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# Climate Change 2013: The Physical Science Basis – Conclusions

## IPCC Working Group I<sup>1</sup>

Conclusions, explanatory notes and figures selected by Daniel Bollinger and Ueli Seemann from the approved Summary for Policymakers, 27 September 2013. IPCC Working Group I, Assessment Report 5 [Source: [www.climatechange2013.org](http://www.climatechange2013.org)].

### 1 Introduction

The Working Group I (WGI) contribution to the IPCC's Fifth Assessment Report (AR5) considers new evidence of climate change based on many independent scientific analyses from observations of the climate system, paleoclimate archives, theoretical studies of climate processes and simulations using climate models. It builds upon the Working Group I contribution to the IPCC's Fourth Assessment Report (AR4), and incorporates subsequent new findings of research. As a component of the fifth assessment cycle, the IPCC Special Report on Managing the Risks of Extreme Events to Advance Climate Change Adaptation (SREX) is an important basis for information on changing weather and climate extremes.

The degree of certainty in key findings [underlined] in this assessment is based on the author teams' evaluations of underlying scientific understanding and is expressed as a qualitative level of confidence (from *very low* to *very high*) and, when possible, probabilistically with a quantified likelihood, type-set in italics (from *exceptionally unlikely* to *virtually certain*). Confidence in the validity of a finding is based on the type, amount, quality, and consistency of evidence (e.g. data, mechanistic understanding, theory, models, expert judgment) and the degree of

agreement<sup>1</sup>). Probabilistic estimates of quantified measures of uncertainty in a finding are based on statistical analysis of observations or model results, or both, and expert judgment. Where appropriate, findings are also formulated as statements of fact without using uncertainty qualifiers.

The basis for substantive paragraphs in this Summary for Policymakers can be found in the chapter sections of the underlying report and in the Technical Summary ([www.climatechange2013.org](http://www.climatechange2013.org)).

### 2 Key findings

#### 2.1 Observed Changes in the Climate System

Observations of the climate system are based on direct measurements and remote sensing from satellites and other platforms. Global-scale observations from the instrumental era began in the mid-19th century for temperature and other variables, with more comprehensive and diverse sets of observations available for the period 1950 onwards. Paleoclimate reconstructions extend some records 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.

Warming of the climate system is unequivocal

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cal, and since the 1950s, many of the observed changes are unprecedented over decades to millennia. The atmosphere and ocean have warmed, the amounts of snow and ice have diminished, sea level has risen, and the concentrations of greenhouse gases have increased.

### Atmosphere

Each of the last three decades has been successively warmer at the Earth's surface than any preceding decade since 1850. In the Northern Hemisphere, 1983–2012 was *likely* the warmest 30-year period of the last 1400 years (*medium confidence*).

For the longest period when calculation of regional trends is sufficiently complete (1901–2012), almost the entire globe has experienced surface warming (Fig. 1). The globally averaged combined land and ocean

surface temperature data as calculated by a linear trend, show a warming of 0.85 [0.65 to 1.06] °C<sup>2</sup>], over the period 1880–2012, when multiple independently produced datasets exist.

In addition to robust multi-decadal warming, global mean surface temperature exhibits substantial decadal and interannual variability. Due to natural variability, trends based on short records are very sensitive to the beginning and end dates and do not in general reflect long-term climate trends. As one example, the rate of warming over the past 15 years (1998–2012; 0.05 [–0.05 to +0.15] °C per decade), which begins with a strong El Niño, is smaller than the rate calculated since 1951 (1951–2012; 0.12 [0.08 to 0.14] °C per decade).

Continental-scale surface temperature reconstructions show, with *high confidence*,

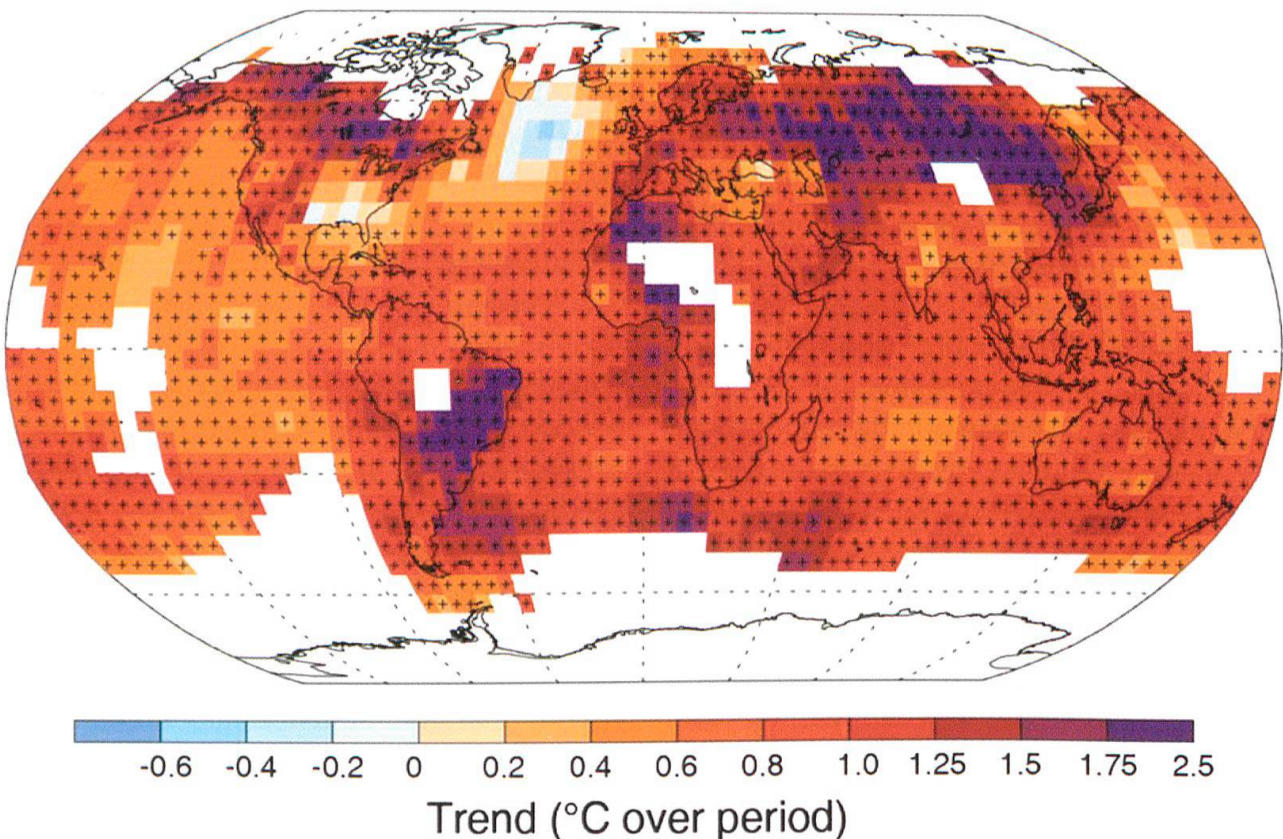


Fig. 1: Map of the observed surface temperature change from 1901 to 2012 derived from temperature trends determined by linear regression from one dataset. Trends have been calculated where data availability permits a robust estimate (i.e., only for grid boxes with greater than 70% complete records and more than 20% data availability in the first and last 10% of the time period). Other areas are white. Grid boxes where the trend is significant at the 10% level are indicated by a + sign.



multidecadal periods during the Medieval Climate Anomaly (year 950 to 1250) that were in some regions as warm as in the late 20th century. These regional warm periods did not occur as coherently across regions as the warming in the late 20th century (*high confidence*).

