Climate updates

What have we learnt since the IPCC 5th Assessment Report?

THE
ROYAL
SOCIETY

List of abbreviations used throughout report:

AR5/AR5/AR6 Fourth/Fifth/Sixth Assessment Report of the IPCC
IPCC Intergovernmental Panel on Climate Change
RCP Representative Concentration Pathway

Climate updates
Issued: November 2017 DES5123
ISBN: 978-1-78252-306-2

This report can be viewed online at
royalsociety.org/climate-change

Cover image
© NanoStockk.

Contents

Introduction

> “Climate change is one of the defining issues of our time.”
>
> Dr Ralph J Cicerone and Sir Paul Nurse, in the foreword to ‘Climate Change: Evidence and Causes. An overview from the Royal Society and the US National Academy of Sciences’, 2014.

Climate has a huge influence on the way we live. For example, it affects the crops we can grow and the diseases we might encounter in particular locations. It also determines the physical infrastructure we need to build to survive comfortably in the face of extremes of heat, cold, drought and flood.

Human emissions of carbon dioxide and other greenhouse gases have changed the composition of the atmosphere over the last two centuries. This is expected to take Earth’s climate out of the relatively stable range that has characterised the last few thousand years, during which human society has emerged. Measurements of ice cores and sea-floor sediments show that the current concentration of carbon dioxide, at just over 400 parts per million, has not been experienced for at least three million years. This causes more of the heat from the Sun to be retained on Earth, warming the atmosphere and ocean. The global average of atmospheric temperature has so far risen by about 1°C compared to the late 19th century, with further increases expected dependent on the trajectory of carbon dioxide emissions in the next few decades.

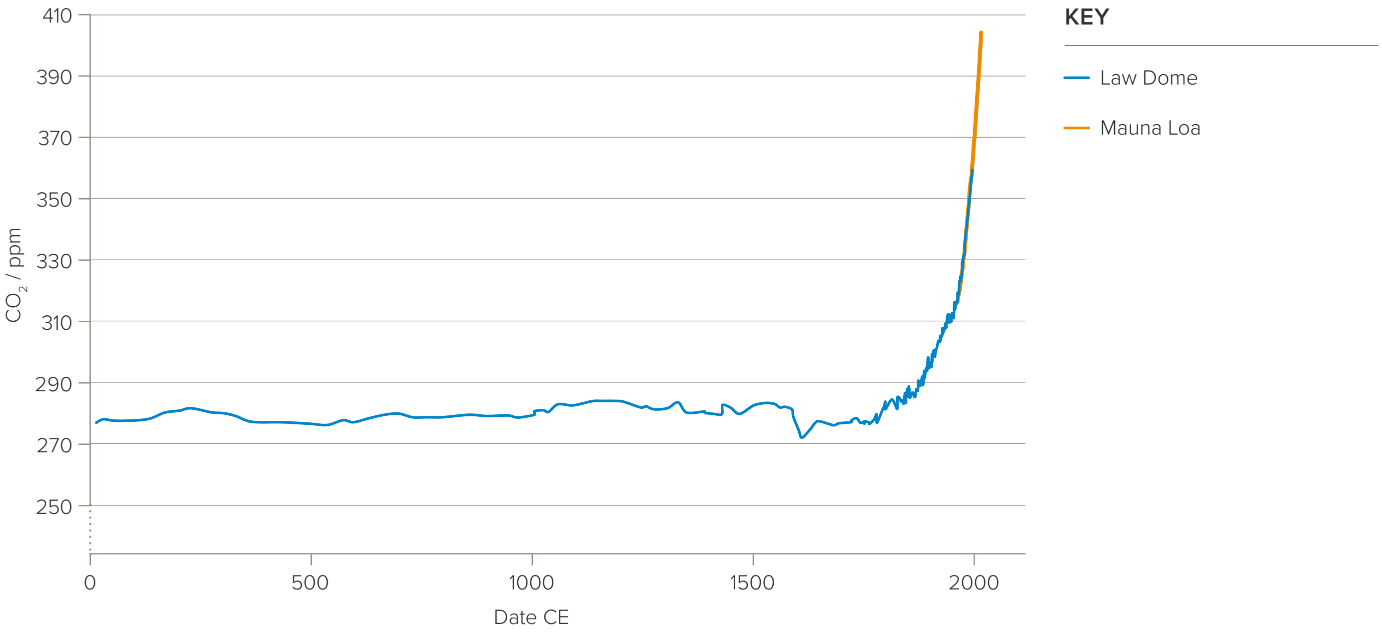
In 2013 and 2014 the Intergovernmental Panel on Climate Change (IPCC) published its fifth assessment report (AR5) assessing the evidence about climate change and its impacts. This assessment considered data from observations and records of the past. It then assessed future changes and impacts based on various scenarios for emissions of greenhouse gases and other anthropogenic factors. In 2015, almost every nation in the world agreed (in the so-called Paris Agreement) to the challenging goal of keeping global average warming to well below 2°C above pre-industrial temperatures while pursuing efforts to limit it to 1.5°C. With the next assessment report (AR6) not due until 2022, it is timely to consider how evidence presented since the publication of AR5 affects the assessments made then.

The Earth’s climate is a complex system. To understand it, and the impact that climate change will have, requires many different kinds of study. Climate science consists of theory, observation and modelling. Theory begins with well-established scientific principles, seeks to understand processes occurring over a range of spatial and temporal scales and provides the basis for models. Observation includes long time series of careful measurements, recent data from satellites, and studies of past climate using archives such as tree rings, ice cores and marine sediments. It also encompasses laboratory and field experiments designed to test and enhance understanding of processes. Computer models of the Earth climate system use theory, calibrated and validated by the observations, to calculate the result of future changes. There are nevertheless uncertainties in estimating future climate. Firstly the course of climate change is dependent on what socioeconomic, political and energy paths society takes. Secondly there remain inevitable uncertainties induced for example by variability in the interactions between different parts of the Earth system and by processes, such as cloud formation, that occur at too small a scale to incorporate precisely in global models.

Assessments such as those of the IPCC describe the state of knowledge at a particular time, and also highlight areas where more research is needed. We are still exploring and improving our understanding of many of the processes within the climate system, but, on the whole, new research confirms the main ideas underpinning climate research, while refining knowledge, so as to reduce the uncertainty in the magnitude and extent of crucial impacts.

FIGURE 1

Historic atmospheric carbon dioxide levels.



Historic atmospheric carbon dioxide levels determined from ice core measurements from Law Dome, East Antarctic and direct measurements at the Mauna Loa Observatory, Hawaii. Data courtesy of NOAA.

This report considers a number of topics that have been a focus of recent attention or where there is significant new evidence. This is by no means a comprehensive review such as that being carried out for the AR6 or in IPCC special reports that are underway. It instead tries to answer, in an authoritative but accessible way, some of the questions that are asked of climate scientists by policymakers and the public. The answers start from the evidence in AR5, updated by expert knowledge and by a necessarily limited assessment of work published since then. A full description of the process used is discussed in the appendix. The information here is supported by supplementary evidence available on the Royal Society webpages (royalsociety.org/climatechange) that describes the evidence base and literature sources used. This report does not attempt to cover every topic, and does not address more distant socioeconomic impacts of climate change such as its possible impact on migration and conflict. In particular, it does not discuss policy questions about how the aims of the Paris climate agreement might be achieved.

Each section of this report is designed to be read on its own, but the document as a whole follows a broad thematic progression, starting with aspects relating to the physical basis of climate change, and progressing through physical impacts towards those related to ecosystems and human wellbeing. The report shows where new studies are starting to fill identified gaps in knowledge. In some cases, new work suggests changes in the probability of certain outcomes occurring, but in most cases the broad statements made by IPCC still appear valid.

How sensitive is global temperature to increasing greenhouse gases?

Summary

In 2013, the IPCC report stated that a doubling of pre-industrial carbon dioxide concentrations would likely produce a long-term warming effect of 1.5 to 4.5°C; the lowest end of that range now seems less likely.

In AR5 IPCC said:

Equilibrium climate sensitivity is likely in the range 1.5°C to 4.5°C.

Transient climate response is likely in the range 1.0°C to 2.5°C.

What is this about?

Climate sensitivity is a measure of how global surface temperature rises in response to increasing atmospheric concentrations of greenhouse gases. Understanding this measure provides insight into the amount of carbon that can be emitted for a given amount of future warming. A higher value of sensitivity implies a lower remaining budget of greenhouse gas emissions to stay below a given warming threshold, and vice versa.

Equilibrium climate sensitivity is the increase in global surface temperature that would arise from the Earth fully adjusting to a doubling of atmospheric carbon dioxide (generally calculated from its preindustrial level). Temperature adjustment is slow, and surface temperatures will continue to rise well after the date of the doubling (even if the concentration of carbon dioxide has then stabilised). In contrast transient climate response is the increase in global surface temperature at the time when doubling of carbon dioxide occurs and relates more directly to the temperature increases we might expect to see in the coming century. The transient response represents a situation in which the climate has not yet fully adjusted and so is smaller than the equilibrium sensitivity.

The heat-trapping properties of carbon dioxide have been known since the 1860s and, if the only thing to change was the carbon dioxide level, it would be straightforward to calculate the warming resulting from a given concentration. However, physical processes, known as climate change feedbacks (due, for example, to changes in humidity, cloud or ice cover) modify the direct impact of carbon dioxide substantially.

Climate sensitivity can be estimated by several different methods. Direct measurements of temperature have been made since 1850, and, prior to that, records can be deduced indirectly from, for example, ice cores formed over 100,000s of years. One method uses this record together with energy-balance models and estimations of the effect of natural and anthropogenic processes to relate historical changes in carbon dioxide concentration to records of surface temperature change. Energy-balance models estimate the global average climate based solely on considerations of heat transfer (to the Earth from the Sun, and from the Earth via infrared radiation). These models make a number of assumptions, including how much heat is taken up by the oceans, and generally do not consider the geographical distribution of warming.

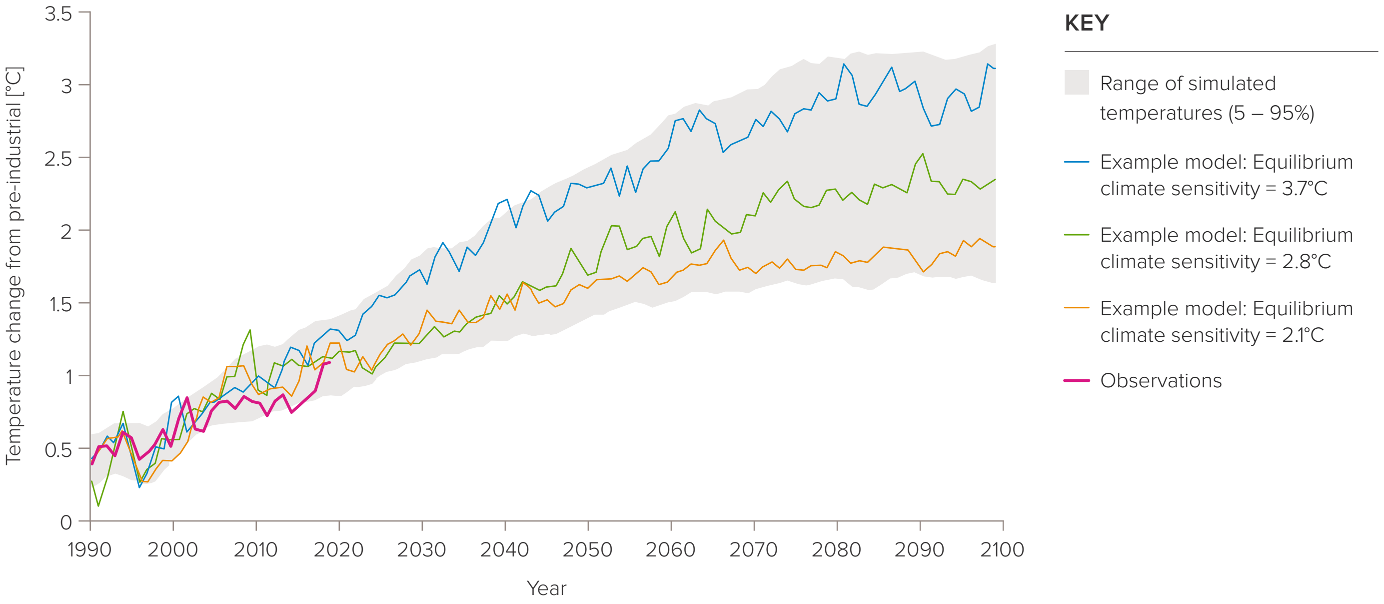
Another method to estimate equilibrium climate sensitivity uses computer simulations with complex global climate models. These models attempt to represent detailed physical processes, such as ocean heat uptake and climate feedbacks, and calculate a resulting sensitivity value. Each method is subject to its own approximations and uncertainties resulting in a range of estimates of sensitivity.

