11.2.2; Box 11.1, FAQ 11.1}

Retrospective prediction experiments have been used to assess forecast quality. There is *high confidence* that the retrospective prediction experiments for forecast periods of up to 10 years exhibit positive skill when verified against observations over large regions of the planet and of the global mean. Observation-based initialization of the forecasts contributes to the skill of predictions of annual mean temperature for the first couple of years and to the skill of predictions of the global-mean surface temperature and the temperature over the North Atlantic, regions of the South Pacific and the tropical Indian Ocean up to 10 years (*high confidence*) partly due to a correction of the forced response. Probabilistic temperature predictions are statistically reliable (see Section 11.2.3 for definition of reliability) due to the correct representation of global trends, but still unreliable at the regional scale when probabilities are computed from the multi-model ensemble (*medium confidence*). Predictions initialized over 2000–2005 improve estimates of the recent global-mean temperature hiatus (*medium confidence*). Predictions of precipitation over continental areas with large forced trends also exhibit positive skill. {11.2.2, 11.2.3; Box 9.2}

#### TS.5.4.1. Projected Near-Term Changes in Climate

Projections of near-term climate show small sensitivity to greenhouse gas scenarios compared to model spread, but substantial sensitivity to uncertainties in aerosol emissions, especially on regional scales and for hydrological cycle variables (*high confidence*). In some regions, the local and regional responses in precipitation and in mean and extreme temperature to land use change will be larger than those due to large-scale greenhouse gases and aerosol forcing (*medium confidence*). These scenarios presume that there are no major volcanic eruptions and that anthropogenic aerosol emissions are rapidly reduced during the near term.. {11.3.1, 11.3.2, 11.3.6}

#### TS.5.4.2 Projected Near-Term Changes in Temperature

In the absence of major volcanic eruptions—which would cause significant but temporary cooling—and, assuming no significant future long term changes in solar irradiance, it is *likely* that the GMST anomaly for the period 2016–2035, relative to the reference period of 1986–2005 will be in the range 0.3°C to 0.7°C (*medium confidence*). This is based on an assessment of observationally-constrained projections and predictions initialized with observations. This range is consistent with the range obtained by using CMIP5 5–95% model trends for 2012–2035. It is also consistent with the CMIP5 5–95% range for all four RCP scenarios of 0.36°C to 0.79°C, using the 2006–2012 reference period, after the upper and lower bounds are reduced by 10% to take into account the evidence that some models may be too sensitive to anthropogenic forcing (see Table TS.1 and Figure TS.14). {11.3.6}

**INSERT FIGURE TS.14 HERE]**

**Figure TS.14:** Synthesis of near-term projections of global mean surface air temperature (GMST). (a) Projections of annual mean GMST 1986–2050 (anomalies relative to 1986–2005) under all RCPs from CMIP5 models (grey and coloured lines, one ensemble member per model), with four observational estimates (HadCRUT4, ERA-Interim, GISTEMP, NOAA) for the period 1986–2012 (black lines). (b) as (a) but showing the 5–95% range of annual mean CMIP5 projections (using one ensemble member per model) for all RCPs using a reference period of 1986–2005 (light grey shade) and all RCPs using a reference period of 2006–2012, together with the observed anomaly for (2006–2012)–(1986–2005) of 0.16°C (dark grey shade). The percentiles for 2006 onwards have been smoothed with a 5 year running mean for clarity. The maximum and minimum values from CMIP5 using all ensemble members and the 1986–2005 reference period are shown by the grey lines (also smoothed). Black lines show annual mean observational estimates. The red shaded region shows the indicative likely range for annual mean GMST during the period 2016–2035 based on the “ALL RCPs Assessed” *likely* range for the 20 year mean GMST anomaly for 2016–2035, which is shown as a black bar in both panels (b) and (c) (see text for details). The temperature scale relative to pre-industrial climate on the right hand side assumes a warming of GMST prior to 1986–2005 of 0.61°C estimated from HadCRUT4. (c) A synthesis of projections for the mean GMST anomaly for 2016–2035 relative to 1986–2005. The box and whiskers represent the 66% and 90% ranges. Shown are: unconstrained SRES CMIP3 and RCP CMIP5 projections; observationally constrained projections for the SRES A1B and, the RCP4.5 and 8.5 scenarios; unconstrained projections for all four RCP scenarios using two reference periods as in panel (b) (light grey and dark grey shades), consistent with panel (b); 90% range estimated using CMIP5 trends for the period 2012–2035 and the observed GMST anomaly for 2012; an overall *likely* (>66%) assessed range for all RCP scenarios. The dots for the CMIP5 estimates show the maximum and minimum values using all ensemble members. The medians (or maximum likelihood estimate; green filled bar) are indicated by a grey band. Adapted from Figure 11.25. See Chapter 11, Section 11.3.6 for details. {Figure 11.25}

There is *high confidence* that higher concentrations of greenhouse gases and lower amounts of sulphate aerosol lead to greater warming. In the near-term, differences in global mean surface air temperature across RCP scenarios for a single climate model are typically smaller than across climate models for a single RCP scenario. In 2030, the CMIP5 multi-model ensemble mean values for global mean temperature differ by less than 0.3°C between the RCP scenarios, whereas the model spread (defined as the 5–95% range of the decadal means of the models) is around 0.8°C. The inter-scenario spread increases in time and by 2050 is comparable to the model spread. Regionally, the largest differences in surface air temperature between RCP scenarios are found in the Arctic. {11.3.2. 11.3.6}

The projected warming of global mean temperatures implies *high confidence* that new levels of warming relative to pre-industrial climate will be crossed, particularly under higher greenhouse gas emissions scenarios. Relative to a reference period of 1850–1900, under RCP4.5 or RCP6.0, it is *more likely than not* that the mean GMST for the period 2016–2035 will be more than 1°C above the mean for 1850–1900, and *very unlikely* that it will be more than 1.5°C above the 1850–1900 mean (*medium confidence*). {11.3.6}

A future volcanic eruption similar in size to the 1991 eruption of Mount Pinatubo would cause a rapid drop in global mean surface air temperature of about 0.5°C in the following year, with recovery over the next few years. Larger eruptions, or several eruptions occurring close together in time, would lead to larger and more persistent effects. {11.3.6}

Possible future changes in solar irradiance could influence the rate at which global mean surface air temperature increases, but there is *high confidence* that this influence will be small in comparison to the influence of increasing concentrations of greenhouse gases in the atmosphere. {11.3.6}

The spatial patterns of near-term warming projected by the CMIP5 models following the RCP scenarios (see Figure TS.15) are broadly consistent with the AR4. It is *very likely* that anthropogenic warming of surface air temperature over the next few decades will proceed more rapidly over land areas than over oceans, and it is *very likely* that the anthropogenic warming over the Arctic in winter will be greater than the global mean warming, consistent with the AR4. Relative to background levels of internally generated variability there is *high confidence* that the anthropogenic warming relative to the reference period is expected to be larger in the tropics and subtropics than in mid-latitudes. {11.3.2}

It is *likely* that in the next decades the frequency of warm days and warm nights will increase in most regions, while the frequency of cold days and cold nights will decrease. Models also project increases in the duration, intensity and spatial extent of heat-waves and warm spells for the near term. These changes may proceed at a different rate than the mean warming. For example, several studies project that European high-

percentile summer temperatures are projected to warm faster than mean temperatures (see also TFE.9). {11.3.2}

#### TS.5.4.3 Projected Near-Term Changes in the Water Cycle

Zonal mean precipitation will *very likely* increase in high and some of the mid latitudes, and will *more likely than not* decrease in the subtropics. At more regional scales precipitation changes may be dominated by a combination of natural internal variability, volcanic forcing and anthropogenic aerosol effects. {11.3.2}

Over the next few decades increases in near-surface specific humidity are *very likely*. It is *likely* that there will be increases in evaporation in many regions. There is *low confidence* in projected changes in soil moisture and surface run off. {11.3.2}

In the near term, it is *likely* that the frequency and intensity of heavy precipitation events will increase over land. These changes are primarily driven by increases in atmospheric water vapor content, but also affected by changes in atmospheric circulation. The impact of anthropogenic forcing at regional scales is less obvious, as regional-scale changes are strongly affected by natural variability and also depend upon the course of future aerosol emissions, volcanic forcing and land use changes (see also TFE.9). {11.3.2}

#### TS.5.4.4 Projected Near-Term Changes in Atmospheric Circulation

Internally generated climate variability and multiple radiative forcing agents (e.g., volcanoes, greenhouse gases, ozone and anthropogenic aerosols) will all contribute to near-term changes in the atmospheric circulation. For example, it is *likely* that the annual-mean Hadley Circulation and the Southern Hemisphere mid-latitude westerlies will shift poleward, while it is *likely* that the projected recovery of stratospheric ozone and increases in greenhouse gas concentrations will have counteracting impacts on the width of the Hadley Circulation and the meridional position of the Southern Hemisphere storm track. Therefore it is *unlikely* that they will continue to expand poleward as rapidly as in recent decades. {11.3.2}

There is *low confidence* in near-term projections of the position and strength of Northern Hemisphere storm tracks. Natural variations are larger than the projected impact of greenhouse gases in the near-term. {11.3.2}

There is *low confidence* in basin-scale projections of changes in intensity and frequency of tropical cyclones in all basins to the mid-21st century. This *low confidence* reflects the small number of studies exploring near-term tropical cyclone activity, the differences across published projections of tropical cyclone activity, and the large role for natural variability. There is *low confidence* in near-term projections for increased tropical cyclone intensity in the Atlantic; this projection is in part due to projected reductions in aerosol loading. {11.3.2}

#### TS.5.4.5 Projected Near-Term Changes in the Ocean

It is *very likely* that globally-averaged surface and vertically-averaged ocean temperatures will increase in the near-term. In the absence of multiple major volcanic eruptions, it is *very likely* that globally-averaged surface and depth-averaged temperatures averaged for 2016–2035 will be warmer than those averaged over 1986–2005. {11.3.3}

It is *likely* that salinity will increase in the tropical and (especially) subtropical Atlantic, and decrease in the western tropical Pacific over the next few decades. Overall, it is *likely* that there will be some decline in the Atlantic Meridional Overturning Circulation by 2050 (*medium confidence*). However, the rate and magnitude of weakening is very uncertain and decades when this circulation increases are also to be expected. {11.3.3}

#### TS.5.4.6 Projected Near-Term Changes in the Cryosphere

A nearly ice-free Arctic Ocean (sea ice extent less than  $10^6$  km<sup>2</sup>) in September is *likely* before mid-century under RCP8.5 (*medium confidence*). This assessment is based on a subset of models that most closely reproduce the climatological mean state and 1979 to 2012 trend of Arctic sea ice cover. It is *very likely* that

there will be further shrinking and thinning of Arctic sea ice cover, and decreases of northern high-latitude spring time snow cover and near surface permafrost as global mean surface temperature rises (see Figures TS.17 and TS.18). There is *low confidence* in projected near-term decreases in the Antarctic sea ice extent and volume. {11.3.4}

#### TS.5.4.7 Possibility of Near-Term Abrupt Changes in Climate

There are various mechanisms that could lead to changes in global or regional climate that are abrupt by comparison with rates experienced in recent decades. The likelihood of such changes is generally lower for the near term than for the long term. For this reason the relevant mechanisms are primarily assessed in the TS.5 sections on long-term changes and in TFE.5. {11.3.4}

#### TS.5.4.8 Projected Near-Term Changes in Air Quality

There is *high confidence* that baseline surface ozone ( $O_3$ ), upon which local pollution builds, will decrease over most regions as rising temperatures enhance global  $O_3$  destruction, but it will increase with rising methane (*high confidence*). Projections based on the RCP scenarios differ regionally, in general projecting 2030 pollution to decrease over Europe, North America, and South America, and to increase over South Asia (*medium confidence*), with mixed results elsewhere. For  $O_3$ , continental-scale changes across the RCPs range from  $-4$  to  $+5$  ppb by 2030 and  $-14$  to  $+5$  ppb by 2100. This range is driven more by pollutant emissions than physical climate changes (*medium confidence*). There is *low confidence* in projecting extreme pollution episodes involving ozone and particulate matter, due to difficulty projecting associated stagnation episodes that involve meteorological blocking. Nevertheless, during extreme pollution episodes, warmer temperatures can trigger positive feedbacks in chemistry and local emissions, further enhancing pollution levels (*medium confidence*). Future air pollution levels under the RCPs, for both surface ozone and particulate matter, are lower than under SRES scenarios with comparable greenhouse gases (*high confidence*). {11.3.5; Annex II}

### TS.5.5 Long-Term Climate Change

#### TS.5.5.1 Projected Long-Term Changes in Global Temperature

Global mean temperatures will continue to rise over the 21st century under all of the RCPs. From around the mid-21st century, the rate of global warming begins to be more strongly dependent on the scenario (Figure TS.15). {12.4.1}

Under the assumptions of the concentration-driven RCPs, global-mean surface temperatures for 2081–2100, relative to 1986–2005 will *likely* be in the 5–95% range of the CMIP5 models;  $0.3^\circ\text{C}$  to  $1.7^\circ\text{C}$  (RCP2.6),  $1.1$  to  $2.6^\circ\text{C}$  (RCP4.5),  $1.4^\circ\text{C}$  to  $3.1^\circ\text{C}$  (RCP6.0),  $2.6^\circ\text{C}$  to  $4.8^\circ\text{C}$  (RCP8.5) (see Table TS.1). With *high confidence*, the 5–95% range of CMIP5 is assessed as *likely* rather than *very likely* based on the assessment of TCR (see TFE.6). The 5–95% range of CMIP5 for global mean temperature change is also assessed as *likely* for mid-21st century, but only with *medium confidence*. With respect to preindustrial conditions, global temperatures averaged in the period 2081–2100 are projected to *likely* exceed  $1.5^\circ\text{C}$  above preindustrial for RCP4.5, RCP6.0 and RCP8.5 (*high confidence*) and are likely to exceed  $2^\circ\text{C}$  above preindustrial for RCP6.0 and RCP8.5 (*high confidence*). Temperature change above  $2^\circ\text{C}$  relative to preindustrial under RCP2.6 is *unlikely* (*medium confidence*). Warming above  $4^\circ\text{C}$  by 2081–2100 is *unlikely* in all RCPs (*high confidence*) except for RCP8.5 where it is *as likely as not* (*medium confidence*). {12.4.1; Tables 12.2, 12.3}

#### [INSERT FIGURE TS.15 HERE]

**Figure TS.15:** Top left: Total global mean radiative forcing for the 4 RCP scenarios based on the MAGICC energy balance model. Note that the actual forcing simulated by the CMIP5 models differs slightly between models. Bottom left: Time series of global annual mean surface air temperature anomalies (relative to 1986–2005) from CMIP5 concentration-driven experiments. Projections are shown for each RCP for the multimodel mean (solid lines) and  $\pm 1.64$  standard deviation (5–95%) across the distribution of individual models (shading). Those ranges are interpreted as “*likely*” changes at the end of the 21st century. Discontinuities at 2100 are due to different numbers of models performing the extension runs beyond the 21st century and have no physical meaning. Numbers in the same colours as the lines indicate the number of different models contributing to the different time periods. Maps: Multimodel ensemble average of annual mean surface air temperature change (compared to 1986–2005 base period) for 2016–2035 and

2081–2100, for RCP2.6, 4.5, 6.0 and 8.5. Hatching indicates regions where the multi model mean signal is less than one standard deviation of internal variability. Stippling indicates regions where the multi model mean signal is greater than two standard deviations of internal variability and where 90% of the models agree on the sign of change. The number of CMIP5 models used is indicated in the upper right corner of each panel. {Box 12.1; Figures 12.4, 12.5, 12.11; Annex I}

### [INSERT TABLE TS.1 HERE]

**Table TS.1:** Projected change in global mean surface air temperature and global mean sea level rise for the mid- and late 21st century. {12.4.1; Table 12.2, Table 13.5}

#### TS.5.5.2 Projected Long-Term Changes in Regional Temperature

There is very high confidence that globally averaged changes over land will exceed changes over the ocean at the end of the 21st century by a factor that is likely in the range 1.4 to 1.7. In the absence of a strong reduction in the Atlantic Meridional Overturning, the Arctic region is projected to warm most (very high confidence) (Figure TS.15). As global mean surface temperature rises, the pattern of atmospheric zonal-mean temperatures show warming throughout the troposphere and cooling in the stratosphere, consistent with previous assessments. The consistency is especially clear in the tropical upper troposphere and the northern high latitudes {12.4.3; Box 5.1}.

It is *virtually certain* that, in most places, there will be more hot and fewer cold temperature extremes as global mean temperatures increase. These changes are expected for events defined as extremes on both daily and seasonal time scales. Increases in the frequency, duration and magnitude of hot extremes along with heat stress are expected, however occasional cold winter extremes will continue to occur. 20-year return values of low temperature events are projected to increase at a rate greater than winter mean temperatures in most regions, with the largest changes in the return values of low temperatures at high latitudes. 20-year return values for high temperature events are projected to increase at a rate similar to or greater than the rate of increase of summer mean temperatures in most regions. Under RCP8.5 it is *likely* that, in most land regions, a current 20-year high temperature event will occur more frequently by the end of the 21st century (at least doubling its frequency, but in many regions becoming an annual or two-year event) and a current 20-year low temperature event will become exceedingly rare (See also TFE.9). {12.4.3}

Models simulate a decrease in cloud amount in the future over most of the tropics and mid-latitudes, due mostly to reductions in low clouds. Changes in marine boundary layer clouds are most uncertain. Increases in cloud fraction and cloud optical depth and therefore cloud reflection are simulated in high latitudes, poleward of 50°. {12.4.3}

#### TS.5.5.3 Projected Long-Term Changes in Atmospheric Circulation

Mean sea level pressure is projected to decrease in high latitudes and increase in the mid-latitudes as global temperatures rise. In the tropics, the Hadley and Walker circulations are *likely* to slow down. Poleward shifts in the mid-latitude jets of about 1 to 2 degrees latitude are *likely* at the end of the 21st century under RCP8.5 in both hemispheres (*medium confidence*), with weaker shifts in the Northern Hemisphere. In austral summer, the additional influence of stratospheric ozone recovery in the Southern Hemisphere opposes changes due to greenhouse gases there, though the net response varies strongly across models and scenarios. Substantial uncertainty and thus *low confidence* remains in projecting changes in Northern Hemisphere storm tracks, especially for the North Atlantic basin. The Hadley cell is *likely* to widen, which translates to broader tropical regions and a poleward encroachment of subtropical dry zones. In the stratosphere, the Brewer-Dobson circulation is *likely* to strengthen. {12.4.4}

#### TS.5.5.4 Projected Long-Term Changes in the Water Cycle

On the planetary scale, relative humidity is projected to remain roughly constant, but specific humidity to increase in a warming climate. The projected differential warming of land and ocean promotes changes in atmospheric moistening that lead to small decreases in near-surface relative humidity over most land areas with the notable exception of parts of tropical Africa (*medium confidence*) (see TFE.1, Figure 1). {12.4.5}

It is *virtually certain* that, in the long term, global precipitation will increase with increased global mean surface temperature. Global mean precipitation will increase at a rate per °C smaller than that of atmospheric

water vapour. It will *likely* increase by 1 to 3% °C<sup>-1</sup> for scenarios other than RCP2.6. For RCP2.6 the range of sensitivities in the CMIP5 models is 0.5 to 4% °C<sup>-1</sup> at the end of the 21st century. {7.6.2, 7.6.3, 12.4.1}

Changes in average precipitation in a warmer world will exhibit substantial spatial variation under RCP8.5. Some regions will experience increases, other regions will experience decreases, and yet others will not experience significant changes at all (see Figure TS.16). There is *high confidence* that the contrast of annual mean precipitation between dry and wet regions and that the contrast between wet and dry seasons will increase over most of the globe as temperatures increase. The general pattern of change indicates that high latitudes are *very likely* to experience greater amounts of precipitation due to the increased specific humidity of the warmer troposphere as well as increased transport of water vapour from the tropics by the end of this century under the RCP8.5 scenario. Many mid-latitude and subtropical arid and semi-arid regions will *likely* experience less precipitation and many moist mid-latitude regions will *likely* experience more precipitation by the end of this century under the RCP8.5 scenario. Maps of precipitation change for the four RCP scenarios are shown in Figure TS.16. {12.4.2, 12.4.5}

Globally, for short-duration precipitation events, a shift to more intense individual storms and fewer weak storms is *likely* as temperatures increase. Over most of the mid-latitude land-masses and over wet tropical regions, extreme precipitation events will *very likely* be more intense and more frequent in a warmer world. The global average sensitivity of the 20-year return value of the annual maximum daily precipitation ranges from 4% per °C of local temperature increase (average of CMIP3 models) to 5.3% per °C of local temperature increase (average of CMIP5 models) but regionally there are wide variations. {12.4.2, 12.4.5}

#### [INSERT FIGURE TS.16 HERE]

**Figure TS.16:** Maps of multi-model results for the scenarios RCP2.6, RCP4.5, RCP6.0 and RCP8.5 in 2081–2100 of average percent change in mean precipitation. Changes are shown relative to 1986–2005. The number of CMIP5 models to calculate the multi-model mean is indicated in the upper right corner of each panel. Hatching indicates regions where the multi model mean signal is less than one standard deviation of internal variability. Stippling indicates regions where the multi model mean signal is greater than two standard deviations of internal variability and where 90% of models agree on the sign of change (see Box 12.1). {Figure 12.22; Annex I}

Annual surface evaporation is projected to increase as global temperatures rise over most of the ocean and is projected to change over land following a similar pattern as precipitation. Decreases in annual runoff are *likely* in parts of southern Europe, the Middle East, and southern Africa by the end of this century under the RCP8.5 scenario. Increases in annual runoff are *likely* in the high northern latitudes corresponding to large increases in winter and spring precipitation by the end of this century under the RCP8.5 scenario. Regional to global-scale projected decreases in soil moisture and increased risk of agricultural drought are *likely* in presently dry regions and are projected with *medium confidence* by the end of this century under the RCP8.5 scenario. Prominent areas of projected decreases in evaporation include southern Africa and north western Africa along the Mediterranean. Soil moisture drying in the Mediterranean and southern African regions is consistent with projected changes in Hadley circulation and increased surface temperatures, so surface drying in these regions as global temperatures increase is *likely* with *high confidence* by the end of this century under the RCP8.5 scenario. In regions where surface moistening is projected, changes are generally smaller than natural variability on the twenty-year time scale. A summary of the projected changes in the water cycle from the CMIP5 models is shown in TFE.1, Figure 1. {12.4.5; Box 12.1}

#### TS.5.5.5 Projected Long-Term Changes in the Cryosphere

It is *very likely* that the Arctic sea ice cover will continue shrinking and thinning year-round in the course of the 21st century as global mean surface temperature rises. At the same time, in the Antarctic, a decrease in sea ice extent and volume is expected, but with *low confidence*. The CMIP5 multi-model projections give average reductions in Arctic sea ice extent for 2081–2100 compared to 1986–2005 ranging from 8% for RCP2.6 to 34% for RCP8.5 in February and from 43% for RCP2.6 to 94% for RCP8.5 in September (*medium confidence*) (Figure TS.17). A nearly ice-free Arctic Ocean (sea ice extent less than 10<sup>6</sup> km<sup>2</sup>) in September before mid-century is *likely* under RCP8.5 (*medium confidence*), based on an assessment of a subset of models that most closely reproduce the climatological mean state and 1979–2012 trend of the Arctic sea ice cover. Some climate projections exhibit 5 to 10 year periods of sharp summer Arctic sea ice decline – even steeper than observed over the last decade – and it is *likely* that such instances of rapid ice loss will occur in the future. There is little evidence in global climate models of a tipping point (or critical

threshold) in the transition from a perennially ice-covered to a seasonally ice-free Arctic Ocean beyond which further sea ice loss is unstoppable and irreversible. In the Antarctic, the CMIP5 multi-model mean projects a decrease in sea ice extent that ranges from 16% for RCP2.6 to 67% for RCP8.5 in February and from 8% for RCP2.6 to 30% for RCP8.5 in September for 2081–2100 compared to 1986–2005. There is however *low confidence* in those projections because of the wide inter-model spread and the inability of almost all of the available models to reproduce the overall increase of the Antarctic sea ice areal coverage observed during the satellite era. {12.4.6, 12.5.5}

It is *very likely* that Northern Hemisphere snow cover will reduce as global temperatures rise over the coming century. A retreat of permafrost extent with rising global temperatures is *virtually certain*. Snow cover changes result from precipitation and ablation changes, which are sometimes opposite. Projections of the Northern Hemisphere spring snow covered area by the end of the 21st century vary between –7% (RCP2.6) and –25% (RCP8.5) decrease and are fairly coherent among models (Figure TS.18). The projected changes in permafrost are a response not only to warming, but also to changes in snow cover, which exerts a control on the underlying soil. By the end of the 21st century, diagnosed near-surface permafrost area is projected to decrease by between 37% (RCP2.6) to 81% (RCP8.5) (*medium confidence*). {12.4.6}

#### [INSERT FIGURE TS.17 HERE]

**Figure TS.17:** Northern Hemisphere sea-ice extent in September over the late 20th century and the whole 21st century for the scenarios RCP2.6, RCP4.5, RCP6.0 and RCP8.5 in the CMIP5 models, and corresponding maps of multi-model results in 2081–2100 of Northern Hemisphere September sea ice extent. In the time series, the number of CMIP5 models to calculate the multi-model mean is indicated (subset in brackets). Time series are given as 5 year running means. The projected mean sea ice extent of a subset of models that most closely reproduce the climatological mean state and 1979–2012 trend of the Arctic sea ice is given (solid lines), with the min-max range of the subset indicated with shading. Black (grey shading) is the modelled historical evolution using historical reconstructed forcings. The CMIP5 multi-model mean is indicated with dashed lines. In the maps, the CMIP5 multi-model mean is given in white color, the results for the subset in grey colour. Filled areas mark the averages over the 2081–2100 period, lines mark the sea ice extent averaged over the 1986–2005 period. The observed sea ice extent is given in pink as a time series and averaged over 1986–2005 as a pink line in the map. {Figures 12.18, 12.29, 12.31}

#### [INSERT FIGURE TS.18 HERE]

**Figure TS.18:** Top: Northern Hemisphere spring (March to April average) relative snow covered area (RSCA) in CMIP5, obtained by dividing the simulated 5-year box smoothed spring snow covered area (SCA) by the simulated average spring SCA of 1986–2005 reference period. Bottom: Northern hemisphere diagnosed near-surface permafrost area in CMIP5, using 20-year average monthly surface air temperatures and snow depths. Lines indicate the multi model average, shading indicates the inter-model spread (one standard deviation). {Figures 12.32, 12.33}

#### TS.5.5.6 Projected Long-Term Changes in the Ocean

Over the course of the 21st century, the global ocean will warm in all RCP scenarios. The strongest warming signal is found at the surface in subtropical and tropical regions. At greater depth the warming is most pronounced in the Southern Ocean. In some regions, ocean warming in the top few hundred meters can exceed 0.5°C (RCP2.6) to 2.5°C (RCP8.5), and 0.3°C (RCP2.6) to 0.7°C (RCP8.5) at a depth of about 1 km by the end of the century. For RCP4.5 by the end of the 21st century, half of the energy taken up by the ocean is in the uppermost 700 m, and 85% is in the uppermost 2000 m. Due to the long time scales of this heat transfer from the surface to depth, ocean warming will continue for centuries, even if greenhouse gas emissions are decreased or concentrations kept constant, and will result in a continued contribution to sea level rise (see Section TS5.7). {12.4.3, 12.4.7}

### TFE.6: Climate Sensitivity and Feedbacks

The description of climate change as a response to a forcing that is amplified by feedbacks goes back many decades. The concepts of radiative forcing and climate feedbacks continue to be refined, and limitations are now better understood; for instance, feedbacks may be much faster than the surface warming, feedbacks depend on the type of forcing agent (e.g., greenhouse gas vs. solar forcing), or may have intrinsic timescales (associated mainly with vegetation change and ice sheets) of several centuries to millennia. The analysis of physical feedbacks in models and from observations remains a powerful framework that provides constraints on transient future warming for different scenarios, on climate sensitivity and, combined with estimates of

carbon cycle feedbacks (see TFE.5), determines the greenhouse gas emissions that are compatible with climate stabilization or targets (see TFE.8). {7.1, 9.7.2, 12.5.3; Box 12.2}

The water vapour/lapse rate, albedo and cloud feedbacks are the principal determinants of equilibrium climate sensitivity (ECS, the equilibrium change in annual mean global surface temperature following a doubling of the atmospheric CO<sub>2</sub> concentration). All of these feedbacks are assessed to be positive, but with different levels of likelihood assigned ranging from likely to extremely likely. Therefore, there is *very high confidence* that the net feedback is strongly positive and the black body response of the climate to a forcing will therefore be amplified. Cloud feedbacks continue to be the largest uncertainty. The net feedback from water vapour and lapse rate changes together is *extremely likely* positive and approximately doubles the black body response. The mean value and spread of these two processes in climate models are essentially unchanged from AR4, but are now supported by stronger observational evidence and better process understanding of what determines relative humidity distributions. Clouds respond to climate forcing mechanisms in multiple ways and individual cloud feedbacks can be positive or negative. Key issues include the representation of both deep and shallow cumulus convection, microphysical processes in ice clouds, and partial cloudiness that results from small-scale variations of cloud-producing and cloud-dissipating processes. New approaches to diagnosing cloud feedback in GCMs have clarified robust cloud responses, while continuing to implicate low cloud cover as the most important source of intermodel spread in simulated cloud feedbacks. The net radiative feedback due to all cloud types is *likely* positive. This conclusion is reached by considering a plausible range for unknown contributions by processes yet to be accounted for, in addition to those occurring in current climate models. Observations alone do not currently provide a robust, direct constraint, but multiple lines of evidence now indicate positive feedback contributions from changes in both the height of high clouds and the horizontal distribution of clouds. The additional feedback from low cloud amount is also positive in most climate models, but that result is not well understood, nor effectively constrained by observations, so *confidence* in it is *low*. {7.2.4, 7.2.5, 7.2.6}

The representation of aerosol-cloud processes in climate models continues to be a challenge. Aerosol and cloud variability at scales significantly smaller than those resolved in climate models, and the subtle responses of clouds to aerosol at those scales, mean that, for the foreseeable future, climate models will continue to rely on parameterizations of aerosol-cloud interactions or other methods that represent subgrid variability. This implies large uncertainties for estimates of the forcings associated with aerosol-cloud interactions. {7.4, 7.5.3, 7.5.4}

Equilibrium climate sensitivity (ECS) and Transient Climate Response (TCR) are useful metrics summarising the global climate system's temperature response to an externally-imposed radiative forcing. ECS is defined as the equilibrium change in annual mean global mean surface temperature following a doubling of the atmospheric CO<sub>2</sub> concentration (see Glossary), while TCR is defined as the annual mean global mean surface temperature change at the time of CO<sub>2</sub> doubling following a linear increase in CO<sub>2</sub> forcing over a period of 70 years (see Glossary). Both metrics have a broader application than these definitions imply: ECS determines the eventual warming in response to stabilisation of atmospheric composition on multi-century timescales, while TCR determines the warming expected at a given time following any steady increase in forcing over a 50- to 100-year timescale. {Box 12.2, 12.5.3}

ECS and TCR can be estimated from various lines of evidence (see TFE.6, Figures 1 and 2). The estimates can be based on the values of ECS and TCR diagnosed from climate models, or they can be constrained by analysis of feedbacks in climate models, patterns of mean climate and variability in models compared to observations, temperature fluctuations as reconstructed from paleoclimate archives, observed and modelled short term perturbations of the energy balance like those caused by volcanic eruptions, and the observed surface and ocean temperature trends since preindustrial. For many applications, the limitations of the forcing-feedback analysis framework and the dependence of feedbacks on timescales and the climate state must be kept in mind. {5.3.1, 5.3.3, 9.7.1, 9.7.2, 9.7.3, 10.8.1, 10.8.2, 12.5.3; Box 5.2; Table 9.5}

Newer studies of constraints on ECS are based on the observed warming since preindustrial, analysed using simple and intermediate complexity models, improved statistical methods, and several different and newer datasets. Together with results from feedback analysis and paleoclimate constraints these studies show ECS is *likely* between 1.5°C to 4.5°C (*medium confidence*) and *extremely unlikely* less than 1.0°C. {5.3.1, 5.3.3, 10.8.2; Box 5.2, 12.2}



Estimates based on AOGCMs and feedback analysis indicate a range of 2 to 4.5°C, with the CMIP5 model mean at 3.2°C, similar to CMIP3. High climate sensitivities are found in some perturbed parameter ensembles models, but recent comparisons of perturbed-physics ensembles against the observed climate find that models with ECS values in the range 3 to 4°C show the smallest errors for many fields. Relationships between climatological quantities and climate sensitivity are often found within a specific perturbed parameter ensemble model but in many cases the relationship is not robust across perturbed parameter ensembles models from different models or in CMIP3/5. The assessed literature suggests that the range of climate sensitivities and transient responses covered by CMIP3/5 cannot be narrowed significantly by constraining the models with observations of the mean climate and variability. Studies based on perturbed parameter ensembles models and CMIP3 support the conclusion that a credible representation of the mean climate and variability is very difficult to achieve with ECSs below 2°C. {9.2.2, 9.7.3; Box 12.2}

New estimates of ECS based on reconstructions and simulations of the Last Glacial Maximum (21,000 years to 19,000 years ago) show that values below 1°C as well as above 6°C are *very unlikely*. In some models climate sensitivity differs between warm and cold climates because of differences in the representation of cloud feedbacks. Estimates of an Earth System sensitivity including slow feedbacks (e.g., ice sheets or vegetation) are even more difficult to relate to climate sensitivity of the current climate state. The main limitations of ECS estimates from paleoclimate states are uncertainties in proxy data, spatial coverage of the data, uncertainties in some forcings, and structural limitations in models used in model-data comparisons. {5.3, 10.8.2, 12.5.3}

Bayesian methods to constrain ECS or TCR are sensitive to the assumed prior distributions. They can in principle yields narrower estimates by combining constraints from the observed warming trend, volcanic eruptions, model climatology, and paleoclimate, and that has been done in some studies, but there is no consensus on how this should be done robustly. This approach is sensitive to the assumptions regarding the independence of the various lines of evidence, the possibility of shared biases in models or feedback estimates, and the assumption that each individual line of evidence is unbiased. The combination of different estimates in this assessment is based on expert judgment. {10.8.2; Box 12.2}

#### **[INSERT TFE.6, FIGURE 1 HERE]**

**TFE.6, Figure 1:** Probability density functions, distributions and ranges for equilibrium climate sensitivity, based on Figure 10.20b plus climatological constraints shown in IPCC AR4 ( Box AR4 10.2 Figure 1), and results from CMIP5 (see Table 9.5). The grey shaded range marks the *likely* 1.5°C to 4.5°C range, grey solid line the *extremely unlikely* less than 1°C, the grey dashed line the *very unlikely* greater than 6°C. Adapted from Box 12.2, Figure 1. See Figure 10.20b and Chapter 10 Supplementary Material for full caption and details. Labels refer to studies since AR4. {Box 12.2, Figure 1}

#### **INSERT TFE.6, FIGURE 2 HERE]**

**TFE.6, Figure 2:** Probability density functions, distributions and ranges (5–95%) for the transient climate response from different studies, based on Figure 10.20a, and results from CMIP5 (black histogram, Table 9.5). The grey shaded range marks the *likely* 1°C to 2.5°C range, the grey solid line marks the *extremely unlikely* greater than 3°C. Adapted from Box 12.2, Figure 2. See Figure 10.20a and Chapter 10 Supplementary Material for full caption and details. {Box 12.2, Figure 2}

Based on the combined evidence from observed climate change including the observed 20th century warming, climate models, feedback analysis and paleoclimate, as discussed above, equilibrium climate sensitivity (ECS) is *likely* in the range 1.5 to 4.5°C with *high confidence*. ECS is positive, *extremely unlikely* less than 1°C (*high confidence*), and *very unlikely* greater than 6°C (*medium confidence*). The tails of the ECS distribution are now better understood. Multiple lines of evidence provide *high confidence* that an ECS value less than 1°C is *extremely unlikely*. The upper limit of the likely range is unchanged compared to AR4. The lower limit of the likely range of 1.5°C is less than the lower limit of 2°C in AR4. This change reflects the evidence from new studies of observed temperature change, using the extended records in atmosphere and ocean. These studies suggest a best fit to the observed surface and ocean warming for ECS values in the lower part of the *likely* range. Note that these studies are not purely observational, because they require an estimate of the response to radiative forcing from models. In addition, the uncertainty in ocean heat uptake remains substantial. Accounting for short-term variability in simple models remains challenging, and it is important not to give undue weight to any short time period which might be strongly affected by internal

variability. On the other hand, AOGCMs show very good agreement with observed climatology with ECS values in the upper part of the 1.5–4.5°C range, but the simulation of key feedbacks like clouds remains challenging in those models. The estimates from the observed warming, paleoclimate, and from climate models are consistent within their uncertainties, each is supported by many studies and multiple datasets, and in combination they provide *high confidence* for the assessed *likely* range. Even though this assessed range is similar to previous reports, confidence today is much higher as a result of high quality and longer observational records with a clearer anthropogenic signal, better process understanding, more and better understood evidence from paleoclimate reconstructions, and better climate models with higher resolution that capture many more processes more realistically. All these lines of evidence individually support the assessed *likely* range of 1.5 to 4.5°C. {3.2, 9.7.3, 10.8; Box 9.2, 13.1}

On timescales of many centuries and longer, additional feedbacks with their own intrinsic timescales (e.g., vegetation, ice sheets) may become important but are not usually modelled in AOGCMs. The resulting equilibrium temperature response to a doubling of CO<sub>2</sub> on millennial timescales or Earth System Sensitivity is less well constrained but *likely* to be larger than ECS, implying that lower atmospheric CO<sub>2</sub> concentrations are compatible with limiting warming to below a given temperature level. These slow feedbacks are less likely to be proportional to global mean temperature change, implying that Earth System Sensitivity changes over time. Estimates of Earth System Sensitivity are also difficult to relate to climate sensitivity of the current climate state. {5.3.3, 10.8.2, 12.5.3}

For scenarios of increasing radiative forcing, TCR is a more informative indicator of future climate change than ECS. This assessment concludes with *high confidence* that the transient climate response (TCR) is *likely* in the range 1°C to 2.5°C, close to the estimated 5–95% range of CMIP5 (1.2°C to 2.4°C), is positive and *extremely unlikely* greater than 3°C. As with the ECS, this is an expert-assessed range, supported by several different and partly independent lines of evidence, each based on multiple studies, models and datasets. TCR is estimated from the observed global changes in surface temperature, ocean heat uptake and radiative forcing including detection/attribution studies identifying the response patterns to increasing greenhouse gas concentrations, and the results of CMIP3 and CMIP5. Estimating TCR suffers from fewer difficulties in terms of state- or time-dependent feedbacks, and is less affected by uncertainty as to how much energy is taken up by the ocean. Unlike ECS, the ranges of TCR estimated from the observed warming and from AOGCMs agree well, increasing our confidence in the assessment of uncertainties in projections over the 21st century. The assessed ranges of ECS and TCR are largely consistent with the observed warming, the estimated forcing, and the projected future warming. {9.7.1, 10.8.1, 12.5.3; Table 9.5}

### ***TS.5.6 Long-Term Projections of Carbon and Other Biogeochemical Cycles***

Projections of the global carbon cycle to 2100 using the CMIP5 Earth System Models (ESMs) represent a wider range of complex interactions between the carbon cycle and the physical climate system.