Changes in many extreme weather and climate events have been observed since about 1950. 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. It is *likely* that the frequency of heat waves has increased in large parts of Europe, Asia and Australia. There are *likely* more land regions where the number of heavy precipitation events has increased than where it has decreased. The frequency or intensity of heavy precipitation events has *likely* increased in North America and Europe. In other continents, confidence in changes in heavy precipitation events is at most *medium*.

## Oceans

Ocean warming dominates the increase in energy stored in the climate system, accounting for more than 90% of the energy accumulated between 1971 and 2010 (*high confidence*). It is *virtually certain* that the upper ocean (0–700 m) warmed from 1971 to 2010, and it *likely* warmed between the 1870s and 1971.

On a global scale, the ocean warming is largest near the surface, and the upper 75 m warmed by 0.11 [0.09 to 0.13] °C per decade over the period 1971–2010.

More than 60% of the net energy increase in the climate system is stored in the upper ocean (0–700 m) during the relatively well-sampled 40-year period from 1971 to 2010, and about 30% is stored in the ocean below 700 m. The increase in upper ocean heat content during this time period estimated from a linear trend is *likely* 17 [15 to 19]  $\times 10^{22}$  J. (A constant supply of heat through the ocean surface at the rate of 1 W m<sup>-2</sup> for 1 year would

increase the ocean heat content by  $1.1 \times 10^{22}$  J).

It is *very likely* that regions of high salinity

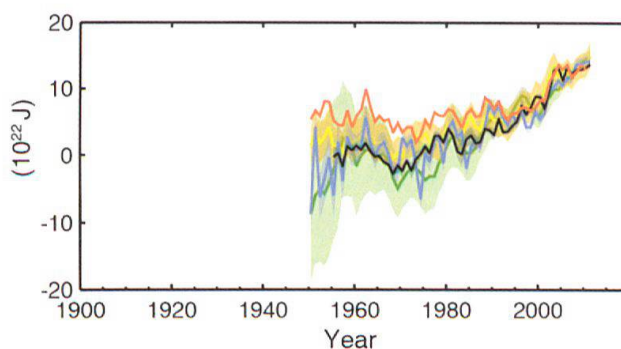


Fig. 2: Change in global mean upper ocean (0–700 m) heat content aligned to 2006–2010, and relative to the mean of all datasets for 1971. All time-series (coloured lines indicating different data sets) show annual values, and where assessed, uncertainties are indicated by coloured shading.

where evaporation dominates have become more saline, while regions of low salinity where precipitation dominates have become fresher since the 1950s. These regional trends in ocean salinity provide indirect evidence that evaporation and precipitation over the oceans have changed (*medium confidence*).

## Cryosphere

Over the last two decades, the Greenland and Antarctic ice sheets have been losing mass, glaciers have continued to shrink almost worldwide, and Arctic sea ice and Northern Hemisphere spring snow cover have continued to decrease in extent (*high confidence*).

The average rate of ice loss from glaciers around the world, excluding glaciers on the periphery of the ice sheets, was *very likely* 226 [91 to 361] Gt yr<sup>-1</sup> over the period 1971–2009, and *very likely* 275 [140 to 410] Gt yr<sup>-1</sup> over the period 1993–2009. (100 Gt yr<sup>-1</sup> of ice loss is equivalent to about 0.28 mm yr<sup>-1</sup> of global mean sea level rise). There is *high confidence* that permafrost temperatures have increased in most regions since the early 1980s. Observed



warming was up to 3 °C in parts of Northern Alaska (early 1980s to mid-2000s) and up to 2 °C in parts of the Russian European North (1971–2010). In the latter region, a considerable reduction in permafrost thickness and areal extent has been observed over the period 1975–2005 (*medium confidence*).

## Sea Level

The rate of sea level rise since the mid-19th century has been larger than the mean rate during the previous two millennia (*high confidence*). Over the period 1901–2010, global mean sea level rose by 0.19 [0.17 to 0.21] m.

Proxy and instrumental sea level data indicate a transition in the late 19th to the early 20th century from relatively low mean rates of rise over the previous two millennia to higher rates of rise (*high confidence*). It is *likely* that the rate of global mean sea level rise has continued to increase since the early 20th century (Fig. 3).

Since the early 1970s, glacier mass loss and ocean thermal expansion from warming together explain about 75% of the observed global mean sea level rise (*high confidence*). Over the period 1993–2010, global mean sea level rise is, with *high confidence*, consistent with the sum of the observed contributions from ocean thermal expansion due to warming (1.1 [0.8 to 1.4] mm yr<sup>-1</sup>), from changes in glaciers (0.76 [0.39 to 1.13] mm yr<sup>-1</sup>), Greenland ice sheet (0.33 [0.25 to 0.41] mm yr<sup>-1</sup>), Antarctic ice sheet (0.27 [0.16 to 0.38] mm yr<sup>-1</sup>), and land water storage (0.38 [0.26 to 0.49] mm yr<sup>-1</sup>). The sum of these contributions is 2.8 [2.3 to 3.4] mm yr<sup>-1</sup>.

There is *very high confidence* that maximum global mean sea level during the last interglacial period (129,000 to 116,000 years ago) was, for several thousand years, at least 5 m higher than present and *high confidence* that it did not exceed 10 m above present. During the last interglacial period, the Greenland ice sheet *very likely* contributed between 1.4 and 4.3 m to the higher global mean sea level, implying with *medium confidence* an addi-

tional contribution from the Antarctic ice sheet. This change in sea level occurred in the context of different orbital forcing and with high-latitude surface temperature, averaged over several thousand years, at least 2 °C warmer than present (*high confidence*).

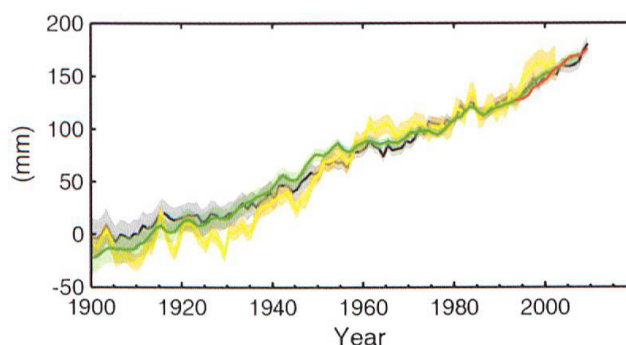


Fig. 3: Global mean sea level relative to the 1900–1905 mean of the longest running dataset, and with all datasets aligned to have the same value in 1993, the first year of satellite altimetry data. All time-series (coloured lines indicating different data sets) show annual values, and where assessed, uncertainties are indicated by coloured shading.

## Carbon and Other Biogeochemical Cycles

The atmospheric concentrations of carbon dioxide (CO<sub>2</sub>), methane, and nitrous oxide have increased to levels unprecedented in at least the last 800,000 years. CO<sub>2</sub> concentrations have increased by 40% since pre-industrial times, primarily from fossil fuel emissions and secondarily from net land use change emissions. The ocean has absorbed about 30% of the emitted anthropogenic carbon dioxide, causing ocean acidification.