What was the basis for the statement in AR5?

Studies using different data sources and methodologies had produced a range of estimates of equilibrium climate sensitivity. In 2007 AR4 concluded that doubling of carbon dioxide concentration would lead to an equilibrium sensitivity in the range 2.0 to 4.5°C. In 2013, AR5 expanded the range to 1.5 to 4.5°C, to reflect some more recent studies based on past observations, but with no best estimate given. The range of transient climate response given in AR5 was 1.0 to 2.5°C.

FIGURE 2

Global mean suface temperature projections.



This graph demonstrates a spread of global mean surface temperature projections from different climate models using a scenario in which CO_2 emissions peak around 2040 and then start to decline. The individual lines are examples from different models with a spread of equilibrium climate sensitivity values within the range that AR5 considered possible. This shows how uncertainty in climate sensitivity dominates the uncertainty in projections of future temperature change for a given CO_2 future. Data courtesy of CMIP5.

What do we know now?

Publications since AR5 continue to show equilibrium sensitivity estimates across the IPCC range. Those based on past observations and energy-balance models generally produce lower values than those derived from the more complex global climate models, including some suggesting ranges extending to values lower than those of AR5. There have, however, been advances in understanding of the reasons for this disparity.

One important advance is that it is now known that as the climate warms it becomes less effective at emitting heat to space, mainly as a result of regional variations in surface warming. This means that climate sensitivity derived from historical data (which typically fails to fully represent regional areas that may be warmer or cooler than the average) gives an underestimate of the value for high carbon dioxide atmospheres. It is also now clear that the very slow changes in patterns of ocean surface warming are inadequately represented in time varying global climate models resulting in an underestimate of climate sensitivity.

Insight has been evolving into the impact of localised processes on warming, for example volcanic eruptions or emission of industrial sulphate particles. The individual impact of these varies from type to type, but models ignoring such regional variations tend to give lower values for sensitivity. Another approach, in which global climate models that have been assessed on the basis of their ability to reproduce observed changes in cloud cover and properties, such as ice content and reflectivity, shows that the best performers generally have higher sensitivities.

Surface temperatures continue to be imperfectly observed. Gaps in the observation network and differences between measurement techniques for land and ocean mean that blending procedures are required to produce a global dataset. It has been demonstrated that incomplete geographical sampling of temperature can impact estimates of sensitivity. For example, the use of data with less coverage over the Arctic, where warming has been larger, has biased some climate sensitivity estimates to be too low.

How might this affect the IPCC statement?

Growing understanding of the complex, non-linear factors determining climate sensitivity is leading to improvements in methodologies for estimating it. A value below 2°C for the lower end of the likely range of equilibrium climate sensitivity now seems less plausible.

How are methane concentrations changing and what does this mean for the climate?

Summary

After an apparent slow-down between 1999 and 2006, atmospheric methane concentrations have entered a period of sustained growth, increasing their contribution to surface warming.

In AR5 IPCC said:

CH_4 [concentrations] began increasing in 2007 after remaining nearly constant from 1999 to 2006.

The exact drivers of this renewed growth are still debated.

What is this about?

Human activity results in a number of drivers of climate change. Carbon dioxide emissions have the largest overall effect, but, for example, increased concentrations of greenhouse gases such as methane and nitrous oxide add to carbon dioxide's warming effect. The non-carbon dioxide drivers of climate change are a continuing research priority, in part because many influence local air quality as well as climate. Methane is the major greenhouse-gas driver of climate change after carbon dioxide, and there have been notable increases in its atmospheric concentration in recent years (and since AR5) that are not yet understood.

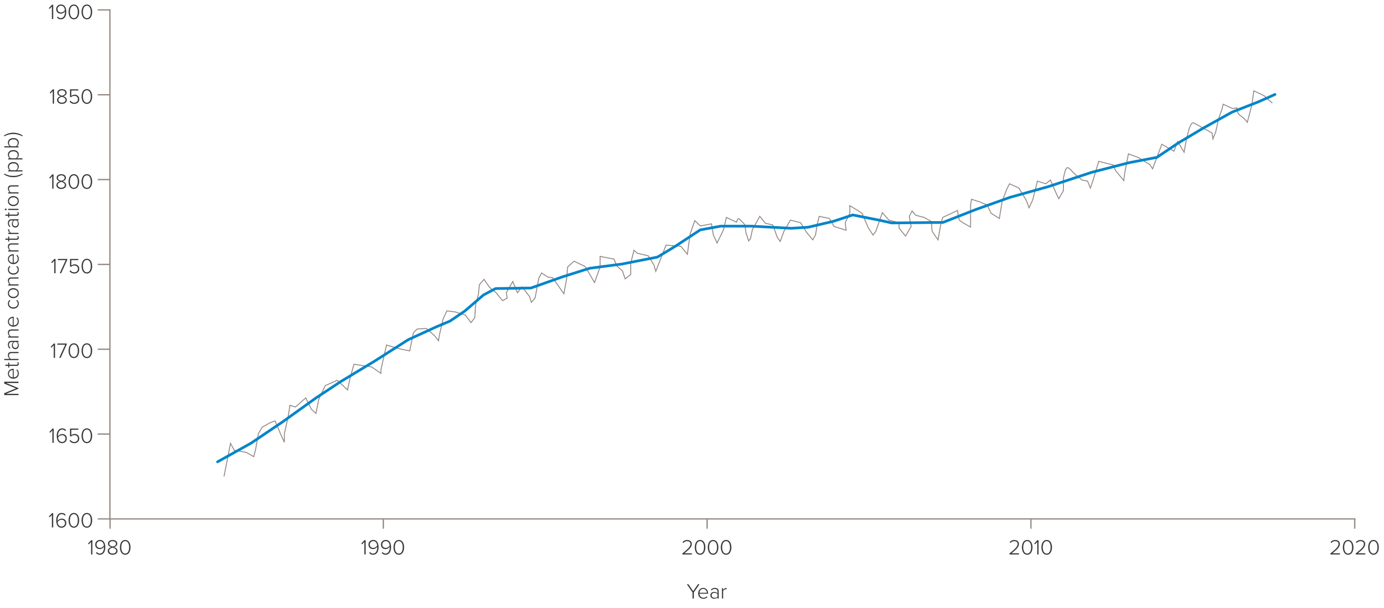
What was the basis for the statement in AR5?

Methane concentrations had increased markedly since the beginning of the industrial era, more than doubling from 770 parts per billion (ppb) approaching 1800 ppb in 2011. This increase was mostly attributed to human activity, including agriculture, waste, landfills, biomass burning and fossil fuel extraction. As for CO_2 evidence from air enclosed in polar ice cores demonstrated that present-day methane concentrations exceed any seen over the past 800,000 years. The growth rate of methane concentrations had not been steady; there was a slow-down in growth from 1990, which was particularly marked between 1999 and 2006. At the time of writing of AR5, there was an indication that this period of slowdown had ended.

The total warming effect of methane emissions for the period 1750 – 2011 was assessed to be about 55% of the size of the warming effect of carbon dioxide emissions over the same period. This value includes methane's direct warming effect and the impact of a number of indirect effects, notably the increase in ozone concentrations that results, via a sequence of atmospheric chemical reactions, from methane emissions.

FIGURE 3

Global monthly mean methane.



Shown here is the globally-averaged and monthly-mean atmospheric methane concentrations measured at marine surface sites by the US NOAA Earth System Research Laboratory. Monthly mean values are shown in black, the blue line is the long term trend with average seasonal cycle removed. Data courtesy of Ed Dlugocencky, NOAA, USA.

What do we know now?

The end of the slowdown in the growth of methane concentrations has been confirmed by continued global measurements. Annual-average concentrations increased from 1800 ppb in 2011, exceeded 1840 ppb in 2016 and may exceed 1850 ppb in 2017. Average growth rates now approach those seen in the 1980s prior to the slow-down. Methane concentration is impacted by the rates of both emission and destruction, and the contributors to the recent changes remain debated. Evidence from the geographical distribution of changes, and from isotopic measurements, indicates that increased emissions have been strongest from biological sources, most likely associated with tropical agriculture and tropical wetlands, but increased emissions from fossil-fuels, due to their extraction and use, may also play a role. There is little evidence of a significant increase in emissions from the Arctic. There is also further evidence that the rate of atmospheric destruction through chemical processes has slowed compared to what it was during the 1999 to 2006 period; the destruction rate is affected by human activity (including emissions of pollutants and concentrations of ozone), but the exact drivers of variations are not yet known.

How might this affect the IPCC statement?

There is no doubt that a period of renewed and sustained growth rate in methane concentrations has occurred since AR5. As a result, estimates of methane's contribution to climate change have increased above those in AR5. Significant debate surrounds the factors that influence these trends, and projections of future emissions will need to focus on both emissions of methane and the rate at which chemical reactions destroy it.

Was there a ‘pause’ in global warming?

Summary

In the 2000s the rate of surface warming was slower than in some previous decades, but the ocean continued to accumulate heat. Globally, 2015 and 2016 were the warmest years on record and seen in this context the multi-decadal warming trend overwhelms shorter term variability.

In AR5 IPCC said:

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.

What is this about?

Earth’s surface temperature, averaged globally over ocean and land areas, is one important measure of climate change. Since pre-industrial times, it has increased by around 1°C. However, the rate of increase has not been constant, and observational data assessed by the IPCC in AR5 suggested only a small increase between 1998 and 2012. This period was referred to as a ‘hiatus’ or ‘pause’ in global warming, and raised questions in the media and elsewhere about whether it was evidence of problems with the models used to project future climate. Since then (and since AR5) global temperature has significantly increased.

What was the basis for the statement in AR5?

More than 90% of the heat energy associated with global warming accumulates in the ocean rather than in the atmosphere. Observations of ocean heat content and sea level rise suggested that over the period of slow surface temperature rise Earth’s climate system had continued to accumulate heat, particularly in the ocean beneath the surface.

It was understood that natural processes cause variability in surface temperatures from year-to-year and decade-to-decade, and hence in the rate of surface warming. Interactions within and between different parts of the climate system (known as ‘internal variability’), volcanic eruptions and fluctuations in the Sun’s energy output all contribute to the overall variability.

There were unresolved questions about the specific processes that had contributed to the slower surface warming seen between 1998 and 2012. The IPCC concluded that both internal variability and reduced heating of the Earth “due to volcanic eruptions and the timing of the downward phase of the 11-year solar cycle” were important factors. With regard to the comparison between models and observations, the IPCC again highlighted the importance of internal variability but acknowledged that weaknesses in some of the models and inaccurate estimates of some forcing agents (such as volcanic eruptions) might be an additional factor.