With *very high confidence*, ocean carbon uptake of anthropogenic CO<sub>2</sub> will continue under all four Representative Concentration Pathways through to 2100, with higher uptake in higher concentration pathways. The future evolution of the land carbon uptake is much more uncertain. A majority of CMIP5 ESMs project a continued net carbon uptake by land ecosystems through 2100. Yet, a minority of models simulate a net CO<sub>2</sub> source to the atmosphere by 2100 due to the combined effect of climate change and land use change. In view of the large spread of model results and incomplete process representation, there is *low confidence* on the magnitude of modelled future land carbon changes. {6.4.3}

There is *high confidence* that climate change will partially offset increases in global land and ocean carbon sinks caused by rising atmospheric CO<sub>2</sub>. Yet, there are regional differences among CMIP5 ESMs, in the response of ocean and land CO<sub>2</sub> fluxes to climate. There is high agreement between models that tropical ecosystems will store less carbon in a warmer climate. There is medium agreement between the CMIP5 ESMs that at high latitudes warming will increase land carbon storage, although none of these models accounts for decomposition of carbon in permafrost, which may offset increased land carbon storage. There is *high confidence* that reductions in permafrost extent due to warming will cause thawing of some currently frozen carbon. However, there is low confidence on the magnitude of carbon losses through CO<sub>2</sub> and CH<sub>4</sub>

emissions to the atmosphere with a range from 50 to more than 250 PgC between 2000 and 2100 for RCP8.5. {6.4.2, 6.4.3}

The loss of carbon from frozen soils constitutes a positive radiative feedback that is missing in current coupled ESM projections. There is high agreement between CMIP5 ESMs that ocean warming and circulation changes will reduce the rate of ocean carbon uptake in the Southern Ocean and North Atlantic, but that carbon uptake will nevertheless persist in those regions. {6.4.2}

It is *very likely*, based on new experimental results and modelling, that nutrient shortage will limit the effect of rising atmospheric CO<sub>2</sub> on future land carbon sinks, for the four RCP scenarios. There is *high confidence* that low nitrogen availability will limit carbon storage on land, even when considering anthropogenic nitrogen deposition. The role of phosphorus limitation is more uncertain. {6.4.6}

For the ESMs simulations driven by CO<sub>2</sub> concentrations, representation of the land and ocean carbon cycle allows quantification of the fossil fuel emissions compatible with the RCP scenarios. Between 2012 and 2100, ESM results imply cumulative compatible fossil fuel emissions of 270 [140 to 410] PgC for RCP2.6, 780 [595 to 1005] PgC for RCP4.5, 1060 [840 to 1250] PgC for RCP6.0, and 1685 [1415 to 1910] PgC for RCP8.5 (CMIP5 model spread) (Figure TS.19). For RCP2.6, the models project an average 50% (range 14–96%) emission reduction by 2050 relative to 1990 levels. It is about *as likely as not* that sustained globally negative emissions will be required to achieve the reductions in atmospheric CO<sub>2</sub> in RCP2.6. See also Box TS.7. {6.4.3; Table 6.12}

#### [INSERT FIGURE TS.19 HERE]

**Figure TS.19:** Compatible fossil fuel emissions simulated by the CMIP5 models for the four RCP scenarios. Top: timeseries of annual emission (PgC yr<sup>-1</sup>). Dashed lines represent the historical estimates and RCP emissions calculated by the integrated assessment models (IAM) used to define the RCP scenarios, solid lines and plumes show results from CMIP5 ESMs (model mean, with 1 standard deviation shaded). Bottom: cumulative emissions for the historical period (1860–2005) and 21st century (defined in CMIP5 as 2006–2100) for historical estimates and RCP scenarios. Left bars are cumulative emissions from the IAMs, right bars are the CMIP5 ESMs multi-model mean estimate, and dots denote individual ESM results. From the CMIP5 ESMs results, total carbon in the land-atmosphere-ocean system can be tracked and changes in this total must equal fossil fuel emissions to the system. Hence the compatible emissions are given by cumulative Emissions =  $\Delta C_A + \Delta C_L + \Delta C_O$ , while emission rate =  $d/dt [C_A + C_L + C_O]$ , where  $C_A$ ,  $C_L$ ,  $C_O$  are carbon stored in atmosphere, land and ocean respectively. Other sources and sinks of CO<sub>2</sub> such as from volcanism, sedimentation or rock weathering, which are very small on centennial timescales are not considered here. {Box 6.4; Figure 6.25}

When forced with RCP8.5 CO<sub>2</sub> emissions, as opposed to the RCP8.5 CO<sub>2</sub> concentrations, CMIP5 ESMs with interactive carbon cycles simulate, on average, a 50 (–140 to +210) ppm (CMIP5 model spread) larger atmospheric CO<sub>2</sub> concentration and a 0.2 (–0.4 to +0.9) °C (CMIP5 model spread) larger global surface temperature increase by 2100. {12.4.8}

It is *virtually certain* that the increased storage of carbon by the ocean will increase acidification in the future, continuing the observed trends of the past decades. Ocean acidification in the surface ocean will follow atmospheric CO<sub>2</sub> and it will also increase in the deep ocean as CO<sub>2</sub> continues to penetrate the abyss. The CMIP5 models consistently project worldwide increased ocean acidification to 2100 under all RCPs. The corresponding decrease in surface ocean pH by the end of 21st century is 0.065 (0.06 to 0.07) for RCP2.6, 0.145 (0.14 to 0.15) for RCP4.5, 0.203 (0.20 to 0.21) for RCP6.0, and 0.31 (0.30 to 0.32) for RCP8.5 (CMIP5 model spread) (Figure TS.20). Surface waters are projected to become seasonally corrosive to aragonite in parts of the Arctic and in some coastal upwelling systems within a decade, and in parts of the Southern Ocean within 1–3 decades in most scenarios. Aragonite, a less stable form of calcium carbonate, undersaturation becomes widespread in these regions at atmospheric CO<sub>2</sub> levels of 500–600 ppm. {6.4.4}

#### [INSERT FIGURE TS.20 HERE]

**Figure TS.20:** (a) Timeseries (model averages and min-max ranges) and (b) maps of multi-model surface ocean pH for the scenarios RCP2.6, RCP4.5, RCP6.0 and RCP8.5 in 2081–2100. The maps in (b) show change in global ocean surface pH in 2081–2100 relative to 1986–2005. The number of CMIP5 models to calculate the multi-model mean is indicated in the upper right corner of each panel. {Figure 6.28}

It is *very likely* that the dissolved oxygen content of the ocean will decrease by 3 to 6% during the 21st century in response to surface warming (see Box 6.5, and Section 6.4.5). CMIP5 models suggest that this decrease in dissolved oxygen will predominantly occur in the subsurface mid-latitude oceans, caused by enhanced stratification, reduced ventilation and warming. However, there is no consensus on the future development of the volume of hypoxic and suboxic waters in the open-ocean because of large uncertainties in potential biogeochemical effects and in the evolution of tropical ocean dynamics. {6.4.5}

With *very high confidence*, the physical, biogeochemical carbon cycle in the ocean and on land will continue to respond to climate change and atmospheric CO<sub>2</sub> increases that arise during the 21st century (see TFE.7 and TFE 8).

### **TFE.7: Carbon Cycle Perturbation and Uncertainties**

The natural carbon cycle has been perturbed since the beginning of the Industrial Revolution (circa 1750) by the anthropogenic release of CO<sub>2</sub> to the atmosphere, virtually all from fossil fuel combustion and land use change, with a small contribution from cement production. Fossil fuel burning is a process related to energy production. Fossil fuel carbon comes from geological deposits of coal, oil and gas that were buried in the Earth crust for millions of years. Land use change CO<sub>2</sub> emissions are related to the conversion of natural ecosystems into managed ecosystems for food, feed and timber production with CO<sub>2</sub> being emitted from the burning of plant material or from the decomposition of dead plants and soil organic carbon. For instance when a forest is cleared, the plant material may be released to the atmosphere quickly through burning or over many years as the dead biomass and soil carbon decay on their own. {6.1, 6.3; Table 6.1}

The human caused excess of CO<sub>2</sub> in the atmosphere is partly removed from the atmosphere by carbon sinks in land ecosystems and in the ocean, currently leaving about 45% of the CO<sub>2</sub> emissions in the atmosphere. Natural carbon sinks are due to physical, biological and chemical processes acting on different time scales. An excess of atmospheric CO<sub>2</sub> supports photosynthetic CO<sub>2</sub> fixation by plants that is stored as plant biomass or in the soil. The residence times of stored carbon on land depends on the compartments (plant / soil) and composition of the organic carbon, with time horizons varying from days to centuries. The increased storage in terrestrial ecosystems not affected by land use change is likely to be caused by enhanced photosynthesis at higher CO<sub>2</sub> levels and N deposition, and changes in climate favoring carbon sinks such as longer growing seasons in mid-to-high latitudes. {6.3, 6.3.1}

The uptake of anthropogenic CO<sub>2</sub> by the ocean is primarily a response to increasing CO<sub>2</sub> in the atmosphere. Excess atmospheric CO<sub>2</sub> absorbed by the surface ocean or transported to the ocean through aquatic systems (e.g., rivers, ground waters) gets buried in coastal sediments or transported to deep waters where it is stored for decades to centuries. The deep ocean carbon can dissolve ocean carbonate sediments to store excess CO<sub>2</sub> on time scales of centuries to millennia. Within a thousand years, the remaining atmospheric fraction of the CO<sub>2</sub> emissions will be between 15 and 40%, depending on the amount of carbon released (TFE.7, Figure 1). On geological time scales of 10,000 years or longer, additional CO<sub>2</sub> is removed very slowly from the atmosphere by rock weathering, pulling the remaining atmospheric CO<sub>2</sub> fraction down to 10 to 25% after 10,000 years. {Box 6.1}

#### **[INSERT TFE.7, FIGURE 1 HERE]**

**TFE.7, Figure 1:** Percentage of initial atmospheric CO<sub>2</sub> perturbation remaining in the atmosphere in response to an idealized instantaneous CO<sub>2</sub> emission pulse in year 0 as calculated by a range of coupled climate-carbon cycle models. Multi-model mean (blue line) and the uncertainty interval ( $\pm 2$  standard deviations, shading) simulated during 100 years (left panel) and 1,000 years (right panel) following the instantaneous emission pulse of 100 PgC. (adapted from Box 6.1, Figure 1). {Box 6.1}

The carbon cycle response to future climate and CO<sub>2</sub> changes can be viewed as two strong and opposing feedbacks. The concentration-carbon feedback determines changes in storage due to elevated CO<sub>2</sub>, and the climate-carbon feedback determines changes in carbon storage due to changes in climate. There is *high confidence* that increased atmospheric CO<sub>2</sub> will lead to increased land and ocean carbon uptake but by an uncertain amount. Models agree on the positive sign of land and ocean response to rising CO<sub>2</sub> but show only medium and low agreement for the magnitude of ocean and land carbon uptake respectively (TFE.7, Figure

2). Future climate change will decrease land and ocean carbon uptake compared to the case with constant climate (*medium confidence*). This is further supported by paleoclimate observations and modelling indicating that there is a positive feedback between climate and the carbon cycle on century to millennial time scales. Models agree on the sign, globally negative, of land and ocean response to climate change but show low agreement on the magnitude of this response, especially for the land (TFE.7, Figure 2). A key update since AR4 is the introduction of nutrient dynamics in some land carbon models, in particular the limitations on plant growth imposed by nitrogen availability. There is *high confidence* that, at the global scale, relative to CMIP5 carbon only ESMs, CMIP5 ESMs including a land nitrogen cycle will reduce the strength of both the concentration-carbon feedback and the climate-carbon feedback of land ecosystems (TFE.7, Figure 2). Inclusion of N-cycle processes increases the spread across the CMIP5 ensemble. The CMIP5 spread in ocean sensitivity to CO<sub>2</sub> and climate appears reduced compared to AR4 (TFE.7, Figure 2). {6.2.3, 6.4.2}

#### [INSERT TFE.7, FIGURE 2 HERE]

**TFE.7, Figure 2:** Comparison of carbon cycle feedback metrics between the ensemble of 7 GCMs and 4 EMICs at the time of AR4 (C<sup>4</sup>MIP) under the SRES-A2 scenario and the 8 CMIP5 models under the 140-year 1% CO<sub>2</sub> increase per year scenario. Black dots represent a single model simulation and coloured bars the mean of the multi-model results, grey dots are used for models with a coupled terrestrial nitrogen cycle. The comparison with C<sup>4</sup>MIP models is for context, but these metrics are known to be variable across different scenarios and rates of change (see Section 6.4.2.2). The SRES A2 scenario is closer in rate of change to a 0.5% CO<sub>2</sub> increase per year scenario and as such it should be expected that the CMIP5 climate-carbon sensitivity terms are comparable, but the concentration-carbon sensitivity terms are likely to be around 20% smaller for CMIP5 than for C<sup>4</sup>MIP due to lags in the ability of the land and ocean to respond to higher rates of CO<sub>2</sub> increase. This dependence on scenario reduces confidence in any quantitative statements of how CMIP5 carbon cycle feedbacks differ from C<sup>4</sup>MIP. {6.4.2}

With *very high confidence*, ocean carbon uptake of anthropogenic CO<sub>2</sub> emissions will continue under all four Representative Concentration Pathways through to 2100, with higher uptake corresponding to higher concentration pathways. The future evolution of the land carbon uptake is much more uncertain, with a majority of models projecting a continued net carbon uptake under all RCPs, but with some models simulating a net loss of carbon by the land due to the combined effect of climate change and land use change. In view of the large spread of model results and incomplete process representation, there is *low confidence* on the magnitude of modelled future land carbon changes. [6.4.3, Figure 6.24]

Biogeochemical cycles and feedbacks other than the carbon cycle play an important role in the future of the climate system, although the carbon cycle represents the strongest of these. Changes in the nitrogen cycle, in addition to interactions with CO<sub>2</sub> sources and sinks, affect emissions of N<sub>2</sub>O both on land and from the ocean. The human-caused creation of reactive nitrogen has increased steadily over the last two decades and is dominated by the production of ammonia for fertilizer and industry, with important contributions from legume cultivation and combustion of fossil fuels. {6.3}

Many processes, however, are not yet represented in coupled climate-biogeochemistry models (e.g., other processes involving other biogenic elements such as P, Si, Fe) so their magnitudes have to be estimated in offline or simpler models, which make their quantitative assessment difficult. It is *likely* that there will be non-linear interactions between many of these processes, but these are not yet well quantified. Therefore any assessment of the future feedbacks between climate and biogeochemical cycles still contains large uncertainty. {6.4}

#### TFE.8: Climate Targets and Stabilization

The concept of stabilization is strongly linked to the ultimate objective of the UNFCCC, which is “to achieve [...] stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system.” Recent policy discussions focused on limits to a global temperature increase, rather than to greenhouse gas concentrations, as climate targets in the context of the UNFCCC objectives. The most widely discussed is that of 2°C, i.e., to limit global temperature increase relative to preindustrial times to below 2°C, but targets other than 2°C have been proposed (e.g., returning warming to well below 1.5°C global warming relative to preindustrial, or returning below an atmospheric CO<sub>2</sub> concentration of 350 ppm). Climate targets generally mean avoiding a warming beyond a predefined

threshold. Climate impacts however are geographically diverse and sector specific, and no objective threshold defines when dangerous interference is reached. Some changes may be delayed or irreversible, and some impacts could be beneficial. It is thus not possible to define a single critical objective threshold without value judgments and without assumptions on how to aggregate current and future costs and benefits. This section does not advocate or defend any threshold or objective, nor does it judge the economic or political feasibility of such goals, but assesses, based on the current understanding of climate and carbon cycle feedbacks, the climate projections following the RCP scenarios in the context of climate targets, and the implications of different long-term temperature stabilization objectives on allowed carbon emissions. Further below it is highlighted that temperature stabilization does not necessarily imply stabilization of the entire Earth system.

Temperature targets imply an upper limit on the total radiative forcing (RF). Differences in RF between the four RCP scenarios are relatively small up to 2030, but become very large by the end of the 21st century and dominated by CO<sub>2</sub> forcing. Consequently, in the near term, global-mean surface temperatures are projected to continue to rise at a similar rate for the four RCP scenarios. Around the mid-21st century, the rate of global warming begins to be more strongly dependent on the scenario. By the end of the 21st century, global mean temperatures will be warmer than present day under all the RCPs, global temperature change being largest (>0.3°C per decade) in the highest RCP8.5 and significantly lower in RCP2.6, particularly after ~2050 when global surface temperature response stabilizes (and declines thereafter) (see Figure TS.15). {11.3.1, 12.3.3, 12.4.1}

In the near term (2016–2035), global mean surface warming is *more likely than not* to exceed 1°C and *very unlikely* to be more than 1.5°C relative to preindustrial (assuming 0.61°C warming has occurred prior to 1986–2005) (*medium confidence*). By the end of the century (2081–2100), global mean surface warming, relative to preindustrial, is *likely* to exceed 1.5°C for RCP4.5, RCP6.0 and RCP8.5 (*high confidence*) and is *likely* to exceed 2°C for RCP6.0 and RCP8.5 (*high confidence*). Global mean surface warming above 2°C under RCP2.6 is *unlikely* (*medium confidence*). Global mean surface warming above 4°C by 2081–2100 is *unlikely* in all RCPs (*high confidence*) except for RCP8.5 where it is *as likely as not* (*medium confidence*). All targets here are defined as global average surface temperature change relative to preindustrial. {11.3.6, 12.4.1; Table 12.3}

Continuing greenhouse gas emissions beyond 2100 as in the RCP8.5 extension induces a total radiative forcing above 12 W m<sup>-2</sup> by 2300, global warming reaching 7.8°C [3.0 to 12.6°C] for 2281–2300 relative to 1986–2005. Under the RCP4.5 extension, where radiative forcing is kept constant (around 4.5 W m<sup>-2</sup>) beyond 2100, global warming reaches 2.5°C [1.5 to 3.5°C]. Global warming reaches 0.6°C [0.0 to 1.2°C] under the RCP2.6 extension where sustained negative emissions lead to a further decrease in radiative forcing, reaching values below present-day radiative forcing by 2300. See also Box TS.7. {12.3.1, 12.4.1, 12.5.1}

The total amount of anthropogenic CO<sub>2</sub> released in the atmosphere since preindustrial (often termed cumulative carbon emission, although it only applies to CO<sub>2</sub> emissions) is a good indicator of the atmospheric CO<sub>2</sub> concentration and hence of the global warming response. The ratio of global mean surface temperature change to total cumulative anthropogenic CO<sub>2</sub> emissions is relatively constant over time and independent of the scenario. This near-linear relationship between total CO<sub>2</sub> emissions and global temperature change makes it possible to define a new quantity, the transient climate response to cumulative carbon emission (TCRE), as the transient global mean surface temperature change for a given amount of cumulated anthropogenic CO<sub>2</sub> emissions, usually 1000 PgC. TCRE is model dependent, as it is a function of the cumulative CO<sub>2</sub> airborne fraction and the transient climate response, both quantities varying significantly across models. Taking into account the available information from multiple lines of evidence (observations, models and process understanding), the near linear relationship between cumulative CO<sub>2</sub> emissions and peak global mean temperature is well established in the literature and robust for cumulative total CO<sub>2</sub> emissions up to about 2000 PgC. It is consistent with the relationship inferred from past cumulative CO<sub>2</sub> emissions and observed warming, is supported by process understanding of the carbon cycle and global energy balance, and emerges as a robust result from the entire hierarchy of models. Expert judgment based on the available evidence suggests that TCRE is *likely* between 0.8°C–2.5°C per 1000 PgC, for cumulative emissions less than about 2000 PgC until the time at which temperature peaks (TFE.8, Figure 1a). {6.4.3, 12.5.4; Box 12.2}

CO<sub>2</sub> induced warming is projected to remain approximately constant for many centuries following a complete cessation of emissions. A large fraction of climate change is thus irreversible on a human time scale, except if net anthropogenic CO<sub>2</sub> emissions were strongly negative over a sustained period. The assessment of TCRE, limiting the warming caused by anthropogenic CO<sub>2</sub> emissions alone to be *likely* less than 2°C, total CO<sub>2</sub> emissions from all anthropogenic sources would need to be below a cumulative budget of about 1000 PgC over the entire industrial era. About half, estimated in the range of 460 to 630 PgC, of this budget was already emitted by 2011 (TFE.8, Figure 1a). Higher emissions in earlier decades therefore imply lower or even negative emissions later on. Accounting for non-CO<sub>2</sub> forcings contributing to peak warming implies lower cumulated CO<sub>2</sub> emissions (TFE.8, Figure 1a). Non-CO<sub>2</sub> forcing constituents are important, requiring either assumptions on how CO<sub>2</sub> emission reductions are linked to changes in other forcings, or separate emission budgets and climate modeling for short lived and long-lived gases. So far, not many studies have considered non-CO<sub>2</sub> forcings. Those that do consider them found significant effects, in particular warming of several tenths of a degree for abrupt reductions in emissions of short-lived species, like aerosols. Accounting for an unanticipated release of greenhouse gases from permafrost or methane hydrates, not included in studies assessed here, would also reduce the anthropogenic CO<sub>2</sub> emissions compatible with a given temperature target. Requiring a higher likelihood of temperatures remaining below a given temperature target would further reduce the compatible emissions (TFE.8, Figure 1c). The concept of a fixed cumulative CO<sub>2</sub> budget holds not just for 2°C, but for any temperature level explored with models so far (up to about 5°C, see Figures 12.44–12.46). Higher temperature targets would allow larger cumulative budgets, while lower temperature target would require lower cumulative budgets (TFE.8, Figure 1). {6.3.1, 12.5.2, 12.5.4}

#### [INSERT TFE.8, FIGURE 1 HERE]

**TFE.8, Figure 1:** Global mean temperature increase since 1861–1880 as a function of cumulative total global CO<sub>2</sub> emissions from various lines of evidence. (a) Decadal average results are shown over all CMIP5 EMIC and ESMs for each RCP respectively, with coloured lines (multi-model average), decadal markers (dots) and with three decades (2001–2010, 2041–2050 and 2091–2100) highlighted with a star, square and diamond, respectively. The historical time period up to decade 2001–2010 is taken from the CMIP5 historical runs prolonged by RCP8.5 for 2005–2010 and is indicated with a black thick line and black symbols. Coloured ranges illustrate the model spread (90% range) over all CMIP5 ESMs and EMICs and do not represent a formal uncertainty assessment. Ranges are filled as long as data of all models is available and until peak temperature. They are faded out for illustrative purposes afterward. CMIP5 simulations with 1% yr<sup>-1</sup> CO<sub>2</sub> increase only are illustrated by the dark grey area (range definition similar to RCPs above) and the black thin line (multi-model average). The light grey cone represents this report's assessment of the transient climate response to emissions (TCRE) from CO<sub>2</sub> only. Estimated cumulative historical CO<sub>2</sub> emissions from 1850 to 2011 with associated uncertainties are illustrated by the grey bar at the bottom of panel a. (b) Comparison of historical model results with observations. The magenta line and uncertainty ranges are based on observed emissions from CDIAC extended by values of the Global Carbon project until 2010 and observed temperature estimates of HadCRUT4. The uncertainties in the last decade of observations are based on the assessment in this report. The black thick line is identical to the one in panel a. The thin green line with crosses is as the black line but for ESMs only. The yellow-brown line and range show these ESM results until 2010, when corrected for HadCRUT4's incomplete geographical coverage over time. All values are given relative to the 1861–1880 base period. All time-series are derived from decadal averages to illustrate the long-term trends. Note that observations are in addition subject to internal climate variability, adding an uncertainty of about 0.1°C. (c) Cumulative CO<sub>2</sub> emissions over the entire industrial era, consistent with four illustrative peak global temperature limits (1.5°C, 2°C, 2.5°C, and 3°C, respectively) when taking into account warming by all forcings. Horizontal bars indicate consistent cumulative emission budgets as a function of the fraction of models (CMIP5 ESMs and EMICs) that at least hold warming below a given temperature limit. Note that the fraction of models cannot be interpreted as a probability. The budgets are derived from the RCP8.5 runs, with relative high non-CO<sub>2</sub> forcing over the 21st century. If non-CO<sub>2</sub> are significantly reduced, the CO<sub>2</sub> emissions compatible with a specific temperature limit might be slightly higher, but only to a very limited degree, as illustrated by the other coloured lines in panel a, which assume significantly lower non-CO<sub>2</sub> forcing. {Figure 12.45}

The climate system has multiple timescales, ranging from annual to multi-millennial, associated with different thermal and carbon reservoirs. These long time scales induce a commitment warming “already in the pipe-line”. Stabilization of the forcing would not lead to an instantaneous stabilization of the warming. For the RCP scenarios and their extensions to 2300, the fraction of realized warming, at that time when radiative forcing stabilizes, would be about 75 to 85% of the equilibrium warming. For a 1% yr<sup>-1</sup> CO<sub>2</sub> increase to 2 × CO<sub>2</sub> or 4 × CO<sub>2</sub> and constant forcing thereafter, the fraction of realized warming would much smaller, about 40 to 70% at the time when the forcing is kept constant. Due to the long timescales in the deep ocean, full equilibrium is reached only after hundreds to thousands of years.

The commitment to past emissions is a persistent warming for hundreds of years, continuing at about the level of warming that has been realized when emissions were ceased. The persistence of this CO<sub>2</sub>-induced warming after emission have ceased results from a compensation between the delayed commitment warming described above and the slow reduction in atmospheric CO<sub>2</sub> resulting from ocean and land carbon uptake. This persistence of warming also results from the nonlinear dependence of radiative forcing on atmospheric CO<sub>2</sub>, i.e., the relative decrease in forcing being smaller than the relative decrease in CO<sub>2</sub> concentration. For high climate sensitivities, and in particular if sulphate aerosol emissions are eliminated at the same time as greenhouse gas emissions, the commitment from past emission can be strongly positive, and is a superposition of a fast response to reduced aerosols emissions and a slow response to reduced CO<sub>2</sub>. {12.5.4}

Stabilization of global temperature does not imply stabilization for all aspects of the climate system. Processes related to vegetation change, changes in the ice sheets, deep ocean warming and associated sea level rise and potential feedbacks linking for example ocean and the ice sheets have their own intrinsic long timescales. Ocean acidification will *very likely* continue in the future as long as the oceans will continue to take up atmospheric CO<sub>2</sub>. Committed land ecosystem carbon cycle changes will manifest themselves further beyond the end of the 21st century. It is *virtually certain* that global mean sea level rise will continue beyond 2100, with sea level rise due to thermal expansion to continue for centuries to millennia. Global mean sea level rise depends on the pathway of CO<sub>2</sub> emissions, not only on the cumulative total; reducing emissions earlier rather than later, for the same cumulative total, leads to a larger mitigation of sea level rise. {6.4.4, 12.5.4, 13.5.4}

## [START BOX TS.7 HERE]

### Box TS.7: Climate Geoengineering Methods

Geoengineering is defined as the deliberate large-scale intervention in the Earth system to counter undesirable impacts of climate change on the planet. Carbon Dioxide Reduction (CDR) aims to slow or perhaps reverse projected increases in the future atmospheric CO<sub>2</sub> concentrations, accelerating the natural removal of atmospheric CO<sub>2</sub> and increasing the storage of carbon in land, ocean and geological reservoirs. Solar Radiation Management (SRM) aims to counter the warming associated with increasing greenhouse gas concentrations by reducing the amount of sunlight absorbed by the climate system. A related technique seeks to deliberately decrease the greenhouse effect in the climate system by altering high-level cloudiness. {6.5, 7.7; FAQ 7.3}

CDR methods could provide mitigation of climate change if CO<sub>2</sub> can be reduced, but there are uncertainties, side effects and risks, and implementation would depend on technological maturity along with economic, political and ethical considerations. CDR would need to be deployed at large-scale and over at least one century to be able to significantly reduce CO<sub>2</sub> concentrations. There are biogeochemical, and currently technical limitations that make it difficult to provide quantitative estimates of the potential for CDR. CO<sub>2</sub> removals from the atmosphere by CDR would be partially offset by outgassing of CO<sub>2</sub> previously stored in ocean and terrestrial carbon reservoirs. Some of the climatic and environmental side effects of CDR methods are associated with altered surface albedo from afforestation, ocean de-oxygenation from ocean fertilization, and enhanced N<sub>2</sub>O emissions. Land-based CDR methods would probably face competing demands for land. The level of confidence on the effectiveness of CDR methods and their side effects on carbon and other biogeochemical cycles is *low*. {6.5; Box 6.2; FAQ 7.3}

Solar Radiation Management (SRM) remains unimplemented and untested but, if realisable, could offset a global temperature rise and some of its effects. There is *medium confidence* that SRM through stratospheric aerosol injection is scalable to counter the radiative forcing (RF) and some of the climate effects expected from a twofold increase in CO<sub>2</sub> concentration. There is no consensus on whether a similarly large RF could be achieved from cloud brightening SRM due to insufficient understanding of aerosol-cloud interactions. It does not appear that land albedo change SRM could produce a large RF. Limited literature on other SRM methods precludes their assessment. {7.7.2, 7.7.3}

Numerous side effects, risks and shortcomings from SRM have been identified. SRM would produce an inexact compensation for the RF by greenhouse gases. Several lines of evidence indicate that SRM would



produce a small but significant decrease in global precipitation (with larger differences on regional scales) if the global surface temperature were maintained. Another side effect that is relatively well characterised is the likelihood of modest polar stratospheric ozone depletion associated with stratospheric aerosol SRM. There could also be other as yet unanticipated consequences {7.6.3, 7.7.3, 7.7}

As long as greenhouse gas concentrations continued to increase, the SRM would require commensurate increase, exacerbating side effects. Additionally, scaling SRM to substantial levels would carry the risk that if the SRM were terminated for any reason, there is *high confidence* that surface temperatures would increase rapidly (within a decade or two) to values consistent with the greenhouse gas forcing, which would stress systems sensitive to the rate of climate change. Finally, SRM would not compensate for ocean acidification from increasing CO<sub>2</sub>. {7.7.3, 7.7.4}

**[END BOX TS.7 HERE]**

### **TS.5.7 Long-Term Projections of Sea Level Change**

#### **TS.5.7.1 Projections of Global Mean Sea Level Change for the 21st Century**

Global mean sea level rise for 2081–2100 (relative to 1986–2005) for the RCPs will *likely* be in the 5–95% ranges derived from CMIP5 climate projections in combination with process-based models of glacier and ice-sheet SMB, with possible ice-sheet dynamical changes assessed from the published literature. These *likely* ranges are 0.26 to 0.54 m (RCP2.6), 0.32 to 0.62 m (RCP4.5), 0.33 to 0.62 m (RCP6.0), 0.45 to 0.81 (RCP8.5) m (*medium confidence*) (see Table TS.1 and Figure TS.21). For RCP8.5 the range at 2100 is 0.53 to 0.97 m. The central projections for global mean sea level rise in all scenarios lie within a range of 0.05 m until the middle of the century, when they begin to diverge; by the end of the century, they have a spread of about 0.3 m. Although RCP4.5 and RCP6.0 are very similar at the end of the century, RCP4.5 has a greater rate of rise earlier in the century than RCP6.0. GMSL rise depends on the pathway of CO<sub>2</sub> emissions, not only on the cumulative total; reducing emissions earlier rather than later, for the same cumulative total, leads to a larger mitigation of sea level rise. {12.4.1, 13.4.1, 13.5.1; Table 13.5}

**[INSERT FIGURE TS.21 HERE]**

**Figure TS.21:** Projections from process-based models with *likely* ranges and median values for global mean sea level rise and its contributions in 2081–2100 relative to 1986–2005 for the four RCP scenarios and scenario SRES A1B used in the AR4. The contributions from ice sheets include the contributions from ice-sheet rapid dynamical change, which are also shown separately. The contributions from ice-sheet rapid dynamics and anthropogenic land water storage are treated as having uniform probability distributions, and as independent of scenario (except that a higher rate of change is used for Greenland ice-sheet outflow under RCP8.5). This treatment does not imply that the contributions concerned will not depend on the scenario followed, only that the current state of knowledge does not permit a quantitative assessment of the dependence. See discussion in Sections 13.5.1 and 13.5.3 and Supplementary Material for methods. Based on current understanding, only the collapse of the marine-based sectors of the Antarctic Ice Sheet, if initiated, could cause global mean sea level to rise substantially above the *likely* range during the 21st century. This potential additional contribution cannot be precisely quantified but there is *medium confidence* that it would not exceed several tenths of a meter during the 21st century. {Figure 13.10}

**[INSERT FIGURE TS.22 HERE]**

**Figure TS.22:** Projections from process-based models of global mean sea level rise relative to 1986–2005 for the four emissions scenarios RCP2.6, RCP4.5, RCP6.0 and RCP8.5. The solid lines show the median projections, the dashed lines show the *likely* ranges for RCP4.5 and RCP6.0, and the shading the *likely* ranges for RCP2.6 and RCP8.5. The time means for 2081–2100 are shown as coloured vertical bars. See Sections 13.5.1 and 13.5.3 and Supplementary Material for methods. Based on current understanding, only the collapse of the marine-based sectors of the Antarctic Ice Sheet, if initiated, could cause global mean sea level to rise substantially above the *likely range* during the 21st century. This potential additional contribution cannot be precisely quantified but there is *medium confidence* that it would not exceed several tenths of a meter during the 21st century. {Table 13.5; Figures 13.10, 13.11}

Confidence in the projected *likely* ranges comes from the consistency of process-based models with observations and physical understanding. The basis for higher projections has been considered and it has been concluded that there is currently insufficient evidence to evaluate the probability of specific levels above the *likely* range. Based on current understanding, only the collapse of marine-based sectors of the Antarctic ice sheet, if initiated, could cause GMSL to rise substantially above the *likely* range during the 21st

century. There is a lack of consensus on the probability for such a collapse, and the potential additional contribution to GMSL rise cannot be precisely quantified, but there is *medium confidence* that it would not exceed several tenths of a meter of sea level rise during the 21st century. {13.5.1, 13.5.3}

Under all the RCP scenarios, the time-mean rate of global mean sea level rise during the 21st century is *very likely* to exceed the rate observed during 1971–2010. In the projections, the rate of rise initially increases. In RCP2.6 it becomes roughly constant (central projection  $\sim 4.5$  mm yr<sup>-1</sup>) before the middle of the century, and subsequently declines slightly. The rate of rise becomes roughly constant in RCP4.5 and RCP6.0 by the end of the century, whereas acceleration continues throughout the century in RCP8.5 (reaching 11 [7 to 15] mm yr<sup>-1</sup> during 2081–2100). {13.5.1; Table 13.5}