The atmospheric concentrations of the greenhouse gases carbon dioxide (CO<sub>2</sub>), methane (CH<sub>4</sub>), and nitrous oxide (N<sub>2</sub>O) have all increased since 1750 due to human activity. In 2011 the concentrations of these greenhouse gases were 391 ppm, 1803 ppb, 324 ppb and exceeded the pre-industrial levels by about 40%, 150%, and 20%, respectively. Concentrations of CO<sub>2</sub>, CH<sub>4</sub>, and N<sub>2</sub>O now substantially exceed the highest concentra-



tions recorded in ice cores during the past 800,000 years. The mean rates of increase in atmospheric concentrations over the past century are, with *very high confidence*, unprecedented in the last 22,000 years.

From 1750 to 2011, CO<sub>2</sub> emissions from fossil fuel combustion and cement production have released 365 [335 to 395] GtC (Gigatons of carbon) to the atmosphere, while deforestation and other land use change are estimated to have released 180 [100 to 260] GtC. This results in cumulative anthropogenic emissions of 545 [460 to 630] GtC.

Of these cumulative anthropogenic CO<sub>2</sub> emissions, 240 [230 to 250] GtC have accumulated in the atmosphere, 155 [125 to 185] GtC have been taken up by the ocean and 150 [60 to 240] GtC have accumulated in natural terrestrial ecosystems (cf. cumulative residual land sink).

Ocean acidification is quantified by decreases in pH. The pH of ocean surface water has decreased by 0.1 since the beginning of the industrial era (*high confidence*), corresponding to a 26% increase in hydrogen ion concentration.

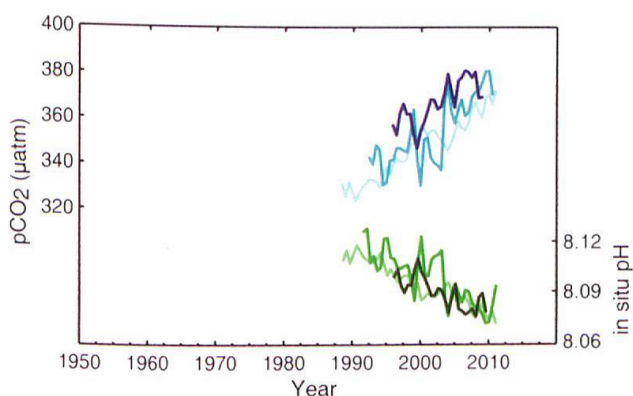


Fig. 4: Partial pressure of dissolved CO<sub>2</sub> at the ocean surface (blue curves) and *in situ* pH (green curves), a measure of the acidity of ocean water. Measurements are from three stations from the Atlantic [29°10'N, 15°30'W – dark blue/dark green; 31°40'N, 64°10'W – blue/green] and the Pacific Oceans [22°45'N, 158°00'W – light blue/light green].

## 2.2 Drivers of Climate Change

Natural and anthropogenic substances and processes that alter the Earth's energy budg-

et are drivers of climate change. Radiative forcing (RF)<sup>3]</sup> quantifies the change in energy fluxes caused by changes in these drivers for 2011 relative to 1750, unless otherwise indicated. Positive RF leads to surface warming, negative RF leads to surface cooling. RF is estimated based on in-situ and remote observations, properties of greenhouse gases and aerosols, and calculations using numerical models representing observed processes. Some emitted compounds affect the atmospheric concentration of other substances. The RF can be reported based on the concentration changes of each substance. Alternatively, the emission-based RF of a compound can be reported, which provides a more direct link to human activities. It includes contributions from all substances affected by that emission. The total anthropogenic RF of the two approaches are identical when considering all drivers. Though both approaches are used in this Summary, emission-based RFs are emphasized.

Total radiative forcing is positive, and has led to an uptake of energy by the climate system. The largest contribution to total radiative forcing is caused by the increase in the atmospheric concentration of CO<sub>2</sub> since 1750.

The RF from emissions of well-mixed greenhouse gases (CO<sub>2</sub>, CH<sub>4</sub>, N<sub>2</sub>O, and Halocarbons) for 2011 relative to 1750 is 3.00 [2.22 to 3.78] W m<sup>-2</sup>. The RF from changes in concentrations in these gases is 2.83 [2.26 to 3.40] W m<sup>-2</sup>.

Emissions of CO<sub>2</sub> alone have caused an RF of 1.68 [1.33 to 2.03] W m<sup>-2</sup>. Including emissions of other carbon-containing gases, which also contributed to the increase in CO<sub>2</sub> concentrations, the RF of CO<sub>2</sub> is 1.82 [1.46 to 2.18] W m<sup>-2</sup>.

Emissions of CH<sub>4</sub> alone have caused an RF of 0.97 [0.74 to 1.20] W m<sup>-2</sup>. This is much larger than the concentration-based estimate of 0.48 [0.38 to 0.58] W m<sup>-2</sup> (unchanged from AR4). This difference in estimates is caused



by concentration changes in ozone and stratospheric water vapour due to CH<sub>4</sub> emissions and other emissions indirectly affecting CH<sub>4</sub>.

The forcing from stratospheric volcanic aerosols can have a large impact on the climate for some years after volcanic eruptions. Several small eruptions have caused a RF of -0.11 [-0.15 to -0.08] W m<sup>-2</sup> for the years 2008–2011, which is approximately twice as strong as during the years 1999–2002.

The RF due to changes in solar irradiance is estimated as 0.05 [0.00 to 0.10] W m<sup>-2</sup>. Satellite observations of total solar irradiance changes from 1978 to 2011 indicate that the last solar minimum was lower than the previous two. This results in a RF of -0.04 [-0.08 to 0.00] W m<sup>-2</sup> between the most recent minimum in 2008 and the 1986 minimum.

The total natural RF from solar irradiance changes and stratospheric volcanic aerosols made only a small contribution to the net radiative forcing throughout the last century, except for brief periods after large volcanic eruptions.

### 2.3 Understanding the Climate System and its Recent Changes

Understanding recent changes in the climate system results from combining observations, studies of feedback processes, and model simulations. Evaluation of the ability of climate models to simulate recent changes requires consideration of the state of all modelled climate system components at the start of the simulation and the natural and anthropogenic forcing used to drive the models. Compared to AR4, more detailed and longer observations and improved climate models now enable the attribution of a human contribution to detected changes in more climate system components.

Human influence on the climate system is clear. This is evident from the increasing greenhouse gas concentrations in the

atmosphere, positive radiative forcing, observed warming, and understanding of the climate system.

#### Evaluation of Climate Models

Climate models have improved since the AR4. Models reproduce observed continental-scale surface temperature patterns and trends over many decades, including the more rapid warming since the mid-20th century and the cooling immediately following large volcanic eruptions (*very high confidence*).

The long-term climate model simulations show a trend in global-mean surface temperature from 1951 to 2012 that agrees with the observed trend (*very high confidence*). There are, however, differences between simulated and observed trends over periods as short as 10 to 15 years (e.g. 1998 to 2012). The observed reduction in surface warming trend over the period 1998–2012 as compared to the period 1951–2012, is due in roughly equal measure to a reduced trend in radiative forcing and a cooling contribution from internal variability, which includes a possible redistribution of heat within the ocean (*medium confidence*). The reduced trend in radiative forcing is primarily due to volcanic eruptions and the timing of the downward phase of the 11-year solar cycle. However, there is *low confidence* in quantifying the role of changes in radiative forcing in causing the reduced warming trend. There is *medium confidence* that internal decadal variability causes to a substantial degree the difference between observations and the simulations; the latter are not expected to reproduce the timing of internal variability. There may also be a contribution from forcing inadequacies and, in some models, an overestimate of the response to increasing greenhouse gas and other anthropogenic forcing (dominated by the effects of aerosols).