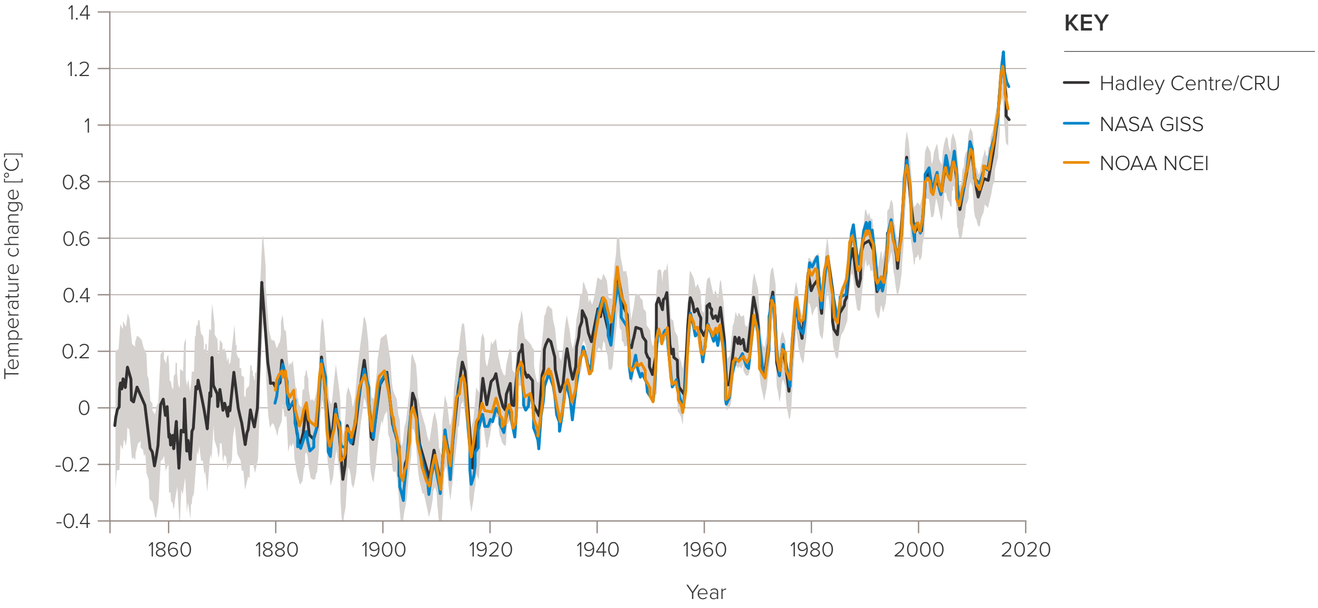
What do we know now?

Globally 2015 and 2016 were the warmest years in the surface temperature record, even allowing for the effects of the strong El Nino that affected both years. Seen in the context of the most recent years, the multi-decadal warming trend overwhelms shorter term variability.

The ‘pause’ apparent in the data used in AR5 can be attributed to two main factors: observational biases and the variability caused by natural processes. There is some evidence that changes in atmospheric aerosols (small particles in the atmosphere) caused by human activities may have been an additional factor.

FIGURE 4

Global temperatures relative to 1850 – 1900.



This graph shows the observed change in global mean surface temperature relative to the average for the period 1850 to 1900. Data are shown from running annual averages of three observational datasets. Grey shading indicates an estimate of uncertainty (5 to 95% range) on the black line. Data courtesy of Met Office/CRU, NASA GISS and NOAA.

Improved understanding of observational biases has shown that the rate of surface warming between 1998 and 2012 was greater than the evidence available at the time of AR5 suggested. There is now more evidence that the handling of observational gaps over the Arctic, a region of rapid warming, is important. When these biases are taken into account, a temporary slowdown in the rate of surface warming can still be seen in the data, albeit less prominently. Research since AR5 has strengthened the conclusion that this slowdown was primarily caused by natural variability, associated partly with variations in the surface temperatures of the Pacific Ocean.

The apparent differences in the rate of global surface temperature rise between models and observations have now been largely reconciled by taking proper account of internal variability, volcanic eruptions, and solar variability, in addition to the biases in the observational records. There are outstanding questions about the mechanisms that shaped the regional pattern of surface temperature change during the ‘pause’ – this is an area of ongoing research.

How might this affect the IPCC statement?

New evidence since AR5 supports the IPCC assessment that the period of slower surface warming that was observed between 1998 and 2012 was a short-term phenomenon not representative of long-term climate change. Despite the ‘pause’ in surface temperature rise, climate change carried on: the Earth continued to accumulate energy, particularly in the ocean, at a rate consistent with warming caused by human activities. In future the rate of surface warming is expected to continue to exhibit year-to-year and decade-to-decade variability in addition to the longer-term trend.

How high could sea level rise because of anthropogenic climate change?

Summary

Global mean sea level will likely rise by no more than a metre by 2100, but if warming is not limited, then its effects on the ocean and ice sheets could make a rise of several metres inevitable over centuries to millennia.

In AR5 IPCC said:

Global mean sea level rise for 2081 – 2100 relative to 1986 – 2005 will likely be in the ranges of 0.26 to 0.55 m for RCP2.6 … and 0.45 to 0.82 m for RCP8.5. 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.

What is this about?

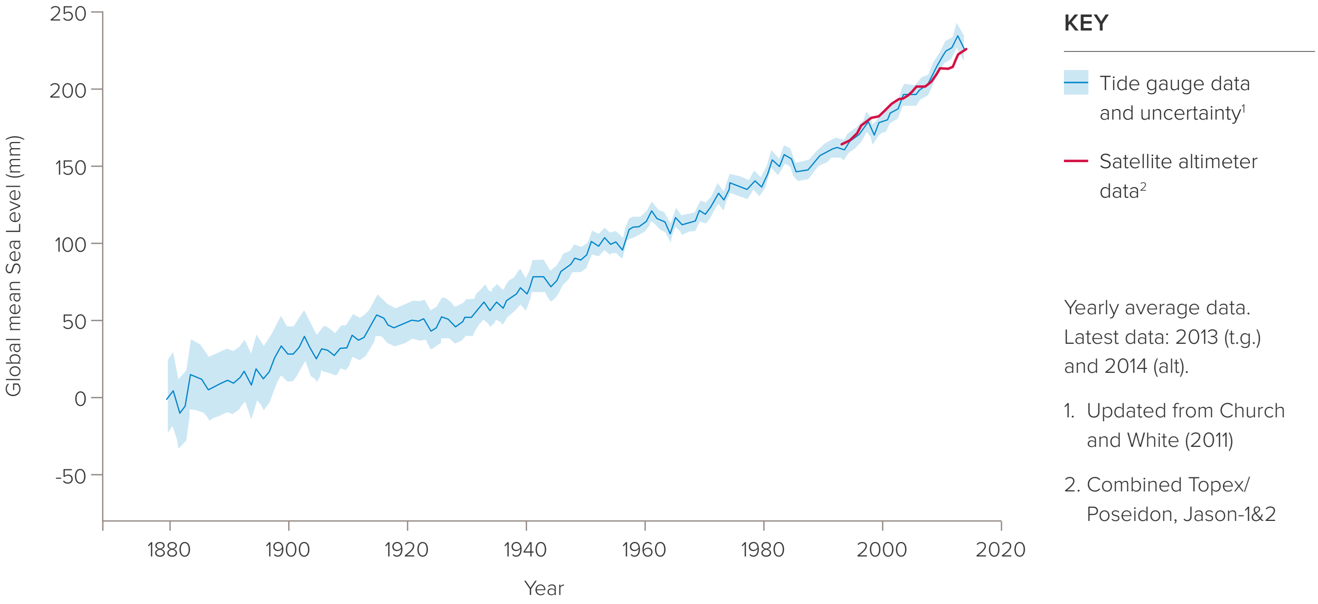
The majority of large cities and 10% of the global population are located in low-lying coastal areas. Coastal floods are, generally, most likely to occur when storms drive the sea onto the land, but their increasing incidence during the 20th century was caused mainly by the rise in sea level (global mean of about 0.2 m since 1901), rather than greater storminess. Assessing the amount and rate of sea level rise into the future is therefore essential for assessing the risks and frequency of such flooding.

What was the basis for the statement in AR5?

Global mean sea level rise is caused by both expansion of the ocean as it gets warmer and addition of water to the ocean due to loss of ice from glaciers and the ice sheets of Greenland and Antarctica. During the 21st century, the largest projected contribution was from thermal expansion. However, the greatest uncertainty related to the contribution from ice sheets, which could become significantly greater after 2100. Surface temperature warming passing an estimated threshold in the range 2 to 4°C above pre-industrial temperatures could lead to the complete loss of the Greenland ice sheet over a millennium or more, with a 7 m rise in global mean sea level. Warming of sea water which is in contact with those parts of the West Antarctic ice sheet resting on land below sea-level could cause partial disintegration of the ice sheet, through a process called ‘marine ice sheet instability’, and lead eventually to several additional metres of global mean sea level rise.

FIGURE 5

Global sea level observations.



Yearly average data.
Latest data: 2013 (t.g.)
and 2014 (alt).

1. Updated from Church and White (2011)
2. Combined Topex/Poseidon, Jason-1&2

This graph demonstrates the global mean sea level from 1880 – 2014. The blue line (with shaded uncertainty) comes from tide gauges scattered around the world's coastlines. The red line comes from a series of satellite-borne radar altimeters, with near-global coverage of the ocean. Data courtesy of CSIRO, updated from Church and White (2011).

What do we know now?

Recent work has confirmed that observed warming of the ocean, contraction of glaciers and sea level change in the last few decades is due mainly to anthropogenic climate warming. An acceleration in the rate of sea level rise since the 1990s is consistent with increasing ice mass loss particularly from the Greenland Ice Sheet. There has recently been more attention paid to the West Antarctic Ice Sheet. Some glaciers there are currently retreating, and this has been suggested to be a sign that marine ice sheet instability is underway. For 2100, under high emissions scenarios, most recently-published estimates for the Antarctic contribution (mainly West Antarctica) to sea level rise do not exceed 0.4m. Global sea level rise from ice loss in both Greenland and Antarctica could however increase in rate beyond 2100, and will continue for centuries under all scenarios.

Concern about the likely long-term sea level rise is heightened by evidence that sea level was 6 – 9 m higher than today during the last interglacial period (125,000 years ago) when new climate reconstructions confirm that polar temperatures were comparable to those expected in 2100.

How might this affect the IPCC statement?

With the exception of one prominent study that projects the loss of most West Antarctic ice by 2500 under even moderate warming scenarios, other recent research is still broadly consistent with the AR5 assessment that marine ice sheet instability contribution to sea level rise will "not exceed several tenths of a meter" by 2100. Thus the AR5 projections still represent current understanding, although suggestions that the contribution could be greater than was previously assessed need further evaluation. Quantitative uncertainties, reflected in the spread of results from recent studies, reinforce the need for better understanding of the processes leading to ice shelf and ice sheet retreat. It is moreover virtually certain that sea level rise will continue for many centuries. In a climate as warm as those projected in many models for 2100 and beyond under high emissions scenarios, large parts of both ice sheets would be lost over millennia, leaving sea level many metres higher than present.

Decreasing Arctic sea ice – is there any influence on the weather in middle latitudes?

Summary

The long-term decrease in Arctic sea ice extent continues and the effect of ice loss on weather at mid-latitudes has become a subject of active scientific research and debate.

In AR5 IPCC said:

The annual mean Arctic sea ice extent decreased over the period 1979 to 2012 with a rate that was very likely in the range 3.5 to 4.1% per decade (range of 0.45 to 0.51 million km^2 per decade), and very likely in the range 9.4 to 13.6% per decade (range of 0.73 to 1.07 million km^2 per decade) for the summer sea ice minimum (perennial sea ice).

What is this about?

The Arctic has warmed more rapidly than elsewhere. There are a number of reasons for this. Warming leads to a reduction in Arctic sea ice area, which leads to less of the Sun's energy being reflected from the surface, and therefore additional warming during the summer, which is mainly absorbed by the ocean. During the winter the reduced Arctic sea ice area allows heat to escape from the ocean to the atmosphere above it. Since 1979, when satellites first enabled a complete picture to be obtained, the reduction of sea ice is striking, particularly in the late summer minimum ice period, when the decrease is at a rate of more than 10% per decade.