In all RCP scenarios, thermal expansion is the largest contribution, accounting for about 30–55% of the total. Glaciers are the next largest. By 2100, 15–55% of the present glacier volume is projected to be eliminated under RCP2.6, and 35 to 85% under RCP8.5 (*medium confidence*). The increase in surface melting in Greenland is projected to exceed the increase in accumulation, and there is *high confidence* that the surface mass balance changes on the Greenland ice sheet will make a positive contribution to sea level rise over the 21st century. On the Antarctic ice sheet, surface melting is projected to remain small, while there is *medium confidence* that snowfall will increase (Figure TS.21). {13.3.3, 13.4.3, 13.4.4, 13.5.1; Table 13.5}

There is *medium confidence* in the ability to model future rapid changes in ice-sheet dynamics on decadal timescales. At the time of the AR4, scientific understanding was not sufficient to allow an assessment of the possibility of such changes. Since the publication of the AR4, there has been substantial progress in understanding the relevant processes as well as in developing new ice-sheet models that are capable of simulating them. However, the published literature as yet provides only a partially sufficient basis for making projections related to particular scenarios. In our projections of GMSL rise by 2081–2100, the *likely* range from rapid changes in ice outflow is 0.03 to 0.20 m from the two ice sheets combined, and its inclusion is the most important reason why the projections are greater than those given in the AR4. {13.1.5, 13.5.1, 13.5.3}

Semi-empirical models are designed to reproduce the observed sea level record over their period of calibration, but do not attribute sea level rise to its individual physical components. For RCPs, some semi-empirical models project a range that overlaps the process-based *likely* range while others project a median and 95-percentile that are about twice as large as the process-based models. In nearly every case, the semi-empirical model 95-percentile is higher than the process-based *likely* range. For 2081–2100 (relative to 1986–2005) under RCP4.5, semi-empirical models give median projections in the range 0.56 to 0.97 m, and their 95-percentiles extend to about 1.2 m. This difference implies either that there is some contribution which is presently unidentified or underestimated by process-based models, or that the projections of semi-empirical models are overestimates. Making projections with a semi-empirical model assumes that sea level change in the future will have the same relationship as it has had in the past to radiative forcing or global mean temperature change. This may not hold if potentially non-linear physical processes do not scale in the future in ways which can be calibrated from the past. There is no consensus in the scientific community about the reliability of SEM projections, and *confidence* in them is assessed to be *low*. {13.5.2, 13.5.3}

#### TS.5.7.2 Projections of Global Mean Sea Level Change Beyond 2100

It is *virtually certain* that global mean sea level rise will continue beyond 2100. The few available model results indicate global mean sea level rise by 2300 to be less than 1 m for greenhouse gas concentrations that peak and decline and do not exceed 500 ppm CO<sub>2</sub>-equivalent but 1 to 3 m for concentrations above 700 ppm CO<sub>2</sub>-equivalent (*medium confidence*). Sea-level rise of 1 to 3 m per degree of warming is expected if the warming is sustained for several millennia (*low confidence*). {13.5.4}

Sea level rise due to ocean thermal expansion will continue for centuries to millennia. The amount of ocean thermal expansion increases with global warming (models give a range of 0.2 to 0.6 m °C<sup>-1</sup>). The glacier contribution decreases over time as their volume (currently  $\sim 0.43$  m sea level equivalent) decreases. In Antarctica, beyond 2100 and with higher greenhouse gas scenarios, the increase in surface melting could exceed the increase in accumulation. {13.5.2, 13.5.4}

The available evidence indicates that global warming greater than a certain threshold would lead to the near-complete loss of the Greenland Ice Sheet over a millennium or more, causing a global mean sea level rise of about 7 m. Studies with fixed present-day ice sheet topography indicate the threshold is greater than 2°C but less than 4°C of global mean surface temperature rise with respect to preindustrial. Taking into account the increased vulnerability of the ice sheet as the surface elevation decreases due to the loss of ice, a study with a dynamical ice sheet suggests the threshold could be as low as 1°C. Considering the present state of scientific uncertainty, a *likely* range cannot be quantified. The complete loss of the ice sheet is not inevitable because this would take a millennium or more; if temperatures decline before the ice sheet is eliminated, the ice sheet might regrow. However, some part of the mass loss might be irreversible, depending on the duration and degree of exceedance of the threshold, because the ice sheet may have multiple steady states, due to its interaction with its regional climate. {13.4.3, 13.5.4}

Currently available information indicates that the dynamical contribution of the ice sheets will continue beyond 2100, but *confidence* in projections is *low*. In Greenland, ice outflow induced from interaction with the ocean is self-limiting as the ice-sheet margin retreats inland from the coast. By contrast, the bedrock topography of Antarctica is such that there may be enhanced rates of mass loss as the ice retreats. About 3.3 m of equivalent global sea level of the West Antarctic ice sheet is grounded on areas with downward sloping bedrock, which may be subject to potential ice loss via the marine ice-sheet instability. Due to relatively weak snowfall on Antarctica and the slow ice motion in its interior, it can be expected that the West Antarctic ice sheet would take at least several thousand years to regrow if it was eliminated by dynamic ice discharge. Consequently any significant ice loss from West Antarctic that occurs within the next century will be irreversible on a multi-centennial to millennial time scale. {13.4.4, 13.5.4}

#### TS.5.7.3 Projections of Regional Sea Level Change

Regional sea level will change due to dynamical ocean circulation changes, changes in the heat content of the ocean, mass redistribution in the entire Earth system, and changes in atmospheric pressure. Ocean dynamical change results from changes in wind and buoyancy forcing (heat and freshwater), associated changes in the circulation, and redistribution of heat and freshwater. Over timescales longer than a few days, regional sea level also adjusts nearly isostatically to regional changes in sea level atmospheric pressure relative to its mean over the ocean. Ice-sheet mass loss (both contemporary and past), glacier mass loss and changes in terrestrial hydrology cause water mass redistribution among the cryosphere, the land and the oceans, giving rise to distinctive regional changes in the solid Earth, Earth rotation and the gravity field. In some coastal locations, changes in the hydrological cycle, ground subsidence associated with anthropogenic activity, tectonic processes, and coastal processes can dominate the relative sea level change, i.e., the change in sea surface height relative to the land. {13.1.3, 13.6.2, 13.6.3, 13.6.4}

By the end of the 21st century, sea level change will have a strong regional pattern, which will dominate over variability, with many regions *likely* experiencing substantial deviations from the global mean change (Figure TS.23). It is *very likely* that over about 95% of the ocean will experience regional sea level rise, while most regions experiencing a sea level fall are located near current and former glaciers and ice sheets. Local sea level changes deviate more than 10% and 25% from the global mean projection for as much as 30% and 9% of the ocean area, respectively, indicating that spatial variations can be very large. Regional changes in sea level reach values of up to 30% above the global mean value in the Southern Ocean and around North America, between 10% to 20% in equatorial regions, and up to 50% below the global mean in the Arctic region and some regions near Antarctica. About 70% of the coastlines worldwide are projected to experience a sea level change within 20% of the global mean sea level change. Over decadal periods, the rates of regional sea level change as a result of climate variability can differ from the global average rate by more than 100%. {13.6.5}

#### [INSERT FIGURE TS.23 HERE]

**Figure TS.23:** Ensemble mean net regional sea level change (m) evaluated from 21 CMIP5 models for the RCP scenarios (a) 2.6, (b) 4.5, (c) 6.0 and (d) 8.5 between 1986–2005 and 2081–2100. Each map includes effects of atmospheric loading, plus land-ice, GIA and terrestrial water sources. {Figure 13.20}

#### TS.5.7.4 Projections of Change in Sea Level Extremes and Waves During the 21st Century

It is *very likely* that there will be a significant increase in the occurrence of future sea level extremes (see also TFE.9, Table 1). This increase will primarily be the result of an increase in mean sea level (*high confidence*), with extreme return periods decreasing by at least an order of magnitude in some regions by the end of the 21st century. There is *low confidence* in region-specific projections of storminess and associated storm surges. {13.7.2}

It is *likely (medium confidence)* that annual mean significant wave heights will increase in the Southern Ocean as a result of enhanced wind speeds. Southern-Ocean generated swells are *likely* to affect heights, periods, and directions of waves in adjacent basins. It is *very likely* that wave heights and the duration of the wave season will increase in the Arctic Ocean as a result of reduced sea-ice extent. In general, there is *low confidence* in region-specific projections due to the *low confidence* in tropical and extratropical storm projections, and to the challenge of down-scaling future wind states from coarse resolution climate models. {13.7.3}

### **TS.5.8 Climate Phenomena and Regional Climate Change**

This section assesses projected changes over the 21st century in large-scale climate phenomena that affect regional climate (Table TS.2). Some of these phenomena are defined by climatology (e.g., monsoons), and some by interannual variability (e.g., El Niño), the latter affecting climate extremes such as floods, droughts and heat waves. Changes in statistics of weather phenomena such as tropical cyclones and extratropical storms are also summarized here. {14.8}

#### **[INSERT TABLE TS.2 HERE]**

**Table TS.2:** Overview of projected regional changes and their relation to major climate phenomena. A phenomenon is considered relevant when there is both sufficient confidence that it has an influence on the given region, and when there is sufficient confidence that the phenomenon will change, particularly under the RCP4.5 or higher end scenarios. See Section 14.8 and Table 14.2 for full assessment of the confidence in these changes, and their relevance for regional climate. {14.8; Table 14.2}

#### **TS.5.8.1 Monsoon Systems**

Global measures of monsoon by the area and summer precipitation are *likely* to increase in the 21st century, while the monsoon circulation weakens. Monsoon onset dates are *likely* to become earlier or not to change much while monsoon withdrawal dates are *very likely* to delay, resulting in a lengthening of the monsoon season (Figure TS.24). The increase in seasonal-mean precipitation is pronounced in the East and South Asian summer monsoons while the change in other monsoon regions is subject to larger uncertainties. {14.2.1}

#### **[INSERT FIGURE TS.24 HERE]**

**Figure TS.24:** Future change in monsoon statistics between the present-day (1986–2005) and the future (2080–2099) based on CMIP5 ensemble from RCP2.6 (dark blue; 19 models), RCP4.5 (blue; 24), RCP6.0 (yellow; 14), and RCP8.5 (red; 24) simulations. (a) GLOBAL: Global monsoon area (GMA), global monsoon intensity (GMI), standard deviation of inter-annual variability in seasonal precipitation (Psd), seasonal maximum 5-day precipitation total (R5d), and monsoon season duration (DUR). Regional land monsoon domains determined by 24 multi-model mean precipitation in the present-day. (b)-(h) Future change in regional land monsoon statistics: seasonal average precipitation (Pav), Psd, R5d, and DUR in (b) North America (NAMS), (c) North Africa (NAF), (d) South Asia (SAS), (e) East Asia (EAS), (f) Australia-Maritime continent (AUSMC), (g) South Africa (SAF), and (h) South America (SAMS). Units are % except for DUR (days). Box-whisker plots show the 10th, 25th, 50th, 75th, and 90th percentiles. All the indices are calculated for the summer season (May–September for the Northern, and November–March for the Southern Hemisphere) over each model's monsoon domains. {Figures 14.3, 14.4, 14.6, 14.7}

There is *medium confidence* that monsoon-related interannual rainfall variability will increase in the future. Future increase in precipitation extremes related to the monsoon is *very likely* in South America, Africa, East Asia, South Asia, Southeast Asia and Australia. {14.2.1, 14.8.5, 14.8.7, 14.8.9, 14.8.11, 14.8.12, 14.8.13}

There is *medium confidence* that overall precipitation associated with the Asian-Australian monsoon will increase but with a north-south asymmetry: Indian monsoon rainfall is projected to increase, while projected changes in the Australian summer monsoon rainfall are small. There is *medium confidence* in that the Indian summer monsoon circulation weakens, but this is compensated by increased atmospheric moisture content,

leading to more rainfall. For the East Asian summer monsoon, both monsoon circulation and rainfall are projected to increase. {14.2.2, 14.8.9, 14.8.11, 14.8.13}

There is *low confidence* in projections of the North American and South American monsoon precipitation changes, but *medium confidence* that the North American monsoon will arrive and persist later in the annual cycle, and *high confidence* in expansion of South American Monsoon area. {14.2.3, 14.8.3, 14.8.4; 14.8.5}

There is *low confidence* in projections of a small delay in the West African rainy season, with an intensification of late-season rains. The limited skills of model simulations for the region suggest *low confidence* in the projections. {14.2.4, 14.8.7}

### TS.5.8.2 Tropical Phenomena

It is *virtually certain* that precipitation change will vary in space, increasing in some regions and decreasing in some others. The spatial distribution of tropical rainfall changes is *likely* shaped by the current climatology and ocean warming pattern. The first effect is to increase rainfall near the currently rainy regions, and the second effect increases rainfall where the ocean warming exceeds the tropical mean. There is *medium confidence* that tropical rainfall projections are more reliable for the seasonal than annual-mean changes. {7.6.2, 12.4.5, 14.3.1}

There is *medium confidence* in future increase in seasonal-mean precipitation on the equatorial flank of the Inter-Tropical Convergence Zone and a decrease in precipitation in the subtropics including parts of North and Central Americas, the Caribbean, South America, Africa and West Asia. There is *medium confidence* that the interannual occurrence of zonally-oriented South Pacific Convergence Zone events will increase, leading possibly to more frequent droughts in the southwest Pacific. There is *medium confidence* that the South Atlantic Convergence Zone will shift southwards, leading to a precipitation increase over southeastern South America and a reduction immediately north of the convergence zone. {14.3.1, 14.8.3, 14.8.4, 14.8.5, 14.8.7, 14.8.11, 14.8.14}

The tropical Indian Ocean is *likely* to feature a zonal pattern with reduced warming and decreased rainfall in the east (including Indonesia), and enhanced warming and increased rainfall in the west (including East Africa). The Indian Ocean dipole mode of interannual variability is *very likely* to remain active, affecting climate extremes in East Africa, Indonesia, and Australia. {14.3.3, 14.8.7, 14.8.12}

There is *low confidence* in the projections for the tropical Atlantic - both for the mean and interannual modes, because of large errors in model simulations in the region. Future projections in Atlantic hurricanes, tropical South American and West African precipitation are therefore of *low confidence*. {14.3.4, 14.6.1, 14.8.5 and 14.8.7}

There is *low confidence* in projections of future changes in the Madden-Julian Oscillation due to the poor skill in model simulations of this intraseasonal phenomenon and the sensitivity to ocean warming patterns. Future projections of regional climate extremes in West Asia, Southeast Asia and Australia are therefore of *low confidence*. {9.5.2, 14.3.4, 14.8.10, 14.8.12, 14.8.13}

### TS.5.8.3 El Niño-Southern Oscillation

El Niño-Southern Oscillation *very likely* remains as a dominant mode of interannual variability in the future and regional rainfall variability it induces *likely* intensifies. Natural modulations of the variance and spatial pattern of El Niño-Southern Oscillation are so large that confidence in any projected change for the 21st century remains *low*. The projected change in El Niño amplitude is small for both RCP4.5 and RCP8.5 compared to the spread of the change among models (Figure TS.25). Over the North Pacific and North America, patterns of temperature and precipitation anomalies related to El Niño and La Niña (teleconnections) are *likely* to move eastwards in the future, while confidence is *low* in changes in climate impacts on other regions including Central and South Americas, the Caribbean, Africa, most of Asia, Australia and most Pacific Islands. {14.4, 14.8.3, 14.8.4, 14.8.5, 14.8.7, 14.8.9, 14.8.11, 14.8.12, 14.8.13, 14.8.14}

**[INSERT FIGURE TS.25 HERE]**

**Figure TS.25:** Standard deviation in CMIP5 multi-model ensembles of sea surface temperature variability over the eastern equatorial Pacific Ocean (Nino3 region: 5°S–5°N, 150°W–90°W), a measure of El Niño amplitude, for the pre-industrial (PI) control and 20th century (20C) simulations, and 21st century projections using RCP4.5 and RCP8.5. Open circles indicate multi-model ensemble means, and the red cross symbol is the observed standard deviation for the 20th century. Box-whisker plots show the 16th, 25th, 50th, 75th, and 84th percentiles. {Figure 14.14}

*TS.5.8.4 Cyclones*

Projections for the 21st century indicate that it is *likely* that the global frequency of tropical cyclones will either decrease or remain essentially unchanged, concurrent with a *likely* increase in both global mean tropical cyclone maximum wind speed and rain rates (Figure TS.26). The influence of future climate change on tropical cyclones is *likely* to vary by region, but there is *low confidence* in region-specific projections. The frequency of the most intense storms will *more likely than not* increase substantially in some basins. More extreme precipitation near the centers of tropical cyclones making landfall are *likely* in North and Central America, East Africa, West, East, South and Southeast Asia as well as in Australia and many Pacific islands. {14.6.1, 14.8.3, 14.8.4, 14.8.7, 14.8.9, 14.8.10, 14.8.11, 14.8.12, 14.8.13, 14.8.14}

**[INSERT FIGURE TS.26 HERE]**

**Figure TS.26:** Projected changes in tropical cyclone statistics. All values represent expected percent change in the average over period 2081–2100 relative to 2000–2019, under an A1B-like scenario, based on expert judgment after subjective normalisation of the model projections. Four metrics were considered: the percent change in I) the total annual frequency of tropical storms, II) the annual frequency of Category 4 and 5 storms, III) the mean Lifetime Maximum Intensity (LMI; the maximum intensity achieved during a storm's lifetime), and IV) the precipitation rate within 200 km of storm center at the time of LMI. For each metric plotted, the solid blue line is the best guess of the expected percent change, and the coloured bar provides the 67% (likely) confidence interval for this value (note that this interval ranges across –100% to +200% for the annual frequency of Category 4 and 5 storms in the North Atlantic). Where a metric is not plotted, there is insufficient data (denoted “X”) available to complete an assessment. A randomly drawn (and coloured) selection of historical storm tracks are underlaid to identify regions of tropical cyclone activity. See Section 14.6.1 for details. {14.6.1}

The global number of extra-tropical cyclones is *unlikely* to decrease by more than a few percent and future changes in storms are *likely* to be small compared to natural interannual variability and substantial variations between models. A small poleward shift is *likely* in the Southern Hemisphere storm track but the magnitude of this change is model-dependent. It is *unlikely* that the response of the North Atlantic storm track in climate projections is a simple poleward shift. There is *medium confidence* in a projected poleward shift in the North Pacific storm track. There is *low confidence* in the impact of storm track changes on regional climate at the surface. More precipitation in extra-tropical cyclones leads to a winter precipitation increase in Arctic, Northern Europe, North America, and the mid-high latitude Southern Hemisphere. {11.3.2, 12.4.4, 14.6.2, 14.8.2, 14.8.3, 14.8.5, 14.8.6, 14.8.13, 14.8.15}

*TS.5.8.5 Annular and Dipolar Modes of Variability*

Future boreal wintertime North Atlantic Oscillation is *very likely* to exhibit large natural variations as observed in the past. The North Atlantic Oscillation is *likely* to become slightly more positive (on average), with some, but not very well documented implications for winter conditions in the Arctic, North America and Eurasia. The austral summer/autumn positive trend in Southern Annular Mode is *likely* to weaken considerably as stratospheric ozone recovers through the mid-21st century with some, but not very well documented, implications for South America, Africa, Australia, New Zealand and Antarctica. {11.3.2, 14.5.2 and 14.8.5, 14.8.7, 14.8.13, 14.8.15}

*TS.5.8.6 Additional Phenomena*

It is *unlikely* that the Atlantic Multi-Decadal Oscillation will change its behaviour as the mean climate changes. However, natural fluctuations in the Atlantic Multi-Decadal Oscillation over the coming few decades are *likely* to influence regional climates at least as strongly as will human-induced changes with implications for Atlantic major hurricane frequency, the West African monsoon, North American and European summer conditions. {14.2.4, 14.5.1, 14.6.1, 14.7.6, 14.8.2, 14.8.3, 14.8.6, 14.8.8}

There is *medium confidence* that the frequency of Northern and Southern Hemisphere blocking will not increase, but *confidence is low* in the trends in blocking intensity and persistence. {Box 14.2}

### TFE.9: Climate Extremes

Assessing changes in climate extremes poses unique challenges, not just because of the intrinsically rare nature of these events, but because they invariably happen in conjunction with disruptive conditions. They are strongly influenced by both small and large-scale weather patterns, modes of variability, thermodynamic processes, land-atmosphere feedbacks and antecedent conditions. Much progress has been made since AR4 including the comprehensive assessment of extremes undertaken by the IPCC Special Report on Managing the Risk of Extreme Events and Disasters to Advance Climate Change Adaptation (SREX) but also due to the amount of observational evidence available, improvements in our understanding and the ability of models to simulate extremes. {1.3.3, 2.6, 7.6, 9.5.4}

For some climate extremes such as droughts, floods and heat waves, several factors need to be combined to produce an extreme event. Analyses of rarer extremes such as 1-in-20 to 1-in-100 year events using Extreme Value Theory are making their way into a growing body of literature. Other recent advances concern the notion of “fraction of attributable risk” that aims to link a particular extreme event to specific causal relationships. {1.3.3, 2.6.1, 2.6.2, 10.6.2, 12.4.3; Box 2.4}

TFE.9, Table 1 indicates the changes that have been observed in a range of weather and climate extremes over the last 50 years, the assessment of the human contribution to those changes, and how those extremes are expected to change in the future. The table also compares the current assessment with that of the AR4 and the SREX where applicable. {2.6, 3.7, 10.6, 11.3, 12.4, 14.6}

#### [INSERT TFE.9, TABLE 1 HERE]

**TFE.9, Table 1:** Extreme weather and climate events: Global-scale assessment of recent observed changes, human contribution to the changes, and projected further changes for the early (2016–2035) and late (2081–2100) 21st century. Bold indicates where the AR5 (black) provides a revised\* global-scale assessment from the SREX (blue) or AR4 (red). Projections for early 21st century were not provided in previous assessment reports. Projections in the AR5 are relative to the reference period of 1986–2005, and use the new RCP scenarios.

#### *Temperature Extremes, Heat Waves and Warm Spells*

It is *very likely* that both maximum and minimum temperature extremes have warmed over most land areas since the mid-20th century. These changes are well simulated by current climate models, and it is *very likely* that anthropogenic forcing has affected the frequency of these extremes and *virtually certain* that further changes will occur. This supports AR4 and SREX conclusions although with greater confidence in the anthropogenic forcing component. {2.6.1, 9.5.4, 10.6.1, 12.4.3}

For land areas with sufficient data there has been an overall increase in the number of warm days and nights. Similar decreases are seen in the number of cold days and nights. It is *very likely* that increases in unusually warm days and nights and/or reductions in unusually cold days and nights including frosts have occurred over this period across most continents. Warm spells or heat waves containing consecutive extremely hot days or nights are often associated with quasi-stationary anticyclonic circulation anomalies and are also affected by pre-existing soil conditions and the persistence of soil moisture anomalies that can amplify or dampen heat waves particularly in moisture-limited regions. Most global land areas, with a few exceptions, have experienced more heat waves since the middle of the 20th century. Several studies suggest that increases in mean temperature account for most of the changes in heat wave frequency, however, heat wave intensity/amplitude is highly sensitive to changes in temperature variability and the shape of the temperature distribution and heat wave definition also plays a role. While in some regions instrumental periods prior to the 1950s had more heat waves (e.g., USA), for other regions such as Europe, an increase in heat wave frequency in the period since the 1950s stands out in long historical temperature series. {2.6, 2.6.1, 5.5.1; Box 2.4; Table 2.12, 2.13; FAQ 2.2}

The observed features of temperature extremes and heat waves are well simulated by climate models and are similar to the spread amongst observationally-based estimates in most regions. Regional downscaling now

offers credible information on the spatial scales required for assessing extremes and improvements in the simulation of the El Niño-Southern Oscillation from CMIP3 to CMIP5 and other large-scale phenomenon is crucial. However simulated changes in frequency and intensity of extreme events is limited by observed data availability and quality issues and by the ability of models to reliably simulate certain feedbacks and mean changes in key features of circulation such as blocking. {2.6, 2.7, 9.4, 9.5.3, 9.5.4, 9.6, 9.6.1, 10.3, 10.6, 14.4; Box 14.2}

Since AR4, the understanding of mechanisms and feedbacks leading to changes in extremes has improved. There continues to be strengthening evidence for a human influence on the observed frequency of extreme temperatures and heat waves in some regions. Near-term (decadal) projections suggest *likely* increases in temperature extremes but with little distinguishable separation between emissions scenarios (TFE.9, Figure 1). Changes may proceed at a different rate than the mean warming however, with several studies showing that projected European high-percentile summer temperatures will warm faster than mean temperatures. Future changes associated with the warming of temperature extremes in the long-term are *virtually certain* and scale with the strength of emissions scenario i.e., greater anthropogenic emissions correspond to greater warming of extremes (TFE.9, Figure 1). For high emissions scenarios, it is *likely* that, in most land regions, a current one-in-20 year maximum temperature event will at least double in frequency but in many regions will become an annual or a one-in-two year event by the end of the 21st century. The magnitude of both high and low temperature extremes is expected to increase at least at the same rate as the mean, but with 20-year return values for low temperature events projected to increase at a rate greater than winter mean temperatures in most regions. {10.6.1, 11.3.2, 12.4.3}

#### [INSERT TFE.9, FIGURE 1 HERE]

**TFE.9, Figure 1:** Global projections of the occurrence of (a) cold days (TN10p)- percentage of days annually with daily maximum surface air temperature (Tmax) below the 10th percentile of Tmax for 1961 to 1990, (b) wettest consecutive 5 days (RX5day) - percentage change in annual maximum consecutive 5-day precipitation totals, (c) warm days (TX90p)-percentage of days annually with daily maximum surface air temperature (Tmax) exceeding the 90th percentile of Tmax for 1961 to 1990 and (d) very wet day precipitation (R95p) - percentage change relative to 1986–2005 of annual precipitation from days >95th percentile. Results are shown from CMIP5 for the RCP2.6, RCP4.5 and RCP8.5 scenarios. Solid lines indicate the ensemble median and shading indicates the interquartile spread between individual projections (25th and 75th percentiles). Maps show (e) the change from 1986–2005 to 2081–2100 in twenty year return values (RV) of daily maximum temperatures, TXx, and (f) the 2081–2100 return period (RP) for rare daily precipitation values, RX1day, that have a 20 year return period during 1986–2005. Both maps are based on the CMIP5 RCP8.5 scenario. See Box 2.4, Table 1 for index definitions. {Figures 11.17, 12.13, 12.26}

#### *Precipitation Extremes*

It is *likely* that the number of heavy precipitation events over land has increased in more regions than it has decreased in since the mid-20th century, and there is *medium confidence* that anthropogenic forcing has contributed to this increase. {2.6.2, 10.6.1}

There has been substantial progress between CMIP3 and CMIP5 in the ability of models to simulate more realistic precipitation extremes. However, evidence suggests that the majority of models underestimate the sensitivity of extreme precipitation to temperature variability or trends especially in the tropics which implies that models may underestimate the projected increase in extreme precipitation in the future. While progress has been made in understanding the processes that drive extreme precipitation, challenges remain in quantifying cloud and convective effects in models for example. The complexity of land-surface and atmospheric processes limits confidence in regional projections of precipitation change, especially over land, although there is a component of a “wet-get-wetter” and “dry-get-drier” response over oceans at the large scale. Even so, there is *high confidence* that, as the climate warms, extreme precipitation rates (e.g., on daily timescales) will increase faster than the time average. Changes in local extremes on daily and sub-daily timescales are expected to increase by roughly 5 to 10% per °C of warming (*medium confidence*). {7.6, 9.5.4}

For the near- and long-term, CMIP5 projections confirm a clear tendency for increases in heavy precipitation events in the global mean seen in the AR4, but there are substantial variations across regions (TFE.9, Figure 1). Over most of the mid-latitude land-masses and over wet tropical regions, extreme precipitation will *very likely* be more intense and more frequent in a warmer world. {11.3.2, 12.4.5}



### ***Floods and Droughts***

There continues to be a lack of evidence and thus *low confidence* regarding the sign of trend in the magnitude and/or frequency of floods on a global scale over the instrumental record. There is *high confidence* that past floods larger than those recorded since 1900 have occurred during the past five centuries in northern and central Europe, western Mediterranean region, and eastern Asia. There is *medium confidence* that modern large floods are comparable to or surpass historical floods in magnitude and/or frequency in the Near East, India, and central North America. {2.6.2, 5.5.5}

Compelling arguments both for and against significant increases in the land area affected by drought and/or dryness since the mid-20th century have resulted in a *low confidence* assessment of observed and attributable large-scale trends. This is primarily due to a lack and quality of direct observations, dependencies of inferred trends on the index choice, geographical inconsistencies in the trends and difficulties in distinguishing decadal scale variability from long term trends. On millennial timescales, there is *high confidence* that proxy information provides evidence of droughts of greater magnitude and longer duration than observed during the 20th century in many regions. There is *medium confidence* that more megadroughts occurred in monsoon Asia and wetter conditions prevailed in arid Central Asia and the South American monsoon region during the Little Ice Age (1450 to 1850) compared to the Medieval Climate Anomaly (950 to 1250). {2.6.2, 5.5.4, 5.5.5, 10.6.1}

Under the RCP8.5 scenario, projections by the end of the century indicate an increased risk of drought is *likely (medium confidence)* in presently dry regions linked to regional to global-scale projected decreases in soil moisture. Soil moisture drying is most prominent in the Mediterranean, Southwest US, and southern Africa, consistent with projected changes in the Hadley circulation and increased surface temperatures, and surface drying in these regions is *likely (high confidence)* by the end of the century under the RCP8.5 scenario. {12.4.5}

### ***Extreme Sea Level***

It is *likely* that the magnitude of extreme high sea level events has increased since 1970 and that most of this rise can be explained by increases in mean sea level. When mean sea level changes is taken into account, changes in extreme high sea levels are reduced to less than 5 mm yr<sup>-1</sup> at 94% of tide gauges. In the future it is *very likely* that there will be a significant increase in the occurrence of sea level extremes and similarly to past observations, this increase will primarily be the result of an increase in mean sea level. {3.7.5, 13.7.2}

### ***Tropical and Extratropical Cyclones***

There is *low confidence* in long-term (centennial) changes in tropical cyclone activity, after accounting for past changes in observing capabilities. However over the satellite era, increases in the frequency and intensity of the strongest storms in the North Atlantic are robust (*very high confidence*). However, the cause of this increase is debated and there is *low confidence* in attribution of changes in tropical cyclone activity to human influence due to insufficient observational evidence, lack of physical understanding of the links between anthropogenic drivers of climate and tropical cyclone activity and the low level of agreement between studies as to the relative importance of internal variability, and anthropogenic and natural forcings. {2.6.3, 10.6.1, 14.6.1}

Some high-resolution atmospheric models have realistically simulated tracks and counts of tropical cyclones and models generally are able to capture the general characteristics of storm tracks and extratropical cyclones with evidence of improvement since the AR4. Storm track biases in the North Atlantic have improved slightly, but models still produce a storm track that is too zonal and underestimate cyclone intensity. {9.4.1, 9.4.5}

While projections indicate that it is *likely* that the global frequency of tropical cyclones will either decrease or remain essentially unchanged, concurrent with a *likely* increase in both global mean tropical cyclone maximum wind speed and rainfall rates, there is lower confidence in region-specific projections of frequency and intensity. However, due to improvements in model resolution and downscaling techniques, it is *more*

*likely than not* that the frequency of the most intense storms will increase substantially in some basins under projected 21st century warming (see Figure TS.26). {11.3.2, 14.6.1}

Research subsequent to the AR4 and SREX continues to support a *likely* poleward shift of storm tracks since the 1950s. However over the last century there is *low confidence* of a clear trend in storminess due to inconsistencies between studies or lack of long-term data in some parts of the world (particularly in the Southern Hemisphere). {2.6.4, 2.7.6}

Despite systematic biases in simulating storm tracks, most models and studies are in agreement that the global number of extra-tropical cyclones is *unlikely* to decrease by more than a few per cent. A small poleward shift is *likely* in the Southern Hemisphere storm track. It is *more likely than not (medium confidence)* for a projected poleward shift in the North Pacific storm track but it is *unlikely* that the response of the North Atlantic storm track is a simple poleward shift. There is *low confidence* in the magnitude of regional storm track changes, and the impact of such changes on regional surface climate. {14.6.2}

## TS.6 Key Uncertainties

This final section of the Technical Summary provides the reader with a short overview of key uncertainties in the understanding of the climate system and the ability to project changes in response to anthropogenic influences. The overview is not comprehensive and does not describe in detail the basis of for these findings. These are found in the main body of this Technical Summary and in the underlying chapters to which each bullet points in the curly brackets.