Climate models that include the carbon cycle (Earth System Models) simulate the



global pattern of ocean-atmosphere CO<sub>2</sub> fluxes, with outgassing in the tropics and uptake in the mid and high latitudes. In the majority of these models the sizes of the simulated global land and ocean carbon sinks over the latter part of the 20th century are within the range of observational estimates.

### Quantification of Climate System Responses

Observational and model studies of temperature change, climate feedbacks and changes in the Earth's energy budget together provide confidence in the magnitude of global warming in response to past and future forcing.

The equilibrium climate sensitivity quantifies the response of the climate system to constant radiative forcing on multi-century time scales. It is defined as the change in global mean surface temperature at equilibrium that is caused by a doubling of the atmospheric CO<sub>2</sub> concentration. Equilibrium climate sensitivity is *likely* in the range 1.5 °C to 4.5 °C (*high confidence*), *extremely unlikely* less than 1 °C (*high confidence*), and *very unlikely* greater than 6 °C (*medium confidence*). The lower temperature limit of the assessed *likely* range is thus less than the 2 °C in the AR4, but the upper limit is the same. This assessment reflects improved understanding, the extended temperature record in the atmosphere and ocean, and new estimates of radiative forcing.

The transient climate response quantifies the response of the climate system to an increasing radiative forcing on a decadal to century timescale. It is defined as the change in global mean surface temperature at the time when the atmospheric CO<sub>2</sub> concentration has doubled in a scenario of concentration increasing at 1% per year. The transient climate response is *likely* in the range of 1.0 °C to 2.5 °C (*high confidence*) and *extremely unlikely* greater than 3 °C.

A related quantity is the transient climate response to cumulative carbon emissions

(TCRE). It quantifies the transient response of the climate system to cumulative carbon emissions. TCRE is defined as the global mean surface temperature change per 1000 GtC emitted to the atmosphere. TCRE is *likely* in the range of 0.8 °C to 2.5 °C per 1000 GtC and applies for cumulative emissions up to about 2000 GtC until the time temperatures peak (Fig. 9).

### Detection and Attribution of Climate Change

Human influence has been detected in warming of the atmosphere and the ocean, in changes in the global water cycle, in reductions in snow and ice, in global mean sea level rise, and in changes in some climate extremes. This evidence for human influence has grown since AR4. It is *extremely likely* that human influence has been the dominant cause of the observed warming since the mid-20th century.

It is *extremely likely* that more than half of the observed increase in global average surface temperature from 1951 to 2010 was caused by the anthropogenic increase in greenhouse gas concentrations and other anthropogenic forcings together. The best estimate of the human induced contribution to warming is similar to the observed warming over this period.

Greenhouse gases contributed a global mean surface warming *likely* to be in the range of 0.5 °C to 1.3 °C over the period 1951–2010, with the contributions from other anthropogenic forcings, including the cooling effect of aerosols, *likely* to be in the range of –0.6 °C to 0.1 °C. The contribution from natural forcings is *likely* to be in the range of –0.1 °C to 0.1 °C, and from internal variability is *likely* to be in the range of –0.1 °C to 0.1 °C. Together these assessed contributions are consistent with the observed warming of approximately 0.6 °C to 0.7 °C over this period.

Over every continental region except Antarctica, anthropogenic forcings have



likely made a substantial contribution to surface temperature increases since the mid-20th century (Fig. 5).

It is *very likely* that anthropogenic forcings have made a substantial contribution to increases in global upper ocean heat con-

tent (0–700 m) observed since the 1970s. There is evidence for human influence in some individual ocean basins.

It is *likely* that anthropogenic influences have affected the global water cycle since 1960. Anthropogenic influences have con-