Despite the long-term average increase in surface temperature at high-latitudes, there has been a wintertime cooling trend both in eastern North America and in central Eurasia over the last 25 years including a number of extremely cold winters (e.g. 2009/10 in northern Eurasia and 2014 in eastern North America). This period coincides with the period of pronounced Arctic sea ice decline. Some research has suggested that warming in regions of reduced sea ice leads to a weakening westerly polar jet stream that is more likely to meander. In such meanders very cold air may reach deep into middle latitudes.

What was the basis for the statement in AR5?

Increased levels of warming in the Arctic and the associated decrease in sea ice had been observed and were in general understood. However, at the time there was no indication of any particular link with changed patterns in extremes of mid-latitude weather and the lack of comment by IPCC reflected this.

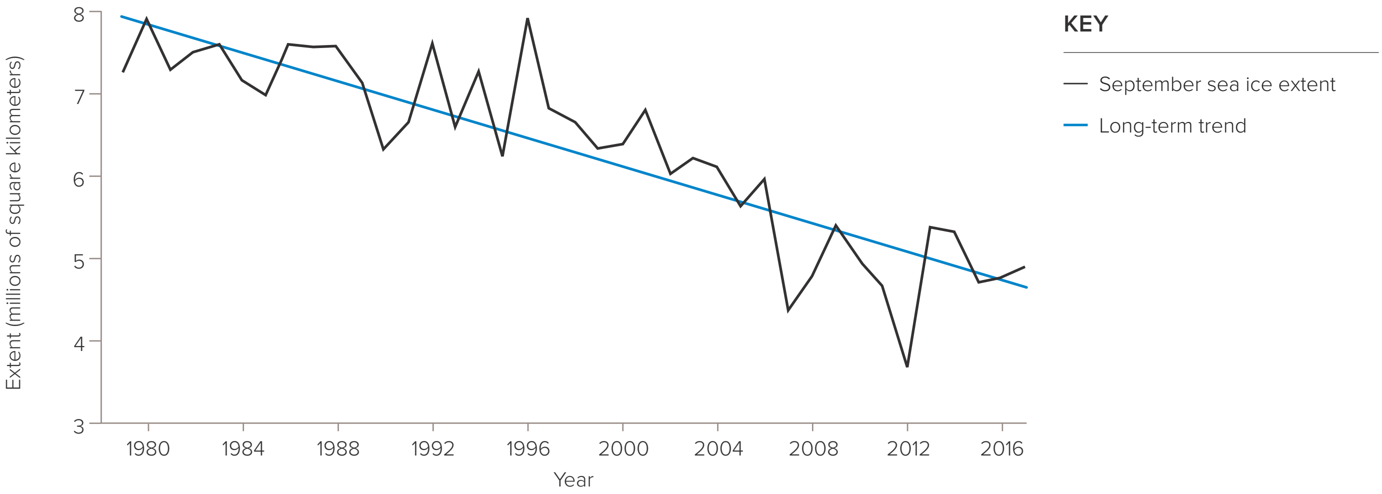
What do we know now?

In the last five years, changes in the extent of Arctic sea ice has been consistent with a general decline and large natural variability from year to year. 2012 had a record September minimum, some 40% below typical values seen in the early 1980s. 2016 and 2017 have seen the smallest March maxima in sea ice area. There is no particular basis for making significant changes to the IPCC projections for future amounts of sea ice.

It is challenging to attribute observed changes in midlatitude weather to Arctic sea ice loss, but there are indications from observations that sea ice loss may be causally linked to changes in wintertime atmospheric circulation over Eurasia that are consistent with the cooling seen there.

FIGURE 6

Arctic sea ice area in September from 1979 to 2017.



Shown here is the extent of Arctic sea ice for each September from 1979 to 2017 (black line), indicating a decline of 13.3% per decade. Data courtesy of National Snow and Ice Data Center, USA.

There has been considerable use of computer models to investigate possible influences of Arctic warming on regional mid-latitude weather, and some theoretical, but conflicting, mechanisms have been proposed. If the weather systems stayed the same, enhanced Arctic warming would mean that the cold air blowing into middle latitudes from Arctic regions would be less cold. However, there is some evidence from models that regional decreases in sea ice, such as in the Barents-Kara Sea (north of Finland and western Russia), can interact with the regional weather systems to increase the likelihood of very cold winter weather in Central Asia, as has been more prevalent since 1990. The nature and strength of linkages between Arctic sea ice loss and midlatitude weather is a focus of considerable current research.

How might this affect the IPCC statement?

Arctic sea ice extent observed in the past five years is consistent with the statements made in AR5 on its general rate of reduction. It is likely that the next IPCC report will include more discussion on linkages between Arctic sea ice loss and midlatitude weather, particularly in Central Asia.

Have temperature and rainfall extremes changed and how will they change in the future?

Summary

Climate change has increased the frequency of heatwaves. The effect on rainfall and tropical storms is more complex and harder to detect, but there is strengthening evidence that warming may increase the intensity of the strongest tropical storms.

In AR5 IPCC said:

It is now very likely that human influence has contributed to observed global scale changes in the frequency and intensity of daily temperature extremes since the mid-20th century, and likely that human influence has more than doubled the probability of occurrence of heat waves in some locations.

There are likely more land regions where the number of heavy precipitation events has increased than where it has decreased.

It is very likely that heat waves will occur with a higher frequency and duration.

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.

What is this about?

Extreme events such as unusual heat, heavy rainfall, month-long droughts, or hourly very intense rainfall can have important impacts, for example on health, food production and infrastructure, especially if they happen infrequently which makes it difficult to adapt. As climate warms, some events that used to be rare, or even unprecedented in the context of today's climate, will become more common, such as summer heat waves, while others will become less common, such as winter cold spells. The warmer atmosphere increases the potential for heavy rainfall in general, even while some regions will receive less rainfall due to changes in atmospheric circulation. As temperature rises evaporation increases and will add to the potential for drought in some regions.

As well as these more direct effects, extreme events can also be affected indirectly by the impacts of changes in vegetation or ecosystems.

What was the basis for the statement in AR5?

The statements in AR5 were based on research considering observed trends in extremes on a globally widespread scale. Observed large-scale changes were compared with changes simulated over the 20th century in climate models, and with changes that are expected from natural climate variability only, attributing them to human influences. Confidence was higher for daily temperature extremes than rainfall extremes. There was also an emerging scientific literature determining to what extent climate change has influenced the likelihood of individual events, such as a particular observed heat wave event for example the European heatwave of 2003.

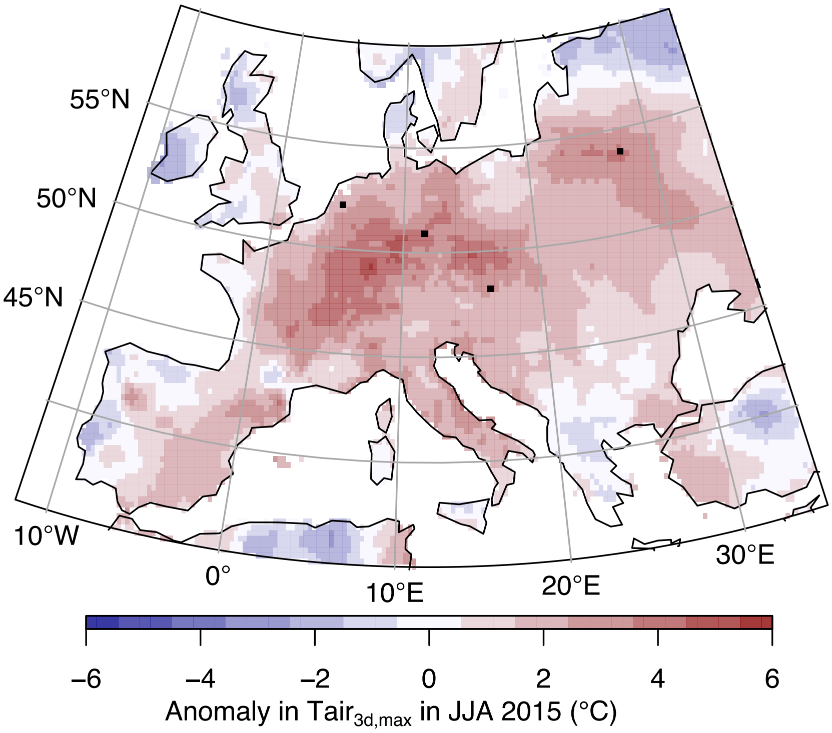
What do we know now?

Observations show that many extremes have continued to become more frequent and intense. Heat waves continued to increase in frequency even between 1998 and 2012, and research indicates an important interaction between dry conditions and heat waves.

Since AR5, analysis of specific extreme events has continued to indicate that human influences have made many individual heat waves much more likely, and cold spells less likely. Methods to quantify this change have improved, and different methods and approaches tend to lead to the same conclusions. Nevertheless some uncertainty remains as changes in atmospheric weather patterns can locally have a strong impact.

FIGURE 7

European heat wave 2015.



Shown here is the temperature anomaly in the seasonal (June, July, August) maximum of daily mean temperatures over three consecutive days over Europe in 2015 relative to the average three-day maximum of 1981 to 2010. Unusually high European summer temperatures were caused by a combination of climate variability and human influence. Climate change has increased the frequency and intensity of short-term heat waves and heat stress such as over the locations considered (dots). Published by Sippel *et al*. 2016 © American Meteorological Society.

It is much more difficult to determine if humans have influenced other types of events, such as drought, or heavy rainfall events. Generally a warmer atmosphere is more conducive to heavy rainfall just because it can hold more water. However, natural climate variability in precipitation is very large, and changes in atmospheric circulation patterns have a substantial influence. Therefore, results of attribution studies for precipitation-related events tend to depend on the type of event that is considered, and what assumptions are used. For example, results will often differ depending on whether a study considers how extreme the rainfall would have been without greenhouse gas increases for the exact same atmospheric conditions, or if it considers how extreme rainfall overall has changed in a region.

2017 was (at least until early October) a very active tropical cyclone season where severe damage was caused. IPCC AR5 indicated low confidence in observed long-term changes of intense tropical cyclone activity, and low confidence in the causes of those changes, but predicted more likely than not increases in intensity by the end of the century in the Western North Pacific and North Atlantic.

There is evidence from physical understanding and modelling that warming may increase the intensity of the strongest tropical cyclones. Also, analysis of model simulations and physical understanding suggest that heavy rainfall associated with tropical cyclones and other extreme storms should increase in a warmer atmosphere, all else being equal. Sea level rise exacerbates the impact of storm surges.

How might this affect the IPCC statement?

Further evidence supports the existing IPCC statements. Temperature extremes have become more frequent globally and rainfall extremes have increased in some regions and these trends are likely to continue in the future. More specific statements about the role that human influence has played in changing the frequency of specific types of events, particularly heat waves, are becoming possible. Improved model simulations and physical understanding may strengthen confidence in projected changes in extreme daily and sub-daily rainfall, and in tropical cyclones and the heavy rainfall and the coastal inundation associated with them.

Are there thresholds beyond which particularly dangerous or irreversible changes may occur?

Summary

There are a number of possible thresholds, but unless warming significantly exceeds expectations it is not expected that the most dangerous ones discussed here will be crossed this century.

In AR5 IPCC said:

It is unlikely that the AMOC [Atlantic Meridional Overturning Circulation] will collapse beyond the end of the 21st century for the scenarios considered but a collapse… for large sustained warming cannot be excluded.

It is very unlikely that CH_4 from clathrates will undergo catastrophic release during the 21st century.

There is low confidence in projections of the collapse of large areas of tropical and/or boreal forests.

What is this about?