### TS.6.1 Key Uncertainties in Observation of Changes in the Climate System

- There is only *medium to low confidence* in the rate of change of tropospheric warming and its vertical structure. Estimates of tropospheric warming rates encompass surface temperature warming rate estimates. There is *low confidence* in the rate and vertical structure of the stratospheric cooling. {2.4.4}
- *Confidence* in global precipitation change over land is *low* prior to 1950 and *medium* afterwards because of data incompleteness. {2.5.1}
- Substantial ambiguity and therefore *low confidence* remains in the observations of global-scale cloud variability and trends. {2.5.7}
- There is *low confidence* in an observed global-scale trend in drought or dryness (lack of rainfall), due to lack of direct observations, methodological uncertainties and choice and geographical inconsistencies in the trends. {2.6.2}
- There is *low confidence* that any reported long-term (centennial) changes in tropical cyclone characteristics are robust, after accounting for past changes in observing capabilities. {2.6.3}
- Robust conclusions on long-term changes in large-scale atmospheric circulation are presently not possible because of large variability on interannual to decadal time scales and remaining differences between data sets. {2.7}
- Different global estimates of sub-surface ocean temperatures have variations at different times and for different periods, suggesting that sub-decadal variability in the temperature and upper heat content (0–700 m) is still poorly characterized in the historical record. {3.2}
- Below ocean depths of 700 m the sampling in space and time is too sparse to produce annual global ocean temperature and heat content estimates prior to 2005. {3.2.4}
- Observational coverage of the ocean deeper than 2000 m is still limited and hampers more robust estimates of changes in global ocean heat content and carbon content. This also limits the quantification of the contribution of deep ocean warming to sea level rise. {3.2, 3.7, 3.8; Box 3.1}

- The number of continuous observational time series measuring the strength of climate relevant ocean circulation features (e.g., the meridional overturning circulation) is limited and the existing time series are still too short to assess decadal and longer trends. {3.6}.
- In Antarctica, available data are inadequate to assess the status of change of many characteristics of sea ice (e.g., thickness and volume). {4.2.3}
- On a global scale the mass loss from melting at calving fronts and iceberg calving are not yet comprehensively assessed. The largest uncertainty in estimated mass loss from glaciers comes from the Antarctic, and the observational record of ice-ocean interactions around both ice sheets remains poor. {4.3.3, 4.4}

#### ***TS.6.2 Key Uncertainties in Drivers of Climate Change***

- Uncertainties in aerosol-cloud interactions and the associated radiative forcing remain large. As a result, uncertainties in aerosol forcing remain the dominant contributor to the overall uncertainty in net anthropogenic forcing, despite a better understanding of some of the relevant atmospheric processes and the availability of global satellite monitoring. {2.2, 7.4, 7.5, 8.5}
- The cloud feedback is *likely* positive but its quantification remains difficult. {7.2}
- Paleoclimate reconstructions and Earth System Models indicate that there is a positive feedback between climate and the carbon cycle, but confidence remains *low* in the strength of this feedback, particularly for the land. {6.4}

#### ***TS.6.3 Key Uncertainties in Understanding the Climate System and its Recent Changes***

- The simulation of clouds has shown modest improvement since AR4, however it remains challenging. {7.2, 9.2.1, 9.4.1, 9.7.2}
- Observational uncertainties for climate variables other than temperature, uncertainties in forcings such as aerosols, and limits in process understanding continue to hamper attribution of changes in many aspects of the climate system. {10.1, 10.3, 10.7}
- Changes in the water cycle remain less reliably modelled in both their changes and their internal variability, limiting confidence in attribution assessments. Observational uncertainties and the large effect of internal variability on observed precipitation also precludes a more confident assessment of the causes of precipitation changes. {2.5.1, 2.5.4, 10.3.2}
- Modelling uncertainties related to model resolution and incorporation of relevant processes become more important at regional scales, and the effects of internal variability become more significant. Therefore, challenges persist in attributing observed change to external forcing at regional scales. {2.4.1, 10.3.1}
- The ability to simulate changes in frequency and intensity of extreme events is limited by the ability of models to reliably simulate mean changes in key features. {10.6.1}
- In some aspects of the climate system, including changes in drought, changes in tropical cyclone activity, Antarctic warming, Antarctic sea ice extent, and Antarctic mass balance *confidence* in attribution to human influence remains *low* due to modelling uncertainties and low agreement between scientific studies. {10.3.1, 10.5.2, 10.6.1}

#### ***TS.6.4 Key Uncertainties in Projections of Global and Regional Climate Change***

- Based on model results there is *medium confidence* in the predictability of yearly to decadal averages of temperature both for the global average and for some geographical regions. Multi-model results for precipitation indicate a generally low predictability. Short-term climate projection is also limited by the *low confidence* in projections of natural forcing. {11.1, 11.2.2, 11.3.1; Box 11.1}
- There is *low confidence* in projections for a poleward shift of the position and strength of Northern Hemisphere storm tracks. {11.3.2, 12.4.4}
- There is generally *low confidence* in basin-scale projections of significant trends in tropical cyclone frequency and intensity in the 21st century. {11.3.2, 14.6.1}
- Projected changes in soil moisture and surface run off are not robust in many regions. {11.3.2, 12.4.5}
- Several components or phenomena in the climate system could potentially exhibit abrupt or nonlinear changes, but for many phenomena there is *low confidence* and little consensus on the likelihood of such events over the 21st century. {12.5.5}
- There is *low confidence* on magnitude of carbon losses through CO<sub>2</sub> or CH<sub>4</sub> emissions to the atmosphere from thawing permafrost. There is *limited confidence* in projected future methane emissions from natural sources due to changes in wetlands and gas hydrate release from the sea floor. {6.4.3}
- There is *medium confidence* in the projected contributions to sea level rise by models of ice sheet dynamics for the 21<sup>st</sup> century, and *low confidence* in their projections beyond 2100. {13.3.3}
- There is *low confidence* in semi-empirical model projections of global mean sea level rise, and no consensus in the scientific community about their reliability. {13.5.2, 13.5.3}
- There is *low confidence* in projections of many aspects of climate phenomena that influence regional climate change, including changes in amplitude and spatial pattern of modes of climate variability. {9.5.3, 14.2–14.7}

## Tables

**Table TS.1:** Projected change in global mean surface air temperature and global mean sea level rise for the mid- and late 21st century. {12.4.1; Table 12.2, Table 13.5}

Variable	Scenario	2046–2065		2081–2100	
		mean	likely range <sup>c</sup>	mean	likely range <sup>c</sup>
Global Mean Surface Temperature Change (°C) <sup>a</sup>	RCP2.6	1.0	0.4 to 1.6	1.0	0.3 to 1.7
	RCP4.5	1.4	0.9 to 2.0	1.8	1.1 to 2.6
	RCP6.0	1.3	0.8 to 1.8	2.2	1.4 to 3.1
	RCP8.5	2.0	1.4 to 2.6	3.7	2.6 to 4.8
		mean	likely range <sup>d</sup>	mean	likely range <sup>d</sup>
Global Mean Sea Level Rise (m) <sup>b</sup>	RCP2.6	0.24	0.17 to 0.31	0.40	0.26 to 0.54
	RCP4.5	0.26	0.19 to 0.33	0.47	0.32 to 0.62
	RCP6.0	0.25	0.18 to 0.32	0.47	0.33 to 0.62
	RCP8.5	0.29	0.22 to 0.37	0.62	0.45 to 0.81

### Notes:

- (a) Based on the CMIP5 ensemble; anomalies calculated with respect to 1986–2005. Using HadCRUT4 and its uncertainty estimate (5–95% confidence interval), the observed warming to the reference period 1986–2005 used for projections is 0.61 [0.55 to 0.67] °C for 1850–1900, 0.30 [0.27 to 0.33] °C for 1961–1990, and 0.11 [0.09 to 0.13] °C for 1980–1999. {2.4.3, Tables 12.2 and 12.3}
- (b) Based on 21 CMIP5 models; anomalies calculated with respect to 1986–2005. Where CMIP5 results were not available for a particular AOGCM and scenario, they were estimated as explained in Chapter 13, Table 13.5. The contributions from ice sheet rapid dynamical change and anthropogenic land water storage are treated as having uniform probability distributions, and as largely independent of scenario. This treatment does not imply that the contributions concerned will not depend on the scenario followed, only that the current state of knowledge does not permit a quantitative assessment of the dependence. Based on current understanding, only the collapse of marine-based sectors of the Antarctic Ice Sheet, if initiated, could cause global mean sea level to rise substantially above the *likely* range during the 21st century. There is *medium confidence* that this additional contribution would not exceed several tenths of a meter of sea level rise during the 21st century.
- (c) Calculated from projections as 5–95% model ranges. These ranges are then assessed to be *likely* ranges after accounting for additional uncertainties or different levels of confidence in models. For projections of global mean surface temperature change in 2046–2065 *confidence* is *medium*, because contributions of radiative forcing and initial conditions to the temperature response uncertainty are larger than for 2081–2100. The likely ranges for 2046–2065 do not take into account the possible influence of factors that lead to near-term (2016–2035) projections of global mean surface temperature that are lower than the 5–95% model ranges, because the influence of these factors on longer term projections has not been quantified because of insufficient scientific understanding. {11.3.6}
- (d) Calculated from projections as 5–95% model ranges. These ranges are then assessed to be *likely* ranges after accounting for additional uncertainties or different levels of confidence in models. For projections of global mean sea level rise *confidence* is *medium* for both time horizons.

**Table TS.2:** Overview of projected regional changes and their relation to major climate phenomena. A phenomenon is considered relevant when there is both sufficient confidence that it has an influence on the given region, and when there is sufficient confidence that the phenomenon will change, particularly under the RCP4.5 or higher end scenarios. See Section 14.8 and Table 14.2 for full assessment of the confidence in these changes, and their relevance for regional climate. {14.8; Table 14.2}

<b>Regions</b>	<b>Projected Major Changes in Relation to Phenomena</b>
<b>Arctic</b> {14.8.2}	Wintertime changes in temperature and precipitation resulting from the small projected increase in NAO; Enhanced warming and sea ice melting; Significant increase in precipitation by mid-century due mostly to enhanced precipitation in Extratropical Cyclones.
<b>North America</b> {14.8.3}	Monsoon precipitation will shift later in the annual cycle; increased precipitation in extra-tropical cyclones will lead to large increases in wintertime precipitation over the northern third of the continent; extreme precipitation increases in tropical cyclones making landfall along the western coast of US and Mexico, the Gulf Mexico, and the eastern coast of US and Canada.
<b>Central America and Caribbean</b> {14.8.4}	Projected reduction in mean precipitation and increase in extreme precipitation; more extreme precipitation in tropical cyclones making landfall along the eastern and western coasts.
<b>South America</b> {14.8.5}	A southward displaced South Atlantic Convergence Zone increases precipitation in the southeast; positive trend in the Southern Annular Mode displaces the extratropical storm track southward, decreasing precipitation in central Chile and increasing it at the southern tip of South America.
<b>Europe and Mediterranean</b> {14.8.6}	Enhanced extremes of storm-related precipitation and decreased frequency of storm-related precipitation over the E. Mediterranean.
<b>Africa</b> {14.8.7}	Enhanced summer monsoon precipitation in West Africa; increased short rain in East Africa due to the pattern of Indian Ocean warming; increased rainfall extremes of landfall cyclones on the east coast (including Madagascar).
<b>Central and North Asia</b> {14.8.8}	Enhanced summer precipitation; enhanced winter warming over North Asia.
<b>East Asia</b> {14.8.9}	Enhanced summer monsoon precipitation; increased rainfall extremes of landfall typhoons on the coast; reduction in the midwinter suppression of extratropical cyclones.
<b>West Asia</b> {14.8.10}	Increased rainfall extremes of landfall cyclones on the Arabian Peninsula; decreased precipitation in NW Asia due to a northward shift of extratropical storm tracks.
<b>South Asia</b> {14.8.11}	Enhanced summer monsoon precipitation; increased rainfall extremes of landfall cyclones on the coasts of the Bay of Bengal and Arabian Sea.
<b>Southeast Asia</b> {14.8.12}	Reduced precipitation in Indonesia during Jul-Oct. due to the pattern of Indian Ocean warming; increased rainfall extremes of landfall cyclones on the coasts of the South China Sea, Gulf of Thailand, and Andaman Sea.
<b>Australia and New Zealand</b> {14.8.13}	Summer monsoon precipitation may increase over northern Australia; More frequent episodes of the zonal South Pacific Convergence Zone may reduce precipitation in northeastern Australia; increased warming and reduced precipitation in New Zealand and southern Australia due to projected positive trend in the Southern Annular Mode; increased extreme precipitation associated with tropical and extratropical storms
<b>Pacific Islands</b> {14.8.14}	Tropical convergence zone changes affect rainfall and its extremes; more extreme precipitation associated with tropical cyclones
<b>Antarctica</b> {14.8.15}	Increased warming over Antarctic Peninsula and west Antarctic related to the positive trend in the Southern Annular Mode; increased precipitation in coastal areas due to a poleward shift of storm track.

**TFE9, Table 1:** Extreme weather and climate events: Global-scale assessment of recent observed changes, human contribution to the changes, and projected further changes for the early (2016–2035) and late (2081–2100) 21st century. Bold indicates where the AR5 (black) provides a revised\* global-scale assessment from the SREX (blue) or AR4 (red). Projections for early 21st century were not provided in previous assessment reports. Projections in the AR5 are relative to the reference period of 1986–2005, and use the new RCP scenarios.

Phenomenon and direction of trend	Assessment that changes occurred (typically since 1950 unless otherwise indicated)	Assessment of a human contribution to observed changes	Likelihood of further changes	
			Early 21st century	Late 21st century
Warmer and/or fewer cold days and nights over most land areas	<i>Very likely</i> [2.6.1] <i>Very likely</i> <i>Very likely</i>	<b>Very likely</b> [10.6.1] <i>Likely</i> <i>Likely</i>	<i>Likely</i> [11.3.2] – –	<i>Virtually certain</i> [12.4.3] <i>Virtually certain</i> <i>Virtually certain</i>
Warmer and/or more frequent hot days and nights over most land areas	<i>Very likely</i> [2.6.1] <i>Very likely</i> <i>Very likely</i>	<b>Very likely</b> [10.6.1] <i>Likely</i> <i>Likely (nights only)</i>	<i>Likely</i> [11.3.2] – –	<i>Virtually certain</i> [12.4.3] <i>Virtually certain</i> <i>Virtually certain</i>
Warm spells/heat waves. Frequency and/or duration increases over most land areas	<b>Medium confidence</b> on a global scale <i>Likely</i> in some regions (a) [2.6.1] <i>Medium confidence in many (but not all) regions</i> <i>Likely</i>	<b>Likely (b)</b> [10.6.2] <i>Not formally assessed</i> <i>More likely than not</i>	Not formally assessed (c) [11.3.2] – –	<i>Very likely</i> [12.4.3] <i>Very likely</i> <i>Very likely</i>
Heavy precipitation events. Increase in the frequency, intensity, and/or amount of heavy precipitation.	<i>Likely</i> more land areas with increases than decreases <i>Very likely</i> in central North America [2.6.2] <i>Likely</i> more land areas with increases than decreases <i>Likely over most land areas</i>	<b>Medium confidence</b> [7.6.5, 10.6.1] <i>Medium confidence</i> <i>More likely than not</i>	<i>Likely</i> over many land areas [11.3.2] – –	<b>Very likely</b> in some areas (d) [12.4.5] <i>Likely</i> over many areas <i>Very likely over most land areas</i>
Increases in intensity and/or duration of drought	<b>Low confidence</b> on a global scale <i>Likely</i> changes in some regions (e) [2.6.2] <i>Medium confidence in some regions</i> <i>Likely in many regions, since 1970 (f)</i>	<b>Low confidence</b> [10.6.1] <i>Medium confidence</i> <i>More likely than not</i>	<i>Low confidence</i> (g) [11.3.2] – –	<b>Likely (medium confidence)</b> on a regional to global scale (h) [12.4.5] <i>Medium confidence in some regions</i> <i>Likely (f)</i>
Increases in intense tropical cyclone activity	<b>Low confidence</b> in long term (centennial) changes <i>Virtually certain</i> in North Atlantic since 1970 [2.6.3] <i>Low confidence</i> <i>Likely (in some regions, since 1970)</i>	<b>Low confidence</b> [10.6.1] <i>Low confidence</i> <i>More likely than not</i>	<i>Low confidence</i> [11.3.2] – –	<b>More likely than not</b> in some basins [14.6] <i>More likely than not</i> in some basins <i>Likely</i>
Increased incidence and/or magnitude of extreme high sea level	<i>Likely</i> (since 1970) [3.7.5] <i>Likely</i> (late 20th century) <i>Likely</i>	Not assessed <i>Likely (i)</i> <i>More likely than not (i)</i>	Not assessed – –	<b>Very likely</b> [13.7.2] <i>Very likely (j)</i> <i>Likely</i>

\* The direct comparison of assessment findings between reports is difficult. For some climate variables, different aspects have been assessed, and the revised guidance note on uncertainties has been used for the SREX and AR5. The availability of new information, improved scientific understanding, continued analyses of data and models, and specific differences in methodologies applied in the assessed studies, all contribute to revised assessment findings.

## Notes:

- (a) *Likely* that heat wave frequency has increased in large parts of Europe, Asia and Australia.
- (b) Attribution is based on available case studies. It is *likely* that human influence has substantially increased the probability of occurrence of some observed heat waves in some locations.
- (c) Models project near-term increases in the duration, intensity and spatial extent of heat waves and warm spells.
- (d) *Very likely* over most of the mid-latitude land-masses and over wet tropical regions.
- (e) The frequency and intensity of drought has *likely* increased in the Mediterranean and West Africa and *likely* decreased in central North America and north-west Australia.
- (f) AR4 assessed the area affected by drought.
- (g) There is *low confidence* in projected changes in soil moisture.
- (h) Regional to global-scale projected decreases in soil moisture and increased agricultural drought are *likely (medium confidence)* in presently dry regions by the end of this century under the RCP8.5 scenario. Soil moisture drying in the Mediterranean, Southwest US and southern African regions is consistent with projected changes in Hadley circulation and increased surface temperatures, so there is *high confidence* in *likely* surface drying in these regions by the end of this century under the RCP8.5 scenario.
- (i) Attribution is based on the close relationship between observed changes in extreme and mean sea level.
- (j) SREX assessed it to be *very likely* that mean sea level rise will contribute to future upward trends in extreme coastal high water levels.



*Climate Change 2013: The Physical Science Basis***Technical Summary**

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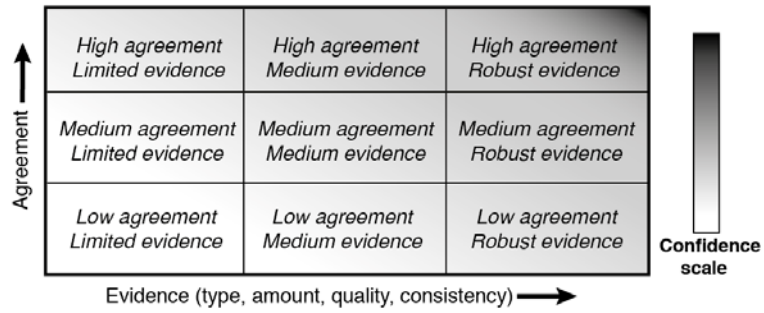
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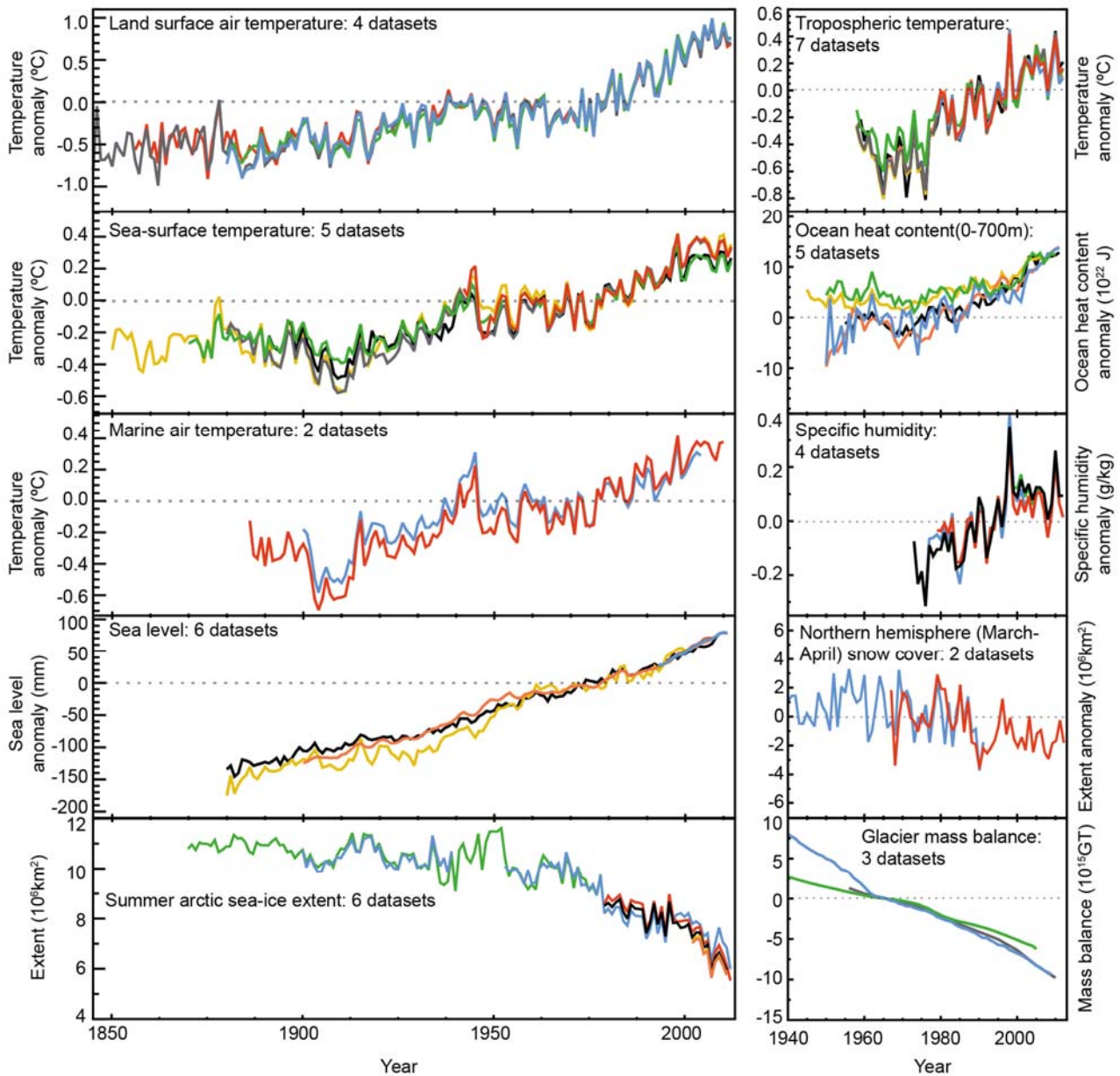
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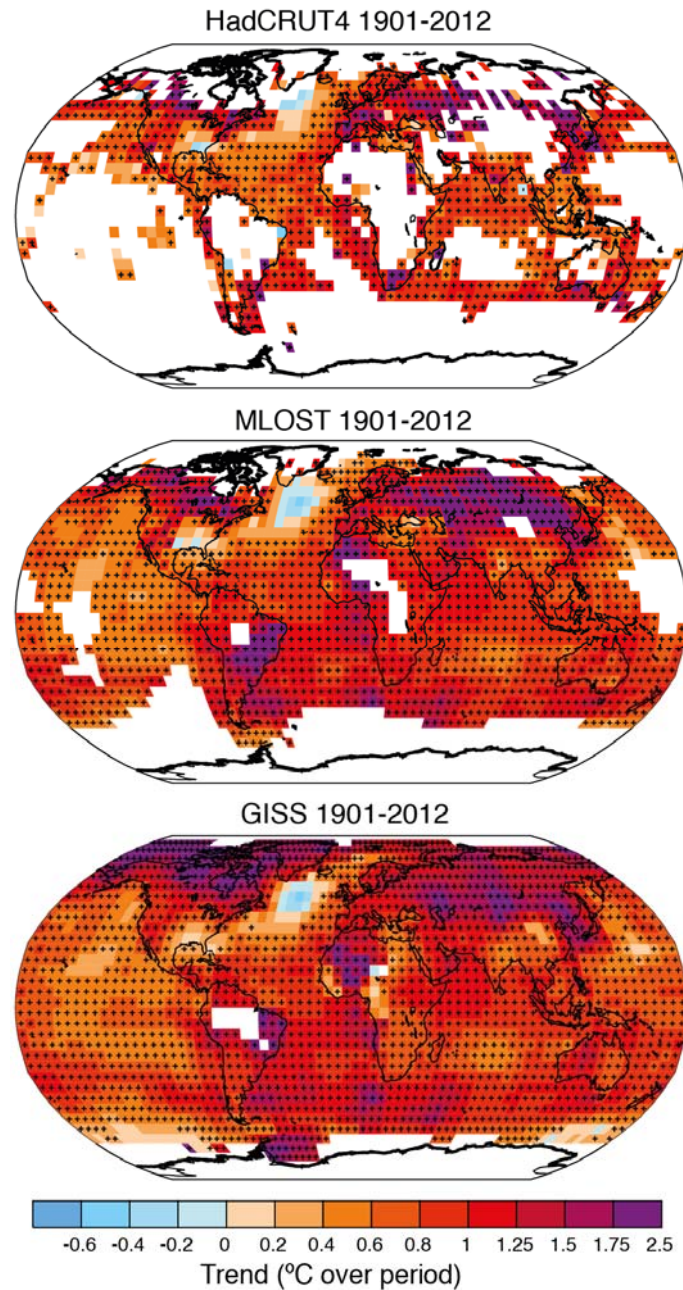
**Figures**



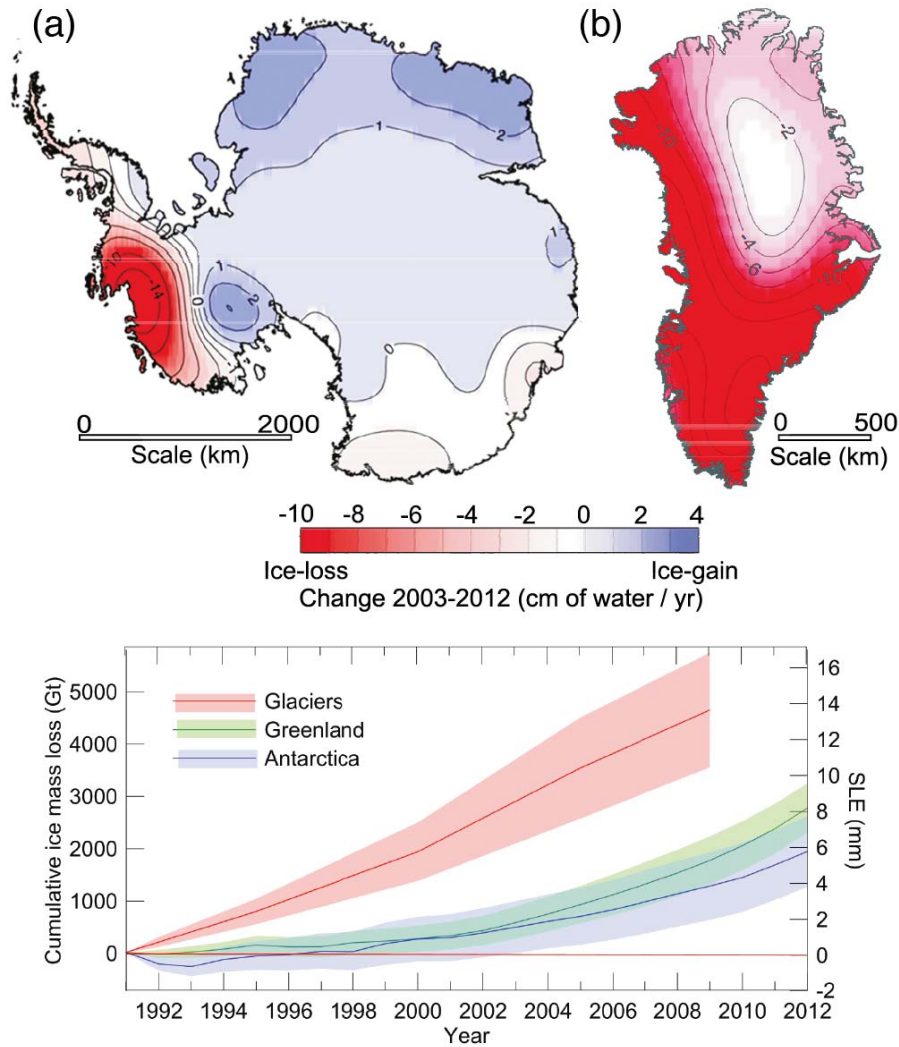
**Box TS.1, Figure 1:** A depiction of evidence and agreement statements and their relationship to confidence. Confidence increases toward the top-right corner as suggested by the increasing strength of shading. Generally, evidence is most robust when there are multiple, consistent independent lines of high-quality. {Figure 1.11}



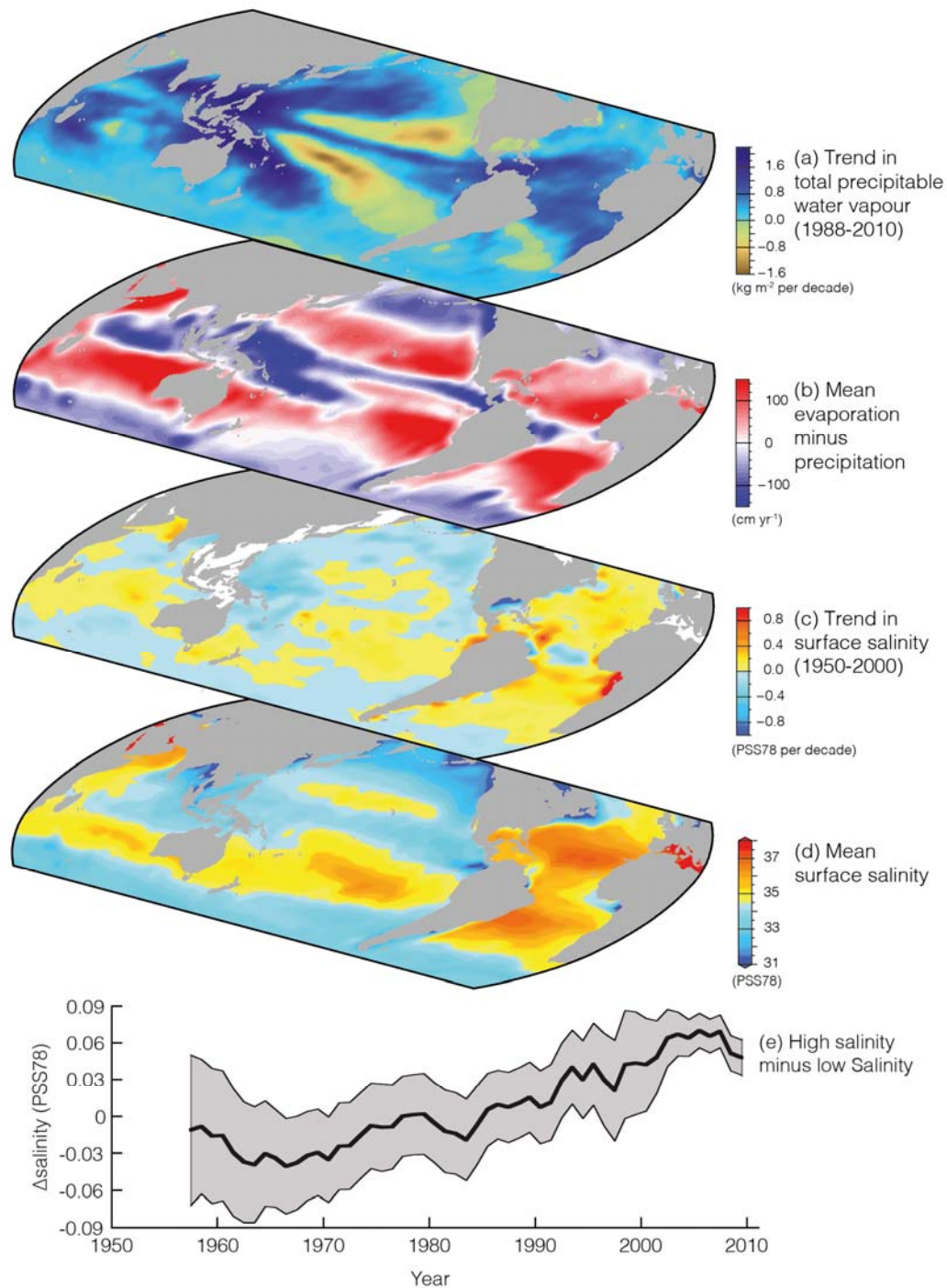
**Figure TS.1:** Multiple complementary indicators of a changing global climate. Each line represents an independently-derived estimate of change in the climate element. The times series presented are assessed in chapters 2, 3, and 4. In each panel all datasets have been normalized to a common period of record. A full detailing of which source datasets go into which panel is given in Chapter 2, Supplementary Material 2.SM.5 and in the respective chapters (See also FAQ 2.1, Figure 1). {2.4, 2.5, 3.2, 3.7, 4.5.2, 4.5.3}



**Figure TS.2:** Change in surface temperature over 1901-2012 as determined by linear trend for three data sets. White areas indicate incomplete or missing data. Trends have been calculated only for those grid boxes with greater than 70% complete records and more than 20% data availability in the first and last 10% of the time period. Black plus signs (+) indicate grid boxes where trends are significant (i.e., a trend of zero lies outside the 90% confidence interval). Differences in coverage primarily reflect the degree of interpolation to account for data void regions undertaken by the dataset providers ranging from none beyond grid box averaging (HadCRUT4) to substantial (GISS). {Figure 2.21}

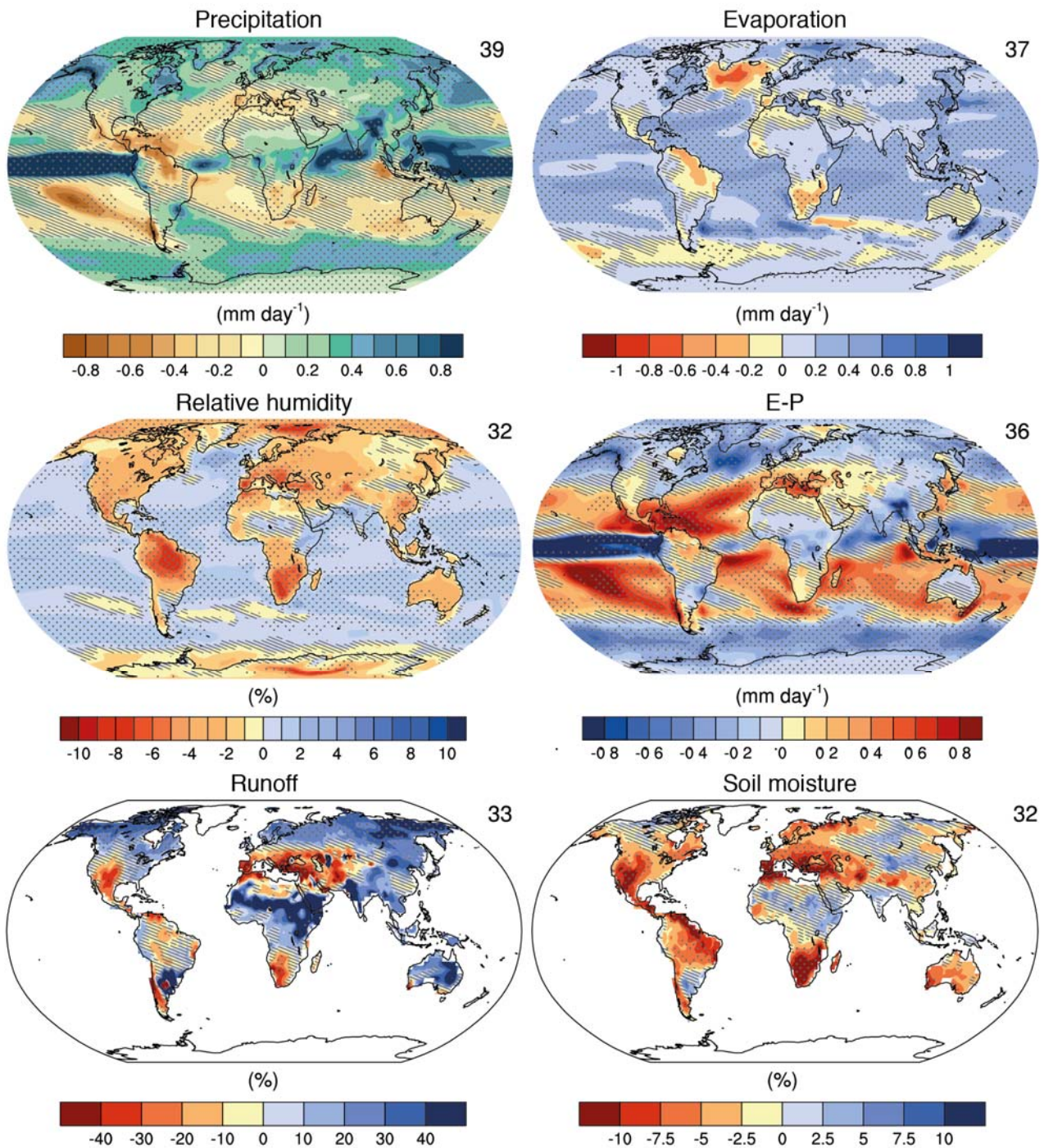


**Figure TS.3:** Upper panels: distribution of ice loss determined from GRACE time-variable gravity for (a) Antarctica and (b) Greenland, shown in centimetres of water per year ( $\text{cm of water yr}^{-1}$ ) for the period 2003 to 2012. Lower panel: the assessment of the total loss of ice from glaciers and ice sheets in terms of sea level equivalent (in mm). The contribution from glaciers excludes those on the periphery of the ice sheets. {4.3.4; Figures 4.12, 4.13, 4.14, 4.16, 4.17}

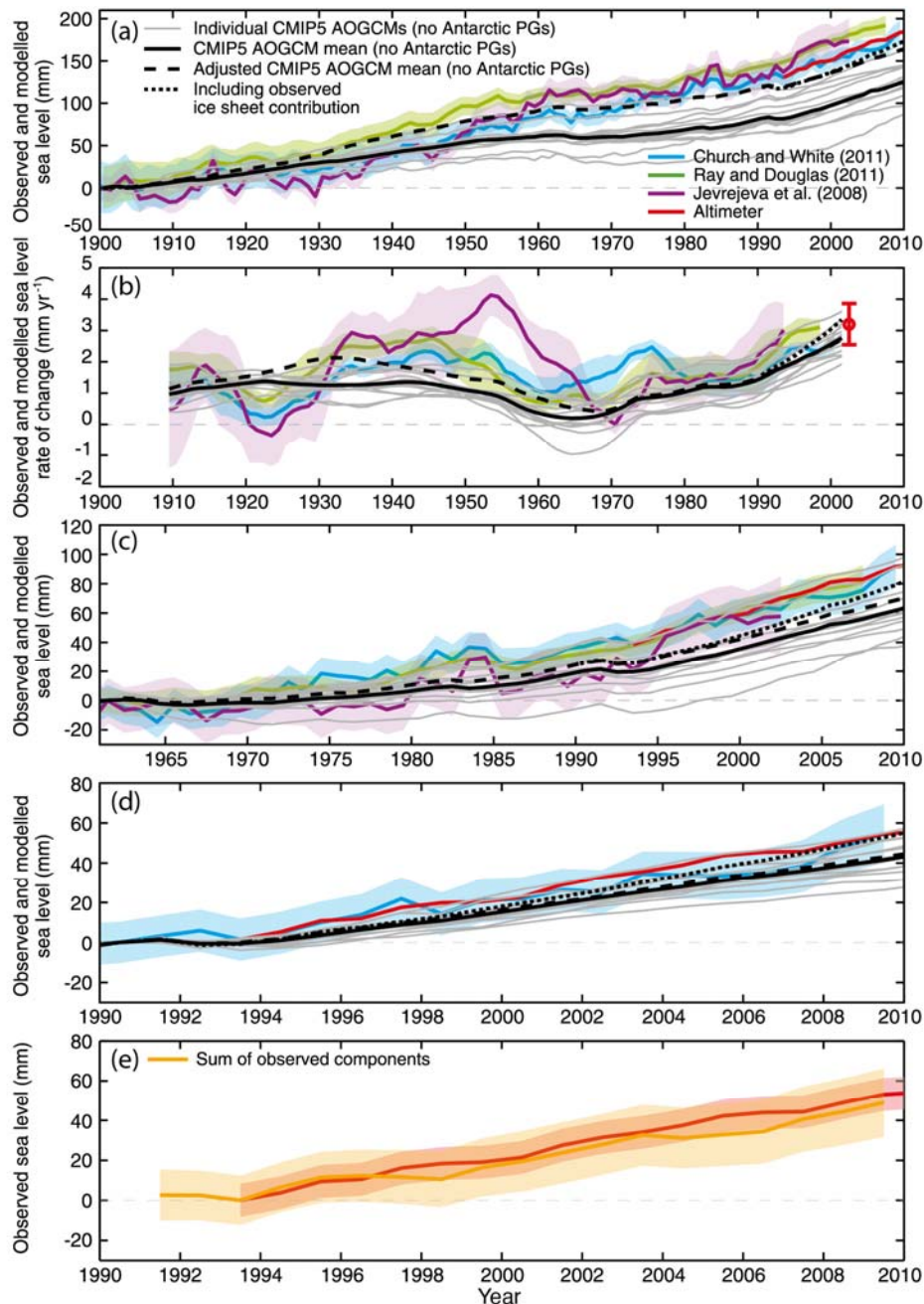


**TFE.1, Figure 1:** Changes in sea surface salinity are related to the atmospheric patterns of Evaporation minus Precipitation (E-P) and trends in total precipitable water: (a) Linear trend (1988 to 2010) in total precipitable water (water vapor integrated from Earth’s surface up through the entire atmosphere) (kg m<sup>-2</sup> per decade) from satellite observations. (b) The 1979–2005 climatological mean net evaporation minus precipitation (cm yr<sup>-1</sup>) from meteorological reanalysis data. (c) Trend (1950 to 2000) in surface salinity (PSS78 per 50years). (d) The climatological-mean surface salinity (PSS78) (blues <35; yellows-reds >35). (e) Global difference between salinity averaged over regions where the sea surface salinity is greater than the global mean sea surface salinity (“High Salinity”) and salinity averaged over regions values below the global mean (“Low Salinity”). Details of data sources: see Figure 3.21 and FAQ 3.3, Figure 1. {3.9}