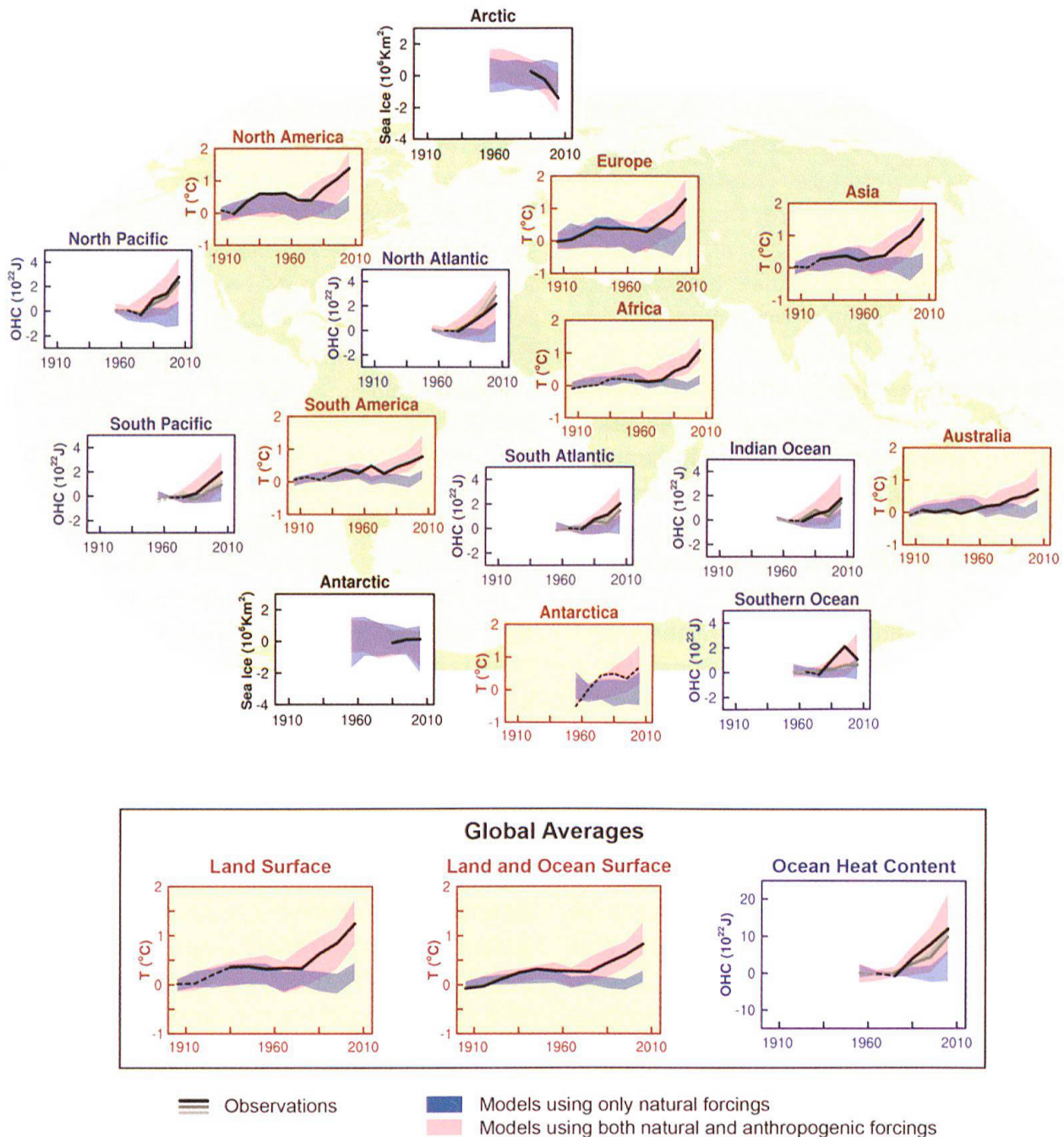


Fig. 5: Comparison of observed and simulated climate change based on three large-scale indicators in the atmosphere, the cryosphere and the ocean: change in continental land surface air temperatures (yellow panels), Arctic and Antarctic September sea ice extent (white panels), and upper ocean heat content in the major ocean basins (blue panels). Global average changes are also given. Anomalies are given relative to 1880–1919 for surface temperatures, 1960–1980 for ocean heat content and 1979–1999 for sea ice. All time-series are decadal averages, plotted at the centre of the decade. For temperature panels, observations are dashed lines if the spatial coverage of areas being examined is below 50%. For ocean heat content and sea ice panels the solid 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, and thus, uncertainty is larger. Model results shown are Coupled Model Intercomparison Project Phase 5 (CMIP5) multi-model ensemble ranges, with shaded bands indicating the 5 to 95% confidence intervals.



tributed to observed increases in atmospheric moisture content in the atmosphere (*medium confidence*), to global-scale changes in precipitation patterns over land (*medium confidence*), to intensification of heavy precipitation over land regions where data are sufficient (*medium confidence*), and to changes in surface and subsurface ocean salinity (*very likely*).

Anthropogenic influences *likely* contributed to the retreat of glaciers since the 1960s and to the increased surface mass loss of the Greenland ice sheet since 1993. Due to a low level of scientific understanding there is *low confidence* in attributing the causes of the observed loss of mass from the Antarctic ice sheet over the past two decades.

It is *very likely* that there is a substantial anthropogenic contribution to the global mean sea level rise since the 1970s. This is based on the *high confidence* in an anthropogenic influence on the two largest contributions to sea level rise, that is thermal expansion and glacier mass loss.

There is *high confidence* that changes in total solar irradiance have not contributed to the increase in global mean surface temperature over the period 1986 to 2008, based on direct satellite measurements of total solar irradiance. There is *medium confidence* that the 11-year cycle of solar variability influences decadal climate fluctuations in some regions. No robust association between changes in cosmic rays and cloudiness has been identified.

## 2.4 Future Global and Regional Climate Change

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. In all RCPs, atmospheric CO<sub>2</sub> concentrations are higher in 2100 relative to present day as a result of a further increase of cumulative emissions of CO<sub>2</sub> to the atmosphere during the 21st century. Projections in the Summary for Policymakers are for the end of the 21st century (2081–2100) given relative to 1986–2005, unless otherwise stated. To place such projections in historical context, it is necessary to consider observed changes between different periods. Based on the longest global surface temperature dataset available, the observed change between the average of the period 1850–1900 and of the AR5 reference period is 0.61 [0.55 to 0.67] °C. However, warming has occurred beyond the average of the AR5 reference period. Hence this is not an estimate of historical warming to present.

Continued emissions of greenhouse gases will cause further warming and changes in all components of the climate system. Limiting climate change will require substantial and sustained reductions of greenhouse gas emissions.

Projections for the next few decades show spatial patterns of climate change similar to those projected for the later 21st century but with smaller magnitude. Internal variability will continue to be a major influence on climate, particularly in the near-term and at the regional scale. By the mid-21st century the magnitudes of the projected changes are substantially affected by the choice of emissions scenario.

### Atmosphere: Temperature

Global surface temperature change for the end of the 21st century is *likely* to exceed 1.5 °C relative to 1850 to 1900 for all RCP scenarios except RCP2.6. It is *likely* to exceed



2 °C for RCP6.0 and RCP8.5, and *more likely than not* to exceed 2 °C for RCP4.5. Warming will continue beyond 2100 under all RCP scenarios except RCP2.6. Warming will continue to exhibit interannual-to-decadal variability and will not be regionally uniform.

The global mean surface temperature change for the period 2016–2035 relative to 1986–2005 will *likely* be in the range of 0.3 °C to 0.7 °C (*medium confidence*). This assessment is based on multiple lines of evidence and assumes there will be no major volcanic eruptions or secular changes in total solar irradiance. Relative to natural internal variability, near-term increases in seasonal mean and annual mean temperatures are expected to be larger in the tropics and subtropics than in mid-latitudes (*high confidence*).

Increase of global mean surface temperatures for 2081–2100 relative to 1986–2005 is projected to *likely* be in the ranges derived from the concentration driven CMIP5 model simulations, that is, 0.3 °C to 1.7 °C (RCP2.6), 1.1 °C to 2.6 °C (RCP4.5), 1.4 °C to 3.1 °C (RCP6.0), 2.6 °C to 4.8 °C (RCP8.5). The Arc-

tic region will warm more rapidly than the global mean, and mean warming over land will be larger than over the ocean (*very high confidence*) (Fig. 6).

It is *virtually certain* that there will be more frequent hot and fewer cold temperature extremes over most land areas on daily and seasonal timescales as global mean temperatures increase. It is *very likely* that heat waves will occur with a higher frequency and duration. Occasional cold winter extremes will continue to occur.

### Atmosphere: Water Cycle

Changes in the global water cycle in response to the warming over the 21st century will not be uniform. The contrast in precipitation between wet and dry regions and between wet and dry seasons will increase, although there may be regional exceptions.

Projected changes in the water cycle over the next few decades show similar large-scale patterns to those towards the end of the century, but with smaller magnitude. Changes in the near-term, and at the regional scale will be strongly influenced by natu-