Several components of the Earth system might have thresholds or “tipping points”. If climate change passes certain levels, abrupt transitions could occur and parts of the climate system could be significantly altered. In some cases, these changes may be irreversible and in others it may take much longer to return to the original state even when the underlying drivers of climate change have ceased. Among the phenomena of concern are:

- Collapse of the Atlantic Meridional Overturning Circulation, which transports ocean heat to North Atlantic surface waters, with widespread consequences for the climate.
- Rapid release of methane from organic carbon in permafrost on land, or from methane hydrates (clathrates) below the ocean floor causing significant further warming.
- Large scale dieback of the Amazon forest and consequential loss of ecosystem and carbon sink.

Potential thresholds for loss of large ice sheets leading to sea level rise, are discussed under the topic of sea level.

What was the basis for the statement in AR5?

AR5 concluded that collapse of the overturning circulation would cause significant global-scale climate disruption, including abrupt cooling around the North Atlantic. Weakening was expected in the 21st century, but an abrupt collapse was not, unless models seriously underestimate sensitivity to heat or freshwater, or the input of meltwater from Greenland is much faster than expected.

Warming at high latitudes will reduce the area of permafrost, and this will cause carbon dioxide and methane to be released to the atmosphere. However there was a wide range of estimates for the magnitude of these emissions. Ocean warming can destabilise clathrates below the sea floor, releasing methane to the ocean. If large volumes reached the atmosphere, this would have a massive warming effect. However, AR5 concluded that oxidation would convert most of the methane to carbon dioxide before it reached the ocean surface, and the slow rate of heat penetration through the sediment meant that the destabilisation of hydrates would be small on century scales.

AR5 recognised that the Amazon rainforest might have a critical threshold, particularly in relation to a rainfall volume below which large scale dieback might be expected. However considering likely scenarios and the combined effects of carbon fertilisation, warming, and changes in rainfall, fire and land use, they gave the cautious statement above.

What do we know now?

New palaeoclimatic measurements have strengthened the evidence linking changes in overturning circulation in the last glacial period to abrupt climate change, indicating that destabilisation of overturning circulation can occur and is associated with climate disruption. However, these occurrences are not direct analogues for today's interglacial period, because they were associated with inputs of meltwater from ice sheets much larger than the one that remains in Greenland.

Modern measurements confirm the variability of the Atlantic Meridional Overturning Circulation on daily, seasonal and interannual timescales, which makes detecting current trends challenging. Recent work suggests that climate models have biases favouring stability. This could imply that the likelihood of circulation collapse has been underestimated, but much more research is needed to reach firm conclusions.

Many new measurements have led to revised estimates of the amounts of carbon stored in permafrost, and the amounts of greenhouse gases released when permafrost thaws. These show that release of permafrost carbon will be a significant positive feedback for climate change; however, release is still expected to be prolonged and gradual rather than abrupt on decadal scales. Several new measurements have suggested a limited influence of current clathrate releases (and indeed from permafrost on land) on the atmosphere. Assuming that the whole ocean does warm significantly, heat will reach larger volumes of clathrates, but this is expected to be gradual, implying a commitment to slow rather than catastrophic release to the ocean.

Many of the factors that influence the nature and health of forest ecosystems have been reported on, but recent modelling studies considering all the interactions and the ecosystem complexity show that there remains much uncertainty about the possibility of substantial spatially-coherent forest loss.

How might this affect the IPCC statement?

Based on current models, significant but gradual reductions in strength of the overturning circulation are expected if warming continues. However, sudden ocean circulation collapse remains unlikely, while still not being excluded, especially beyond 2100. Ocean warming implies a long-term commitment to some clathrate destabilisation with timescales up to millennia, but not necessarily to significant methane release into the atmosphere. The cautious IPCC statement about the Amazon as a whole is still valid.

In summary, gradual climate change could trigger abrupt changes – with large regional and potentially global impacts – associated with thresholds in the Earth system. The possibility of crossing any of these thresholds increases with each increment of warming. However, although surprises cannot be excluded, there is no compelling evidence that the thresholds discussed here will be crossed this century, or that the IPCC statements need significant amendment.

Image
Amazon rainforest. © Ildo Frazao.

Is the land taking up carbon dioxide because of faster plant growth?

Summary

Increasing atmospheric carbon dioxide increases plant growth, in turn removing carbon dioxide from the atmosphere, but this increased removal is counteracted by the challenge of continued climate change for terrestrial ecosystems.

In AR5 IPCC said:

With high confidence, the carbon dioxide fertilisation effect will lead to enhanced NPP [net primary production], but significant uncertainties remain on the magnitude of this effect, given the lack of experiments outside of temperate climates.

What is this about?

Plants use the energy of sunlight to convert carbon dioxide into sugars, through photosynthesis. The total amount of carbon taken up by an area of land each year is gross primary production. About half of this carbon is used to create new plant material, called net primary production, the other half being released to the atmosphere by plant respiration. Plant material eventually decays with most of the dead carbon being consumed or broken down by fungi, bacteria, animals or by fire, and carbon being released back to the atmosphere as a result. The net carbon balance of an ecosystem is the balance between these processes of carbon uptake and release.

Increasing atmospheric carbon dioxide concentration increases photosynthesis and reduces transpiration, generally leading to increased plant growth and water use efficiency. The processes of plant death and carbon release lag behind, resulting in net carbon uptake by the ecosystem. According to terrestrial ecosystem models, this ‘carbon dioxide fertilisation’ is the main cause of the net uptake of carbon dioxide emissions by the land (the land carbon sink). It is also thought to be the main cause of the observed increase in vegetation leaf cover (the ‘greening’ of the biosphere) as more carbon is being allocated to leaves.

What was the basis for the statement in AR5?

IPCC concluded that CO_2 ‘fertilisation’ leads to enhanced primary production, with net primary production increasing by 20 to 25% for a doubling of carbon dioxide over pre-industrial levels. However, nitrogen and phosphorus availability were considered very likely to limit that increase, with nitrogen limitation prevalent in temperate and boreal ecosystems and phosphorus limitation in the tropics.

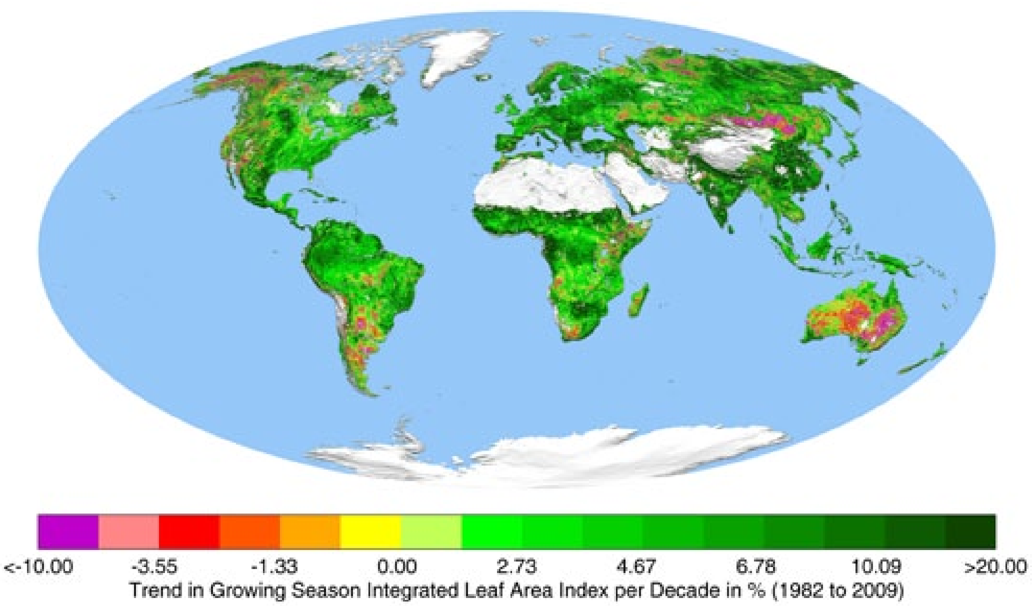
What do we know now?

Global observations

Several lines of evidence point to an increase in primary production over the industrial period. Observed changes in global atmospheric CO_2 and oxygen concentrations indicate, with a high degree of confidence, that the terrestrial biosphere is absorbing around one third of anthropogenic CO_2 emissions, thereby acting as a brake on the rate of atmospheric CO_2 increase. Satellite observations of vegetation cover show widespread ‘greening’. Models suggest that this greening is predominantly due to CO_2 fertilisation, because of increased water-use efficiency as atmospheric CO_2 rises, although climate and land use change have also contributed. The large increase observed in the amplitude of the atmospheric carbon dioxide seasonal cycle (especially at high latitudes) has been predominantly caused by increasing photosynthesis, as a response to CO_2 fertilisation (and potentially also climate change at high latitudes). Independent atmospheric observations of carbonyl sulphide – which is taken up with CO_2 during photosynthesis, but not released again – indicate that gross primary production increased by circa 30% during the 20th century. Long-term field inventories also support a long-term carbon sink in the world’s forests.

FIGURE 8

Observed trend in vegetation ‘greening’ as inferred from satellite data.



Shown here is the vegetation ‘greening’ trend since the 1980s, as seen from space. Zhu *et al.* explain the trend as mainly due to increasing atmospheric CO_2 concentration, but longer growing seasons in the north and forest regrowth in mid-latitudes, have also contributed. Increasing primary production has been caused partly by this greening but also by more efficient photosynthesis due to increasing CO_2. From: Zaichun Zhu, Peking University.

Global models

In AR5 only two of the Earth System models used included a coupled carbon-nitrogen cycle which accounted for nitrogen availability effects. Both models used the same land model, which showed greatly reduced CO_2 fertilisation and a greatly reduced climate-carbon cycle feedback. Although carbon-only models are expected to overestimate land carbon sinks, recent analyses have shown that the extremely low responses found with the two carbon-nitrogen models in AR5 are probably unrealistic.

Limits to carbon dioxide fertilisation

Current understanding shows that reality is more complex than was indicated in AR5. In some ecosystems the effect of CO_2 on plant growth is independent of nitrogen availability; other ecosystems have shown little or no CO_2 effect under low nitrogen availability. Much less is known about the influence of phosphorus availability, which may be particularly constraining in tropical ecosystems. First experimental results from a forest experiencing phosphorus limitation have suggested no response of plant growth to increasing CO_2, but there are still no experiments in mature tropical forests. Another factor that may limit CO_2 fertilisation is forest demography, with tree mortality accelerating as a result of enhanced tree growth.

Fertilisation versus climate feedbacks

The positive effect of increasing CO_2 on the land carbon cycle currently dominates over the negative effect of climate change (primarily the warming induced increase in soil carbon decomposition rate). Further climate change will affect this balance and reduce land carbon sinks efficiency, with regional droughts reducing productivity and higher temperatures accelerating rates of decomposition. Conversely, between 2002 and 2014 the growth rate of atmospheric CO_2 stayed relatively constant despite a continued increased of anthropogenic emissions, indicating an increase in the size of carbon sinks. Recent studies suggest that the reduced level of surface warming in that period led to a slowdown in temperature-driven ecosystem respiration. How long land carbon dioxide uptake will continue to dominate over release is unknown.

How might this affect the IPCC statement?

The statement in AR5 remains true. Increasing atmospheric carbon dioxide continues to increase net primary production and so leads to a proportion of that extra carbon dioxide being removed from the atmosphere. However, there are still large uncertainties about the geographic distribution, and the future, of the land carbon sink. The benefit of increased plant growth (including of crops, which are discussed later) will be reduced if rising temperatures and change in precipitation cause heat stress or water stress and reduce plant productivity.

How do increasing carbon dioxide concentrations impact ocean life and fisheries?

Summary

Carbon dioxide emissions are resulting in warming, deoxygenation and acidification of the ocean and this poses significant risk to ocean ecosystems including those relied on for food and livelihoods.

In AR5 IPCC said:

Marine organisms will face progressively lower oxygen levels and high rates and magnitudes of ocean acidification, with associated risks exacerbated by rising ocean temperature extremes.

Climate change adds to the threats of over-fishing and other non-climatic stressors.

What is this about?