## Annual mean hydrological cycle change (RCP8.5: 2081-2100)

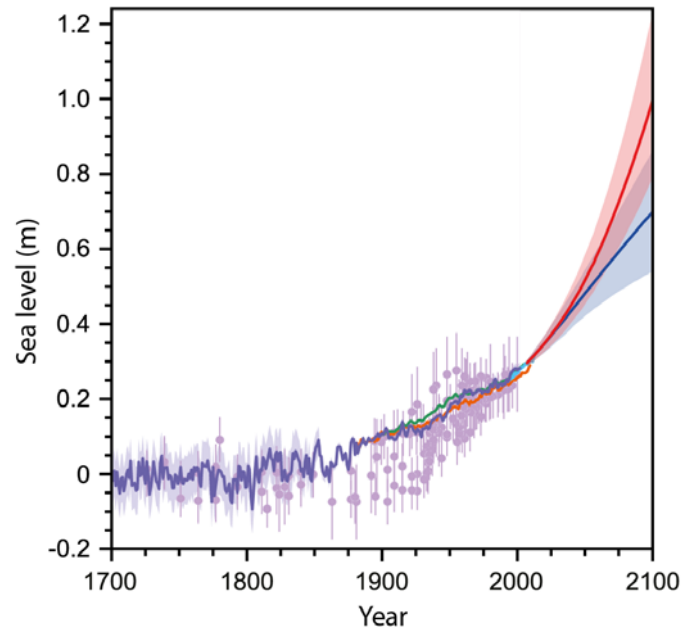


**TFE.1, Figure 2:** Annual mean changes in precipitation (P), evaporation (E), relative humidity, E-P, runoff and soil moisture, for 2081–2100 relative to 1986–2005 under the RCP8.5 scenario (see Box TS.6). The number of CMIP5 models to calculate the multi-model mean is indicated in the upper right corner of each panel. Hatching indicates regions where the multi model mean is less than one standard deviation of internal variability. Stippling indicates regions where the multi model mean is greater than two standard deviations of internal variability and where 90% of models agree on the sign of change (see Box 12.1). {Figures 12.25–12.27}

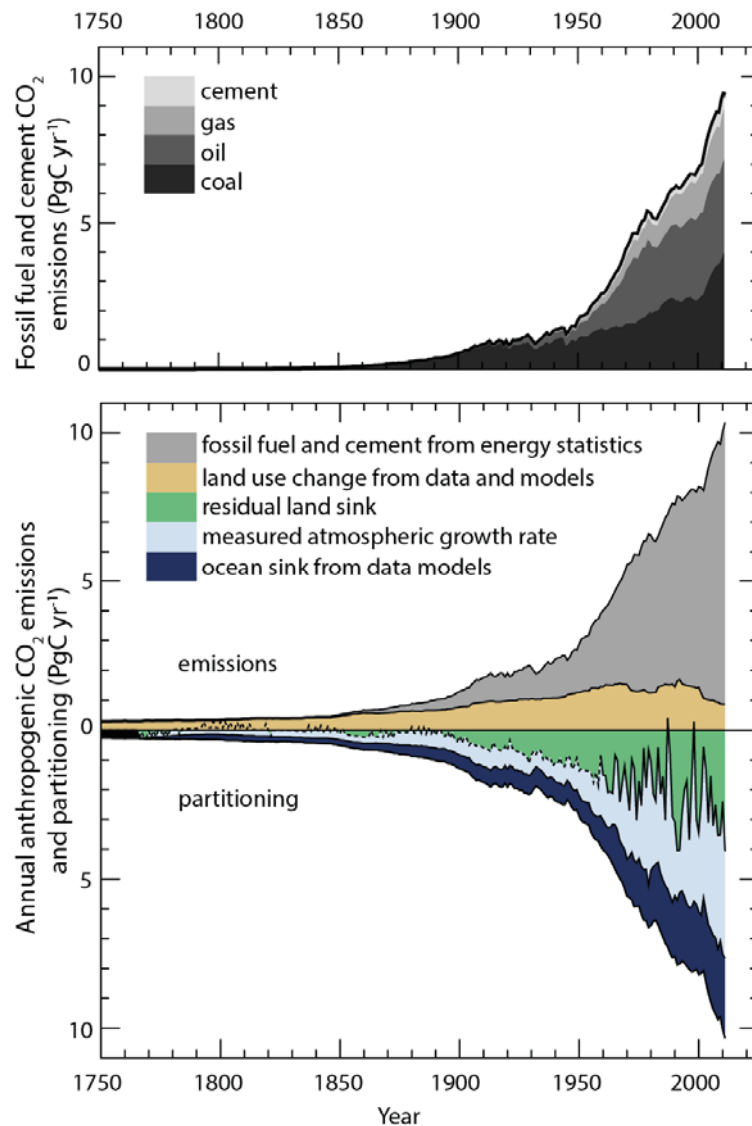


**TFE.2, Figure 1:** Comparison of the observed global mean sea level rise from the sum of the modelled contributions from ocean thermal expansion, glaciers (excluding glaciers peripheral to the Antarctic ice sheet, PGs) and changes in land-water storage. In panels (a)-(d): the grey lines are results for individual CMIP5 AOGCMs; the black line is the model mean plus a correction for the omission of volcanic forcing in the AOGCM control experiments; the adjusted model mean (dashed black line) is the sum of the corrected model mean thermal expansion, the change in land-water storage, the glacier estimate using observed (rather than modelled) climate, and an illustrative long-term ice-sheet contribution (of  $0.1 \text{ mm yr}^{-1}$ ); the adjusted model mean including the observed ice sheet contribution (dotted black line) begins in 1993 and includes the ice-sheet contributions, but excludes the glaciers peripheral to both the Greenland Ice Sheet and the Antarctic Ice Sheet, to avoid double counting because the observational ice-sheet estimates include the peripheral glaciers; three estimates of global mean sea level, with the shading indicating the uncertainty estimates (two standard deviations) are shown; the satellite altimetry data since 1993 are shown in red. The modelled sea level is given (a) for the period 1900 to 2010, (b) the rates of sea level change for the same period, with the satellite altimetry data shown as a red dot for the rate, (c) for 1961 to 2010 and (d) for 1990 to 2010. Panel (e) compares the sum of the observed contributions (orange) and the observed sea level from the satellite altimetry data (red). {13.3; Figure 13.7}

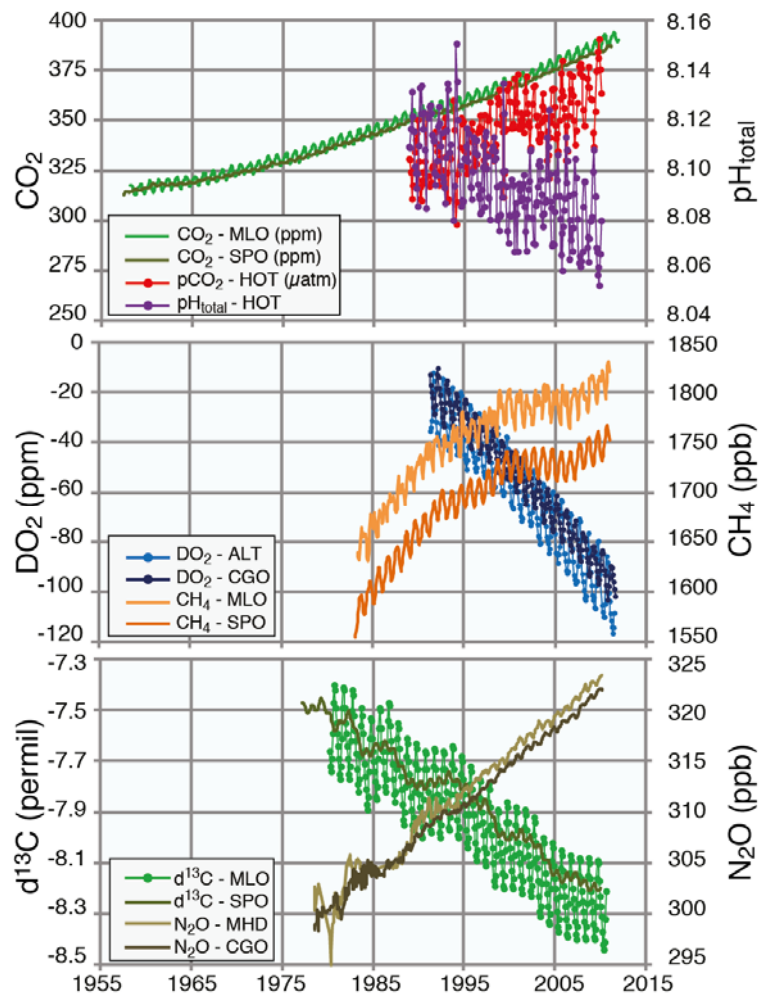




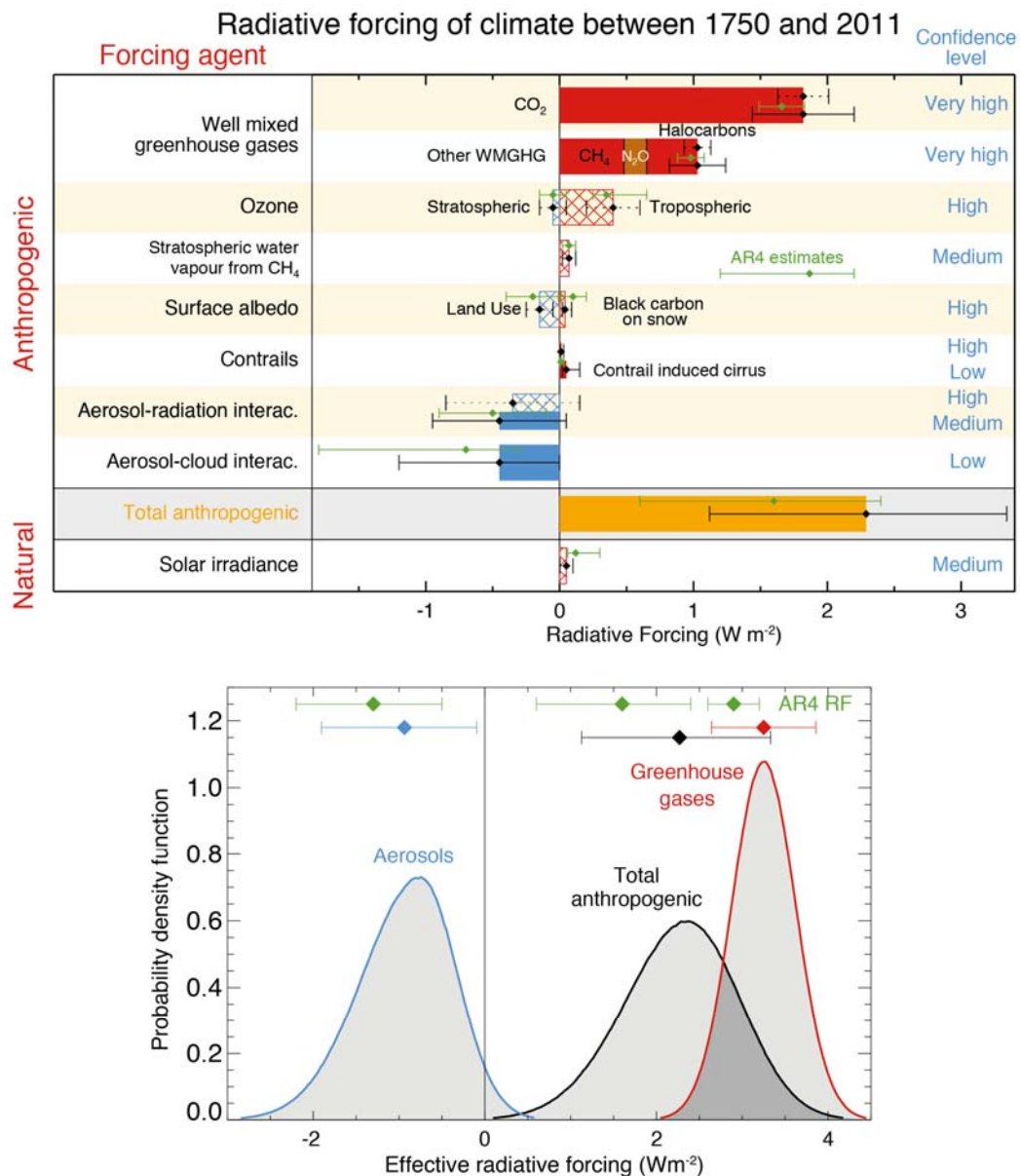
**TFE.2, Figure 2:** Compilation of paleo sea level data (purple), tide gauge data (blue, red and green), altimeter data (light blue), and central estimates and likely ranges for projections of global-mean sea level rise from the combination of CMIP5 and process-based models for RCP2.6 (blue) and RCP8.5 (red) scenarios, all relative to pre-industrial values. {Figures 13.3, 13.11, 13.27}



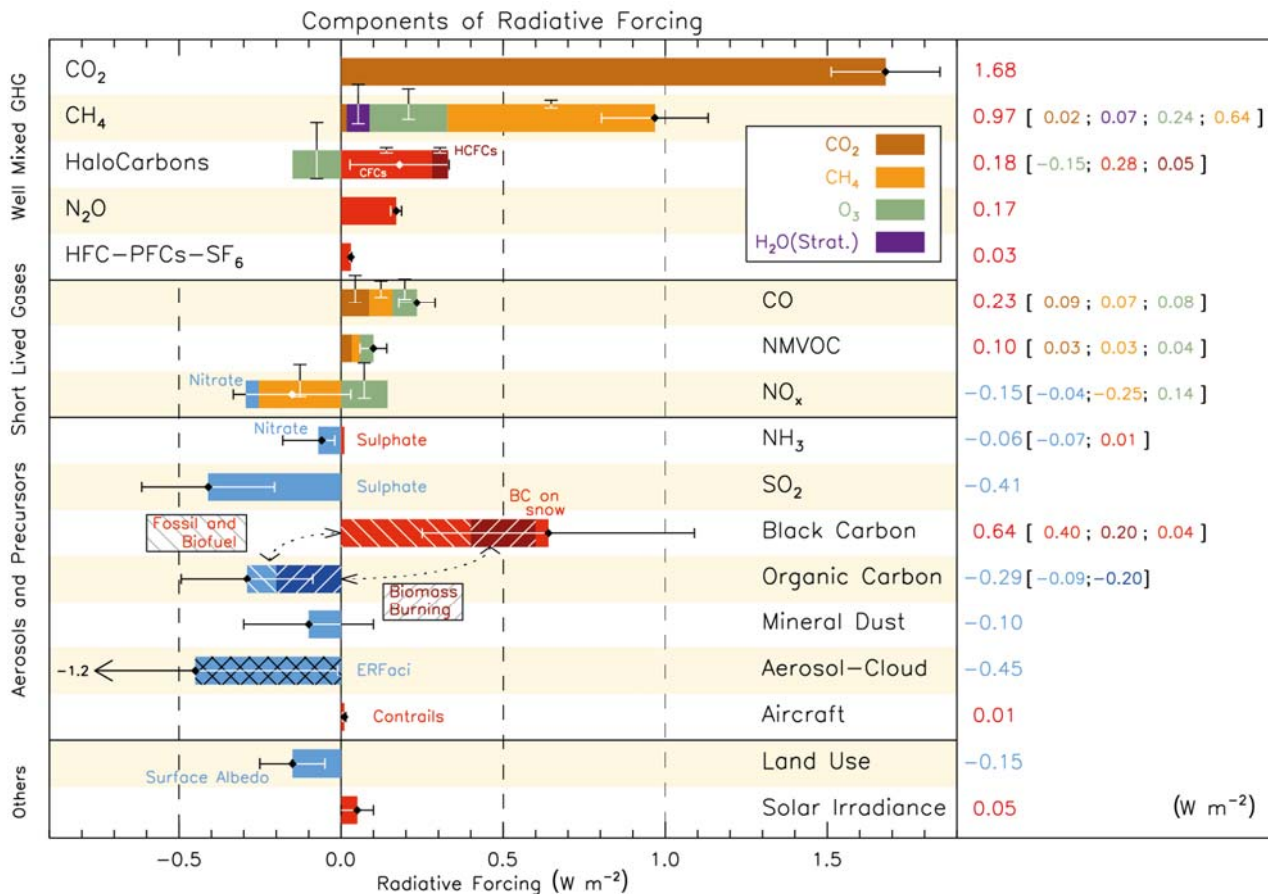
**Figure TS.4:** Annual anthropogenic CO<sub>2</sub> emissions and their partitioning among the atmosphere, land and ocean (PgC yr<sup>-1</sup>) from 1750 to 2011. (Top) Fossil fuel and cement CO<sub>2</sub> emissions by category, estimated by the Carbon Dioxide Information Analysis Center (CDIAC). (Bottom) Fossil fuel and cement CO<sub>2</sub> emissions as above. CO<sub>2</sub> emissions from net land use change, mainly deforestation, are based on land cover change data (see Table 6.2). The atmospheric CO<sub>2</sub> growth rate prior to 1959 is based on a spline fit to ice core observations and a synthesis of atmospheric measurements from 1959. The fit to ice core observations does not capture the large interannual variability in atmospheric CO<sub>2</sub> and is represented with a dashed line. The ocean CO<sub>2</sub> sink is from a combination of models and observations. The residual terrestrial sink (term in green in the figure) is computed from the residual of the other terms. The emissions and their partitioning only include the fluxes that have changed since 1750, and not the natural CO<sub>2</sub> fluxes (e.g., atmospheric CO<sub>2</sub> uptake from weathering, outgassing of CO<sub>2</sub> from lakes and rivers, and outgassing of CO<sub>2</sub> by the ocean from carbon delivered by rivers; see Figure 6.1) between the atmosphere, land and ocean reservoirs that existed before that time and still exist today. The uncertainties in the various terms are discussed in chapter 6 and reported in Table 6.1 for decadal mean values. {Figure 6.8}



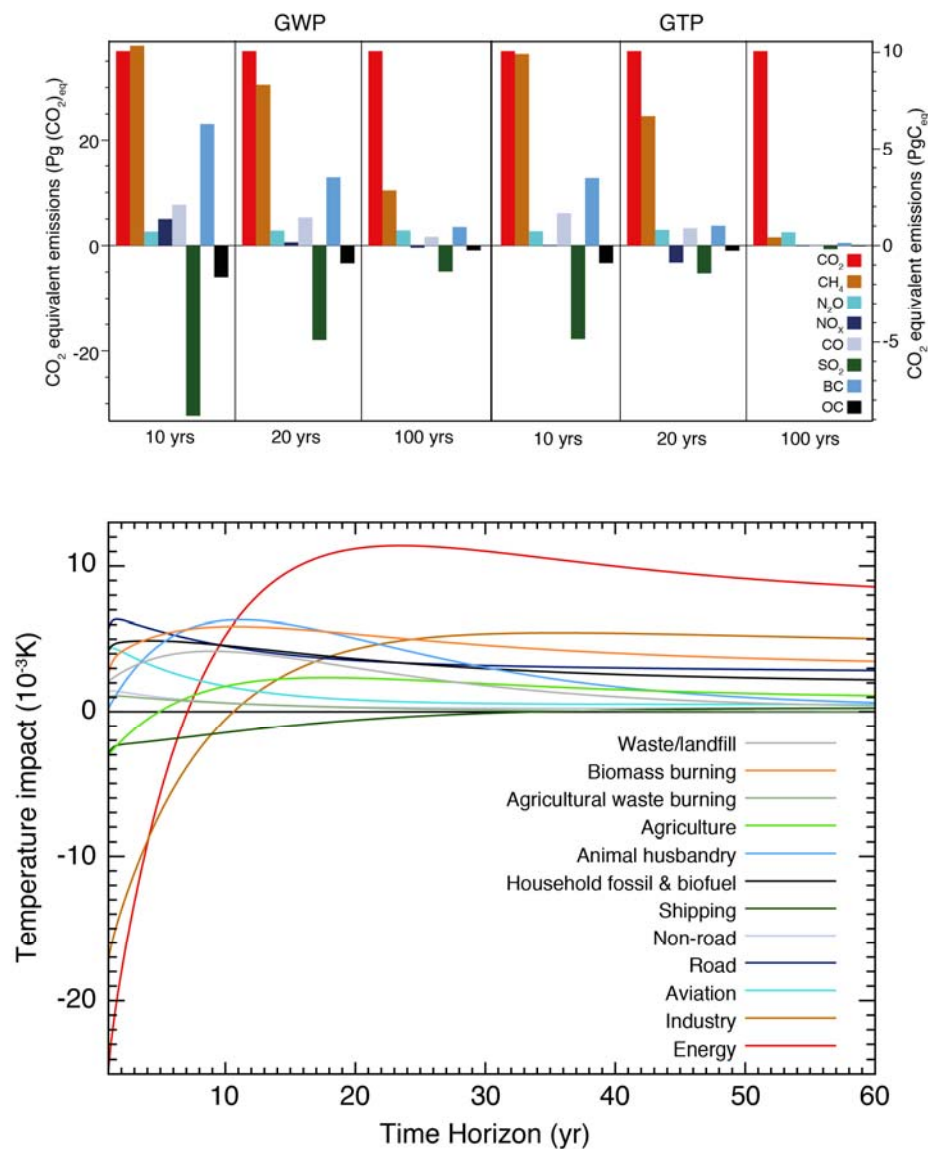
**Figure TS.5:** Atmospheric concentration of CO<sub>2</sub>, oxygen, <sup>13</sup>C/<sup>12</sup>C stable isotope ratio in CO<sub>2</sub>, as well as CH<sub>4</sub> and N<sub>2</sub>O atmospheric concentrations and oceanic surface observations of pCO<sub>2</sub> and pH, recorded at representative time series stations in the Northern and the Southern Hemispheres. MLO: Mauna Loa Observatory, Hawaii; SPO: South Pole; HOT: Hawaii Ocean Time-Series station; MHD: Mace Head, Ireland; CGO: Cape Grim, Tasmania; ALT: Alert, Northwest Territories, Canada. {Figure 6.3, FAQ 3.2, Figure 1}



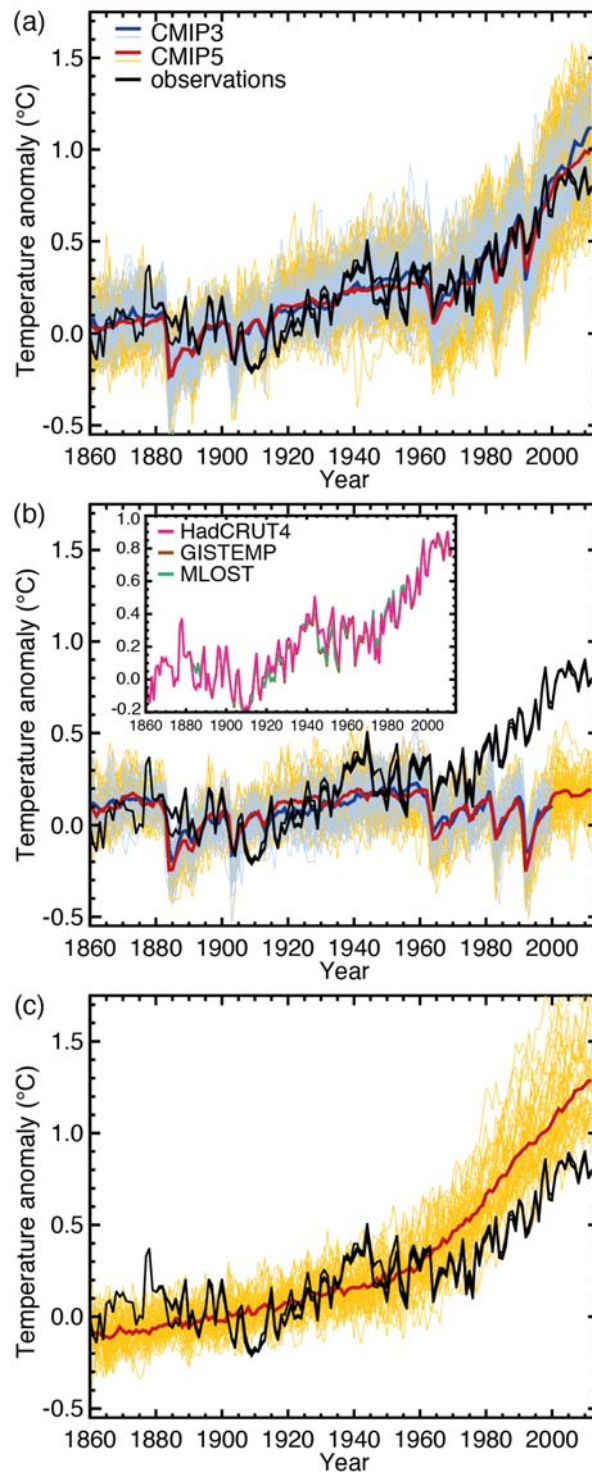
**Figure TS.6:** Radiative Forcing (RF) and Effective Radiative Forcing (ERF) of climate change during the industrial era. Top: Forcing by concentration change between 1750 and 2011 with associated uncertainty range (solid bars are ERF, hatched bars are RF, green diamonds and associated uncertainties are for RF assessed in AR4). Bottom: Probability Density Functions for the ERF, for the aerosol, well-mixed greenhouse gas (WMGHG) and total. The green lines show the AR4 RF 90% confidence intervals and can be compared with the red, blue and black lines which show the AR5 ERF 90% confidence intervals (although RF and ERF differ, especially for aerosols). The ERF from surface albedo changes and combined contrails and contrail induced cirrus is included in the total anthropogenic forcing, but not shown as a separate probability density function. For some forcing mechanisms (ozone, land use, solar) the RF is assumed to be representative of the ERF but an additional uncertainty of 17% is added in quadrature to the RF uncertainty. {Figures 8.15, 8.16}



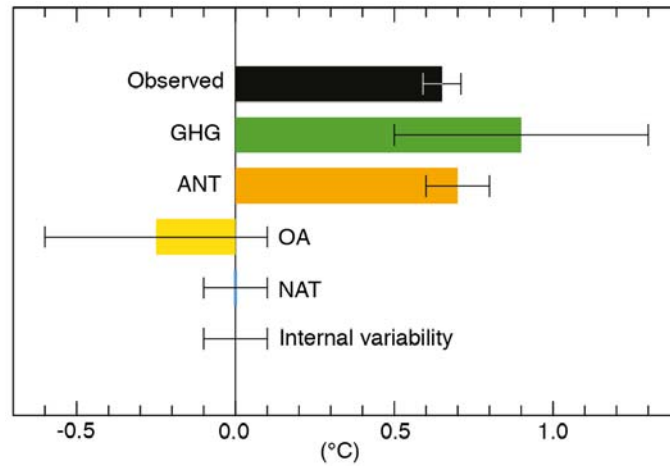
**Figure TS.7:** Radiative forcing of climate change during the industrial era shown by emitted components from 1750 to 2011. The horizontal bars indicate the overall uncertainty, while the vertical bars are for the individual components (vertical bar lengths proportional to the relative uncertainty, with a total length equal to the bar width for a  $\pm 50\%$  uncertainty). Best estimates for the totals and individual components (from left to right) of the response are given in the right column. Values are RF except for the ERF of aerosol-cloud interactions (ERF<sub>aci</sub>). An additional rapid adjustment to aerosol-radiation interactions of  $-0.1$  [ $-0.3$  to  $+0.1$ ]  $W m^{-2}$  is attributable primarily to black carbon (ERF<sub>ari</sub>-RF<sub>ari</sub> in Figure TS.6). CFCs= Chlorofluorocarbons, HCFCs= Hydrochlorofluorocarbons, HFCs=Hydrofluorocarbons, PFCs= Perfluorocarbons, NMVOG= Non-Methane Volatile Organic Compounds, BC= Black Carbon. {Figure 8.17}



**Figure TS.8:** (Upper Panel) Global anthropogenic present-day emissions weighted by the Global Warming Potential (GWP) and the Global Temperature change Potential (GTP) for the chosen time horizons. Year 2008 (single-year pulse) emissions weighted by GWP, which is the global mean radiative forcing per unit mass emitted integrated over the indicated number of years relative to the forcing from CO<sub>2</sub> emissions, and GTP which estimates the impact on global mean temperature based on the temporal evolution of both radiative forcing and climate response per unit mass emitted relative to the impact of CO<sub>2</sub> emissions. The units are “CO<sub>2</sub> equivalents” which reflects equivalence only in the impact parameter of the chosen metric (integrated RF over the chosen time horizon for GWP; temperature change at the chosen point in time for GTP), given as Pg(CO<sub>2</sub>)eq (left axis) and PgCeq (right axis) (see footnote 5). (Bottom Panel) The Absolute GTP (AGTP) as a function of time multiplied by the present-day emissions of all compounds from the indicated sectors is used to estimate global mean temperature response (AGTP is the same as GTP, except is not normalized by the impact of CO<sub>2</sub> emissions). There is little change in the relative values for the sectors over the 60–100 year time horizon. The effects of aerosol-cloud interactions and aviation-induced cirrus are not included in the upper panel. {Figures 8.32, 8.33}

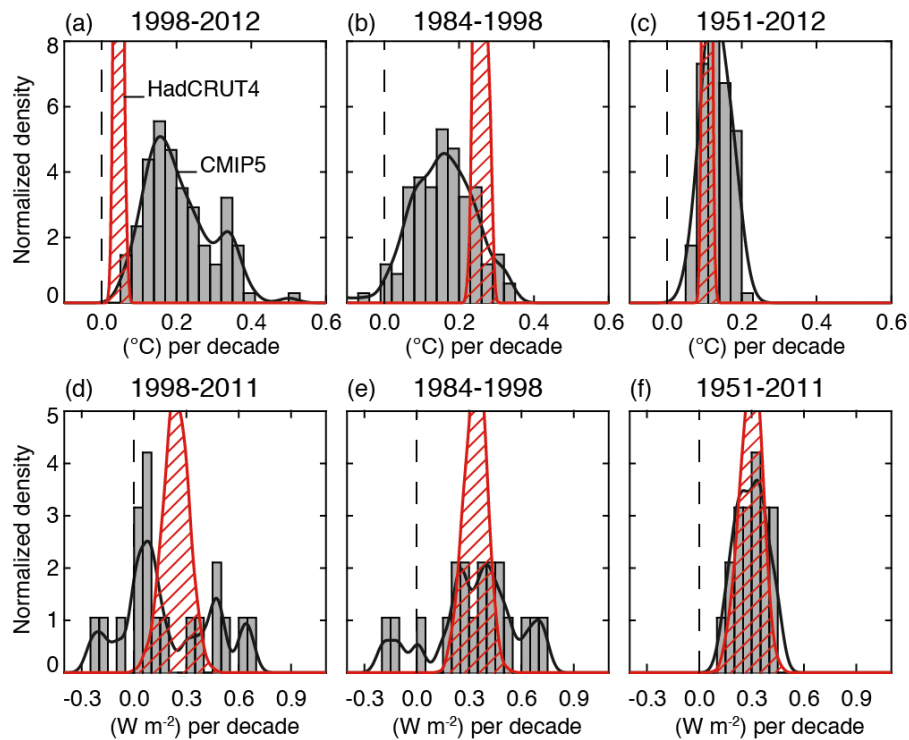


**Figure TS.9:** Three observational estimates of global mean surface temperature (black lines) from HadCRUT4, GISTEMP, and MLOST, compared to model simulations (CMIP3 models – thin blue lines and CMIP5 models – thin yellow lines) with anthropogenic and natural forcings (a), natural forcings only (b) and greenhouse gas forcing only (c). Thick red and blue lines are averages across all available CMIP5 and CMIP3 simulations respectively. All simulated and observed data were masked using the HadCRUT4 coverage (since this dataset has the most restricted spatial coverage), and global average anomalies are shown with respect to 1880–1919, where all data are first calculated as anomalies relative to 1961–1990 in each grid box. Inset to (b) shows the three observational datasets distinguished by different colours. {Figure 10.1}

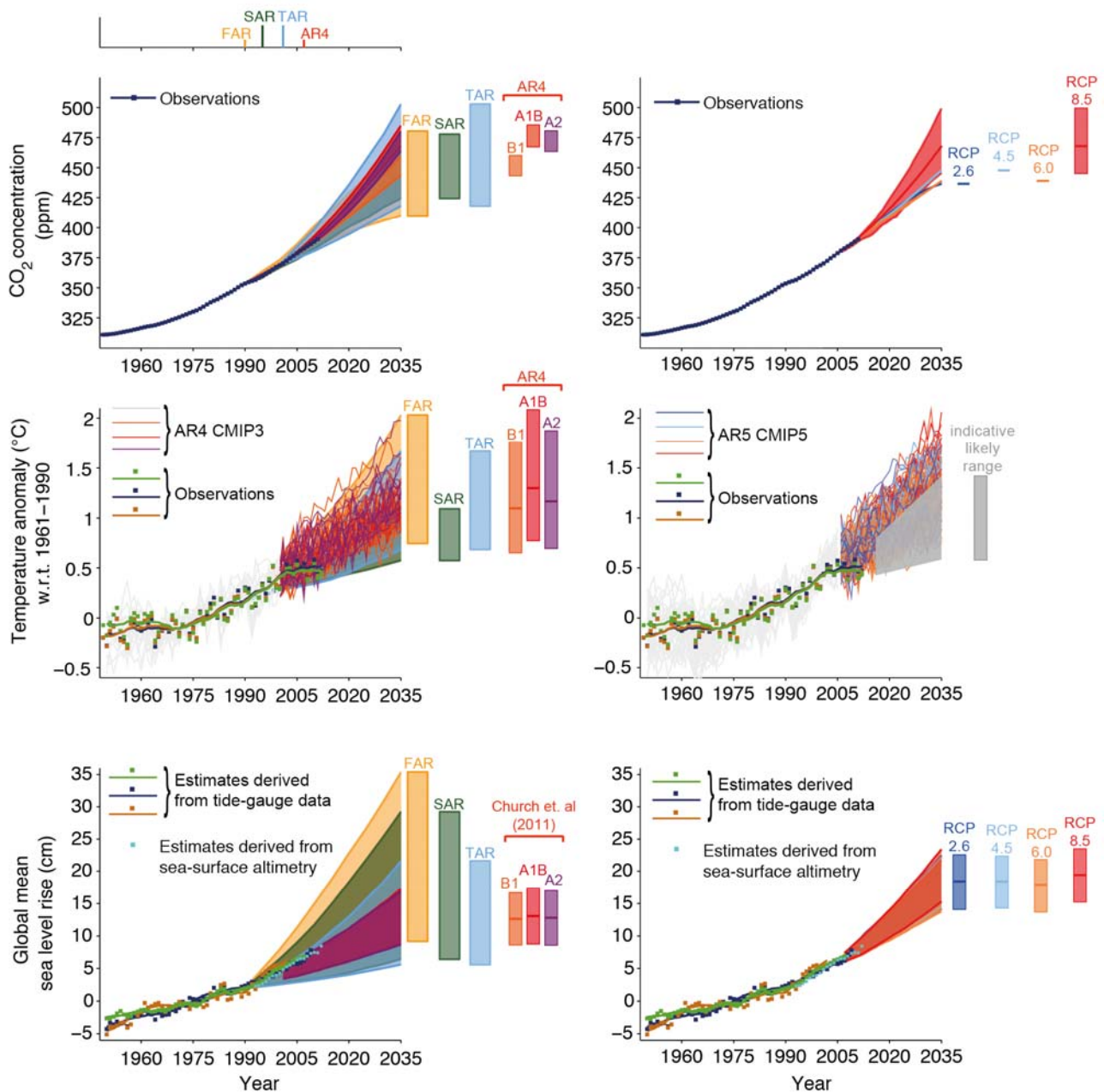


**Figure TS.10:** Assessed *likely* ranges (whiskers) and their midpoints (bars) for warming trends over the 1951–2010 period due to well-mixed greenhouse gases (GHG), anthropogenic forcings (ANT), anthropogenic forcings other than well-mixed greenhouse gases (OA), natural forcings (NAT), and internal variability. The trend in the HadCRUT4 observations is shown in black with its 5 to 95% uncertainty range due only to observational uncertainty in this record. {Figure 10.5}