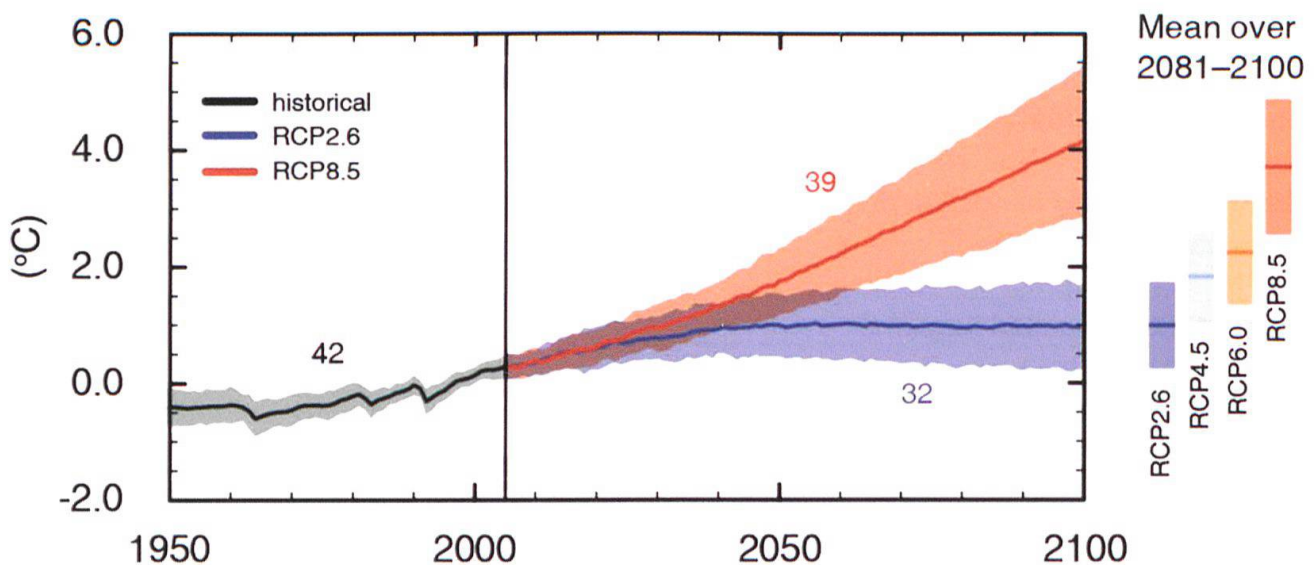


Fig. 6: CMIP5 multi-model simulated time series from 1950 to 2100 for change in global annual mean surface temperature relative to 1986–2005. Time series of projections and a measure of uncertainty (shading) are shown for scenarios RCP2.6 (blue, relatively low CO<sub>2</sub>) and RCP8.5 (red, relatively high CO<sub>2</sub>). Black (grey shading) is the modelled historical evolution using historical reconstructed forcings. The mean and associated uncertainties averaged over 2081–2100 are given for all RCP scenarios as colored vertical bars. The numbers of CMIP5 models used to calculate the multi-model mean is indicated.



ral internal variability and may be affected by anthropogenic aerosol emissions.

Extreme precipitation events over most of the mid-latitude land masses and over wet tropical regions will *very likely* become more intense and more frequent by the end of this century, as global mean surface temperature increases.

Globally, it is *likely* that the area encompassed by monsoon systems will increase over the 21st century. While monsoon winds are *likely* to weaken, monsoon precipitation is *likely* to intensify due to the increase in atmospheric moisture. Monsoon onset dates are *likely* to become earlier or not to change much. Monsoon retreat dates will *likely* be delayed, resulting in lengthening of the monsoon season in many regions.

## Ocean

The global ocean will continue to warm during the 21st century. Heat will penetrate from the surface to the deep ocean and affect ocean circulation.

The strongest ocean warming is projected for the surface in tropical and Northern Hemisphere subtropical regions. At greater depth the warming will be most pronounced in the Southern Ocean (*high confidence*). Best estimates of ocean warming in the top one hundred meters are about 0.6 °C (RCP2.6) to 2.0 °C (RCP8.5), and about 0.3 °C (RCP2.6) to 0.6 °C (RCP8.5) at a depth of about 1000 m by the end of the 21st century. It is *very likely* that the Atlantic Meridional Overturning Circulation (AMOC) will weaken over the 21st century. Best estimates and range for the reduction from CMIP5 are 11% (1 to 24%) in RCP2.6 and 34% (12 to 54%) in RCP8.5. It is *likely* that there will be some decline in the AMOC by about 2050, but there may be some decades when the AMOC increases due to large internal variability.

It is *very unlikely* that the AMOC will undergo an abrupt transition or collapse in the 21st century for the scenarios considered. There is *low confidence* in assessing the evo-

lution of the AMOC beyond the 21st century because of the limited number of analyses and equivocal results. However, a collapse beyond the 21st century for large sustained warming cannot be excluded.

## Cryosphere

It is *very likely* that the Arctic sea ice cover will continue to shrink and thin and that Northern Hemisphere spring snow cover will decrease during the 21st century as global mean surface temperature rises. Global glacier volume will further decrease.

By the end of the 21st century, the global glacier volume, excluding glaciers on the periphery of Antarctica, is projected to decrease by 15 to 55% for RCP2.6, and by 35 to 85% for RCP8.5 (*medium confidence*).

Year-round reductions in Arctic sea ice extent are projected by the end of the 21st century from multi-model averages. These reductions range from 43% for RCP2.6 to 94% for RCP8.5 in September and from 8% for RCP2.6 to 34% for RCP8.5 in February (*medium confidence*). In the Antarctic, a decrease in sea ice extent and volume is projected with *low confidence* for the end of the 21st century as global mean surface temperature rises.

## Sea Level

Global mean sea level will continue to rise during the 21st century. Under all RCP scenarios the rate of sea level rise will *very likely* exceed that observed during 1971–2010 due to increased ocean warming and increased loss of mass from glaciers and ice sheets (Fig. 7).

In the RCP projections, thermal expansion accounts for 30 to 55% of 21st century global mean sea level rise, and glaciers for 15 to 35%. The increase in surface melting of the Greenland ice sheet will exceed the increase in snowfall, leading to a positive contribution from changes in surface mass balance to future sea level (*high confidence*). While



surface melting will remain small, an increase in snowfall on the Antarctic ice sheet is expected (*medium confidence*), resulting in a negative contribution to future sea level from changes in surface mass balance. Changes in outflow from both ice sheets combined will *likely* make a contribution in the range of 0.03 to 0.20 m by 2081–2100 (*medium confidence*).

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. However, there is *medium confidence* that this additional contribution would not exceed several tenths of a meter of sea level rise during the 21st century.

Sea level rise will not be uniform. By the end of the 21st century, it is *very likely* that sea level will rise in more than about 95% of the ocean area. About 70% of the coastlines worldwide are projected to experience sea level change within 20% of the global mean sea level change.

### Carbon and Other Biogeochemical Cycles

Climate change will affect carbon cycle processes in a way that will exacerbate the

increase of CO<sub>2</sub> in the atmosphere (*high confidence*). Further uptake of carbon by the ocean will increase ocean acidification.

Ocean uptake of anthropogenic CO<sub>2</sub> will continue under all four RCPs through to 2100, with higher uptake for higher concentration pathways (*very high confidence*). The future evolution of the land carbon uptake is less certain. A majority of models project a continued land carbon uptake under all RCPs, but some models simulate a land carbon loss due to the combined effect of climate change and land use change.

Based on Earth System Models, there is *high confidence* that the feedback between climate and the carbon cycle is positive in the 21st century; that is, climate change will partially offset increases in land and ocean carbon sinks caused by rising atmospheric CO<sub>2</sub>. As a result more of the emitted anthropogenic CO<sub>2</sub> will remain in the atmosphere. A positive feedback between climate and the carbon cycle on century to millennial time scales is supported by paleoclimate observations and modelling.