The ocean plays a key role in regulating climate. It has absorbed about 25% of anthropogenic carbon dioxide emissions since 1750. This has had the effect of causing the oceans to become more acidic. The ocean has also absorbed about 90% of Earth's additional heat since the 1970s, but this has led to ocean warming and decreasing oxygen content (due to reduced oxygen solubility caused by warming and decreased supply to the ocean interior due to less mixing). These changes have important consequences not only for marine biodiversity and ecosystems but also for the goods and services they provide, including protein and other nutrients from fin fish and shellfish, coastal protection, and livelihoods for hundreds of millions of people. The ocean's content of carbon, oxygen, acidity and heat would continue to change long after atmospheric carbon dioxide emissions cease, as the changes only spread slowly into deeper waters, but the extent and rate of carbon dioxide emissions will affect the magnitude of the changes.

What was the basis for the statement in AR5?

AR5 concluded that increasing carbon dioxide and temperature will cause changes in global marine species' distributions and reduction of marine biodiversity in sensitive regions. Evidence for these changes came from model projections of ocean warming and acidification under different emission scenarios, numerous laboratory and field studies, and meta-analyses. Whilst global ocean warming is expected to cause the number of species and fisheries catch potential to increase (on average) at mid and high latitudes, decreases are projected in the tropics and in semi-enclosed seas. IPCC also assessed that progressive expansion of ocean minimum zones and anoxic 'dead zones' will further constrain fish habitats. Such changes would challenge the sustained productivity of fisheries and the provision of other ecosystem services, especially in tropical regions.

What do we know now?

Many new studies have further documented effects attributed to acidification. It also appears that deoxygenation is happening faster than was projected by models. Effects, including coral bleaching, have been attributed to warming which continues to occur in all oceans. There have been new studies on the complex effects of multiple stressors on biodiversity, ecosystems and fisheries.

Other studies have shown that local variability in conditions and the response of different species can result in complex food-web interactions. There is potential for a shift or reduction in the ranges of some species, or even loss of some ecosystems, such as those supported by corals, with reduced functioning of the food web. Whilst some species may be able to acclimate, many will not.

There is increasing evidence that a high emissions scenario will significantly alter many ecosystems and food webs through increased warming, acidification and deoxygenation and the spread of oxygen minimum zones or their combination. Not all of the impacts would necessarily be negative but these stressors can threaten fin fisheries and shellfish aquaculture in vulnerable regions. A low emissions scenario reduces the overall risk, but even in this case the risk to current coral reef ecosystems, for example, remains high. The potential loss of tropical coral reefs would not just reduce local biodiversity but would also have major consequences for coastal protection, tourism, income, livelihoods and fisheries.

The nutrition (protein and micro-nutrient supply) of about 1.4 billion people is at risk as fish make up a significant proportion of their animal-based food. Climate change under a high emission scenario is projected to reduce fish catch by about 5% globally and 30% in tropical regions. The communities that live there are the most vulnerable, due to their dependency on wild fish, their poor current adaptive capacity, and projected increases in food demand (related to population growth).

How might this affect the IPCC statement?

On this basis we expect the IPCC statements to stand. Climate change will place multiple stresses on many marine organisms, potentially resulting in decreases of biodiversity, changes to species distribution and altering marine food webs and ecosystems. The evidence base is now stronger and more complex and diverse. The combined impacts of warming, deoxygenation and acidification on marine ecosystems and fisheries may lead to a more adverse risk assessment, but studying and attributing their combined impacts is difficult.

Image
A coral reef off the Island of Bermuda supporting a biodiverse community of fish and invertebrates, which are vital to the livelihood of local people, as they provide the basis for fisheries and tourism, and protect the coast from storm surges. © Dr Alexander Venn, Centre Scientifique de Monaco.

How will climate change affect food production on land?

Summary

Increasing carbon dioxide can increase crop yields while high temperature and drought in some regions can decrease them. The aggregate impact at global level is for climate change above 2°C to reduce yields.

In AR5 IPCC said:

For wheat, rice, and maize in tropical and temperate regions, climate change without adaptation is projected to negatively impact production for local temperature increases of 2°C or more above late-20th-century levels, although individual locations may benefit.

What is this about?

Wheat, rice and maize are staple crops and feeding the growing human population depends on their continued success. Climate change poses a range of effects: the increased concentration of carbon dioxide can increase crop yields, while changes in temperature and rainfall will have a variety of effects, with very high temperatures and drought both adversely affecting yield. Taking all factors into account, AR5 concluded that a change of 2°C or more above late-20th-century levels will adversely affect yields and food production.

What was the basis for the statement in AR5?

The statements were based on a global analysis of studies up to 2013 reporting climate impacts on crop yields. While climate change impacts were variable across crop types and by region, the global impacts on food production for these crops were negative.

What do we know now?

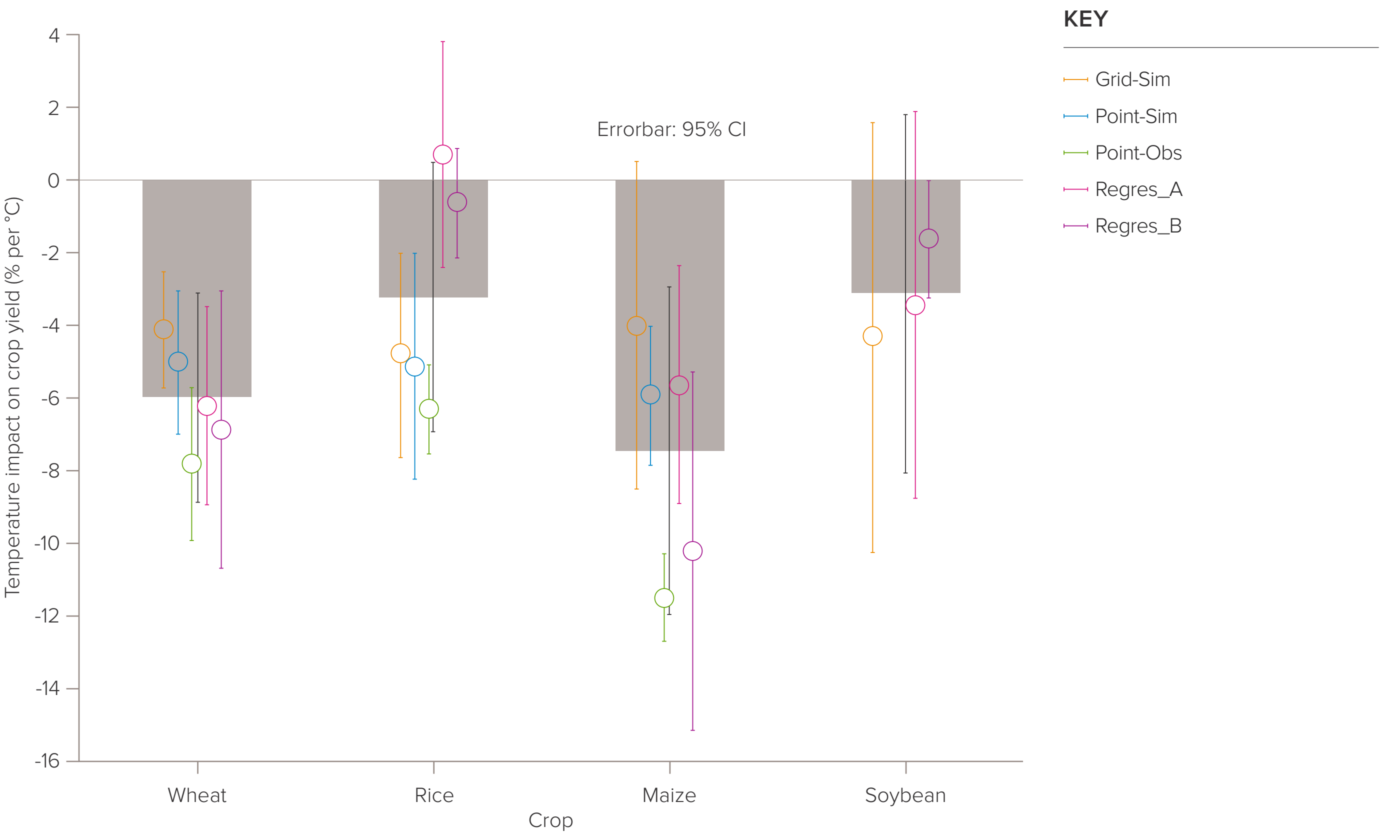
Some studies since 2013 project somewhat lower impacts than those estimated in the analysis on which the IPCC statement is based, and more regional nuance has emerged, with some regions expected to see increasing yields for some crops. The conclusions in the original statement are not altered (see figure), though new studies point strongly to the importance of accounting for how land use and cropping intensity might change.

Since 2013, there has been more emphasis on nutrition, and not only on yield change. Higher-yielding wheat crops adapted to higher temperatures, or growing under increased atmospheric carbon dioxide concentrations, may produce grain of poorer nutritional quality under climate change.

AR5 considered productivity changes in yields for the three major cereals, but since 2013, we can also say more about the impact of climate change on other crops and rangelands (open lands used for grazing). Subsequent analyses have examined potential changes in food production as a result of changes in the area suitable for agriculture, though greater confidence in the conclusions of such studies requires the further inclusion of other criteria for crop growth and development, soil nutrient availability and the incorporation of uncertainty and sensitivity analyses. Rangelands will be impacted by climate change, but this may not necessarily translate to large impacts in animal production because of the capacity to intensify livestock production through production systems transitions, dietary supplementation and other means.

FIGURE 9

Global crop yield changes in response to temperature increase.



Impacts on crop yields per 1°C increase in global temperature are shown for a range of estimation methods (Grid-Sim, Point-Sim, Point-Obs, Regres_A, Regres_B). Filled bars represent the means of all methods. The bars indicate that the yields of wheat, rice, maize and soybean will decrease in response to global temperature increase. Full caption can be found in the supplementary information. Data were published by Zhao *et al* in 2017. © PNAS.

The need for transformative adaptation in agriculture might be large, and different depending on the climate scenario and socio-technical development pathways. Since 2013, the costs of adaptation for agriculture have been estimated at 3% of total agricultural production costs in 2045 ($145 billion), somewhat higher than reflected in the literature available in 2013. Since grass yields are less affected by climate change than arable crop yields, production system shifts towards mixed livestock-cropping systems appear to be a cost effective adaptation option.

How might this affect the IPCC statement?

On this basis we expect the conclusions to stand, though the evidence base is now stronger and more nuanced.

What is the influence of climate change on water availability across the globe?

Summary

Climate change will lead to reductions in water resources in many water-stressed regions, particularly in the dry subtropics, but the changes will vary between regions and there remains considerable uncertainty in the magnitude of change.

In AR5 IPCC said:

Freshwater-related risks of climate change increase significantly with increasing greenhouse gas concentrations.

Climate change over the 21st century is projected to reduce renewable surface water and groundwater resources significantly in most dry subtropical regions, intensifying competition for water among sectors.

What is this about?

The availability and reliability of water supplies have a major influence on societies and economies. Where resources are limited or unreliable, societies have tended to develop infrastructure and institutional arrangements to reduce risks. Areas with limited or unreliable resources are found in dry subtropical regions, but resources can also be placed under pressure where demands are high. Future river flows and groundwater recharge will be affected by climate change, and impacts vary between catchments. Globally, changes are predominantly determined by changes in precipitation and at this global scale, wet regions are projected generally to get wetter, and dry regions to get drier. Increases in evaporation exaggerate the effects of reductions in precipitation and can offset small increases. In some places (for example downstream of parts of the Himalayas) future river flows will be affected by changes in the volume of meltwater from glaciers.

Future water availability and reliability are also affected by other changes in the catchment (such as land use change) and by changes in demands for water resources. These depend on future population change and patterns of exploitation of water resources. At the local scale, these other drivers may be more significant for future reliability of water supply than climate change.

What was the basis for the statement in AR5?

The AR5 conclusions were based on a small number of global-scale assessments of change in river flows and recharge, a larger number of local-scale studies and on changes in runoff as simulated by climate models.