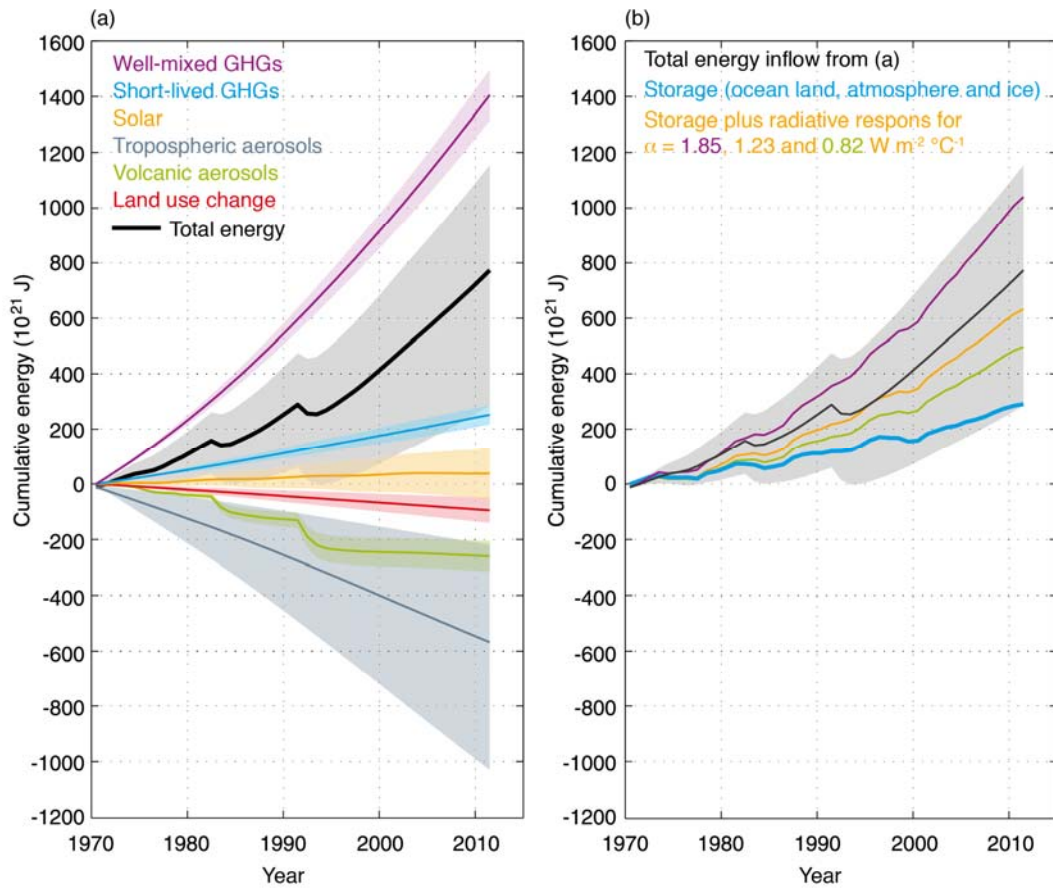


**Box TS.3, Figure 1:** Top: Observed and simulated GMST trends in  $^{\circ}\text{C}$  per decade, over the periods 1998–2012 (a), 1984–1998 (b), and 1951–2012 (c). For the observations, 100 realisations of the HadCRUT4 ensemble are shown (red, hatched). The uncertainty displayed by the ensemble width is that of the statistical construction of the global average only, in contrast to the trend uncertainties quoted in Section 2.4.3, which include an estimate of internal climate variability. Here, by contrast, internal variability is characterised through the width of the model ensemble. For the models, all 114 available CMIP5 historical realisations are shown, extended after 2005 with the RCP4.5 scenario and through 2012 (grey, shaded). Bottom: Trends in effective radiative forcing (ERF, in  $\text{W m}^{-2}$  per decade) over the periods 1998–2011 (d), 1984–1998 (e), and 1951–2011 (f). The figure shows AR5 best-estimate ERF trends (red, hatched) and CMIP5 ERF (grey, shaded). Black lines are smoothed versions of the histograms. Each histogram is normalised so that its area sums up to one. {2.4.3, 8.5.2; Box 9.2; Figure 8.18, Box 9.2, Figure 1}

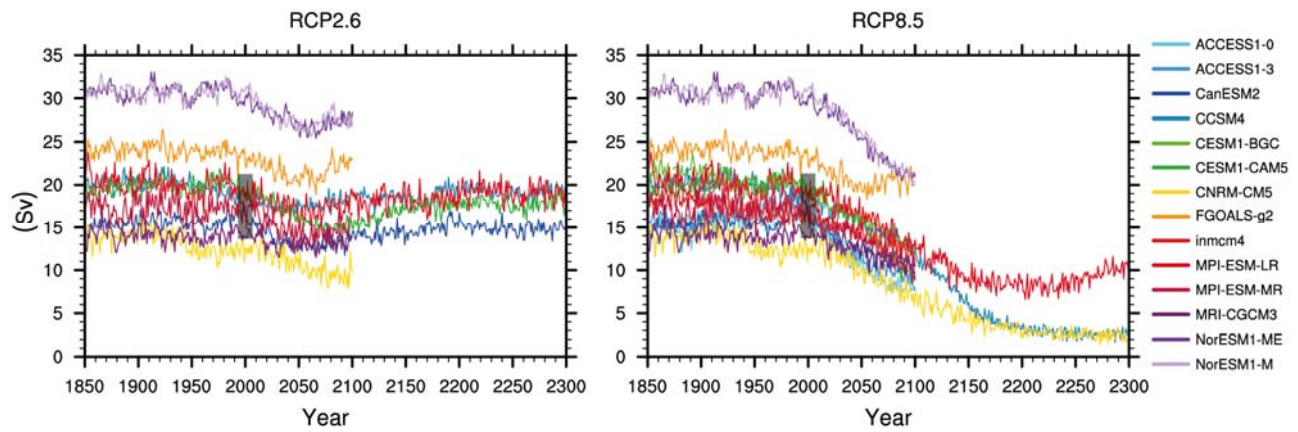


**TFE.3, Figure 1:** (top: left) Observed globally and annually averaged CO<sub>2</sub> concentrations in parts per million (ppm) since 1950 compared with projections from the previous IPCC assessments. Observed global annual CO<sub>2</sub> concentrations are shown in dark blue. The shading shows the largest model projected range of global annual CO<sub>2</sub> concentrations from 1950 to 2035 from FAR (First Assessment Report; Figure A.3 in the Summary for Policymakers (SPM) of IPCC 1990), SAR (Second Assessment Report; Figure 5b in the TS of IPCC 1996), TAR (Third Assessment Report; Appendix II of IPCC 2001), and for the A2, A1B and B1 scenario presented in the AR4 (Fourth Assessment Report; Figure 10.26). (top: right) Same observed globally averaged CO<sub>2</sub> concentrations and the projections from this report. Only RCP8.5 has a range of values since the emission driven scenarios were only carried out for this RCP. For the other RCPs the best estimate is given. (middle: left) Estimated changes in the observed globally and annually averaged surface temperature anomaly relative to 1961-1990 (in °C) since 1950 compared with the range of projections from the previous IPCC assessments. Values are harmonized to start from the same value at 1990. Observed global annual temperature anomaly, relative to 1961–1990, from three datasets is shown as squares (NASA (dark blue), NOAA (warm mustard), and the UK Hadley Centre (bright green) data sets). The coloured shading shows the projected range of global annual mean near surface temperature change from 1990 to 2035 for models used in FAR (Figure 6.11), SAR (Figure 19 in the TS of IPCC 1996), TAR (full range of TAR, Figure 9.13(b)). TAR results are based on the simple climate model analyses presented in this assessment and not on the individual full three-dimensional climate model simulations. For the AR4 results are presented as single model runs of the CMIP3 ensemble for the historical

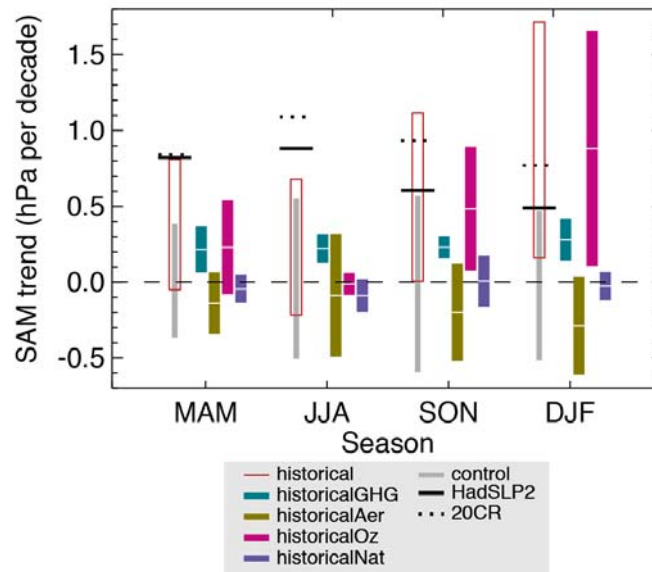
period from 1950-2000 (light grey lines) and for three scenarios (A2, A1B and B1) from 2001-2035. For the three SRES scenarios the bars show the CMIP3 ensemble mean and the likely range given by -40 % to +60% of the mean as assessed in Meehl et al. (2007). The publication years of the assessment reports are shown. (middle; right) Projections of annual mean global mean surface air temperature (GMST) for 1950–2035 (anomalies relative to 1961–1990) under different RCPs from CMIP5 models (light grey and coloured lines, one ensemble member per model), and observational estimates the same as the middle left panel. The grey shaded region shows the indicative likely range for annual mean GMST during the period 2016–2035 for all RCPs (see Figure TS.14 for more details). The grey bar shows this same indicative likely range for the year 2035. (bottom: left) Estimated changes in the observed global annual mean sea level (GMSL) since 1950. Different estimates of changes in global annual sea level anomalies from tide gauge data (dark blue, warm mustard, dark green) and based on annual averages of altimeter data (light blue ) starting in 1993 (the values have been aligned to fit the 1993 value of the tide gauge data). Squares indicate annual mean values, solid lines smoothed values. The shading shows the largest model projected range of global annual sea level rise from 1950 to 2035 for FAR (Figures 9.6 and 9.7), SAR (Figure 21 in TS of IPCC, 1996), TAR (Appendix II of IPCC, 2001; updated) based on the Coupled Model Intercomparison Project Phase 3 (CMIP3) model results available at the time of AR4 using the SRES A1B scenario. Note that in the AR4 no full range was given for the sea level projections for this period. Therefore, the figure shows results only for the SRES-A1B scenario that have been published subsequent to the AR4. The bars at the right hand side of each graph show the full range given for 2035 for each assessment report. The publication years of the assessment reports are shown. Appendix 1.A for details on the data and calculations used to create these figures. (bottom: right) Same observational estimate as bottom left. The bars are the "likely ranges (medium confidence) for global mean sea level rise at 2081-2100 with respect to 1986-2005 following the four RCPs. See Chapters 1, 11 and 13 for more details. {Figures 1.4, 1.5, 1.10, 11.9, 11.19, 11.25, 13.11}



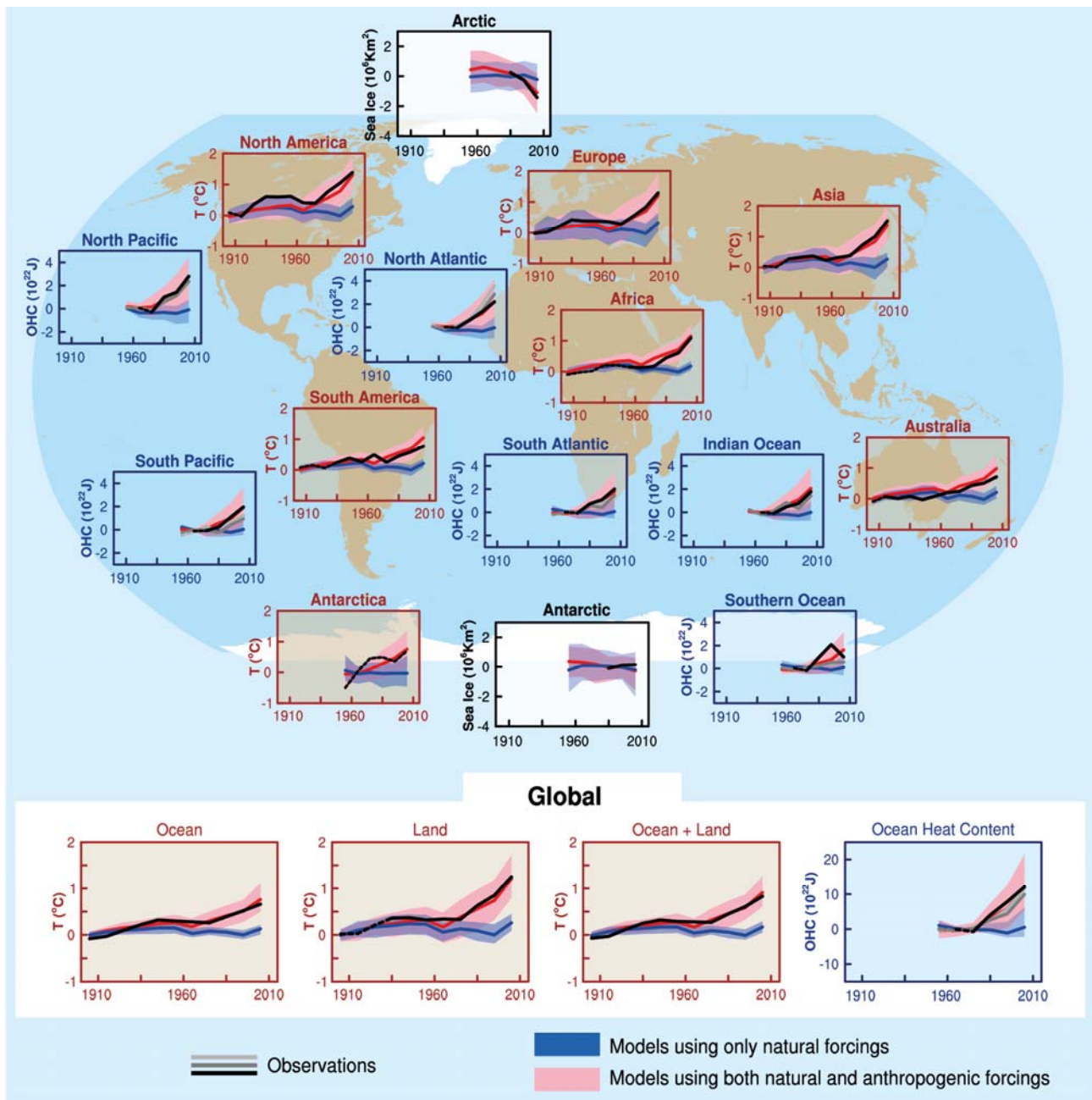
**TFE.4, Figure 1:** The Earth's energy budget from 1970 through 2011. (a) The cumulative energy inflow into the Earth system from changes in well-mixed and short-lived greenhouse gases, solar forcing, tropospheric aerosol forcing, volcanic forcing, and changes in surface albedo due to land-use change (all relative to 1860-1879) are shown by the coloured lines; these contributions are added to give the total energy inflow (black; contributions from black carbon on snow and contrails as well as contrail-induced cirrus are included but not shown separately). (b) The cumulative total energy inflow from (a, black) is balanced by the sum of the energy uptake of the Earth system (blue; energy absorbed in warming the ocean, the atmosphere, and the land, as well as in the melting of ice) and an increase in outgoing radiation inferred from changes in the global-mean surface temperature. The sum of these two terms is given for a climate feedback parameter  $\alpha$  of 2.47, 1.23, and  $0.82 \text{ W m}^{-2} \text{ }^{\circ}\text{C}^{-1}$ , corresponding to an equilibrium climate sensitivity of  $1.5^{\circ}\text{C}$ ,  $3.0^{\circ}\text{C}$ , and  $4.5^{\circ}\text{C}$ , respectively;  $1.5^{\circ}\text{C}$ – $4.5^{\circ}\text{C}$  is assessed to be the *likely* range of equilibrium climate sensitivity. The energy budget would be closed for a particular value of  $\alpha$  if the corresponding line coincided with the total energy inflow. For clarity, all uncertainties (shading) shown are *likely* ranges. {Box 12.2; Box 13.1, Figure 1}



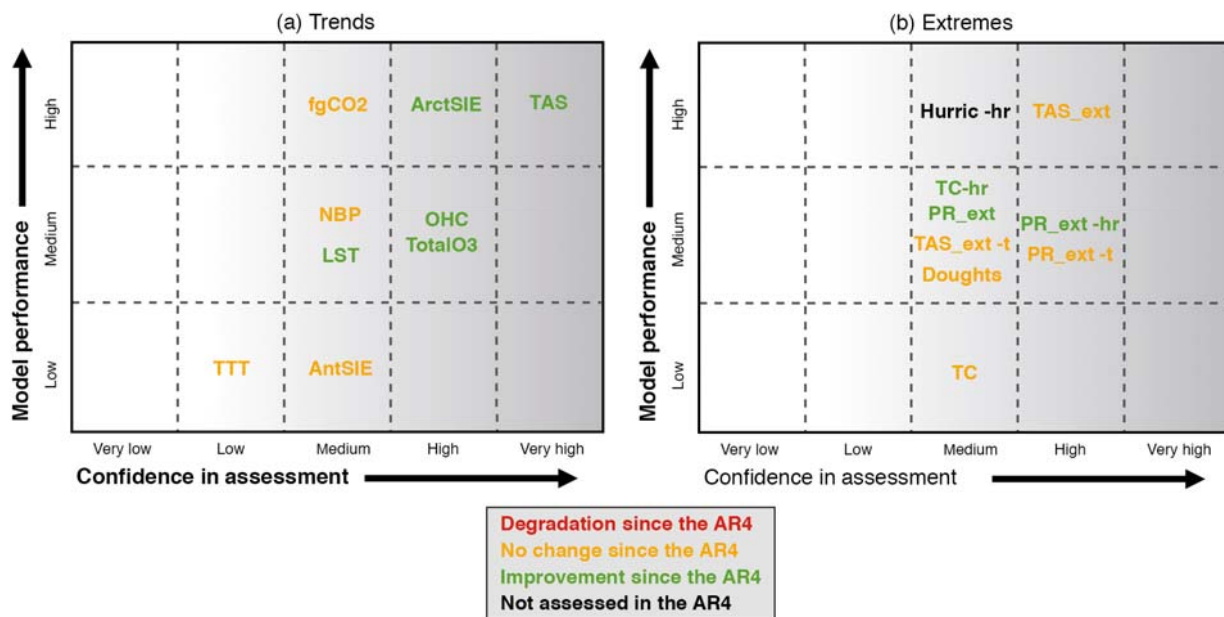
**TFE.5, Figure 1:** Atlantic Meridional Overturning Circulation strength at 30°N (Sv) as a function of year, from 1850 to 2300 as simulated by different AOGCMs in response to scenario RCP2.6 (left) and RCP8.5 (right). The vertical black bar shows the range of AMOC strength measured at 26°N, from 2004 to 2011 {Figure 3.11, 12.35}



**Figure TS.11:** Simulated and observed 1951–2011 trends in the Southern Annular Mode (SAM) index by season. The SAM index is a difference between zonal mean sea level pressure (SLP) at 40°S and 65°S. The SAM index is defined without normalization, so that the magnitudes of simulated and observed trends can be compared. Black lines show observed trends from the HadSLP2r dataset (solid), and the 20th century Reanalysis (dotted). Grey bars show 5th–95th percentile ranges of control trends, and red boxes show the 5th–95th percentile range of trends in historical simulations including anthropogenic and natural forcings. Coloured bars show ensemble mean trends and their associated 5–95% confidence ranges simulated in response to greenhouse gas (light green), aerosol (dark green), ozone (magenta) and natural forcing changes (blue) in CMIP5 individual-forcing simulations. {Figure 10.13b}



**Figure TS.12:** Detection and attribution signals (decadal averages) in the climate system, at regional scales (top panels) and global scales (bottom 4 panels). Brown panels are land surface temperature time series, blue panels are ocean heat content time series, and white panels are sea-ice time series. Each panel shows observations (black or black and shades of grey), and the 5–95% range of the simulated response to natural forcings (blue shading) and natural and anthropogenic forcings (pink shading), together with the corresponding ensemble means (dark blue and dark red respectively). The observed surface temperature is from HadCRUT4. Three observed records of ocean heat content (OHC) are shown. Sea-ice anomalies (rather than absolute values) are plotted and based on models in Figure 10.16. The observations are either solid or dashed and indicate the quality of the observations and estimates. For land and ocean surface temperatures panels and precipitation panels, solid observation lines indicate where spatial coverage of areas being examined, is above 50% coverage and dashed observation lines where coverage is below 50%. For example, data coverage of Antarctica never goes above 50% of the land area of the continent. For ocean heat content and sea-ice panels the solid observations line is where the coverage of data is good and higher in quality, and the dashed line is where the data coverage is only adequate. This figure is based in Figure 10.21 except presented as decadal averages rather than yearly averages. {Figure 10.21}



**Box TS.4, Figure 1:** Summary of how well the current-generation climate models simulate important features of the climate of the 20th century. Confidence in the assessment increases towards the right as suggested by the increasing strength of shading. Model quality increases from bottom to top. The colour coding indicates improvements from the models available at the time of the AR4 to the current assessment. There have been a number of improvements since the AR4, and some some modelled quantities are not better simulated. The major climate quantities are listed in this summary and none shows degradation. The assessment is mostly based on the multi-model mean, not excluding that deviations for individual models could exist. Assessed model quality is simplified for representation in this figure; details of each assessment are found in Chapter 9. {9.8.1; Figure 9.44}

The figure highlights the following key features, with the sections that back up the assessment added in brackets:

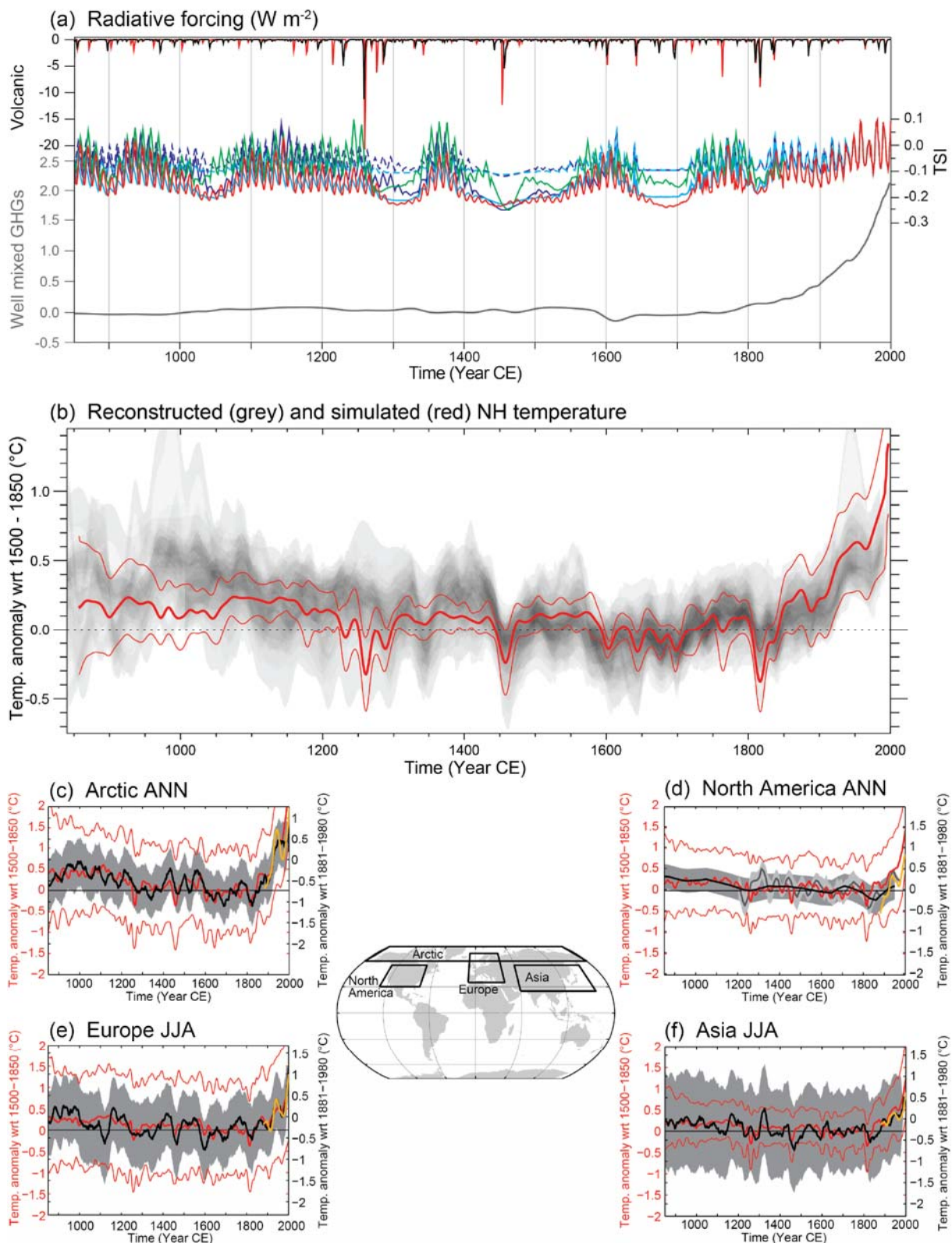
**(a) Trends in:**

AntSIE:	Antarctic sea-ice extent {9.4.3}
ArctSIE:	Arctic sea-ice extent {9.4.3}
fgCO2:	Global ocean carbon sink {9.4.5}
LST:	Lower-stratospheric temperature {9.4.1.}
NBP:	Global land carbon sink {9.4.5}
OHC:	Global ocean heat content {9.4.2}
TotalO3:	Total-column ozone {9.4.1}
TAS:	Surface air temperature {9.4.1}
TTT:	Tropical tropospheric temperature {9.4.1}

**(b) Extremes:**

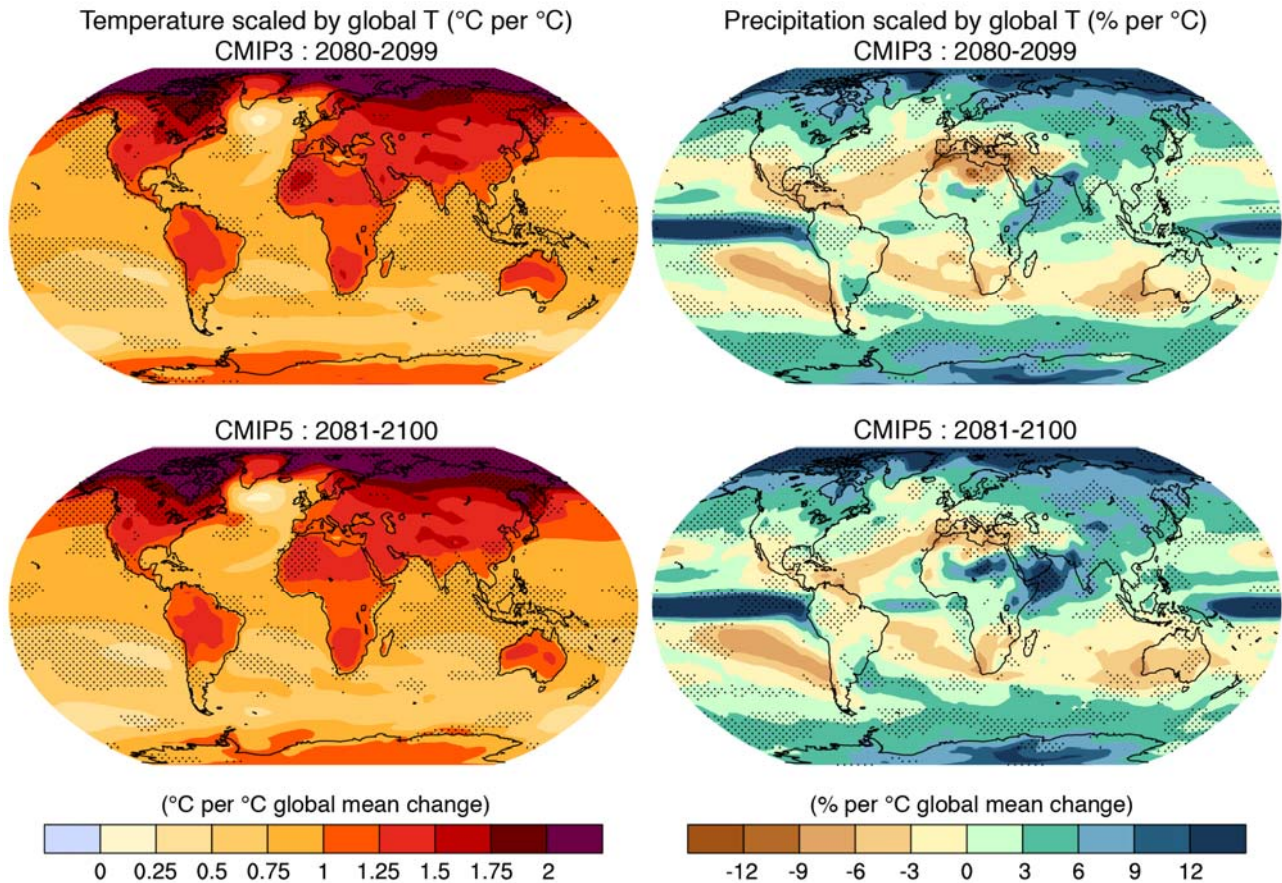
Droughts	Droughts {9.5.4}
Hurric-hr	Year-to-year count of Atlantic hurricanes in high-resolution AGCMs {9.5.4}
PR_ext	Global distribution of precipitation extremes {9.5.4}
PR_ext-hr	Global distribution of precipitation extremes in high-resolution AGCMs {9.5.4}
PR_ext-t	Global trends in precipitation extremes {9.5.4}
TAS_ext	Global distributions of surface air temperature extremes {9.5.4}
TAS_ext-t	Global trends in surface air temperature extremes {9.5.4}
TC	Tropical cyclone tracks and intensity {9.5.4}
TC-hr	Tropical cyclone tracks and intensity in high-resolution AGCMs {9.5.4}



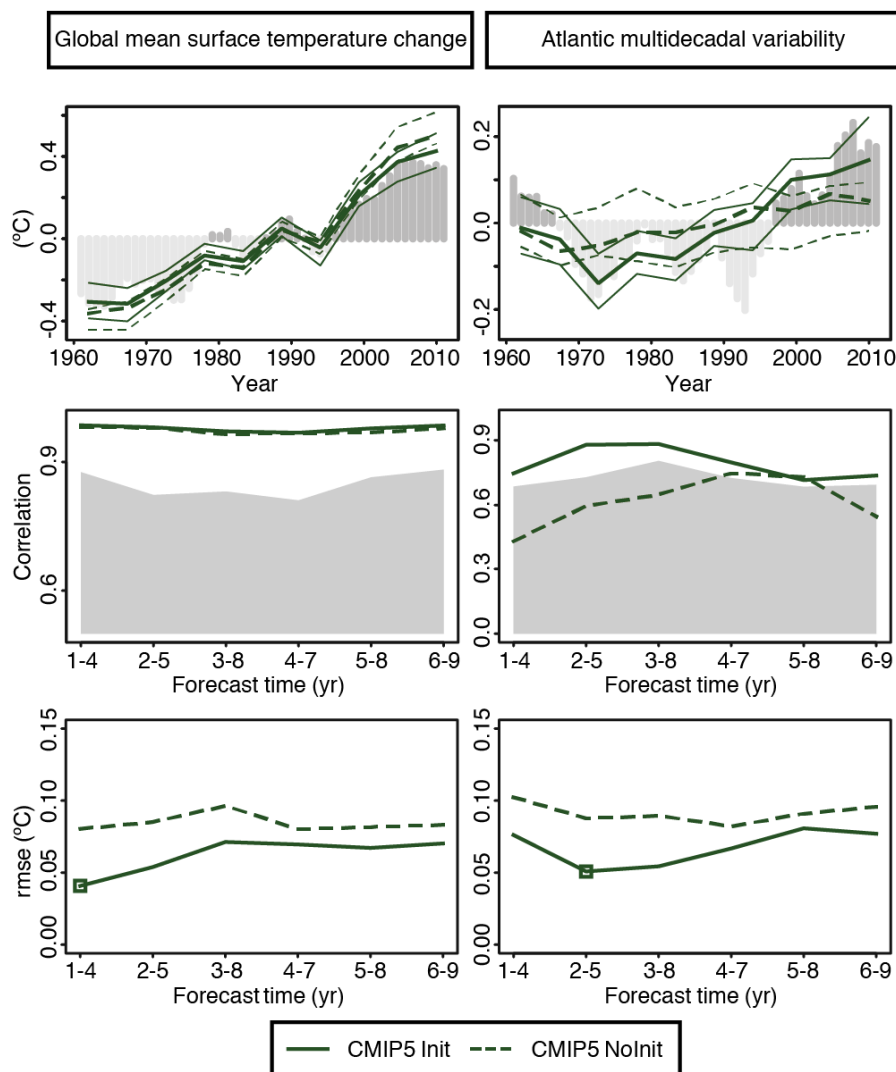


**Box TS.5, Figure 1:** Last-millennium simulations and reconstructions. (a) 850–2000 PMIP3/CMIP5 radiative forcing due to volcanic, solar and well mixed greenhouse gas. Different colors illustrate the two existing datasets for volcanic forcing (CEA and GRA) and the four estimates of solar forcing (DB, MEA, SBF and VSK). For solar forcing, solid (dashed) lines stand for reconstruction variants in which background changes in irradiance are (not) considered; (b) 850–2000 PMIP3/CMIP5 simulated (red) and reconstructed (shading) NH temperature changes. The thick red line depicts the multi-model mean while the thin red lines show the multi-model 90% range. The overlap of reconstructed temperatures is shown by grey shading; all data are expressed as anomalies from their 1500–1850 mean and smoothed

with a 30-year filter. Note that some reconstructions represent a smaller spatial domain than the full NH or a specific season, while annual temperatures for the full NH mean are shown for the simulations. (c), (d), (e) and (f) Arctic and North America annual mean temperature, and Europe and Asia June-July-August (JJA) temperature, from 950 to 2000 from reconstructions (black line), and PMIP3/CMIP5 simulations (thick red, multi-model mean; thin red 90% multi-model range). All red curves are expressed as anomalies from their 1500–1850 mean and smoothed with a 30-year filter. The shaded envelope depicts the uncertainties from each reconstruction (Arctic: 90% confidence bands, North American:  $\pm 2$  standard deviation, Asia:  $\pm 2$  root mean square error, Europe: 95% confidence bands). For comparison with instrumental record, the CRUTEM4 dataset is shown (yellow line). All lines are smoothed by applying a 30 year moving average. Map shows the individual regions for each reconstruction. {5.3.5; Table 5.A.1; Figures 5.1, 5.8, 5.12}