Cumulative CO<sub>2</sub> emissions (from fossil fuel, cement, industry, and waste sectors) for the 2012–2100 period compatible with the RCP

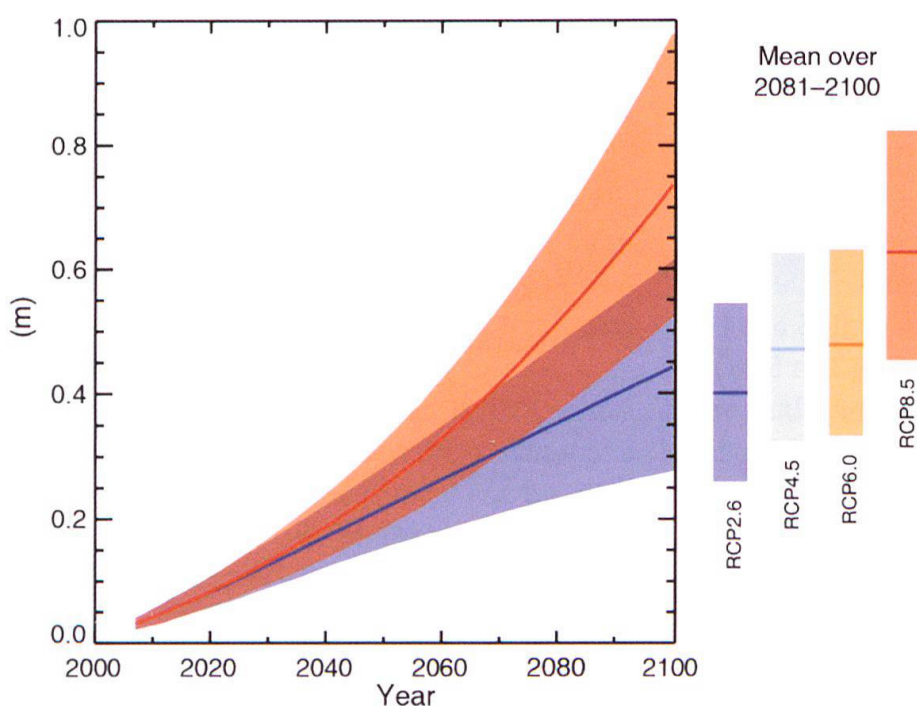


Fig. 7: Projections of global mean sea level rise over the 21st century relative to 1986–2005 from the combination of the CMIP5 ensemble with process-based models, for RCP2.6 and RCP8.5. The assessed *likely* range is shown as a shaded band. The assessed *likely* ranges for the mean over the period 2081–2100 for all RCP scenarios are given as coloured vertical bars, with the corresponding median value given as a horizontal line.



atmospheric CO<sub>2</sub> concentrations, as derived from 15 Earth System Models, range from 140 to 410 GtC for RCP2.6, 595 to 1005 GtC for RCP4.5, 840 to 1250 GtC for RCP6.0, and 1415 to 1910 GtC for RCP8.5.

The release of CO<sub>2</sub> or CH<sub>4</sub> to the atmosphere from thawing permafrost carbon stocks over the 21st century is assessed to be in the range of 50 to 250 GtC for RCP8.5 (*low confidence*).

### Climate Stabilization, Climate Change Commitment and Irreversibility

Cumulative emissions of CO<sub>2</sub> largely determine global mean surface warming by the late 21st century and beyond (Fig. 9). Most aspects of climate change will persist for many centuries even if emissions of CO<sub>2</sub> are stopped. This represents a substantial multi-century climate change commitment created by past, present and future emissions of CO<sub>2</sub>.

Limiting the warming caused by anthropogenic CO<sub>2</sub> emissions alone with a probability of >33%, >50%, and >66% to less than 2 °C since the period 1861–1880 (first 20-year period available from the models), will

require cumulative CO<sub>2</sub> emissions from all anthropogenic sources to stay between 0 and about 1560 GtC, 0 and about 1210 GtC, and 0 and about 1000 GtC since that period respectively. These upper amounts are reduced to about 880 GtC, 840 GtC, and 800 GtC respectively, when accounting for non-CO<sub>2</sub> forcings as in RCP2.6. An amount of 531 [446 to 616] GtC was already emitted by 2011.

A large fraction of anthropogenic climate change resulting from CO<sub>2</sub> emissions is irreversible on a multi-century to millennial time scale, except in the case of a large net removal of CO<sub>2</sub> from the atmosphere over a sustained period. Surface temperatures will remain approximately constant at elevated levels for many centuries after a complete cessation of net anthropogenic CO<sub>2</sub> emissions. Due to the long time scales of heat transfer from the ocean surface to depth, ocean warming will continue for centuries. Depending on the scenario, about 15 to 40% of emitted CO<sub>2</sub> will remain in the atmosphere longer than 1,000 years.

It is *virtually certain* that global mean sea level rise will continue beyond 2100, with sea

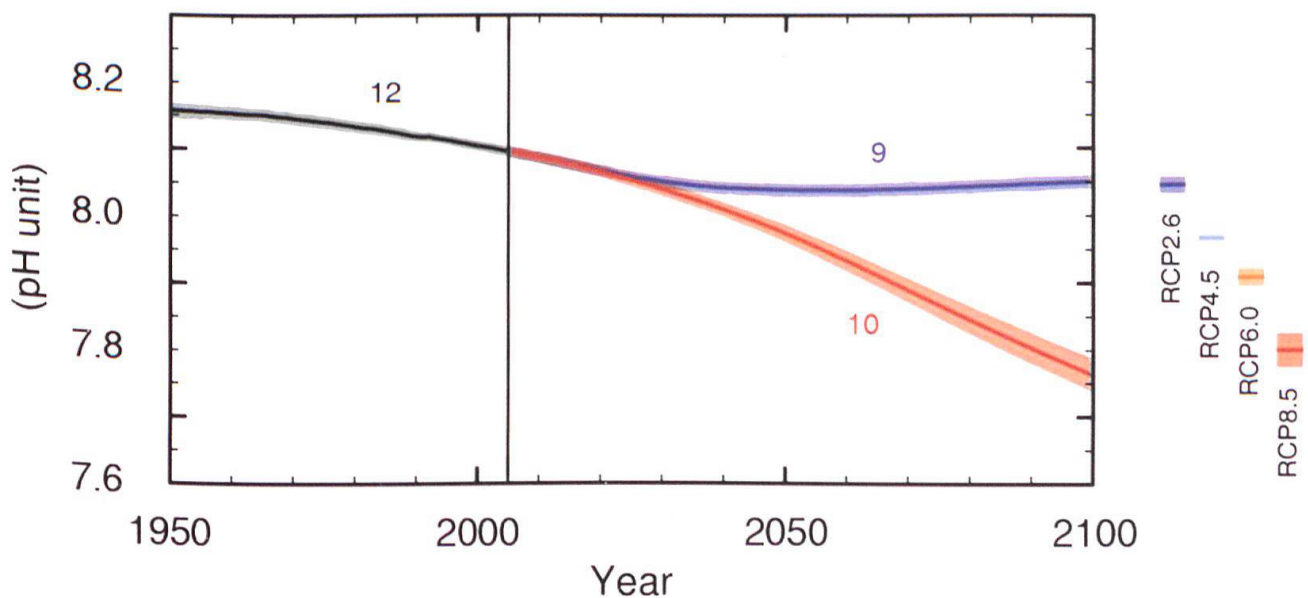


Fig. 8: CMIP5 multi-model simulated time series from 1950 to 2100 for global mean ocean surface pH. Time series of projections and a measure of uncertainty (shading) are shown for scenarios RCP2.6 (blue) and RCP8.5 (red). Black (grey shading) is the modelled historical evolution using historical reconstructed forcings. The mean and associated uncertainties averaged over 2081–2100 are given for all RCP scenarios as colored vertical bars. The numbers of CMIP5 models used to calculate the multi-model mean is indicated.