What do we know now?

The strong relationship between changes in precipitation and changes in river runoff has been confirmed by more global and local-scale studies. Projected reductions in runoff and groundwater resources are large in dry subtropical regions. Research using the current generation of climate models has shown that the 'wet gets wetter and dry gets drier' paradigm does not necessarily hold at the local scale and in all seasons.

Studies published since the AR5 have used multiple hydrological models as well as scenarios constructed from an ensemble of climate models to estimate hydrological changes. This wider range of evidence has resulted in larger assessed uncertainty ranges. Differences between hydrological models' representation of evaporation and, to a lesser extent, processes during the cold season (the simulation of snow cover and the effect of soil freezing and thawing on runoff generation) have been shown to result in different magnitudes of response to the same change in climate.

A small number of studies have shown that vegetation changes stimulated by increasing carbon dioxide can influence the water cycle at the catchment scale. The effects vary with catchment vegetation and current climate (specifically whether the amount of evaporation that occurs is limited by the amount of water available rather than the energy available), but there is increasing evidence that the effects of carbon dioxide may be substantial in forested catchments and also in semi-arid environments where increased carbon dioxide leads to increased vegetation cover and therefore greater evaporation and less runoff or recharge. The effect at the regional and global scale is currently uncertain.

How might this affect the IPCC statement?

The IPCC statement was very qualitative and remains valid. Climate change is still projected to lead to reductions in water resources in many regions, particularly in the dry subtropics.

Image

Homosassa, Florida. © CampPhoto.

What is the influence of climate change on species extinction?

Summary

Extinction rates are expected to rise, particularly at higher rates of climate change, and most seriously for those species unable to adapt in response.

In AR5 IPCC said:

A large fraction of both terrestrial and freshwater species faces increased extinction risk under projected climate change during and beyond the 21st century, especially as climate change interacts with other stressors, such as habitat modification, overexploitation, pollution, and invasive species.

What is this about?

Species depend upon local climates for suitable conditions, in a predictable seasonal cycle. Both conditions, such as food and pollinators, and abiotic onditions, such as water and shelter, can be disrupted by climate change. This can in turn cause alterations to the abundance and distribution of species, and lead to local extinctions and/or geographical range shifts. The consequences will be more serious if new climate conditions cause species to go extinct globally or if resulting changes to biological communities have effects on key ecosystem functions including, for example, the carbon cycle.

What was the basis for the statement in AR5?

There was high confidence that species extinction rates would increase with the magnitude and rate of climate change, but low confidence in the fraction of species at increased risk, the regional and taxonomic focus, and the time frame over which extinctions could occur. Different mechanisms by which species might adapt to climate change, including dispersal, behavioural, genetic and evolutionary plasticity were all noted as significant but poorly understood.

What do we know now?

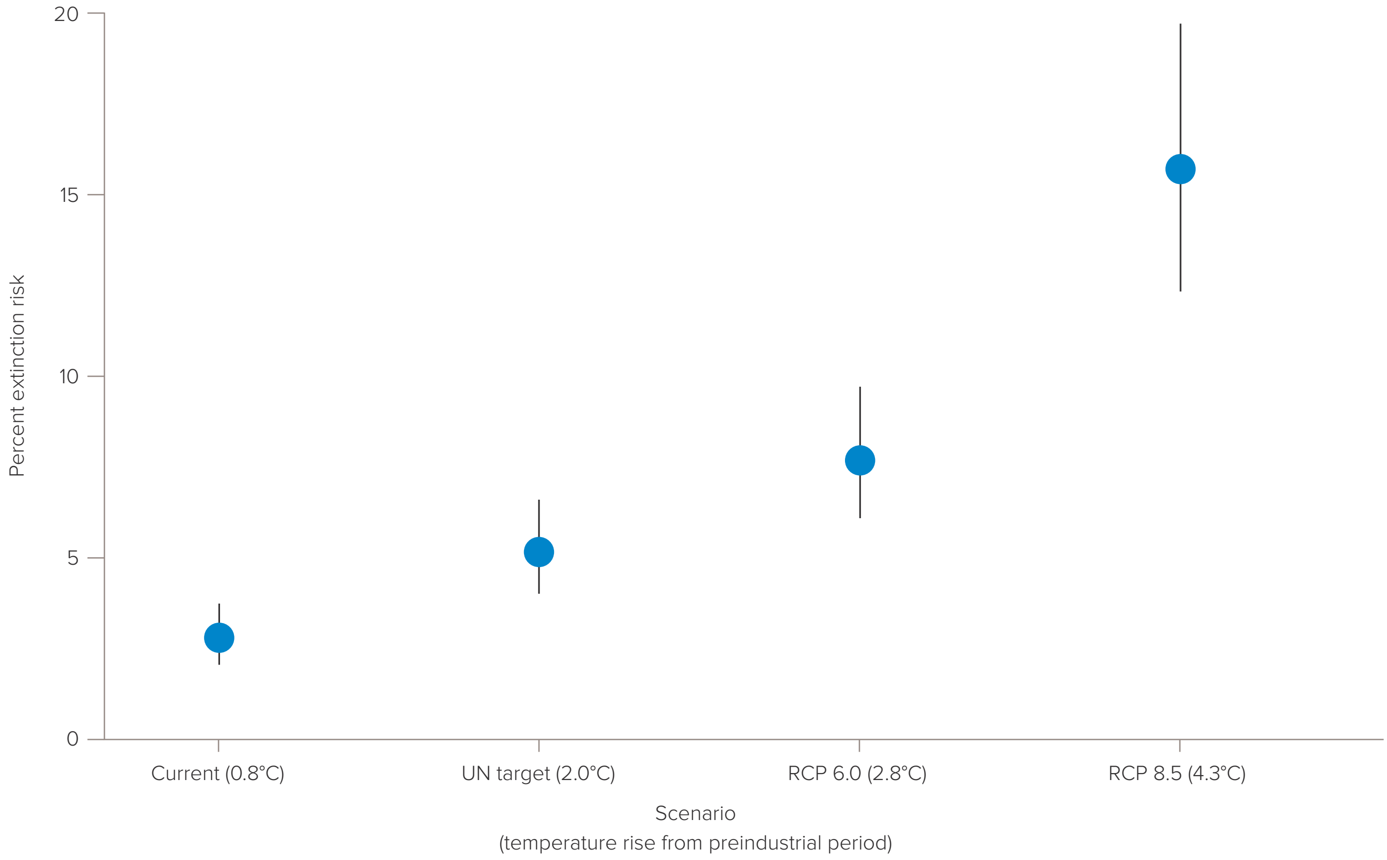
A synthesis of 131 species extinction studies concluded that 1 in 6 (16%) species might go extinct under high emission pathways compared to less than 3% under current levels of warming. This reduces to 1 in 20 (5.2%) under the international policy target of 2°C (see Figure); but with considerable variation depending on geographical region, type of species, and model assumptions. When global biodiversity was modelled under alternative socioeconomic growth pathways, mean species abundance was found to decline by 18 – 35% and extinction risk to increase for 8 – 23% of species under the high emissions pathway. Local extinctions have been shown to vary spatially as well as with the extent of climate change: in marine areas local extinctions are expected to be concentrated near the equator and local invasions to be more common in temperate regions.

All these estimates have high uncertainty because many other biotic and abiotic factors determine species persistence and interact with climate changes. A common mismatch in spatial scale between climate models and species biology means models may have particularly poor predictive power for small-bodied and small-range species, which is especially significant given recent evidence of the important role of microclimates in providing refuges.

Species vary widely in their responses to climate changes. Empirical studies have identified certain demographic, ecological and genetic factors that explain variation in species vulnerability, as well as significant interactions between these, and with other stressors. Those species with poor dispersal ability, small ranges, facing physical barriers, with ecological specialisations and without a resting or dormancy period have been shown to be especially vulnerable.

FIGURE 10

Predicted extinction risk from various climate change scenarios.



The percentage of species at risk from climate change accelerates with global temperature rise. Figure prepared by Mark C. Urban, University of Connecticut, USA, using meta-analysis data in 2015. For more information see supplementary information online.

The capacity for adaptation and the limits to the rate of adaptive responses, through genetic, behavioural or ecological mechanisms remains a critical gap in understanding. Recent theoretical and empirical studies are starting to reveal those factors that will limit the rate and effectiveness of adaptation, but an overall predictive framework remains elusive and the complexities are unlikely to be resolved soon.

How might this affect the IPCC statement?

There is very strong evidence that changes in population abundance and local extinctions are common responses to a changing climate and that these increase with greater rates and intensities of climate change (see Figure). New findings do not change the IPCC message. Increasingly detailed understanding highlights yet more uncertainty about the rate of extinction and about the most strongly affected species and ecological communities. Robust risk assessment and modelling methods, to guide conservation decisions being taken now, remain a research priority. Traditional conservation actions, such as species conservation planning and protected areas, have been shown to continue to be effective, even in a rapidly changing environment.

QUESTION THIRTEEN

How will aspects of human health be affected by climate change?

Summary

Human health will be affected by climate change in multiple ways, with impacts including those from extreme heat, food availability, and changes in the geographical occurrence of infectious diseases.

In AR5 IPCC said:

Throughout the 21st century, climate change is expected to lead to increases in ill-health in many regions and especially in developing countries with low income, as compared to a baseline without climate change.

What is this about?

The human health effects of climate change are an important concern in seeking to keep warming below 2°C (or 1.5°C). These occur through several mechanisms with a variety of impacts. This section considers some new research on a limited subset of these mechanisms: the impacts of changes in exposure to heat stress, increased infectious disease risk, and effects on nutrition. These are clearer now than before AR5. Other impacts, including potentially far-reaching effects mediated through social and economic disruption such as increasing poverty, conflict, and migration are not considered here.

What was the basis for the statement in AR5?

AR5 considered that climate change will act initially by exacerbating existing health problems. It is likely that rising temperatures have already increased the risk of heat-related death and illness. Particularly under high emissions scenarios, impacts on health were expected to increase substantially and to be greatest where other stressors, promoted by low economic and social development, inhibit adaptation and resilience.

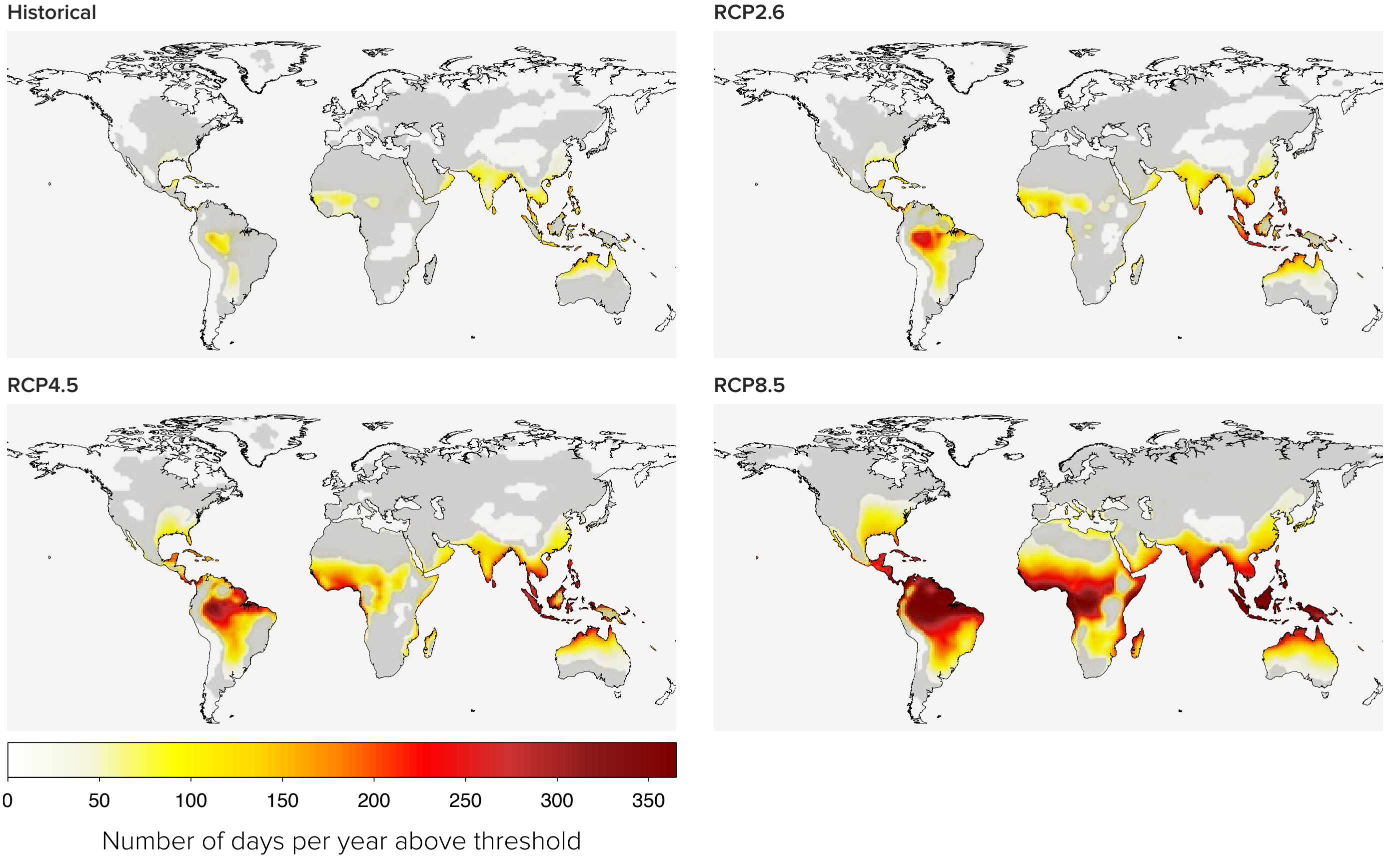
What do we know now?