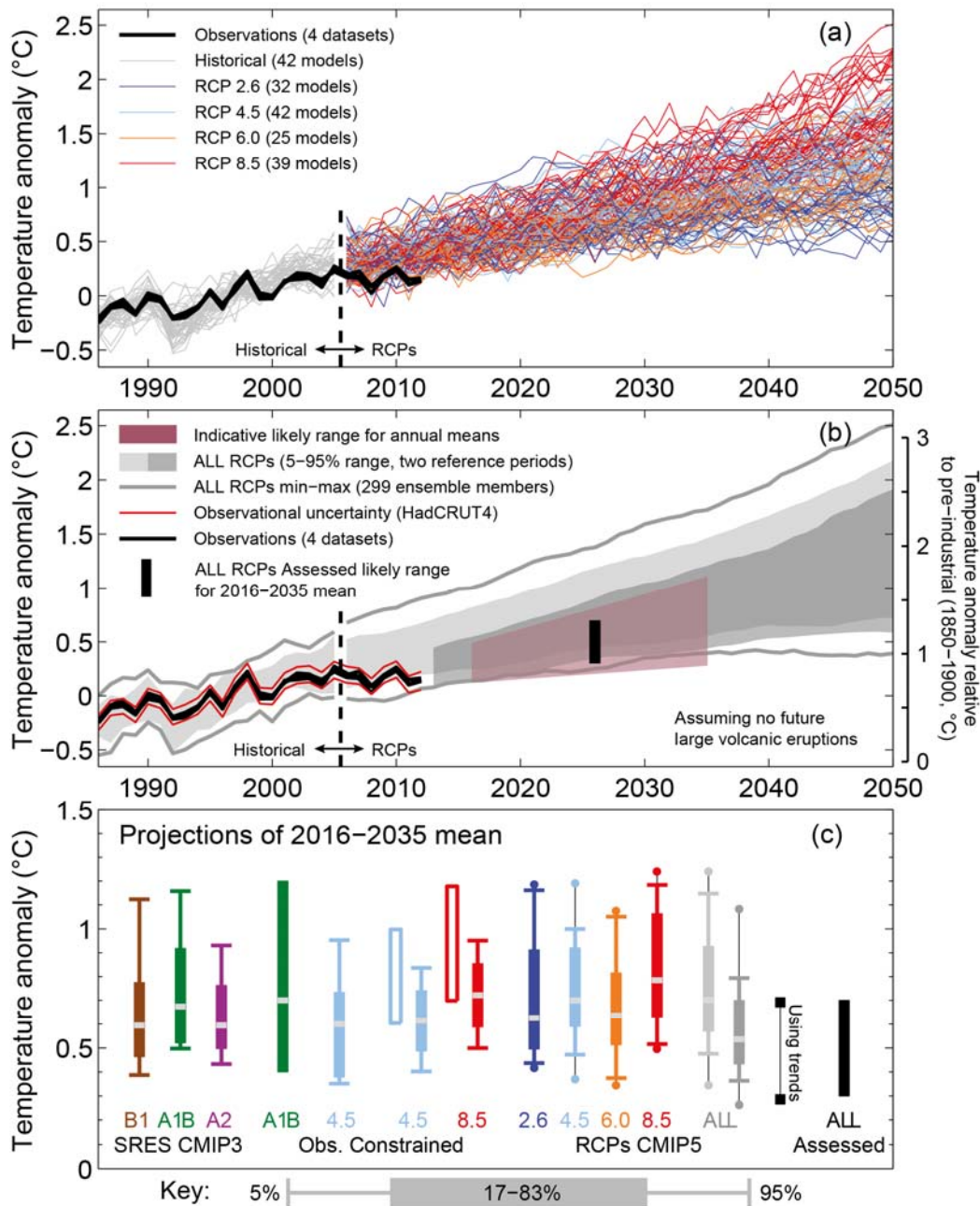


**Box TS.6, Figure 1:** Patterns of temperature (left column) and percent precipitation change (right column) for the CMIP3 models average (first row) and CMIP5 models average (second row), scaled by the corresponding global average temperature changes. The patterns are computed in both cases by taking the difference between the averages over the last twenty years of the 21st century experiments (2080–2099 for CMIP3 and 2081–2100 for CMIP5) and the last twenty years of the historic experiments (1980–1999 for CMIP3, 1986–2005 for CMIP5) and rescaling each difference by the corresponding change in global average temperature. This is done first for each individual model, then the results are averaged across models. Stippling indicates a measure of significance of the difference between the two corresponding patterns obtained by a bootstrap exercise. Two subsets of the pooled set of CMIP3 and CMIP5 ensemble members of the same size as the original ensembles, but without distinguishing CMIP3 from CMIP5 members, were randomly sampled 500 times. For each random sample the corresponding patterns and their difference are computed, then the true difference is compared, grid-point by grid-point, to the distribution of the bootstrapped differences, and only grid-points at which the value of the difference falls in the tails of the bootstrapped distribution (less than the 2.5 percentiles or the 97.5 percentiles) are stippled. {Figure 12.41}



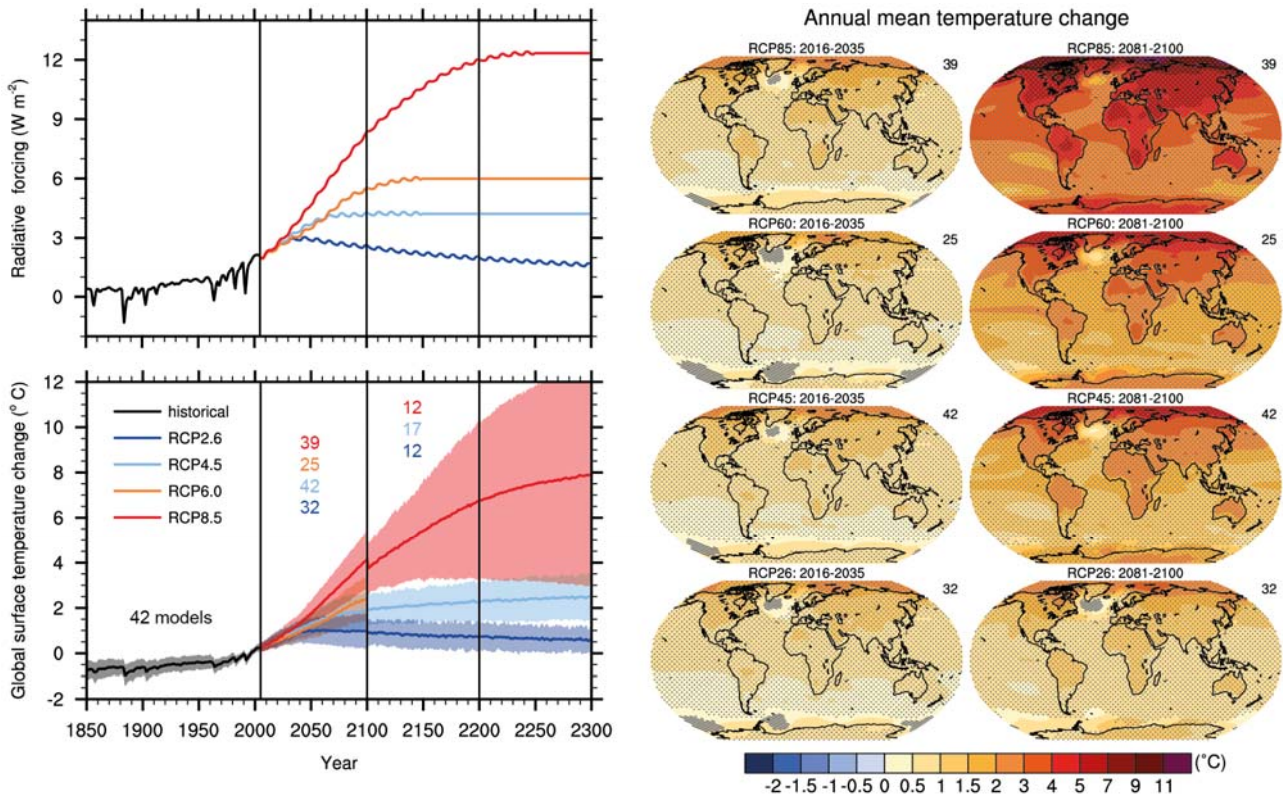
**Figure TS.13:** Decadal prediction forecast quality of several climate indices. Top row: Time series of the 2–5 year average ensemble-mean initialized hindcast anomalies and the corresponding non-initialized experiments for three climate indices: Global Mean Surface Temperature (GMST, left) and the Atlantic Multidecadal Variability (AMV, right). The observational time series, GISS global-mean temperature and ERSST for the AMV, are represented with dark grey (positive anomalies) and light grey (negative anomalies) vertical bars, where a four-year running mean has been applied for consistency with the time averaging of the predictions. Predicted time series are shown for the CMIP5 Init (solid) and NoInit (dotted) simulations with hindcasts started every five years over the period 1960–2005. The lower and upper quartile of the multi-model ensemble are plotted using thin lines. The AMV index was computed as the sea surface temperature anomalies averaged over the region Equator–60°N and 80°W–0°W minus the sea surface temperature anomalies averaged over 60°S–60°N. Note that the vertical axes are different for each time series. Middle row: Correlation of the ensemble-mean prediction with the observational reference along the forecast time for four-year averages of the three sets of CMIP5 hindcasts for Init (solid) and NoInit (dashed). The one-sided 95% confidence level with a *t* distribution is represented in grey. The effective sample size has been computed taking into account the autocorrelation of the observational time series. A two-sided *t* test (where the effective sample size has been computed taking into account the autocorrelation of the observational time series) has been used to test the differences between the correlation of the initialized and non-initialized experiments, but no differences were found statistically significant with a confidence equal or higher than 90%. Bottom row: Root mean square error (RMSE) of the ensemble-mean prediction along the forecast time for four-year averages of the CMIP5 hindcasts for Init (solid) and NoInit (dashed). A two-sided *F* test (where the effective sample size has been computed taking into account the autocorrelation of the observational time series) has been used to test the ratio between the RMSE of the Init and NoInit, and those forecast times with differences statistically significant with a confidence equal or higher than 90% are indicated with an open square. {Figure 11.3}

### Global mean temperature near-term projections relative to 1986–2005



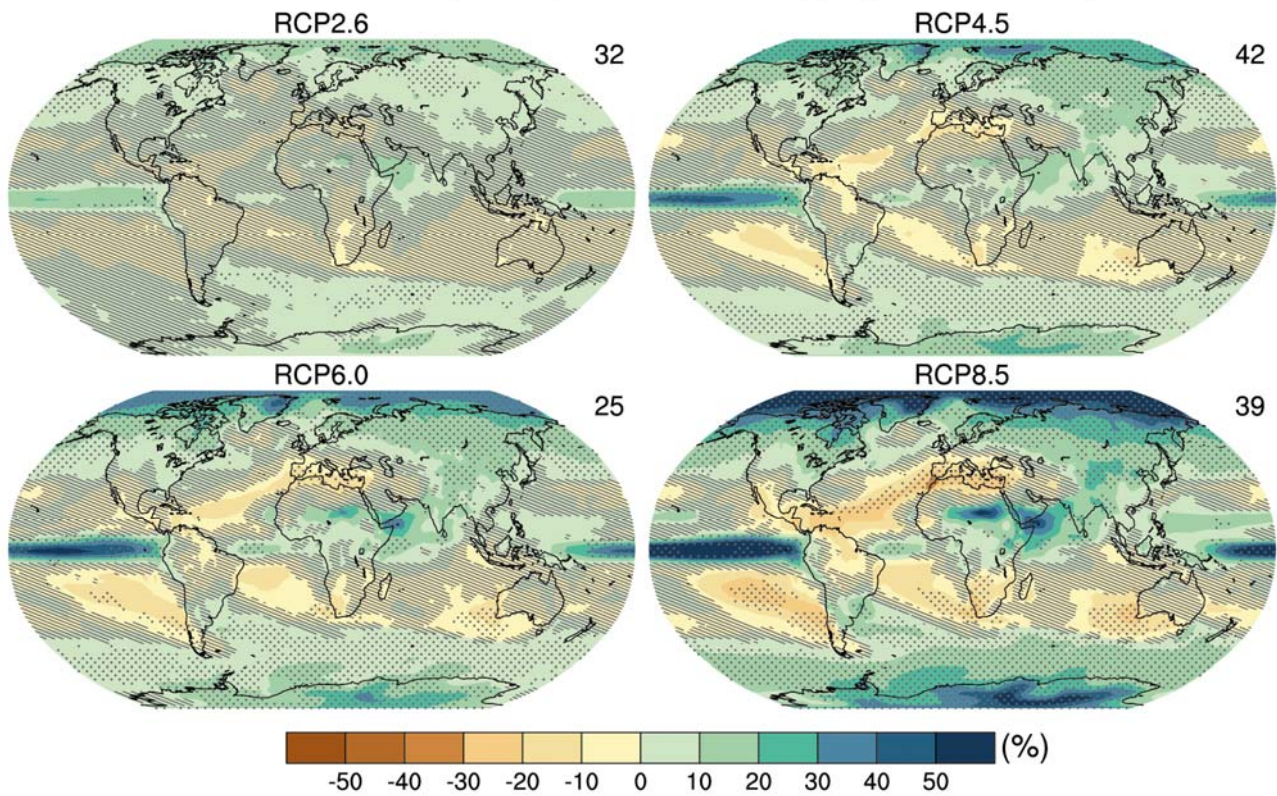
**Figure TS.14:** Synthesis of near-term projections of global mean surface air temperature (GMST). (a) Projections of annual mean GMST 1986–2050 (anomalies relative to 1986–2005) under all RCPs from CMIP5 models (grey and coloured lines, one ensemble member per model), with four observational estimates (HadCRUT4, ERA-Interim, GISTEMP, NOAA) for the period 1986–2012 (black lines). (b) as (a) but showing the 5–95% range of annual mean CMIP5 projections (using one ensemble member per model) for all RCPs using a reference period of 1986–2005 (light grey shade) and all RCPs using a reference period of 2006–2012, together with the observed anomaly for (2006–2012)–(1986–2005) of 0.16°C (dark grey shade). The percentiles for 2006 onwards have been smoothed with a 5 year running mean for clarity. The maximum and minimum values from CMIP5 using all ensemble members and the 1986–2005 reference period are shown by the grey lines (also smoothed). Black lines show annual mean observational estimates. The red shaded region shows the indicative likely range for annual mean GMST during the period 2016–2035 based on the “ALL RCPs Assessed” likely range for the 20 year mean GMST anomaly for 2016–2035, which is shown as a black bar in both panels (b) and (c) (see text for details). The temperature scale relative to pre-industrial climate on the right hand side assumes a warming of GMST prior to 1986–2005 of 0.61°C estimated from HadCRUT4. (c) A synthesis of projections for the mean GMST anomaly for 2016–2035 relative to 1986–2005. The box and whiskers represent the 66% and 90% ranges. Shown are: unconstrained SRES CMIP3 and RCP CMIP5 projections; observationally

constrained projections for the SRES A1B and, the RCP4.5 and 8.5 scenarios; unconstrained projections for all four RCP scenarios using two reference periods as in panel (b) (light grey and dark grey shades), consistent with panel (b); 90% range estimated using CMIP5 trends for the period 2012–2035 and the observed GMST anomaly for 2012; an overall *likely* (>66%) assessed range for all RCP scenarios. The dots for the CMIP5 estimates show the maximum and minimum values using all ensemble members. The medians (or maximum likelihood estimate; green filled bar) are indicated by a grey band. Adapted from Figure 11.25. See Chapter 11, Section 11.3.6 for details. {Figure 11.25}



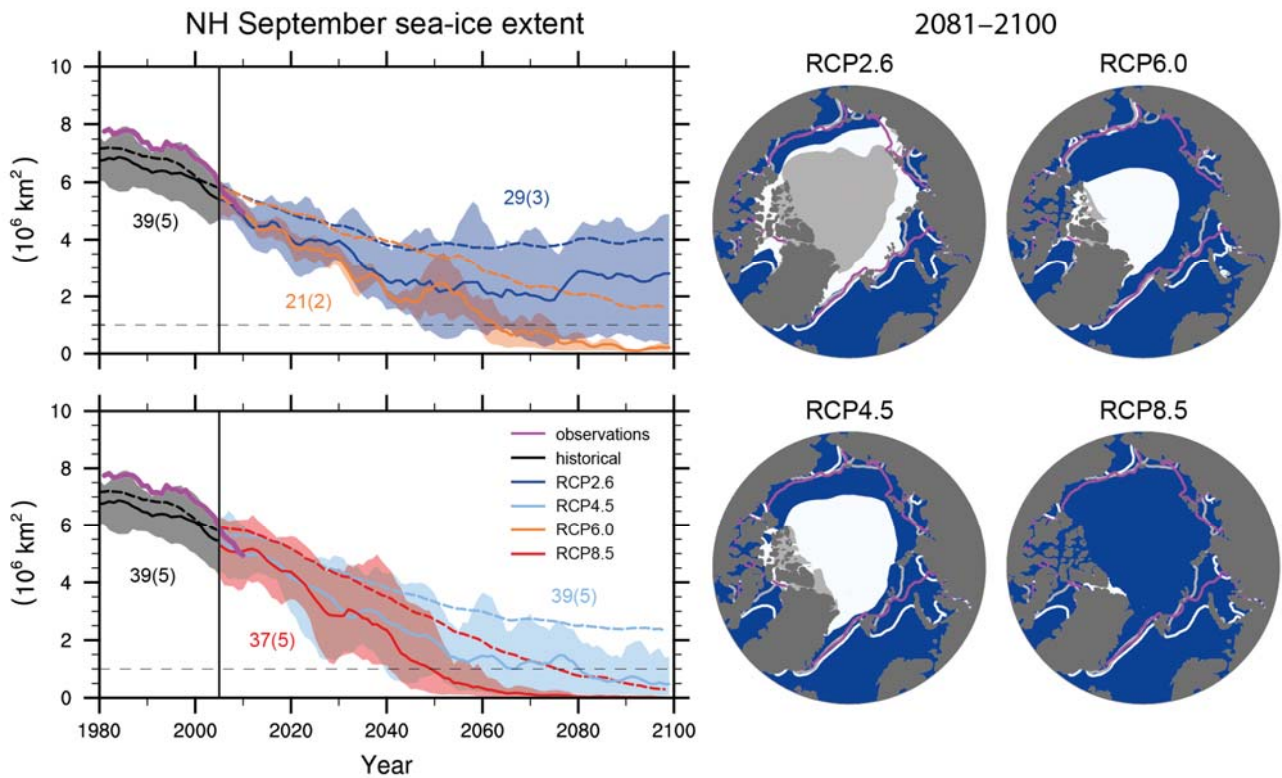
**Figure TS.15:** Top left: Total global mean radiative forcing for the 4 RCP scenarios based on the MAGICC energy balance model. Note that the actual forcing simulated by the CMIP5 models differs slightly between models. Bottom left: Time series of global annual mean surface air temperature anomalies (relative to 1986–2005) from CMIP5 concentration-driven experiments. Projections are shown for each RCP for the multimodel mean (solid lines) and  $\pm 1.64$  standard deviation (5–95%) across the distribution of individual models (shading). Those ranges are interpreted as “likely” changes at the end of the 21st century. Discontinuities at 2100 are due to different numbers of models performing the extension runs beyond the 21st century and have no physical meaning. Numbers in the same colours as the lines indicate the number of different models contributing to the different time periods. Maps: Multimodel ensemble average of annual mean surface air temperature change (compared to 1986–2005 base period) for 2016–2035 and 2081–2100, for RCP2.6, 4.5, 6.0 and 8.5. Hatching indicates regions where the multi model mean signal is less than one standard deviation of internal variability. Stippling indicates regions where the multi model mean signal is greater than two standard deviations of internal variability and where 90% of the models agree on the sign of change. The number of CMIP5 models used is indicated in the upper right corner of each panel. {Box 12.1; Figures 12.4, 12.5, 12.11; Annex I}

## Annual mean precipitation change (2081-2100)

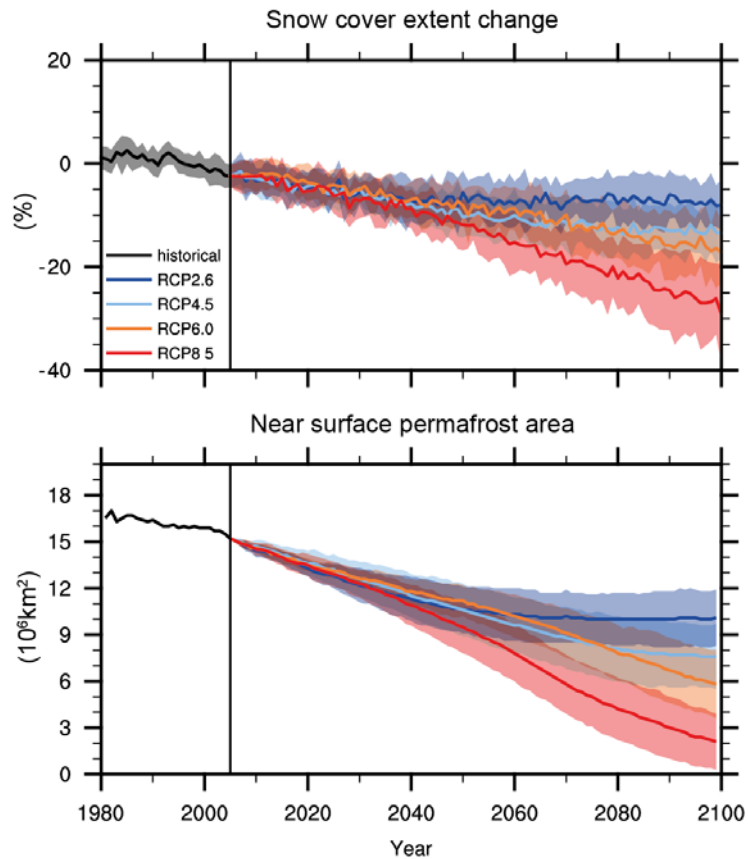


**Figure TS.16:** Maps of multi-model results for the scenarios RCP2.6, RCP4.5, RCP6.0 and RCP8.5 in 2081–2100 of average percent change in mean precipitation. Changes are shown relative to 1986–2005. The number of CMIP5 models to calculate the multi-model mean is indicated in the upper right corner of each panel. Hatching indicates regions where the multi model mean signal is less than one standard deviation of internal variability. Stippling indicates regions where the multi model mean signal is greater than two standard deviations of internal variability and where 90% of models agree on the sign of change (see Box 12.1). {Figure 12.22; Annex I}

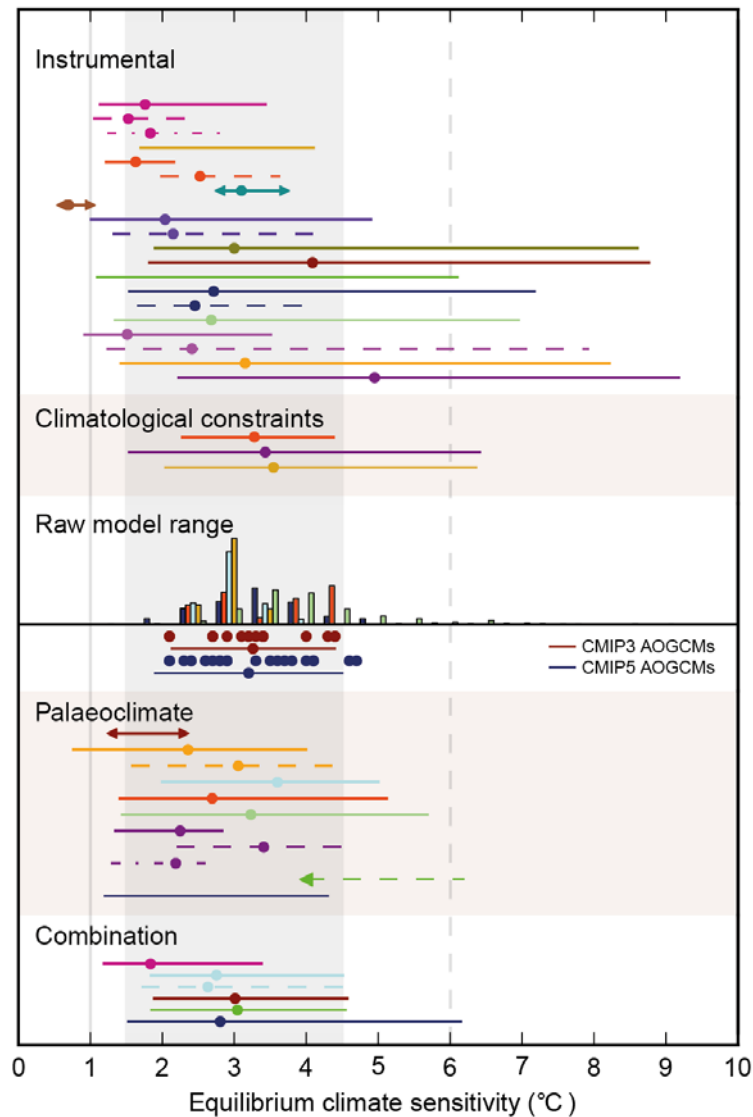




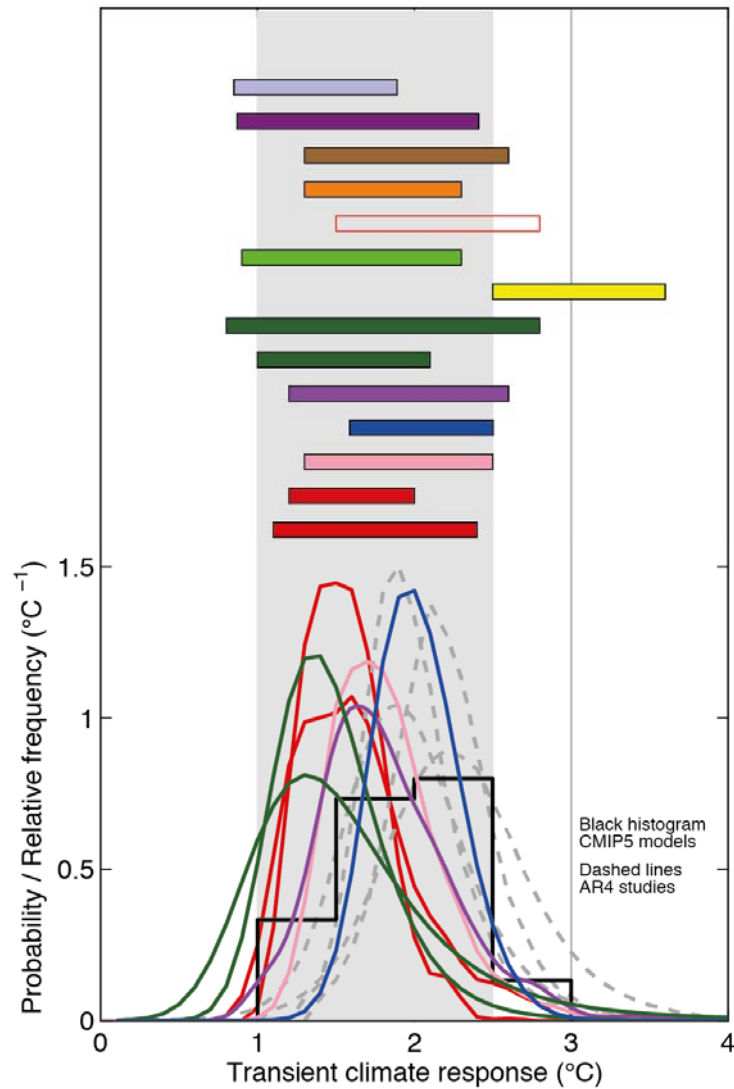
**Figure TS.17:** Northern Hemisphere sea-ice extent in September over the late 20th century and the whole 21st century for the scenarios RCP2.6, RCP4.5, RCP6.0 and RCP8.5 in the CMIP5 models, and corresponding maps of multi-model results in 2081–2100 of Northern Hemisphere September sea ice extent. In the time series, the number of CMIP5 models to calculate the multi-model mean is indicated (subset in brackets). Time series are given as 5 year running means. The projected mean sea ice extent of a subset of models that most closely reproduce the climatological mean state and 1979–2012 trend of the Arctic sea ice is given (solid lines), with the min-max range of the subset indicated with shading. Black (grey shading) is the modelled historical evolution using historical reconstructed forcings. The CMIP5 multi-model mean is indicated with dashed lines. In the maps, the CMIP5 multi-model mean is given in white color, the results for the subset in grey colour. Filled areas mark the averages over the 2081–2100 period, lines mark the sea ice extent averaged over the 1986–2005 period. The observed sea ice extent is given in pink as a time series and averaged over 1986–2005 as a pink line in the map. {Figures 12.18, 12.29, 12.31}



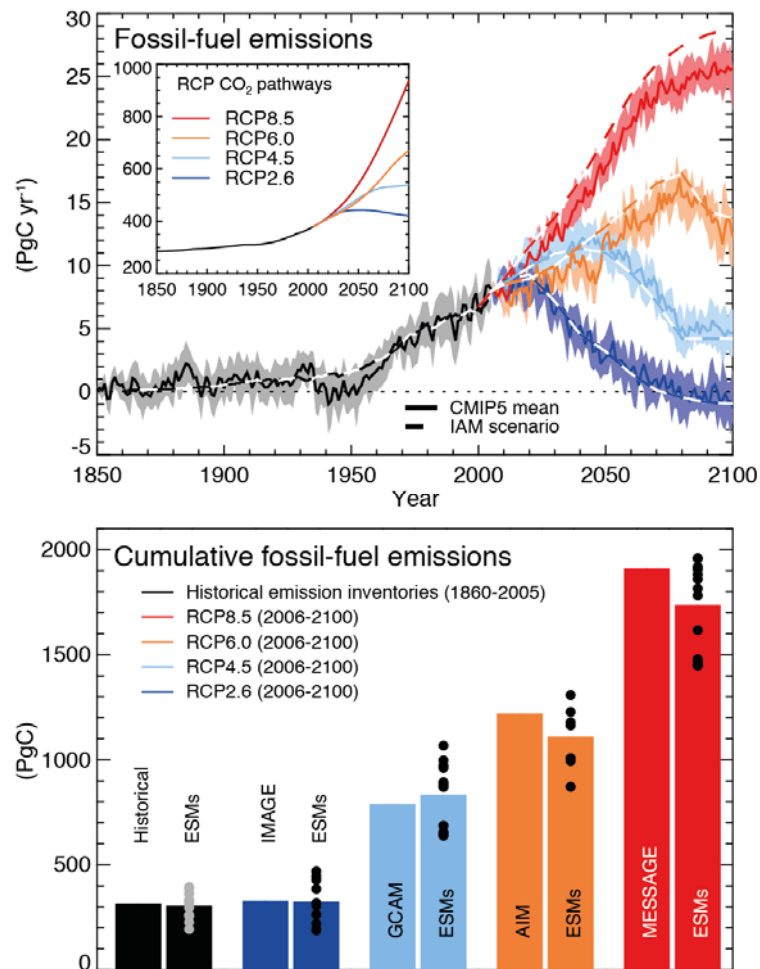
**Figure TS.18:** Top: Northern Hemisphere spring (March to April average) relative snow covered area (RSCA) in CMIP5, obtained by dividing the simulated 5-year box smoothed spring snow covered area (SCA) by the simulated average spring SCA of 1986–2005 reference period. Bottom: Northern hemisphere diagnosed near-surface permafrost area in CMIP5, using 20-year average monthly surface air temperatures and snow depths. Lines indicate the multi model average, shading indicates the inter-model spread (one standard deviation). {Figures 12.32, 12.33}



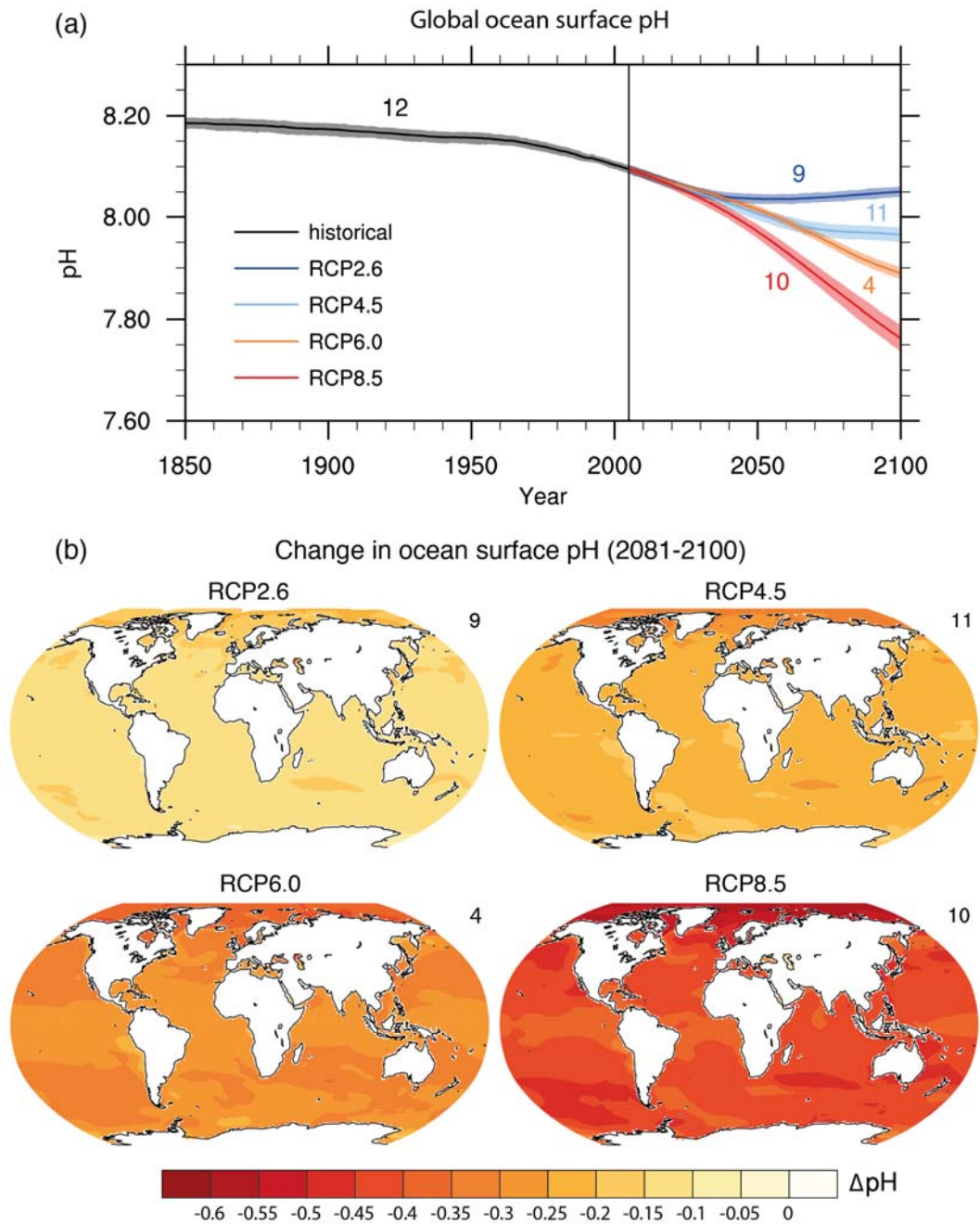
**TFE.6, Figure 1:** Probability density functions, distributions and ranges for equilibrium climate sensitivity, based on Figure 10.20b plus climatological constraints shown in IPCC AR4 ( Box AR4 10.2 Figure 1), and results from CMIP5 (see Table 9.5). The grey shaded range marks the *likely* 1.5°C to 4.5°C range, grey solid line the *extremely unlikely* less than 1°C, the grey dashed line the *very unlikely* greater than 6°C. Adapted from Box 12.2, Figure 1. See Figure 10.20b and Chapter 10 Supplementary Material for full caption and details. Labels refer to studies since AR4. {Box 12.2, Figure 1}



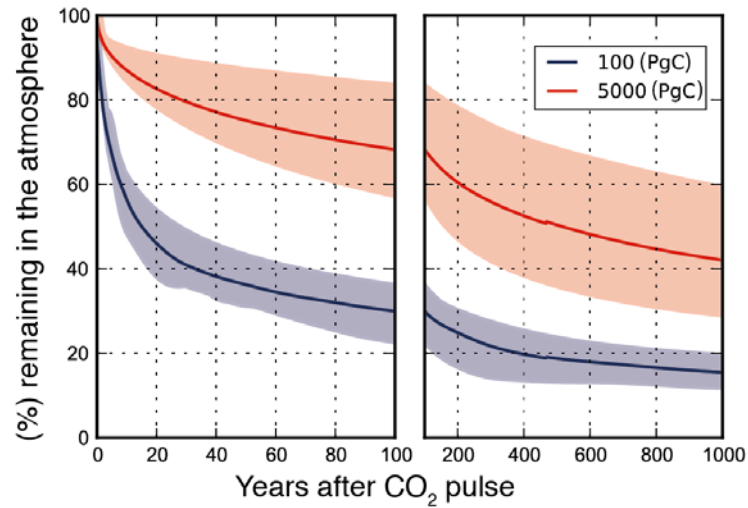
**TFE.6, Figure 2:** Probability density functions, distributions and ranges (5–95%) for the transient climate response from different studies, based on Figure 10.20a, and results from CMIP5 (black histogram, Table 9.5). The grey shaded range marks the *likely* 1°C to 2.5°C range, the grey solid line marks the *extremely unlikely* greater than 3°C. Adapted from Box 12.2, Figure 2. See Figure 10.20a and Chapter 10 Supplementary Material for full caption and details. {Box 12.2, Figure 2}