level rise due to thermal expansion to continue for many centuries. The few available model results that go beyond 2100 indicate global mean sea level rise above the pre-industrial level by 2300 to be less than 1 m for a radiative forcing that corresponds to CO<sub>2</sub> concentrations that peak and decline and remain below 500 ppm, as in the scenario RCP2.6. For a radiative forcing that corresponds to a CO<sub>2</sub> concentration that is above 700 ppm but below 1500 ppm, as in the scenario RCP8.5, the projected rise is

1 m to more than 3 m (*medium confidence*). Sustained mass loss by ice sheets would cause larger sea level rise, and some part of the mass loss might be irreversible. There is *high confidence* that sustained warming greater than some 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 up to 7 m. Current estimates indicate that the threshold is greater than about 1 °C (*low confidence*) but less than about 4 °C (*medium confidence*)

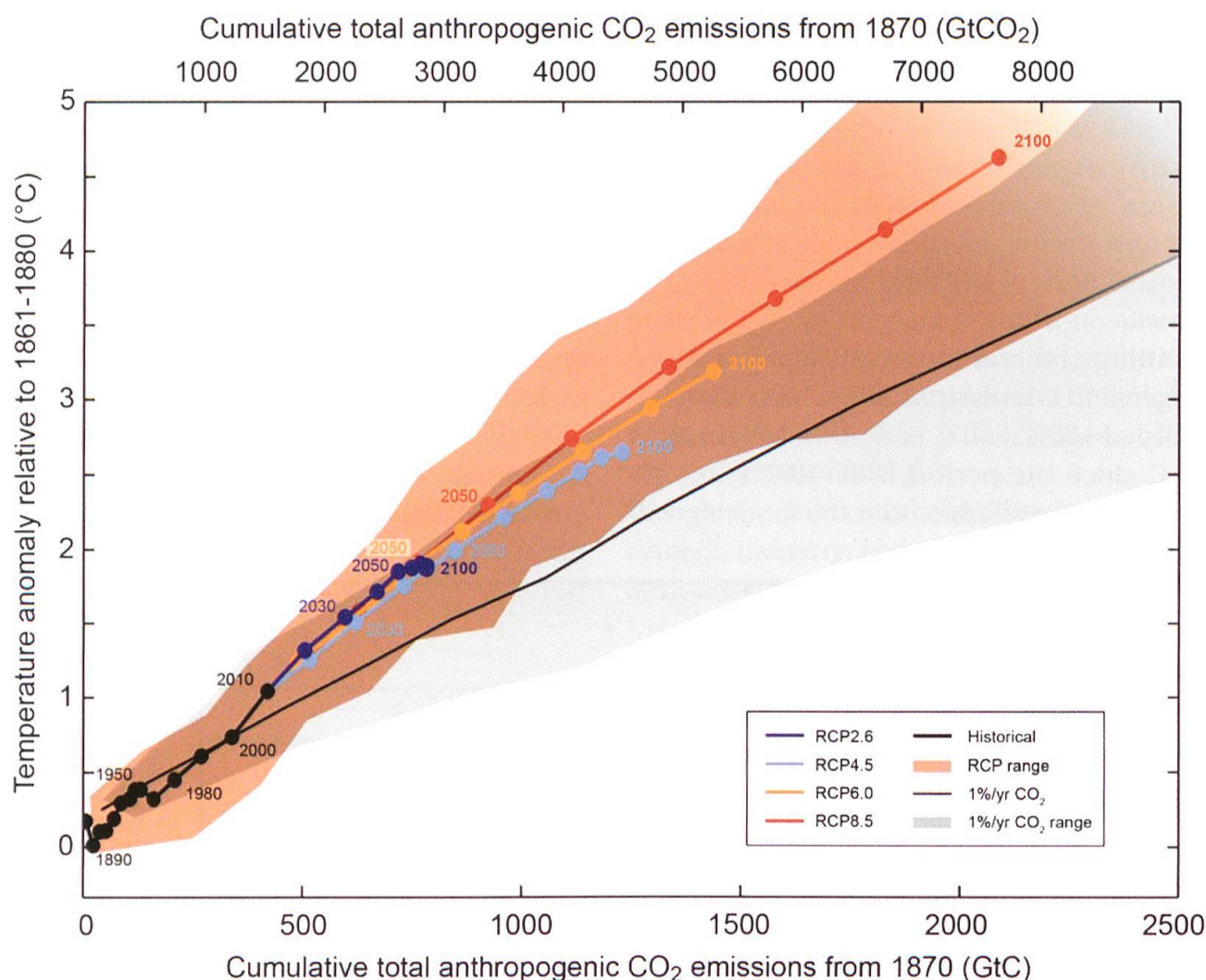


Fig. 9: Global mean surface temperature increase as a function of cumulative total global CO<sub>2</sub> emissions from various lines of evidence. Multi-model results from a hierarchy of climate-carbon cycle models for each RCP until 2100 are shown with coloured lines and decadal means (dots). Some decadal means are indicated for clarity (e.g. 2050 indicating the decade 2041–2050). Model results over the historical period (1860–2010) are indicated in black. The coloured plume illustrates the multi-model spread over the four RCP scenarios and fades with the decreasing number of available models in RCP8.5. The multi-model mean and range simulated by CMIP5 models, forced by a CO<sub>2</sub> increase of 1% per year (1% per year CO<sub>2</sub> simulations), is given by the thin black line and grey area. For a specific amount of cumulative CO<sub>2</sub> emissions, the 1% per year CO<sub>2</sub> simulations exhibit lower warming than those driven by RCPs, which include additional non-CO<sub>2</sub> drivers. All values are given relative to the 1861–1880 base period. Decadal averages are connected by straight lines.



global mean warming with respect to pre-industrial. Abrupt and irreversible ice loss from a potential instability of marine-based sectors of the Antarctic Ice Sheet in response to climate forcing is possible, but current evidence and understanding is insufficient to make a quantitative assessment.

## Notes

<sup>1)</sup> The following terms have been used to indicate the assessed likelihood of an outcome or a result: virtually certain 99–100% probability, very likely 90–100%, likely 66–100%, about as likely as not 33–66%, unlikely 0–33%, very unlikely 0–10%, exceptionally unlikely 0–1%. Additional terms (extremely likely: 95–100%, more likely than not >50–100%, and extremely unlikely 0–5%) may also be used when appropriate. Assessed likelihood is typeset in italics, e.g. *very likely*.

<sup>2)</sup> In the WG I 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. Uncertainty intervals are not necessarily symmetric about the corresponding best estimate. A best estimate of that value is also given where available.

<sup>3)</sup> The strength of drivers is quantified as *Radiative Forcing* (RF) in units watts per square metre ( $\text{W m}^{-2}$ ) as in previous IPCC assessments. RF is the change in energy flux caused by a driver, and is calculated at the tropopause or at the top of the atmosphere. In the traditional RF concept employed in previous IPCC reports all surface and tropospheric conditions are kept fixed. In calculations of RF for well-mixed greenhouse gases and aerosols in this report, physical variables, except for the ocean and sea ice, are allowed to respond to perturbations with rapid adjustments. The resulting forcing is called Effective Radiative Forcing (ERF) in the underlying report. This change reflects the scientific progress from previous assessments and results in a better indication of the eventual temperature response for these drivers. For all drivers other than well-mixed greenhouse gases and aerosols, rapid adjustments are less well characterized and assumed to be small, and thus the traditional RF is used.