Since the IPCC AR5 report there have been a number of new estimates of the extent to which populations will be exposed to extreme levels of heat. For example recent work shows that, even with global warming of only 1.5°C and midrange population growth, over 350 million more people could be exposed to hazardous levels of heat by 2050 in cities such as Lagos and Shanghai. Another new study identified a threshold in air temperature and relative humidity beyond which increased deaths occur. Around 30% of the world's population is currently exposed, for at least 20 days a year, to conditions exceeding this threshold. By 2100, this percentage is projected to increase to around 48% under an intermediate emission pathway (RCP 4.5) and around 74% under high emissions pathway (RCP8.5) (see Figure). Social adaptation could reduce exposure to these conditions, but would not affect their occurrence.

High income regions will also experience serious consequences and a study of ten large metropolitan areas in the USA showed that under a high emissions scenario towards the end of the century eight of them would experience increases in heat related deaths exceeding projected reductions in cold related deaths, in some cases by a large amount. Furthermore substantially fewer deaths are projected under a lower emissions scenario. Results of large multi-country analyses indicates that increased heat-related deaths will greatly exceed reductions in cold-related mortality in some regions particularly under high emission scenarios, in particular warmer and poorer areas that are projected to include a substantial proportion of the global population. Most studies on the effects of temperature have focused on adults but a recent study of seven cities in Korea shows substantial increases in infant mortality, both total and from sudden infant death syndrome (SIDS), with high temperatures in the period before death.

FIGURE 11

Temperature and humidity thresholds.



Historical

RCP2.6

RCP4.5

RCP8.5

Shown here is the geographical distribution of days per year on which excess deaths due to temperature and humidity are projected under different emission scenarios. (a) shows the average between 1995 and 2005 (historical experiment), and (b – d) the projected average between 2090 and 2100. For full description see Mora *et al* 2017. © Nature.

Dengue accounts for about 390 million infections annually. The two main mosquito vector species are affected by multiple drivers including climate change. Several modelling studies since 2013 have confirmed that climate change would cause dengue to expand into areas at the edge of current distribution ranges. One study suggests that the population exposure to the main vector (as well as other diseases spread by mosquitoes) would increase by 8 – 12% due to climate change alone, amplifying the larger increase in exposure caused by population growth.

The complex influence of climate change on health via nutrition is illustrated by a modelling study which projected that by 2050, climate change will lead to per-person reductions of about 3% in global food availability compared to a reference scenario, together with an important reduction in fruit and vegetable consumption. These declines are estimated to lead to a net increase of about 500,000 deaths annually.

How might this affect the IPCC statement?

The new evidence discussed above provides a basis for replacing qualitative statements with more quantitative ones, and for targeting specific adaptation and mitigation strategies that can reduce the excess fatalities incurred.

Appendix

This section explains some of the methodology and terminology used in the remainder of the report.

Methodology

This report touches on a limited list of topics, considered by the working group to be areas of particular interest or progress in recent years. They are by no means a comprehensive list of issues that are discussed in the scientific literature or in popular articles. For example, quantifying the role of aerosols (small particles in the atmosphere) in climate is important, but is not covered here.

For each topic, the most relevant conclusion from the AR5 was chosen, and a lead author and critical reviewer were appointed from within the working group authorship. Authors surveyed recent literature to examine work (including review articles) that addressed the chosen IPCC quotation and other relevant conclusions. They used this, contributions from other researchers and their expert judgement to produce the final sections, which were discussed and agreed by the whole group. Peer review was then undertaken by a small review group (consisting of people not involved in the drafting), and final revisions were made on the basis of their comments.

This process is far below the level of scrutiny that is carried out over several years by writing teams in producing the IPCC statements. However we believe that we have captured the main advances, confirmations, and new issues that have arisen, allowing us to assess whether the IPCC statements remain valid.

IPCC and terminology

The IPCC Fifth Assessment Report (AR5) was produced in stages. The Working Group (WG) 1 report was published in 2013, WG2 and 3 in 2014, and the synthesis report in 2015. However for inclusion in the report, findings had to have been submitted into the literature at different dates in 2013 for all 3 WG reports. For this reason, we assess here findings that have appeared in the literature since the cutoff dates in 2013, and this is what we mean when we refer to advances “since AR5” or “since the last IPCC report”.

The next full IPCC report is due to be finalised in 2022, with WG reports ready in 2021. There will also be three special reports: The Special Report on Global Warming of 1.5°C (SR15) will be finalised in September 2018; the Special Report on the Ocean and Cryosphere in a Changing Climate (SROCC), and the Special Report on Climate Change and Land (SRCCL) will be finalised in September 2019. These will provide a more authoritative conclusion on some of the issues we consider.

In making projections about future change AR5 used 4 different ‘representative concentration pathways’ (RCPs). These are time series of future greenhouse gas and aerosol concentrations intended to represent the results of different scenarios, in particular for socioeconomics and energy use. These RCPs were used as the input to climate models in many cases. The pathway with the lowest concentrations of greenhouse gases, RCP2.6 represents scenarios with extreme mitigation measures, much beyond those currently agreed between nations. The highest concentration scenario, RCP8.5, represents a highly industrialised, low mitigation scenario. In the report we sometimes refer to a high or low emissions scenario. Most often in such cases we are referring to model studies using RCP8.5 or RCP2.6 respectively, although occasionally this refers to studies using a previous generation of scenarios. The supplementary information will, where appropriate, use the technical terminology that the main text avoids.

Throughout IPCC publications, levels of confidence and uncertainty in statements are described using calibrated language. Confidence is described as from ‘very low’ to ‘very high’ based upon the level of evidence and agreement between sources, and likelihood is described from ‘exceptionally unlikely’ (≤ 1% probability) to ‘virtually certain’ (≥ 99% probability). Such terms have been retained in the IPCC quotations, but elsewhere in this report they are not used with these calibrated meanings.

Working Group members

The members of the Working Group involved in producing this report are listed below. The Working Group members acted in an individual and not organisational capacity and declared any conflicts of interest. They contributed on the basis of their own expertise and good judgement. The Royal Society gratefully acknowledges their contribution.

Working Group	
Professor Eric Wolff FRS (Chair)	University of Cambridge
Professor Nigel Arnell	University of Reading
Professor Pierre Friedlingstein	University of Exeter
Professor Jonathan Gregory FRS	University of Reading / Met Office Hadley Centre
Professor Joanna Haigh CBE FRS	Imperial College London
Sir Andy Haines FMedSci	London School of Hygiene and Tropical Medicine
Professor Ed Hawkins	University of Reading
Professor Gabriele Hegerl FRS	University of Edinburgh
Sir Brian Hoskins CBE FRS	Imperial College London
Dame Georgina Mace DBE FRS	University College London
Professor Iain Colin Prentice	Imperial College London
Professor Keith Shine FRS	University of Reading
Professor Peter Smith FRS	University of Aberdeen
Professor Rowan Sutton	University of Reading
Dr Carol Turley OBE	Plymouth Marine Laboratory

Royal Society staff

Many staff at the Royal Society contributed to the production of this report. The project team are listed below.

Royal Society Staff	
Helene Margue	Policy Adviser
Elizabeth Surkovic	Head of Policy, Resilience and Emerging Technologies
Dr Richard Walker	Senior Policy Adviser

Review panel

This report has been reviewed by a number of independent experts. The Review Panel members were not asked to endorse the conclusions of the report, but to act as independent referees of its technical content and presentation. Panel members acted in a personal and not an organisational capacity and were asked to declare any potential conflicts of interest. The Royal Society gratefully acknowledges the contribution of the reviewers.

The review panel	
Professor Stephen Belcher	Met Office Hadley Centre
Professor Alex Halliday FRS	Vice-President, Royal Society
Professor Gideon Henderson FRS	University of Oxford
The Lord Krebs Kt FMedSci FRS	University of Oxford
Professor Yadvinder Malhi FRS	University of Oxford
Professor John Mitchell FRS	Met Office Hadley Centre
The Lord Oxburgh KBE HonFREng FRS	House of Lords
Professor Tim Palmer CBE FRS	University of Oxford
Professor John Shepherd CBE FRS	University of Southampton
Professor Theodore Shepherd FRS	University of Reading
Dr Emily Shuckburgh	British Antarctic Survey
Dame Julia Slingo DBE FRS	Former Chief Scientific Adviser, Met Office Hadley Centre

Acknowledgments

This project would also not have been possible without contributions from a range of individuals.
In particular we wish to thank:

Acknowledgements
Professor Andrew Challinor, University of Leeds
Dr Ed Dlugokencky, US National Oceanic and Atmospheric Administration
Natalya Gallo, Scripps Institution of Oceanography
Dr Mario Herrero, The Commonwealth Scientific and Industrial Research Organisation
Chris Jones, Met Office Hadley Centre
Professor John Roy Porter, Supagro Montpellier
Professor Corinne Le Quere FRS, University of East Anglia
Dr Richard Pearson, University College London
Dr Doug Smith, Met Office Hadley Centre
Dr Peter Stott, Met Office Hadley Centre
Professor Chris Thomas FRS, University of York
Professor Mark Urban, University of Connecticut
Dr Phillip Williamson, University of East Anglia
Dr Richard Wood, Met Office Hadley Centre
Dr Tim Woollings, University of Oxford

The Royal Society is a self-governing Fellowship of many of the world's most distinguished scientists drawn from all areas of science, engineering, and medicine. The Society's fundamental purpose, as it has been since its foundation in 1660, is to recognise, promote, and support excellence in science and to encourage the development and use of science for the benefit of humanity.

The Society's strategic priorities emphasise its commitment to the highest quality science, to curiosity-driven research, and to the development and use of science for the benefit of society. These priorities are:

- Promoting excellence in science
- Supporting international collaboration
- Demonstrating the importance of science to everyone

For further information
The Royal Society
6 – 9 Carlton House Terrace
London SW1Y 5AG

T +44 20 7451 2500
E science.policy@royalsociety.org
W royalsociety.org

Registered Charity No 207043

9 781782 523062

ISBN: 978-1-78252-306-2
Issued: November 2017 DES5123_1