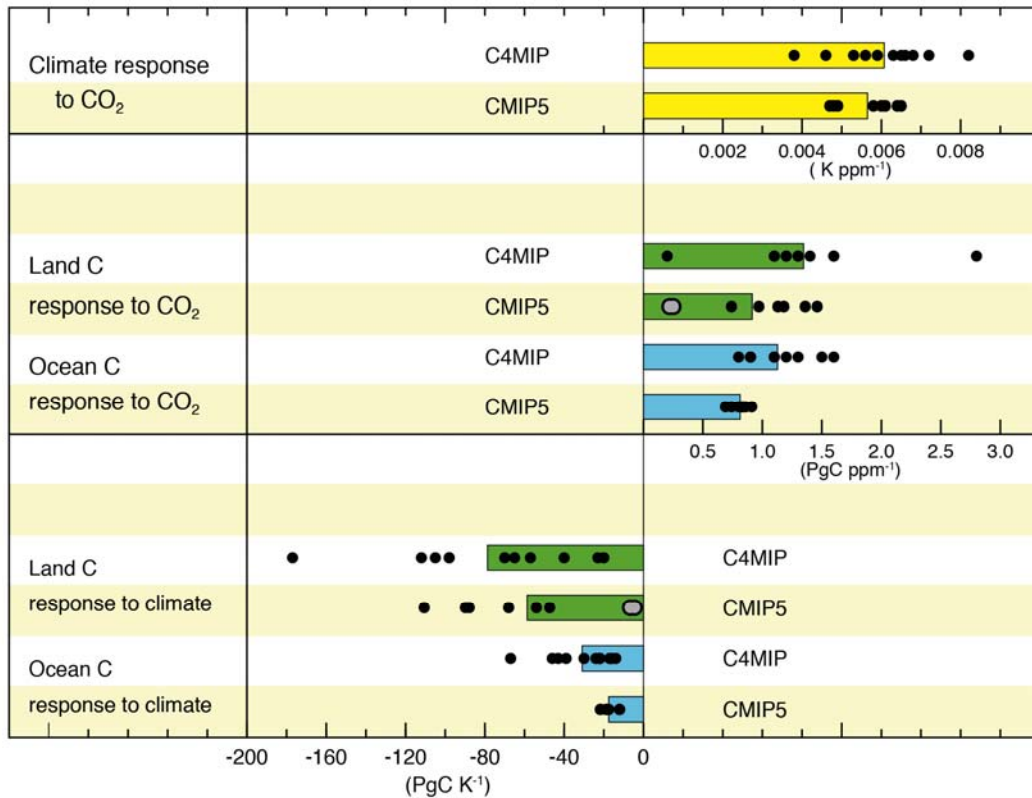
**Figure TS.19:** Compatible fossil fuel emissions simulated by the CMIP5 models for the four RCP scenarios. Top: timeseries of annual emission ( $\text{PgC yr}^{-1}$ ). Dashed lines represent the historical estimates and RCP emissions calculated by the integrated assessment models (IAM) used to define the RCP scenarios, solid lines and plumes show results from CMIP5 ESMs (model mean, with 1 standard deviation shaded). Bottom: cumulative emissions for the historical period (1860–2005) and 21st century (defined in CMIP5 as 2006–2100) for historical estimates and RCP scenarios. Left bars are cumulative emissions from the IAMs, right bars are the CMIP5 ESMs multi-model mean estimate, and dots denote individual ESM results. From the CMIP5 ESMs results, total carbon in the land-atmosphere-ocean system can be tracked and changes in this total must equal fossil fuel emissions to the system. Hence the compatible emissions are given by cumulative Emissions =  $\Delta C_A + \Delta C_L + \Delta C_O$ , while emission rate =  $d/dt [C_A + C_L + C_O]$ , where  $C_A$ ,  $C_L$ ,  $C_O$  are carbon stored in atmosphere, land and ocean respectively. Other sources and sinks of  $\text{CO}_2$  such as from volcanism, sedimentation or rock weathering, which are very small on centennial timescales are not considered here. {Box 6.4; Figure 6.25}



**Figure TS.20:** (a) Timeseries (model averages and min-max ranges) and (b) maps of multi-model surface ocean pH for the scenarios RCP2.6, RCP4.5, RCP6.0 and RCP8.5 in 2081–2100. The maps in (b) show change in global ocean surface pH in 2081–2100 relative to 1986–2005. The number of CMIP5 models to calculate the multi-model mean is indicated in the upper right corner of each panel. {Figure 6.28}

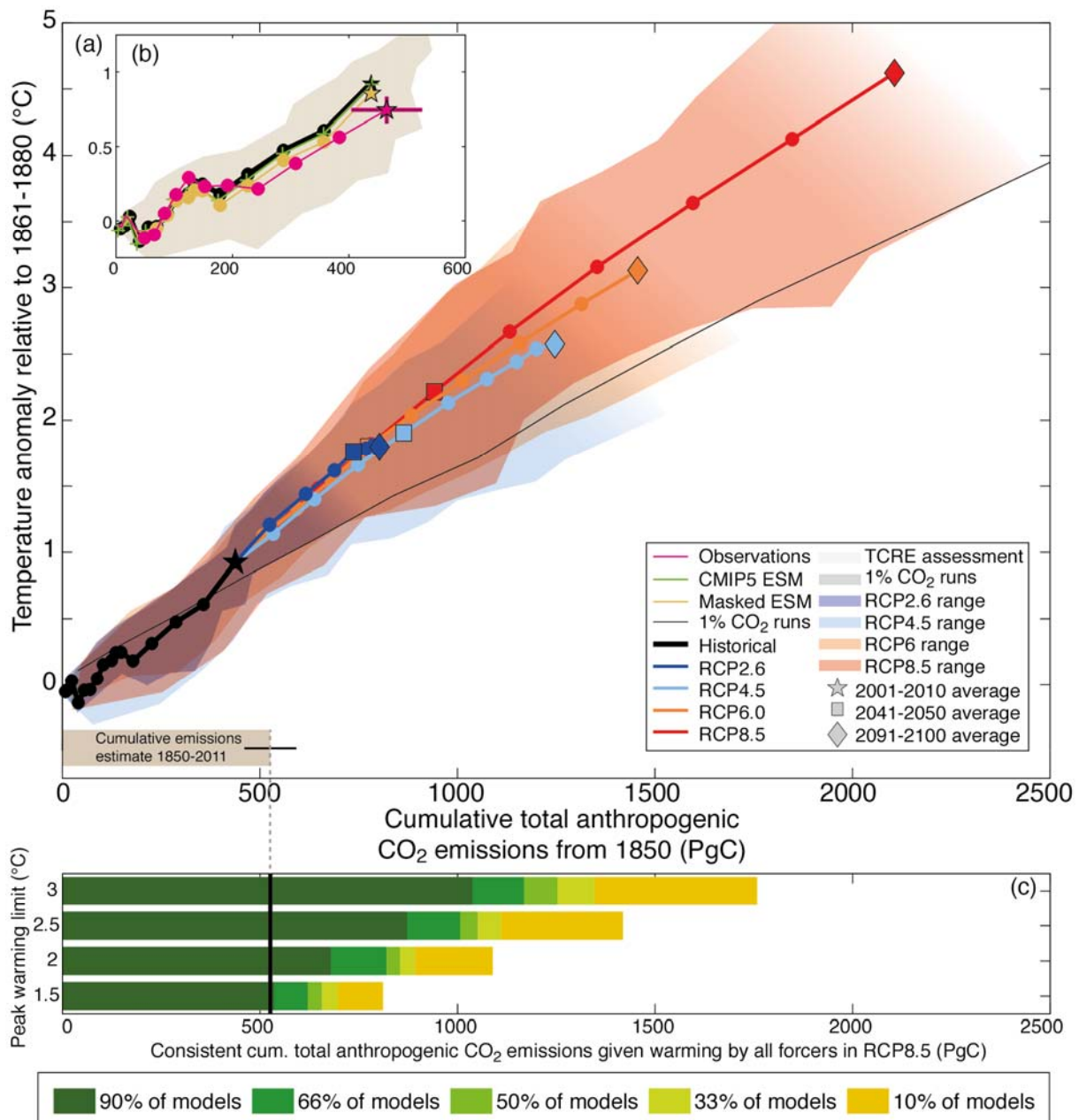


**TFE.7, Figure 1:** Percentage of initial atmospheric CO<sub>2</sub> perturbation remaining in the atmosphere in response to an idealized instantaneous CO<sub>2</sub> emission pulse in year 0 as calculated by a range of coupled climate-carbon cycle models. Multi-model mean (blue line) and the uncertainty interval ( $\pm 2$  standard deviations, shading) simulated during 100 years (left panel) and 1,000 years (right panel) following the instantaneous emission pulse of 100 PgC. (adapted from Box 6.1, Figure 1). {Box 6.1}



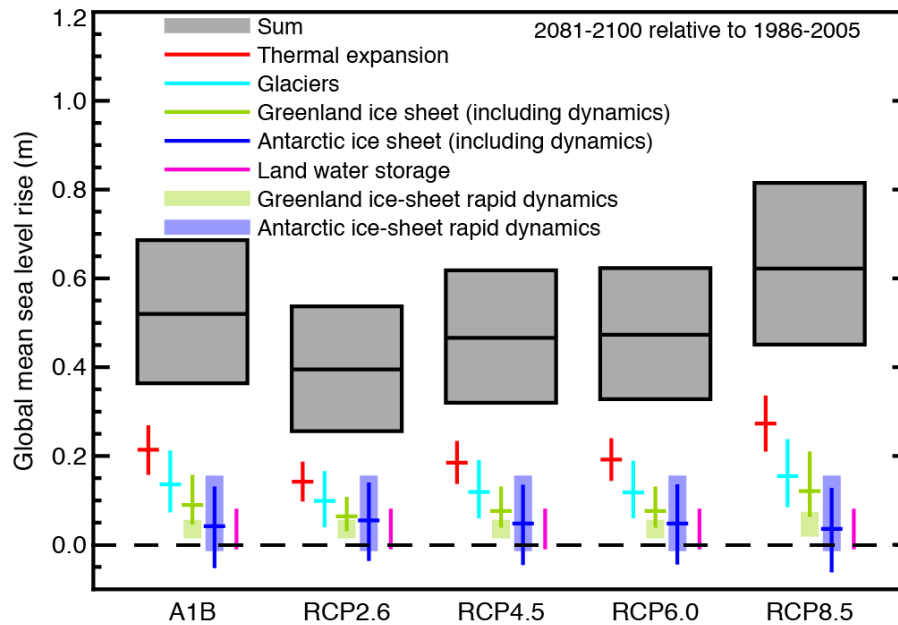
**TFE.7, Figure 2:** Comparison of carbon cycle feedback metrics between the ensemble of 7 GCMs and 4 EMICs at the time of AR4 (C<sup>4</sup>MIP) under the SRES-A2 scenario and the 8 CMIP5 models under the 140-year 1% CO<sub>2</sub> increase per year scenario. Black dots represent a single model simulation and coloured bars the mean of the multi-model results, grey dots are used for models with a coupled terrestrial nitrogen cycle. The comparison with C<sup>4</sup>MIP models is for context, but these metrics are known to be variable across different scenarios and rates of change (see Section 6.4.2.2). The SRES A2 scenario is closer in rate of change to a 0.5% CO<sub>2</sub> increase per year scenario and as such it should be expected that the CMIP5 climate-carbon sensitivity terms are comparable, but the concentration-carbon sensitivity terms are likely to be around 20% smaller for CMIP5 than for C<sup>4</sup>MIP due to lags in the ability of the land and ocean to respond to higher rates of CO<sub>2</sub> increase. This dependence on scenario reduces confidence in any quantitative statements of how CMIP5 carbon cycle feedbacks differ from C<sup>4</sup>MIP. {6.4.2}



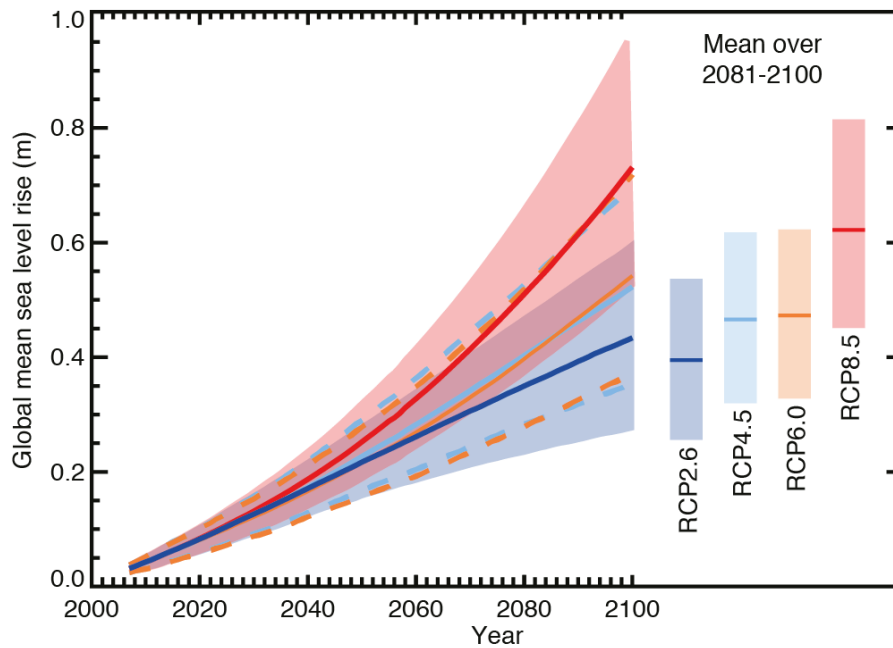


**TFE.8, Figure 1:** Global mean temperature increase since 1861–1880 as a function of cumulative total global CO<sub>2</sub> emissions from various lines of evidence. (a) Decadal average results are shown over all CMIP5 EMIC and ESMs for each RCP respectively, with coloured lines (multi-model average), decadal markers (dots) and with three decades (2001–2010, 2041–2050 and 2091–2100) highlighted with a star, square and diamond, respectively. The historical time period up to decade 2001–2010 is taken from the CMIP5 historical runs prolonged by RCP8.5 for 2005–2010 and is indicated with a black thick line and black symbols. Coloured ranges illustrate the model spread (90% range) over all CMIP5 ESMs and EMICs and do not represent a formal uncertainty assessment. Ranges are filled as long as data of all models is available and until peak temperature. They are faded out for illustrative purposes afterward. CMIP5 simulations with 1% yr<sup>-1</sup> CO<sub>2</sub> increase only are illustrated by the dark grey area (range definition similar to RCPs above) and the black thin line (multi-model average). The light grey cone represents this report’s assessment of the transient climate response to emissions (TCRE) from CO<sub>2</sub> only. Estimated cumulative historical CO<sub>2</sub> emissions from 1850 to 2011 with associated uncertainties are illustrated by the grey bar at the bottom of panel a. (b) Comparison of historical model results with observations. The magenta line and uncertainty ranges are based on observed emissions from CDIAC extended by values of the Global Carbon project until 2010 and observed temperature estimates of HadCRUT4. The uncertainties in the last decade of observations are based on the assessment in this report. The black thick line is identical to the one in panel a. The thin green line with crosses is as the black line but for ESMs only. The yellow-brown line and range show these ESM results until 2010, when corrected for HadCRUT4’s incomplete geographical coverage over time. All values are given relative to the 1861–1880 base period. All time-series are derived

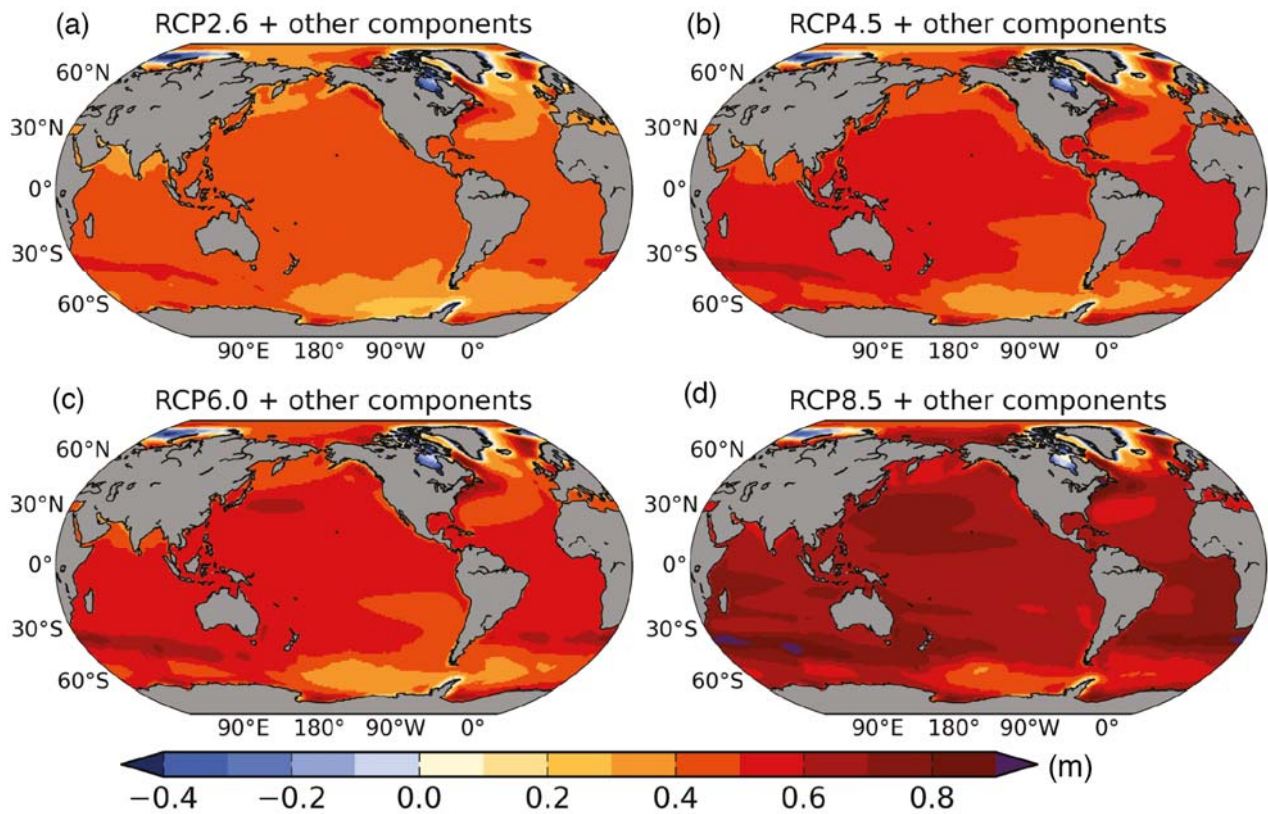
from decadal averages to illustrate the long-term trends. Note that observations are in addition subject to internal climate variability, adding an uncertainty of about 0.1°C. (c) Cumulative CO<sub>2</sub> emissions over the entire industrial era, consistent with four illustrative peak global temperature limits (1.5°C, 2°C, 2.5°C, and 3°C, respectively) when taking into account warming by all forcings. Horizontal bars indicate consistent cumulative emission budgets as a function of the fraction of models (CMIP5 ESMs and EMICs) that at least hold warming below a given temperature limit. Note that the fraction of models cannot be interpreted as a probability. The budgets are derived from the RCP8.5 runs, with relative high non-CO<sub>2</sub> forcing over the 21st century. If non-CO<sub>2</sub> are significantly reduced, the CO<sub>2</sub> emissions compatible with a specific temperature limit might be slightly higher, but only to a very limited degree, as illustrated by the other coloured lines in panel a, which assume significantly lower non-CO<sub>2</sub> forcing. {Figure 12.45}



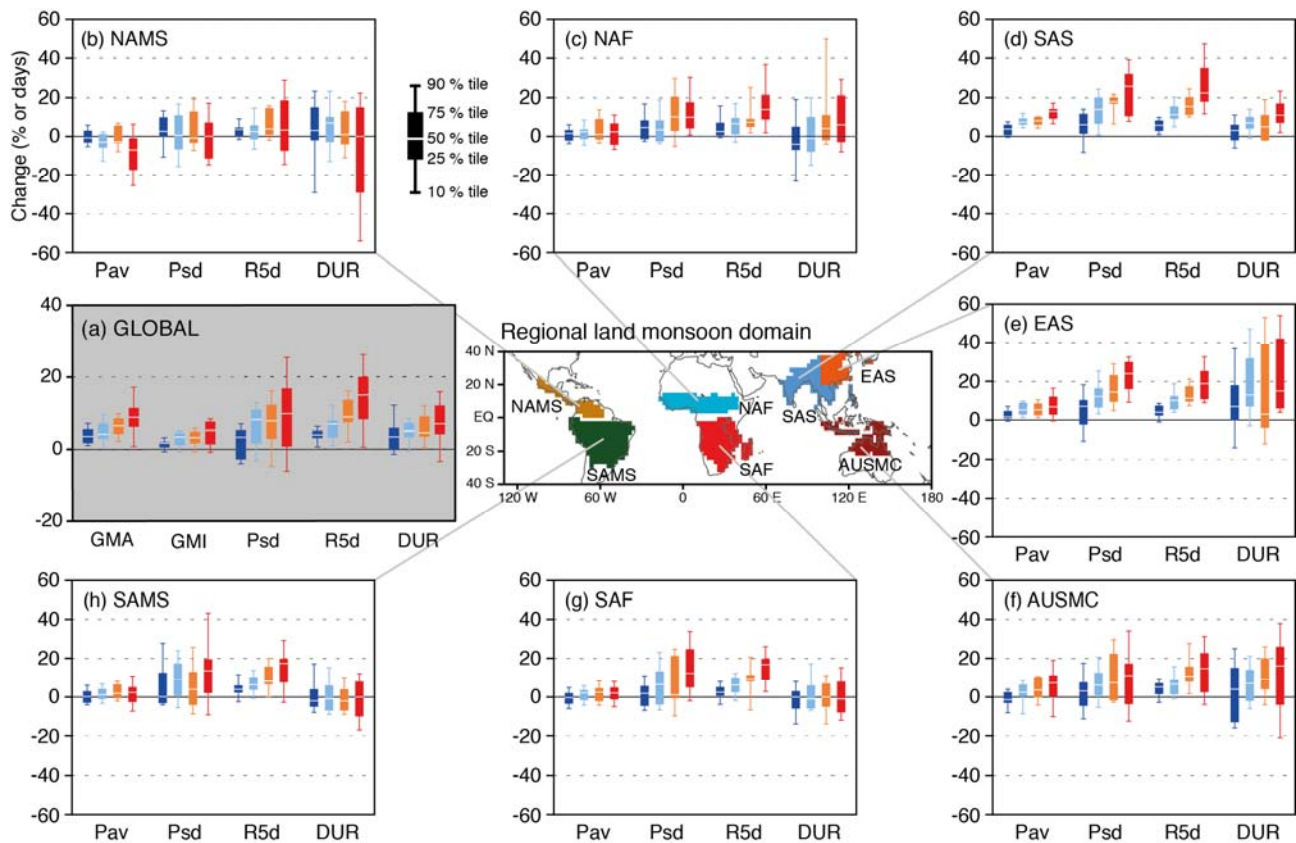
**Figure TS.21:** Projections from process-based models with *likely* ranges and median values for global mean sea level rise and its contributions in 2081–2100 relative to 1986–2005 for the four RCP scenarios and scenario SRES A1B used in the AR4. The contributions from ice sheets include the contributions from ice-sheet rapid dynamical change, which are also shown separately. The contributions from ice-sheet rapid dynamics and anthropogenic land water storage are treated as having uniform probability distributions, and as independent of scenario (except that a higher rate of change is used for Greenland ice-sheet outflow under RCP8.5). This treatment does not imply that the contributions concerned will not depend on the scenario followed, only that the current state of knowledge does not permit a quantitative assessment of the dependence. See discussion in Sections 13.5.1 and 13.5.3 and Supplementary Material for methods. Based on current understanding, only the collapse of the marine-based sectors of the Antarctic Ice Sheet, if initiated, could cause global mean sea level to rise substantially above the *likely* range during the 21st century. This potential additional contribution cannot be precisely quantified but there is *medium confidence* that it would not exceed several tenths of a meter during the 21st century. {Figure 13.10}



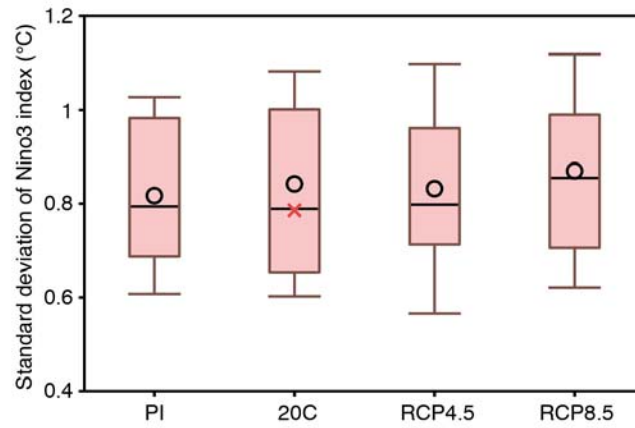
**Figure TS.22:** Projections from process-based models of global mean sea level rise relative to 1986–2005 for the four emissions scenarios RCP2.6, RCP4.5, RCP6.0 and RCP8.5. The solid lines show the median projections, the dashed lines show the *likely* ranges for RCP4.5 and RCP6.0, and the shading the *likely* ranges for RCP2.6 and RCP8.5. The time means for 2081–2100 are shown as coloured vertical bars. See Sections 13.5.1 and 13.5.3 and Supplementary Material for methods. Based on current understanding, only the collapse of the marine-based sectors of the Antarctic Ice Sheet, if initiated, could cause global mean sea level to rise substantially above the *likely* range during the 21st century. This potential additional contribution cannot be precisely quantified but there is *medium confidence* that it would not exceed several tenths of a meter during the 21st century. {Table 13.5; Figures 13.10, 13.11}



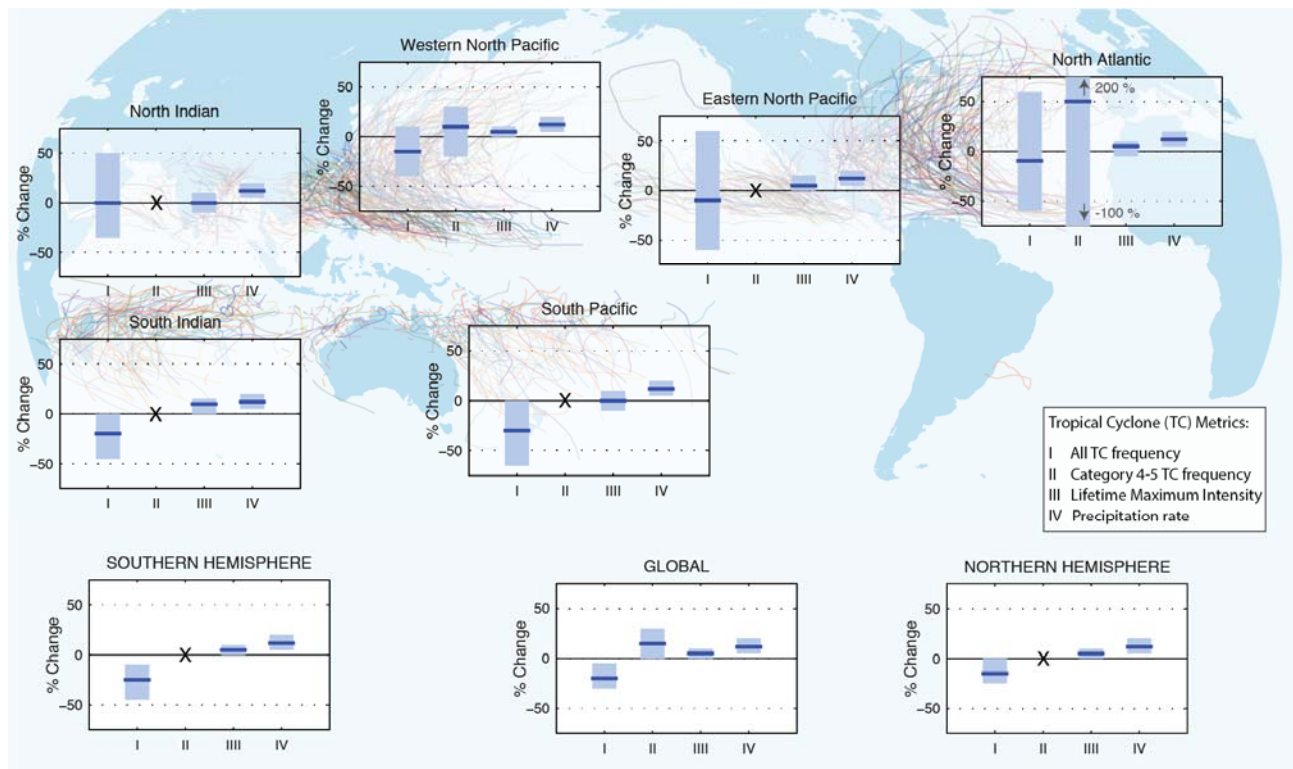
**Figure TS.23:** Ensemble mean net regional sea level change (m) evaluated from 21 CMIP5 models for the RCP scenarios (a) 2.6, (b) 4.5, (c) 6.0 and (d) 8.5 between 1986–2005 and 2081–2100. Each map includes effects of atmospheric loading, plus land-ice, GIA and terrestrial water sources. {Figure 13.20}



**Figure TS.24:** Future change in monsoon statistics between the present-day (1986–2005) and the future (2080–2099) based on CMIP5 ensemble from RCP2.6 (dark blue; 19 models), RCP4.5 (blue; 24), RCP6.0 (yellow; 14), and RCP8.5 (red; 24) simulations. (a) GLOBAL: Global monsoon area (GMA), global monsoon intensity (GMI), standard deviation of inter-annual variability in seasonal precipitation (Psd), seasonal maximum 5-day precipitation total (R5d), and monsoon season duration (DUR). Regional land monsoon domains determined by 24 multi-model mean precipitation in the present-day. (b)–(h) Future change in regional land monsoon statistics: seasonal average precipitation (Pav), Psd, R5d, and DUR in (b) North America (NAMS), (c) North Africa (NAF), (d) South Asia (SAS), (e) East Asia (EAS), (f) Australia-Maritime continent (AUSMC), (g) South Africa (SAF), and (h) South America (SAMS). Units are % except for DUR (days). Box-whisker plots show the 10th, 25th, 50th, 75th, and 90th percentiles. All the indices are calculated for the summer season (May–September for the Northern, and November–March for the Southern Hemisphere) over each model’s monsoon domains. {Figures 14.3, 14.4, 14.6, 14.7}

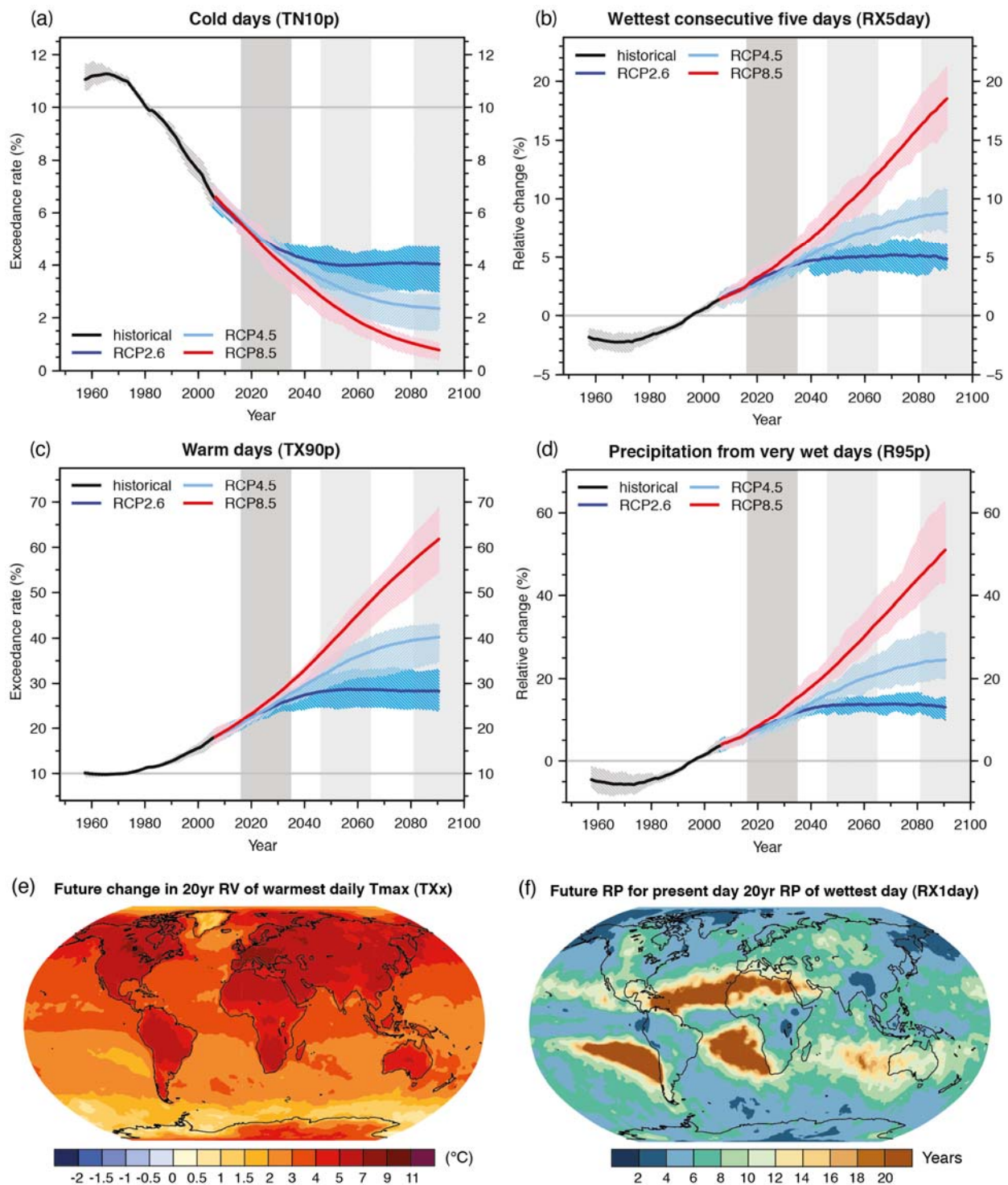


**Figure TS.25:** Standard deviation in CMIP5 multi-model ensembles of sea surface temperature variability over the eastern equatorial Pacific Ocean (Niño3 region: 5°S–5°N, 150°W–90°W), a measure of El Niño amplitude, for the pre-industrial (PI) control and 20th century (20C) simulations, and 21st century projections using RCP4.5 and RCP8.5. Open circles indicate multi-model ensemble means, and the red cross symbol is the observed standard deviation for the 20th century. Box-whisker plots show the 16th, 25th, 50th, 75th, and 84th percentiles. {Figure 14.14}



**Figure TS.26:** Projected changes in tropical cyclone statistics. All values represent expected percent change in the average over period 2081–2100 relative to 2000–2019, under an A1B-like scenario, based on expert judgment after subjective normalisation of the model projections. Four metrics were considered: the percent change in I) the total annual frequency of tropical storms, II) the annual frequency of Category 4 and 5 storms, III) the mean Lifetime Maximum Intensity (LMI; the maximum intensity achieved during a storm’s lifetime), and IV) the precipitation rate within 200 km of storm center at the time of LMI. For each metric plotted, the solid blue line is the best guess of the expected percent change, and the coloured bar provides the 67% (likely) confidence interval for this value (note that this interval ranges across –100% to +200% for the annual frequency of Category 4 and 5 storms in the North Atlantic). Where a metric is not plotted, there is insufficient data (denoted “X”) available to complete an assessment. A randomly drawn (and coloured) selection of historical storm tracks are underlaid to identify regions of tropical cyclone activity. See Section 14.6.1 for details. {14.6.1}





**TFE.9, Figure 1:** Global projections of the occurrence of (a) cold days (TN10p)- percentage of days annually with daily maximum surface air temperature (Tmax) below the 10th percentile of Tmax for 1961 to 1990, (b) wettest consecutive 5 days (RX5day) - percentage change in annual maximum consecutive 5-day precipitation totals, (c) warm days (TX90p)-percentage of days annually with daily maximum surface air temperature (Tmax) exceeding the 90th percentile of Tmax for 1961 to 1990 and (d) very wet day precipitation (R95p) - percentage change relative to 1986–2005 of annual precipitation from days >95th percentile. Results are shown from CMIP5 for the RCP2.6, RCP4.5 and RCP8.5 scenarios. Solid lines indicate the ensemble median and shading indicates the interquartile spread between individual projections (25th and 75th percentiles). Maps show (e) the change from 1986–2005 to 2081–2100 in twenty year return values (RV) of daily maximum temperatures, TXx, and (f) the 2081–2100 return period (RP) for rare daily precipitation values, RX1day, that have a 20 year return period during 1986–2005. Both maps are based on the CMIP5 RCP8.5 scenario. See Box 2.4, Table 1 for index definitions. {Figures 11.17, 12.13, 12.26}